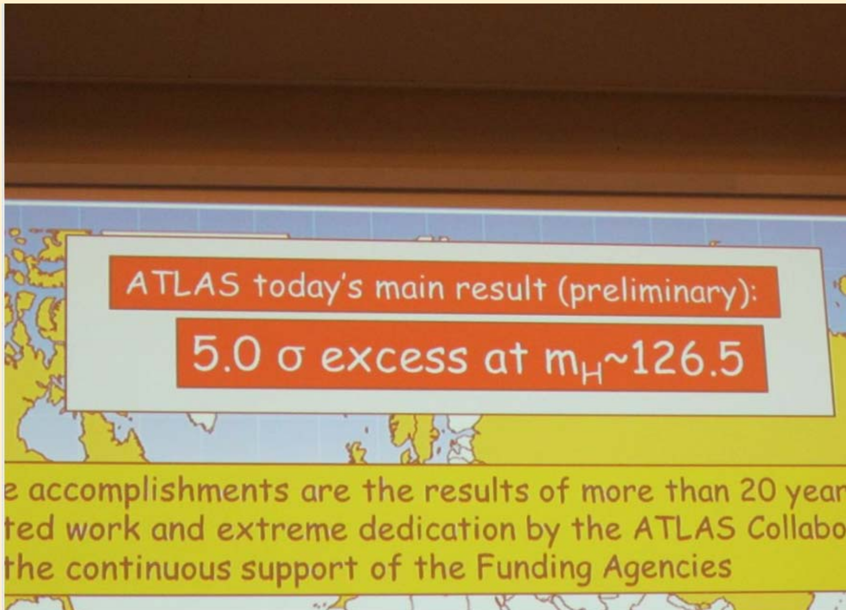
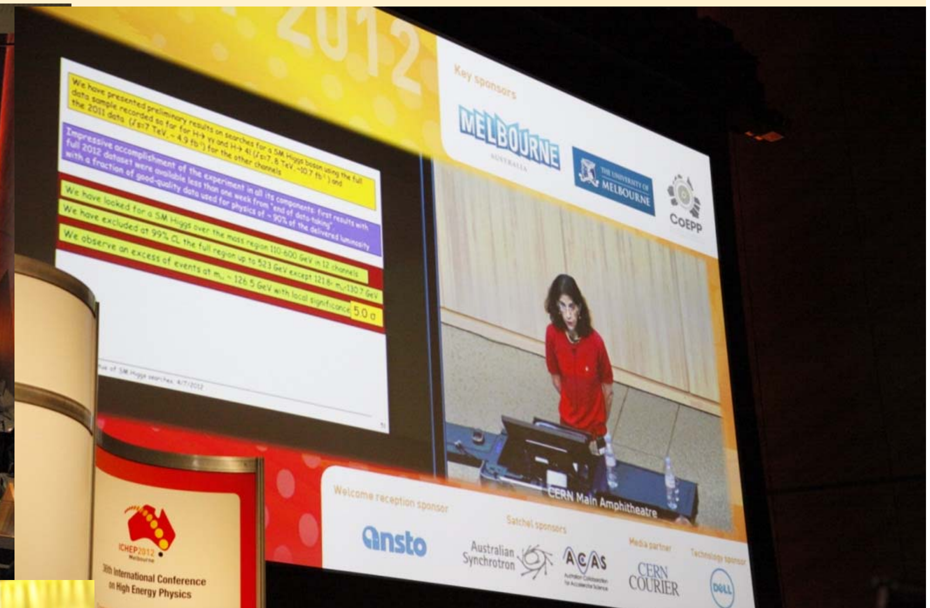
CERN July 4, 2012



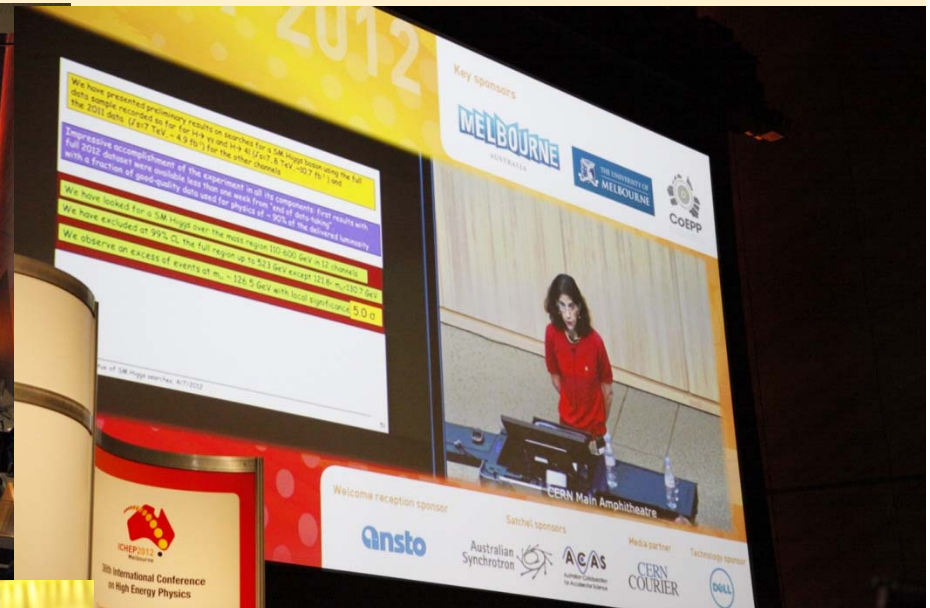
AND in Melbourne, Australia at the ICHEP meeting

….

ICHEP Melbourne July 4, 2012



ICHEP Melbourne July 4, 2012



ATLAS July4 2012 (CERN)

Following CMS & ATLAS presentations


Joe Incandela -CMS


Fabiola Gianotti -ATLAS

Rolf-Dieter Heuer CERN DG


Englert and Higgs


Gerald Guralnik


Carl Hagen

How we got there…..

1982: Snowmass – first discussions of the SSC (US)

1983: HEPAP recommends US SSC project - endorsed (40 TeV CM)
– Ronald Reagan "throw deep"

1984 First studies for high-energy pp collider in the 27 km LEP tunnel

1989 : Start of SLC and LEP e+e- colliders

1990: I go to SSC for 1 year - that becomes 3 years

1993 : SSC is cancelled ☹ US physicists join the LHC

1994 : LHC approved by the CERN Council

1995 : Top-quark discovered at the Tevatron

1996 : Construction of LHC machine and experiments begin design/fab

2000 : LEP2 shut down

2003 : Begin installation of LHC machine and experiments

2009 : November:23, first LHC collisions ($\sqrt{s}$ = 900 GeV CM energy)

2010 : First collisions at $\sqrt{s}$ = 7 TeV

2012: ATLAS and CMS discover a new boson H → γγ and 4leptons
with mass 125 GeV

2012/13 : Boson confirmed to be Higgs Boson

2013: LHC shutdown for upgrade to 14 TeV CM (7 TeV per beam)

2013: François Englert and Peter Higgs awarded Noble Prize

2015: LHC program to restart at 14 TeV CM energy – MORE TO COME

Discovery modes

Higgs → γγ

σ x BR ~ 50 fb, m_H ~ 126 GeV

- ❑ Simple topology: two high-p_T isolated photons E_T (γ_1, γ_2) > 40, 30 GeV
- ❑ Main background: γγ continuum (irreducible)
- ❑ Background smooth but HUGE → small S/B ratio (~ 3%)

- ❑ Need excellent γγ mass resolution
- ❑ Electromagnetic calorimeter performance crucial to observe narrow signal peak above background

ATLAS after applying all selection criteria expects (m_H~ 126 GeV):
~ 500 signal events & ~ 18000 background events in mass window

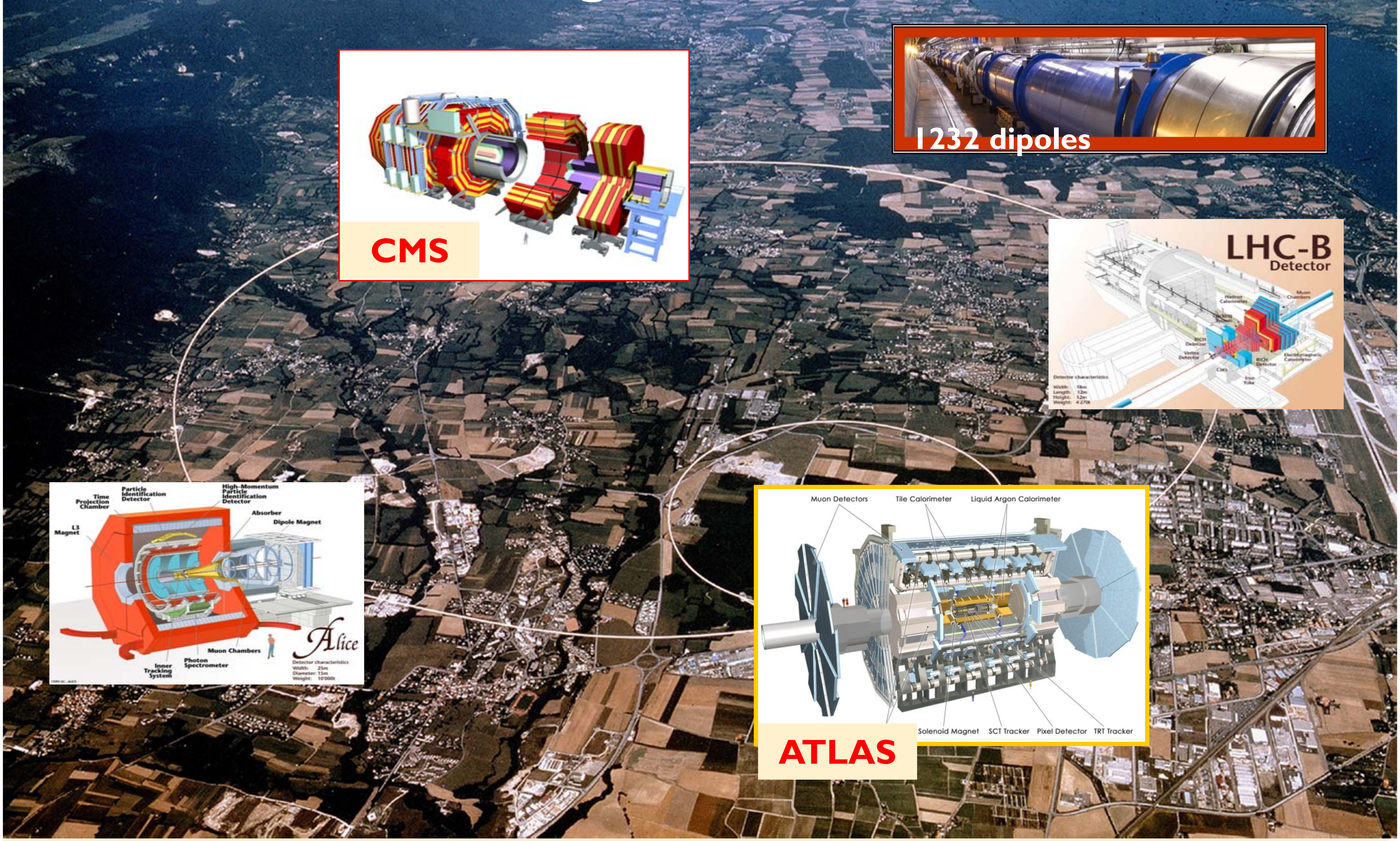
Higgs → ZZ* → 4l (4e, 4μ, 2e2μ)

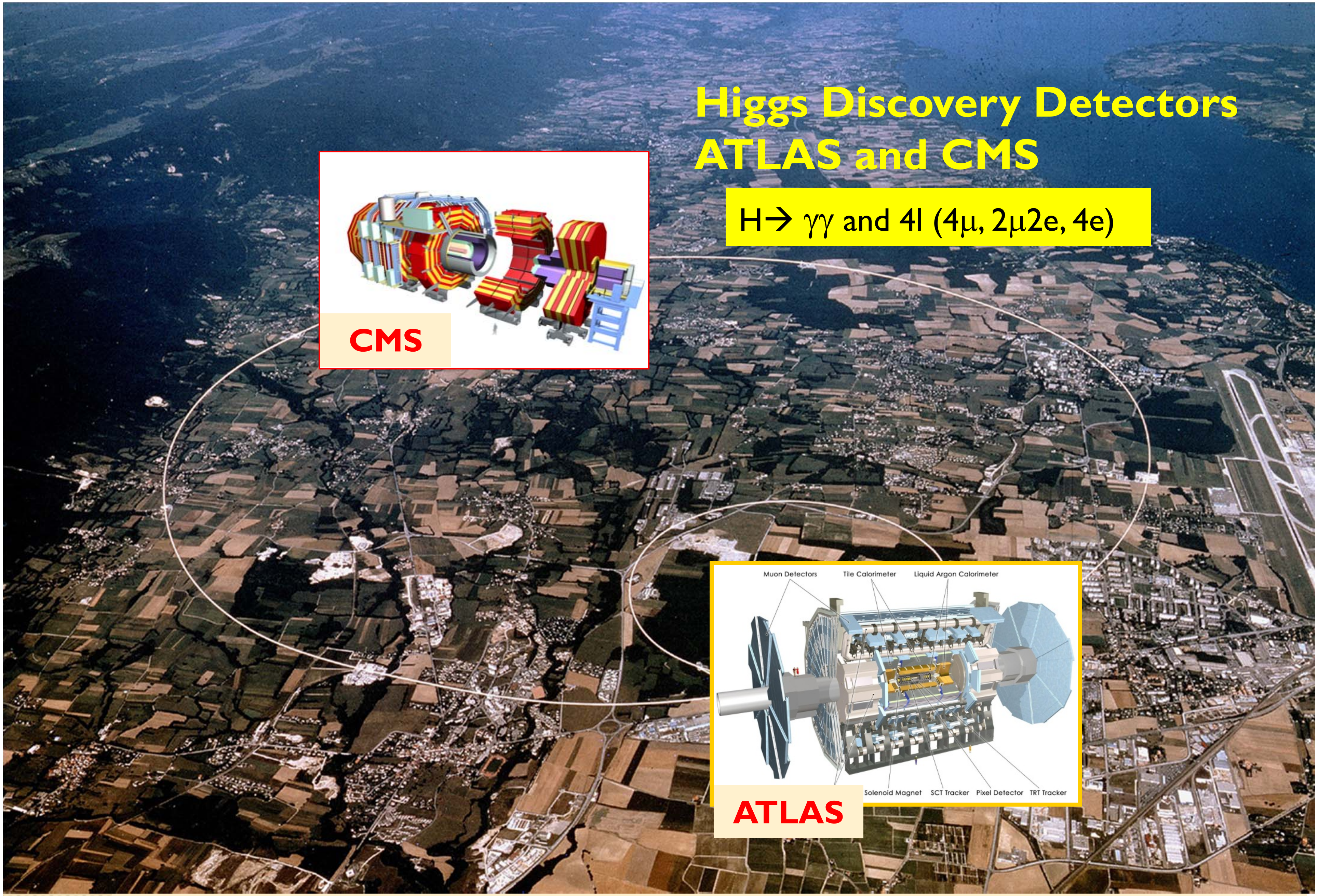
σ x BR ~ 2.5 fb, m_H ~ 126 GeV GeV

- Small cross-section
- mass can be reconstructed
- Small background → large S/B ratio ~ 1.5
- Irreducible background from ZZ(*) → 4l

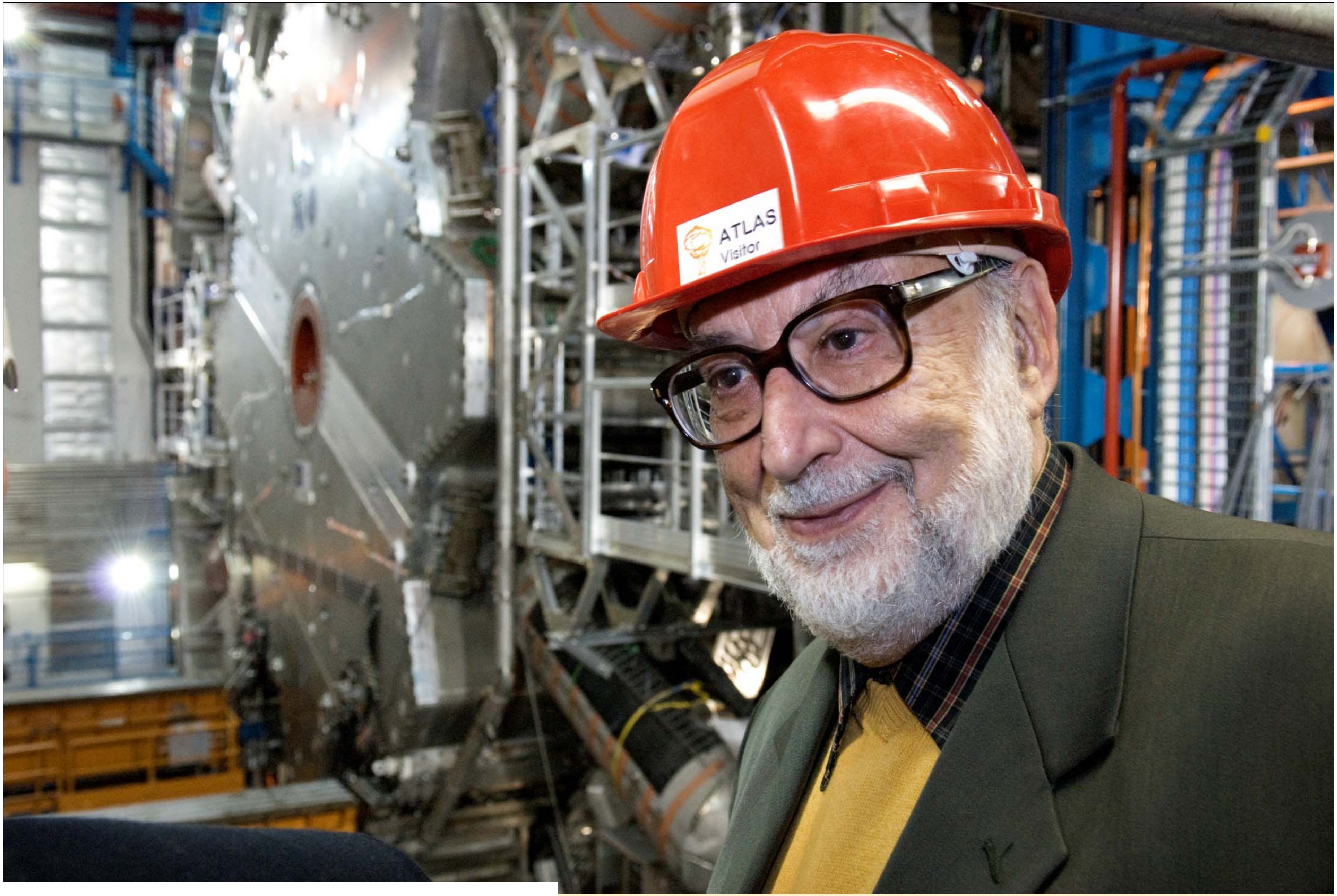
The Large Hadron Collider

Four large detectors



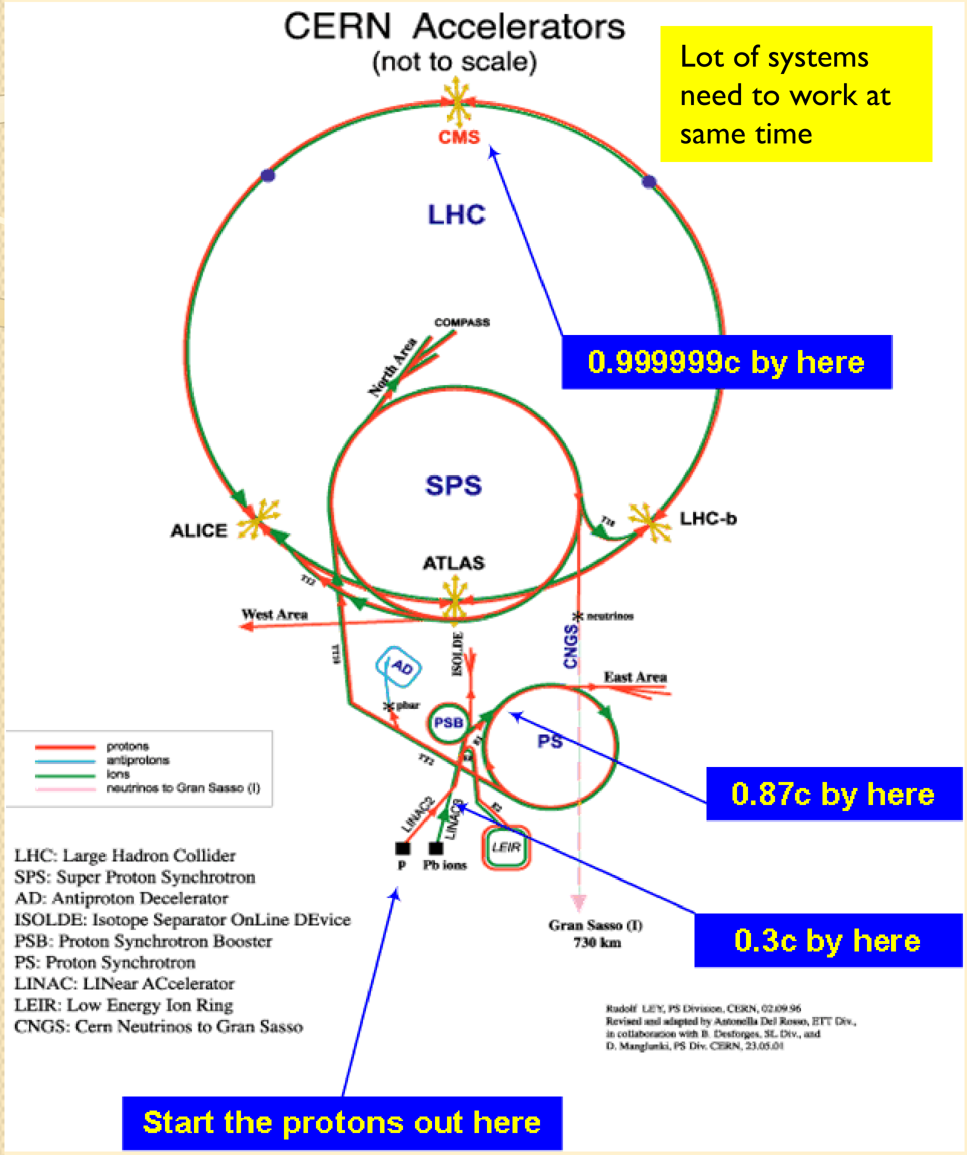

Higgs Discovery Detectors
ATLAS and CMS
H→ γγ and 4l (4μ, 2μ2e, 4e)
CMS
Muon Detectors
Tile Calorimeter
Liquid Argon Calorimeter
Solenoid Magnet
SCT Tracker
Pixel Detector
TRT Tracker
ATLAS

Peter Higgs in the ATLAS cavern



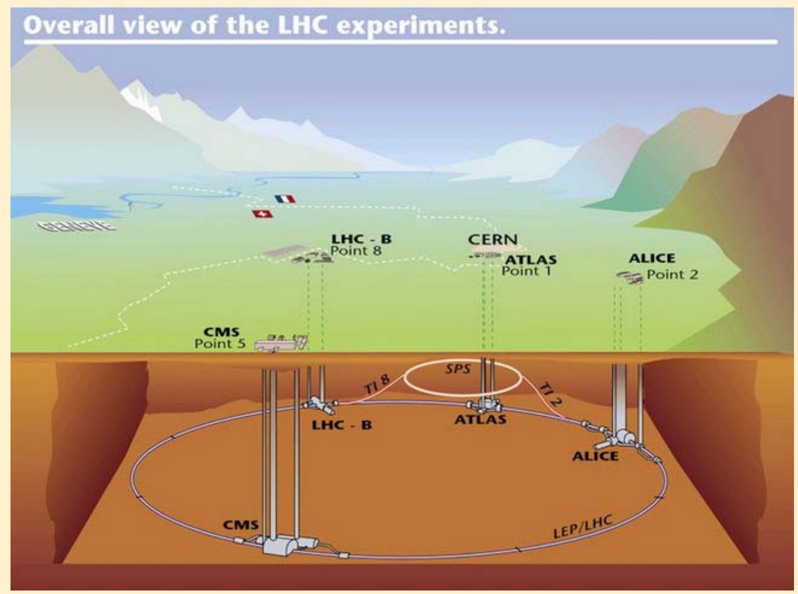
François Englert in the ATLAS cavern

The Large Hadron Collider-LHC

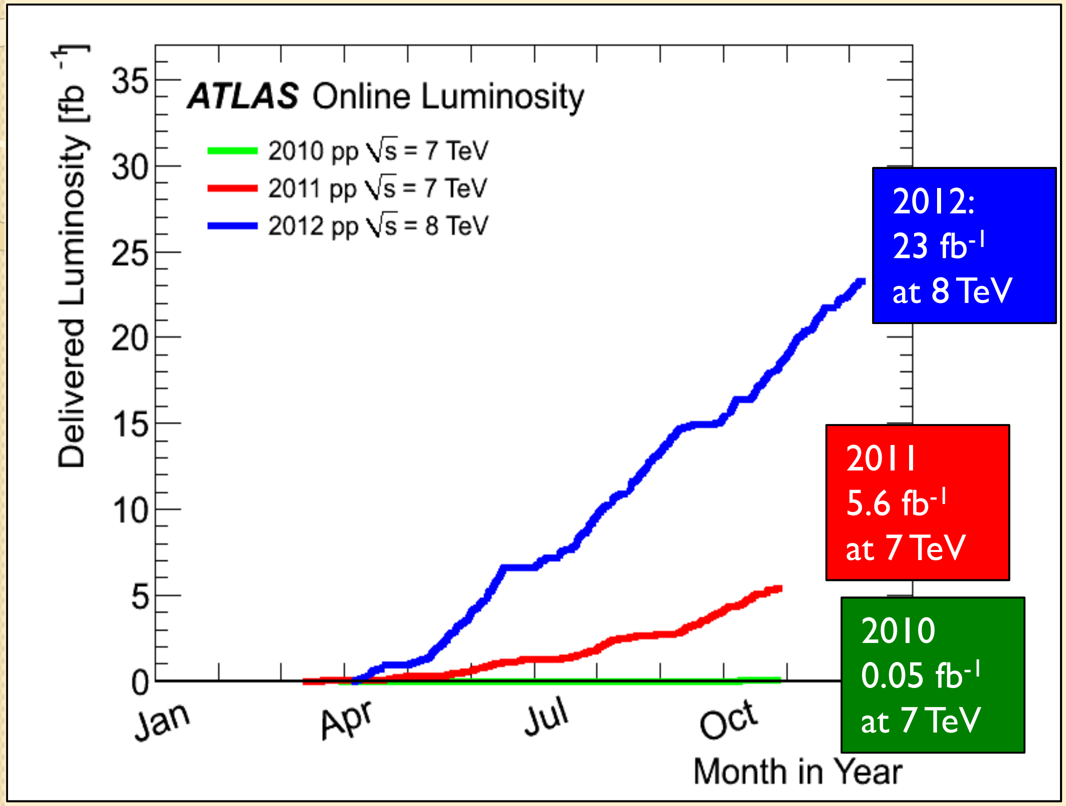


The LHC

- Circumference 27 km
- Up to 175 m underground
- Total number of magnets 9 553
- Number of dipoles 1 232
- Operation temperature 1.9 K (Superfluid He)



First High Energy Run 2010-12



Luminosity (L)

n. of protons per bunch; n. of bunches; n. of turns per second

$$L = \frac{N^2 k_b f}{4\pi\sigma_x\sigma_y}$$

beam size at IP

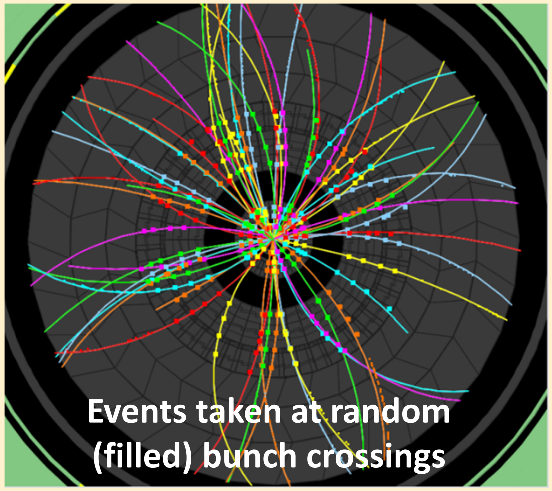
Luminosity has units of cm^{-2}s^{-1}

➡ Lσ_κ number of k-events/s

Peak instantaneous luminosity:
~ 7.7 x10^{33} cm^{-2} s^{-1} (2012)

High Luminosity allows us to search for rare phenomenon - small cross section , BUT….

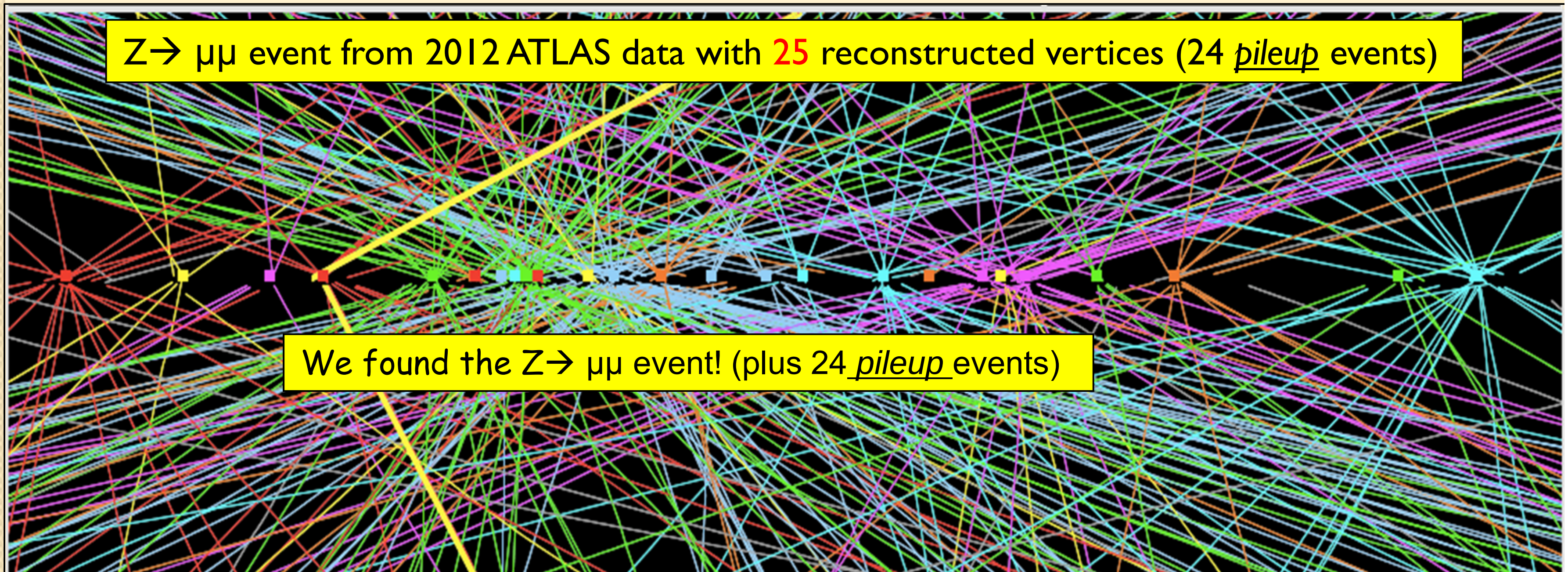
Challenges of High Luminosity



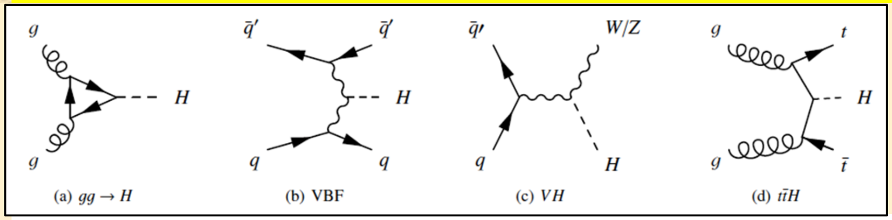
2010 Avg ~ 2 *pileup* events

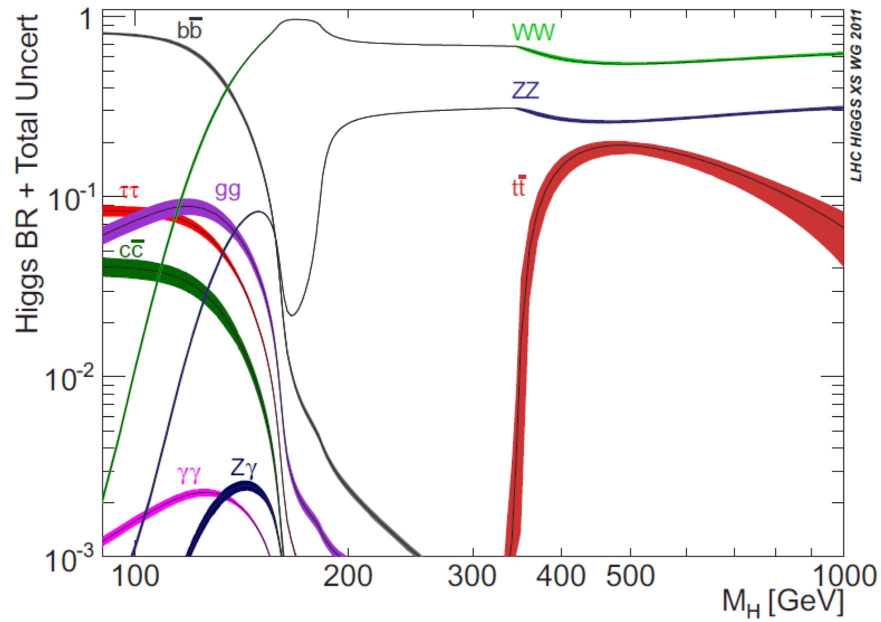
2011 Avg ~ 10 *pileup* events

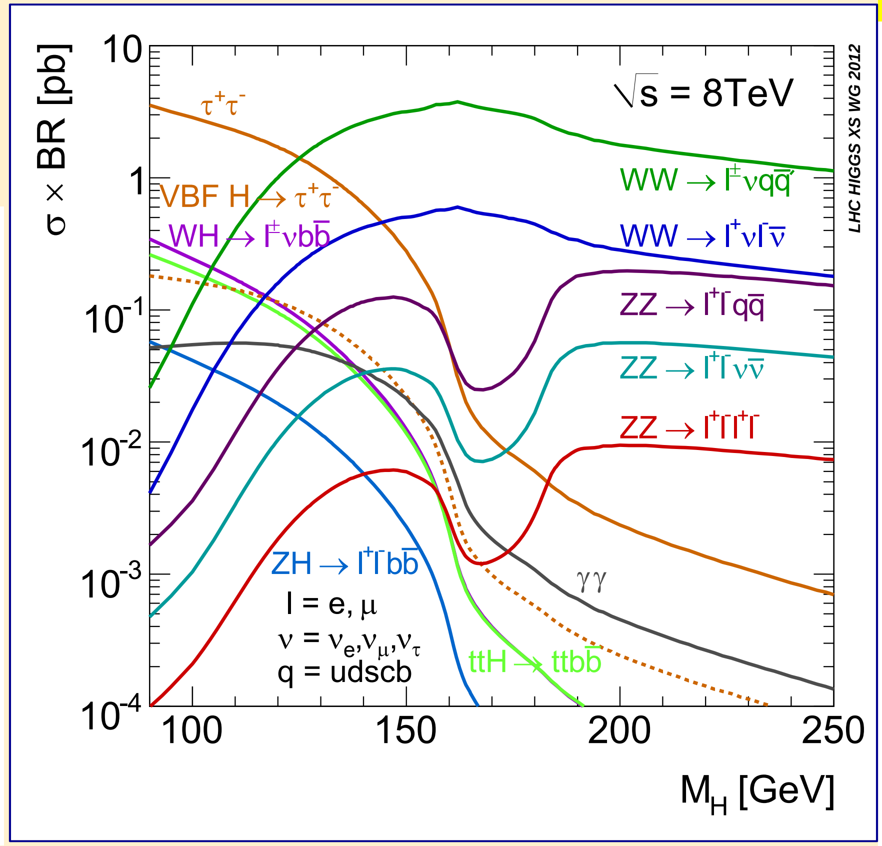
2012 Avg ~ 20 *pileup* events



SM Higgs production cross-section and decay modes







Big thanks to theory community for NLO/NNLO cross-section and background calculations

Most sensitive channels (120 < m_H < 130 GeV)

H→ ZZ*→ 4l, H→ γγ discovery mode (7/4/12)

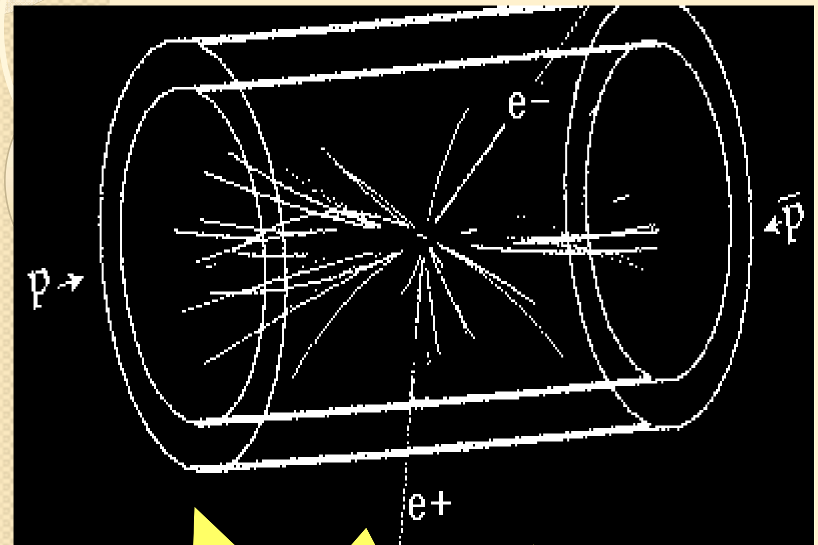
H→ ννW*→ lν lν (2013), H→ ττ

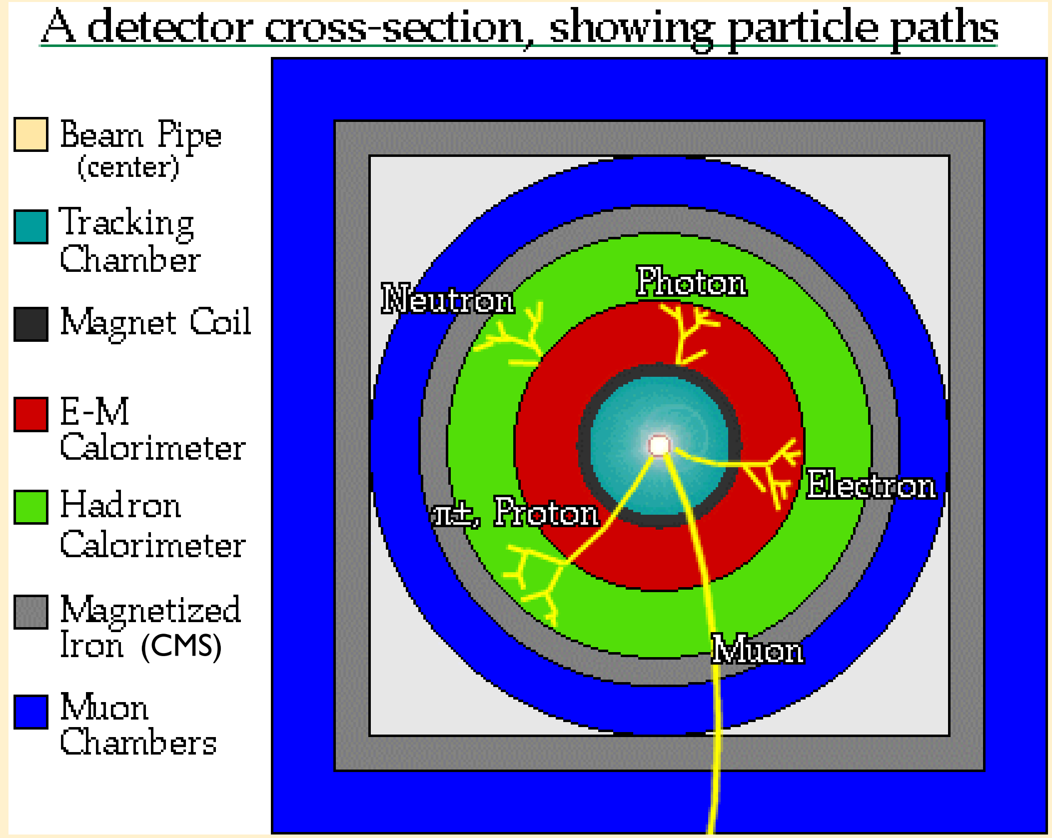
W/ZH→ W/Z bb (coming soon)

Complex analyses: rates very small,

Signal/Background is small, and final states complex

Generic Collider Detector



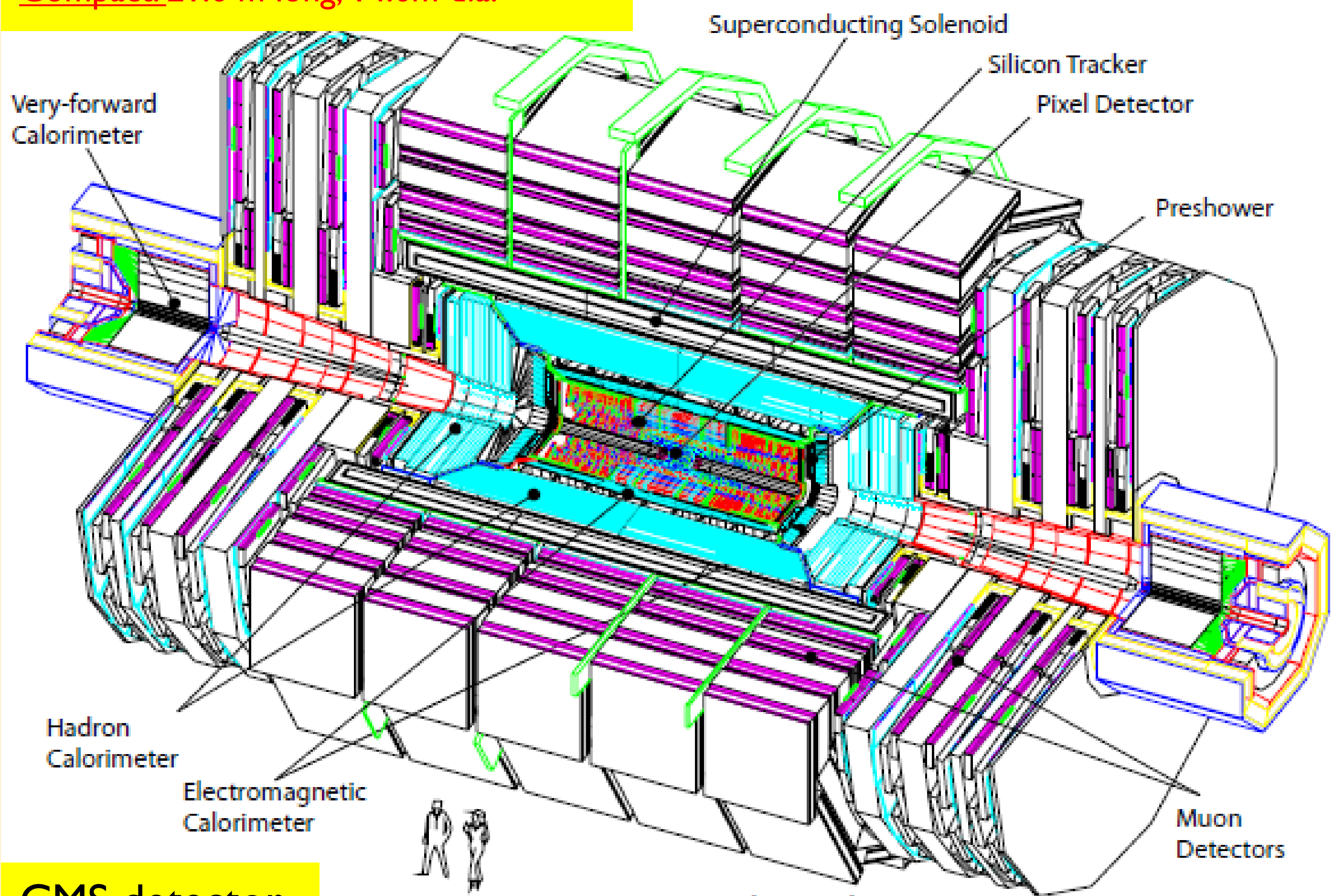


Energy & Momentum conservation in transverse plane

Large detectors needed to measure and absorb high-E particles from LHC collisions

Higgs Boson Discovery (2012) relied heavily on the electromagnetic calorimeter and the muon detectors in both CMS and ATLAS to detect H→γγ and H→4leptons(4μ, 2μ2e, 4e)

Compact: 21.6 m long, 14.6m dia.

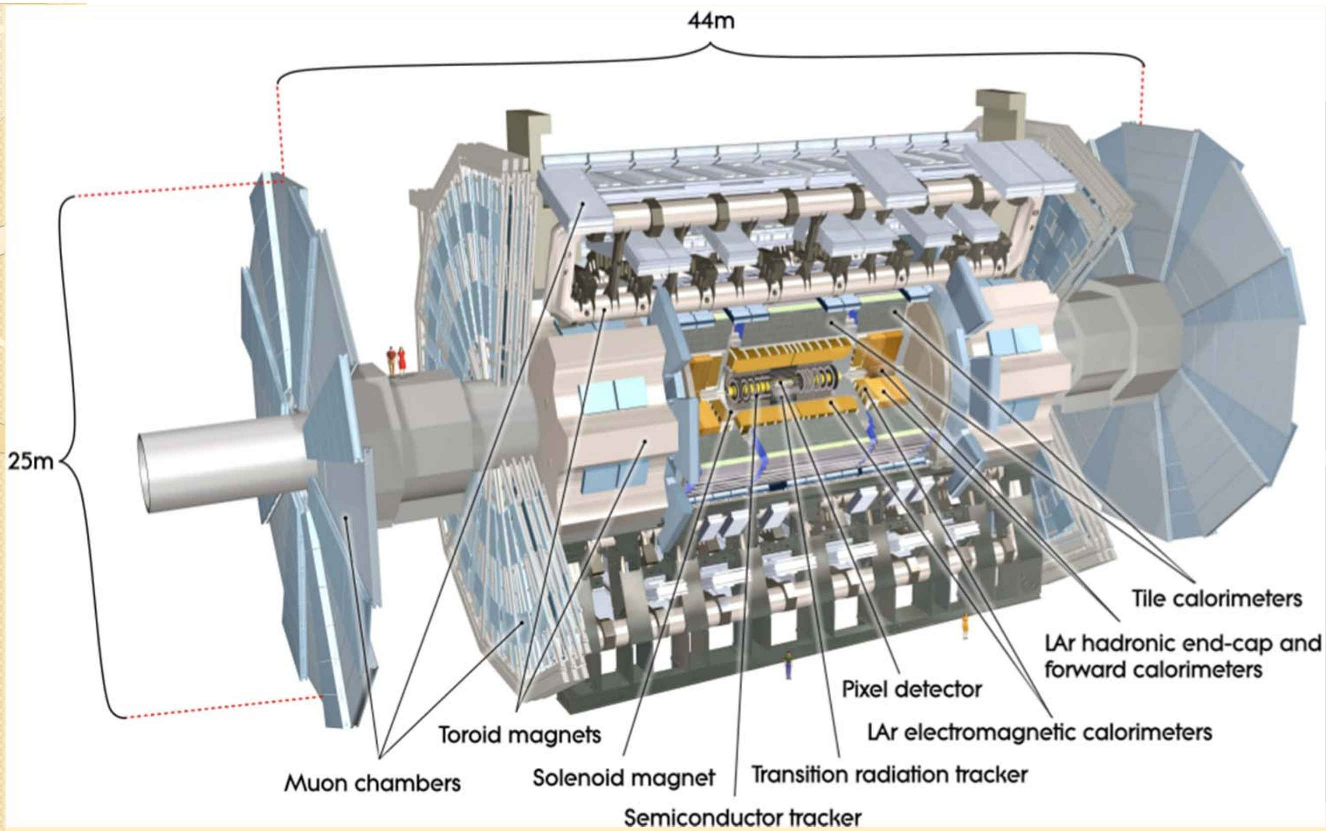


CMS detector

Superconducting solenoid
(13m long, 6m ID) 4-T –
bending - 12 T-m before muon system
Inner tracker/calorimeter inside
-tracking volume a cylinder
(2.6m dia 5.8m long,)

Inner tracker - 3 layers
Si pixel detectors at IP
followed by 10 layers of
Si Micostrip detectors

EM calorimeter
lead tungstate
($PbWO_4$) crystals



ATLAS Detector

Diameter ~ 25 m
Length ~ 46 m
Weight ~ 7000 tons

100 M electronic channels
3000 km of cables

Magnet System

3 Air core Toroids- 8 coils each
4 T (On Superconductor)

Solenoid ~2T
Inside EM Calorimeter

Muon Spectrometer (MS)
Air Core Toroid Magnetic Field

Muon ID and momentum measurement
Trajectory Measurements
- Monitored Drift Tubes
- Cathode Strip Chambers

Trigger Chambers
- Thin Gap Chambers
- Resistive Plate Chambers

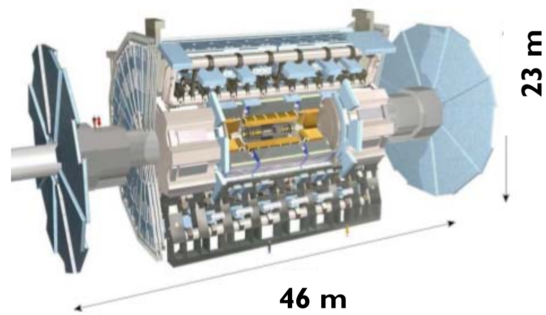
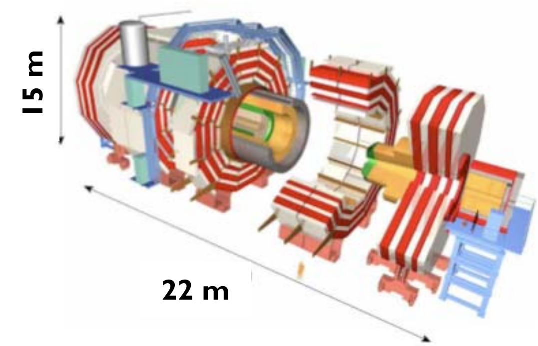
ATLAS - A Toroidal LHC Apparatus

Combined performance of MS and inner tracker give

$$\frac{\sigma_{p_T}}{p_T} \sim 4\% \ (at \ 50 \ GeV)$$

$$\sim 11\% \ (\text{at } 1 \text{ TeV})$$

ATLAS and CMS Comparison

Subsystem	ATLAS	CMS
Overview		
Magnet System	Solenoid 2T – Calorimeters outside Three air-core toroids	Solenoid 3.8T Calorimeters inside
Inner Tracker	Pixels/Si-strip/TRT - Part ID dE/dx $\sigma_{p_T}/p_T \sim 5\text{X}10^{-4} p_T \oplus 0.01$	Pixel & Si strips - Part. ID dE/dx $\sigma_{p_T}/p_T \sim 1.5\text{X}10^{-4} p_T \oplus 0.005$
EM CAL	Pb-LAr Sampl. – longitudinal seg. $\sigma_E/E \sim 10\%/\sqrt{E} \oplus 0.007$	Pb Tungstate Cryst. – no long. seg. $\sigma_E/E \sim 3\%/\sqrt{E} \oplus 0.5\%$
HCAL	Fe-Scint & Cu-LAr fwd $\geq 11\lambda_0$ $\sigma_E/E \sim 50\%/\sqrt{E} \oplus 0.03$	Brass-Scint. $\geq 11\lambda_0$ tail catcher $\sigma_E/E \sim 100\%/\sqrt{E} \oplus 0.05$
Muon Spectrometer ATLAS to η = 2.7 CMS to η = 2.4	Air Core – drift tubes (stand alone) σ_{p_T}/p_T ~ 4% (at 50 GeV) ~ 11% (at 1 TeV)	Instrumented Fe return σ_{p_T}/p_T ~ 1% (at 50 GeV) ~ 10% (at 1 TeV)

ATLAS and CMS Comparison

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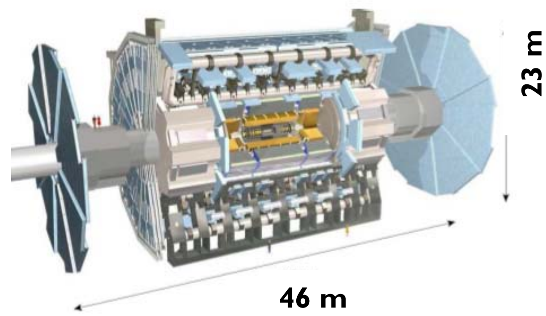
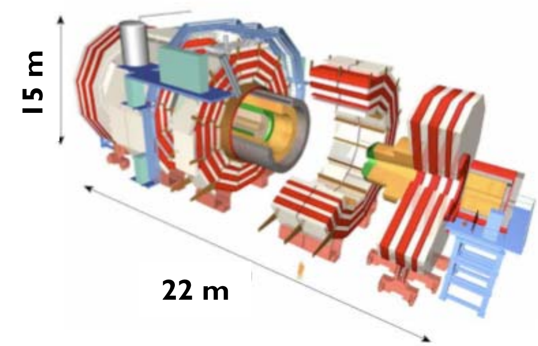
Overview		
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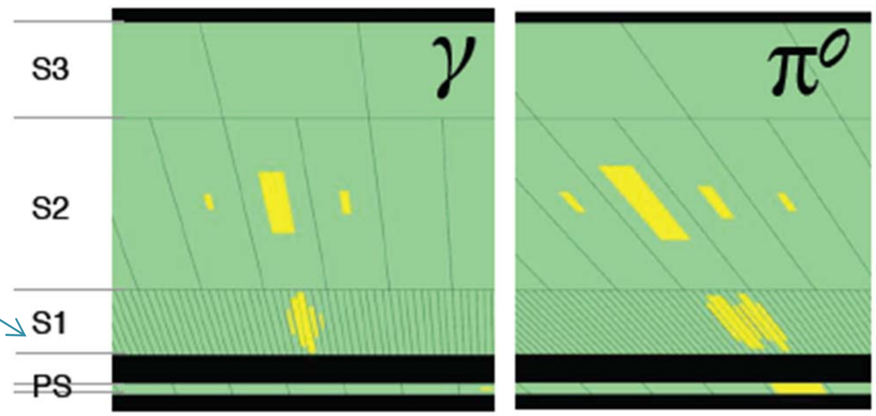
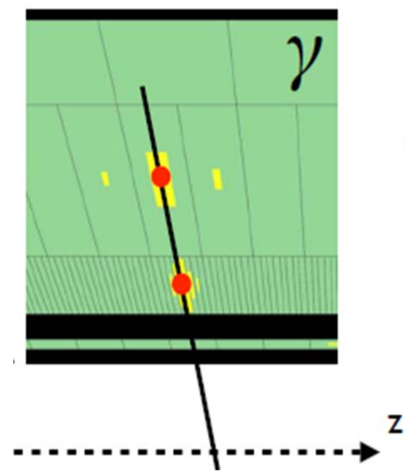
Features of Atlas Calorimeter

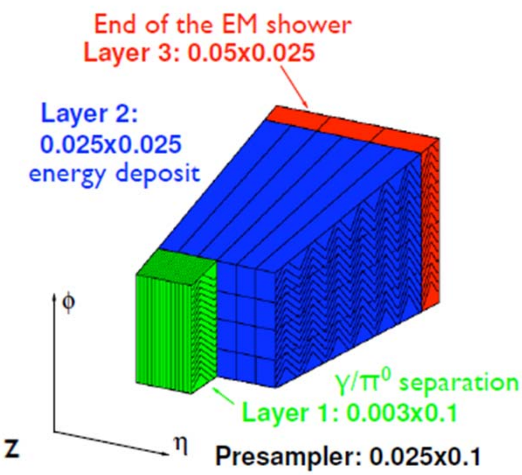
- Electromagnetic Calorimeter longitudinally segmented
- **Used to improve $\gamma\gamma$ mass resolution**
- **Used to separate single γ from $\pi^0 \rightarrow \gamma\gamma$**
- Low-energy hadronic jets with 50 to 100 GeV deposit most of the energy in the EM calorimeter-material in ID plus ECAL
- This feature used by ATLAS to search for long-lived particles that decay to hadron jets in HCAL.

EM Calorimeter

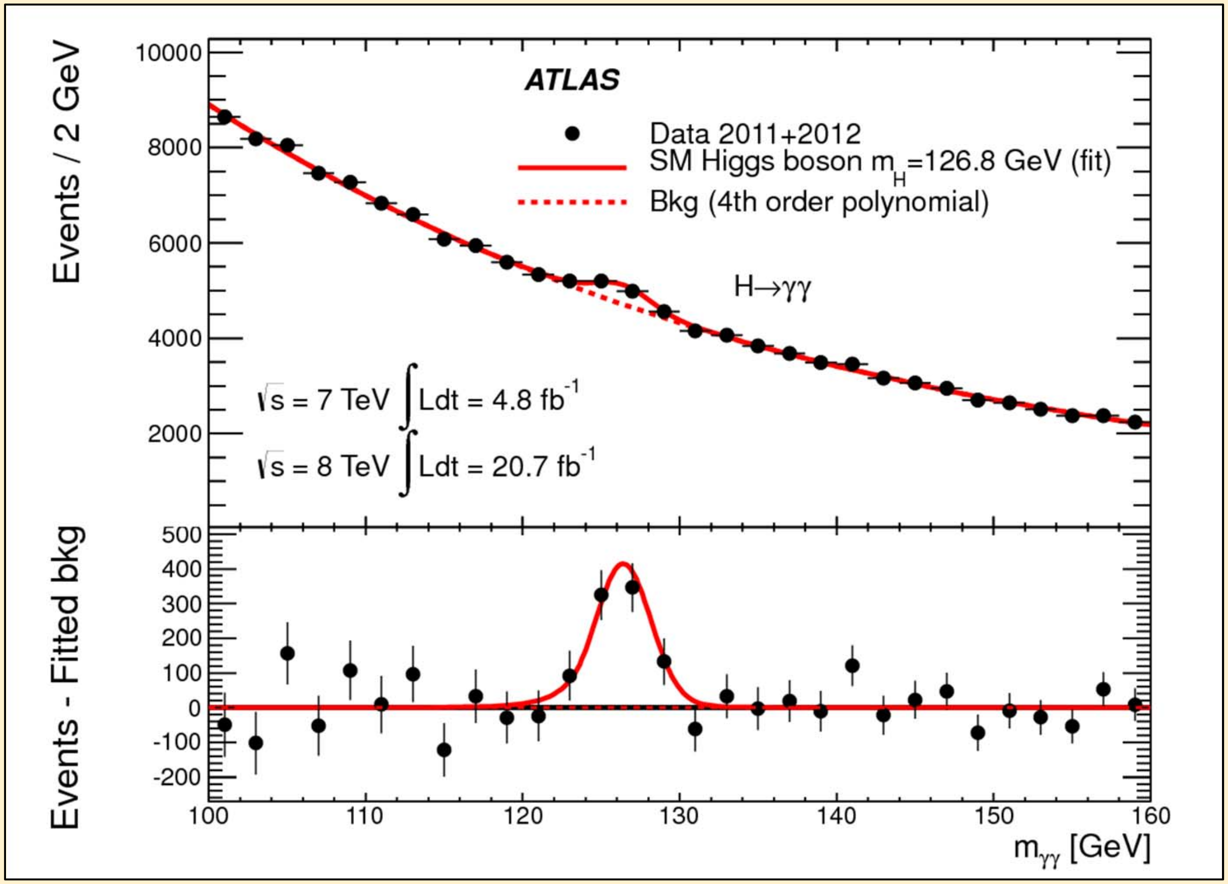
- Photon ID based on longitudinal and lateral segmentation of the ECAL (shower shapes)
- **High granularity in S1 results in good rejection efficiency for $\pi^0 \rightarrow \gamma\gamma$**
- **Photon direction from shower centroids in layers 1 & 2 gives longitudinal (z) position**
- For two γ (cf. H → γγ) combine to improve z resolution of vertex
- Get γ direction in layers 1 & 2 for each γ find longitudinal position, z, of primary vertex (IP).
- **Vertex with pointing ~1.6-1.8 cm in z, without the longitudinal spread of IP is 5.6 cm**







ATLAS H→ γγ

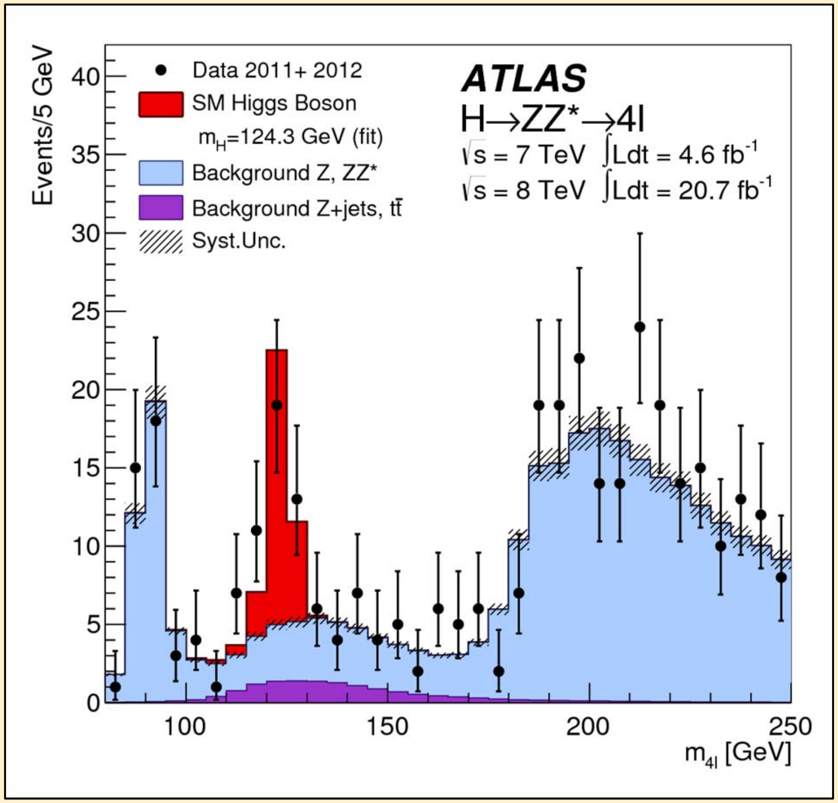


- ❑ Clear peak at $m_H \sim 126.5$ GeV:
- ❑ Probability it comes from background fluctuation: ~ 10^{-13}
  → 7.4 σ signal significance
  (4.3 σ expected from SM H)

Stability of EM calorimeter vs time during 2012 better than 0.1%

H→ 4leptons

4l mass spectrum after all selections; for full 2012 data sample



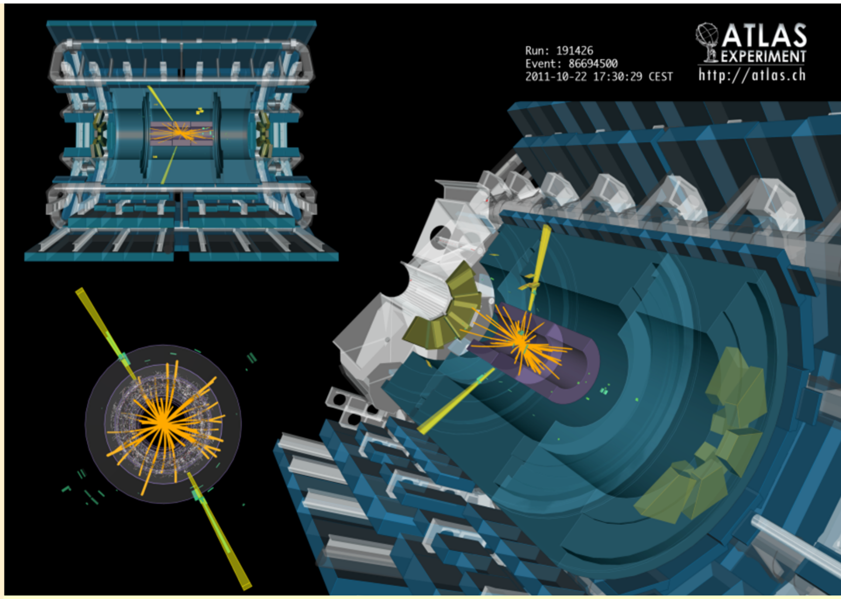
In the region 125 ± 5 GeV

Observed	32 events
Expected from background only	11.3 ± 1.4
Expected from Higgs signal	16 ± 1.9

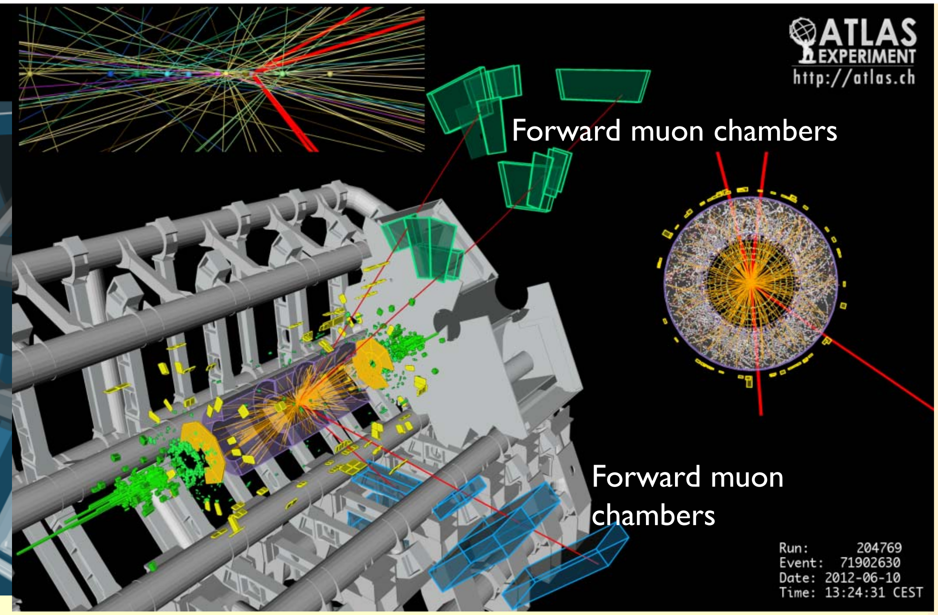
	4μ	2e2μ	4e
Data	13	13	6
Expected S/B	1.9	1.3	1.1

Muon momentum scale known to ~ 0.2%

- Clear peak at m_H ~ 124.5 GeV
- Probability it comes from background fluctuation: ~ 10^{-10} → 6.6 σ signal significance
 (4.4 σ expected from SM H)



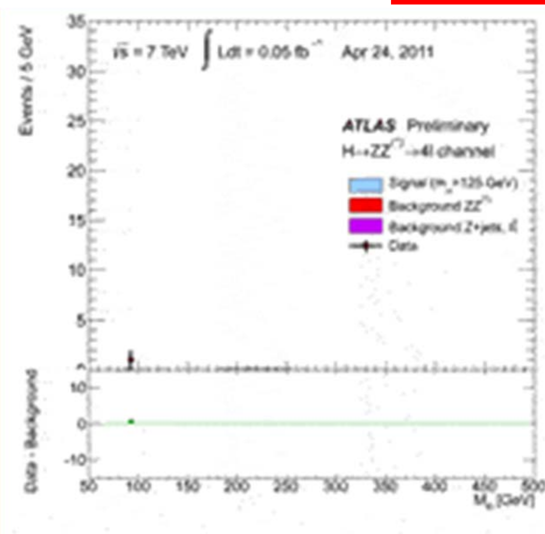
Higgs boson decaying into two photons

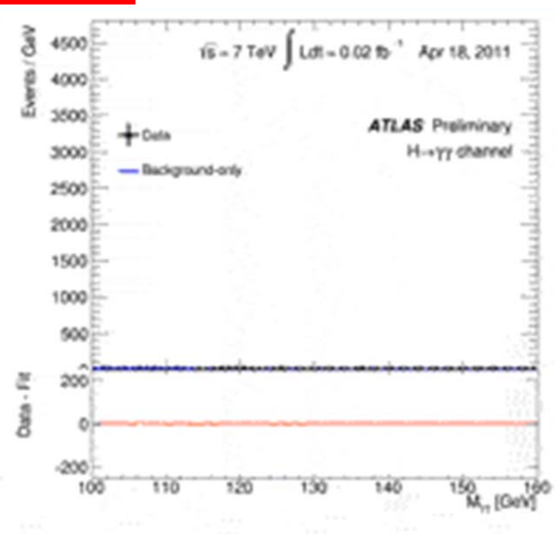


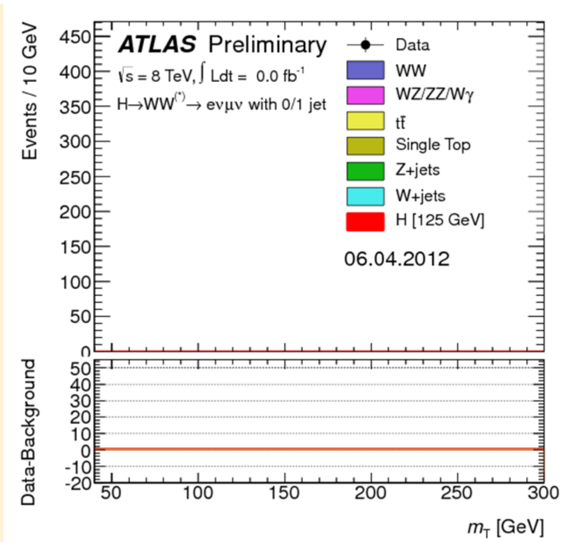
Higgs boson decaying into four muons

H → 4l ← **Discovery modes** → H→ γγ

H→ WW* →eν μν

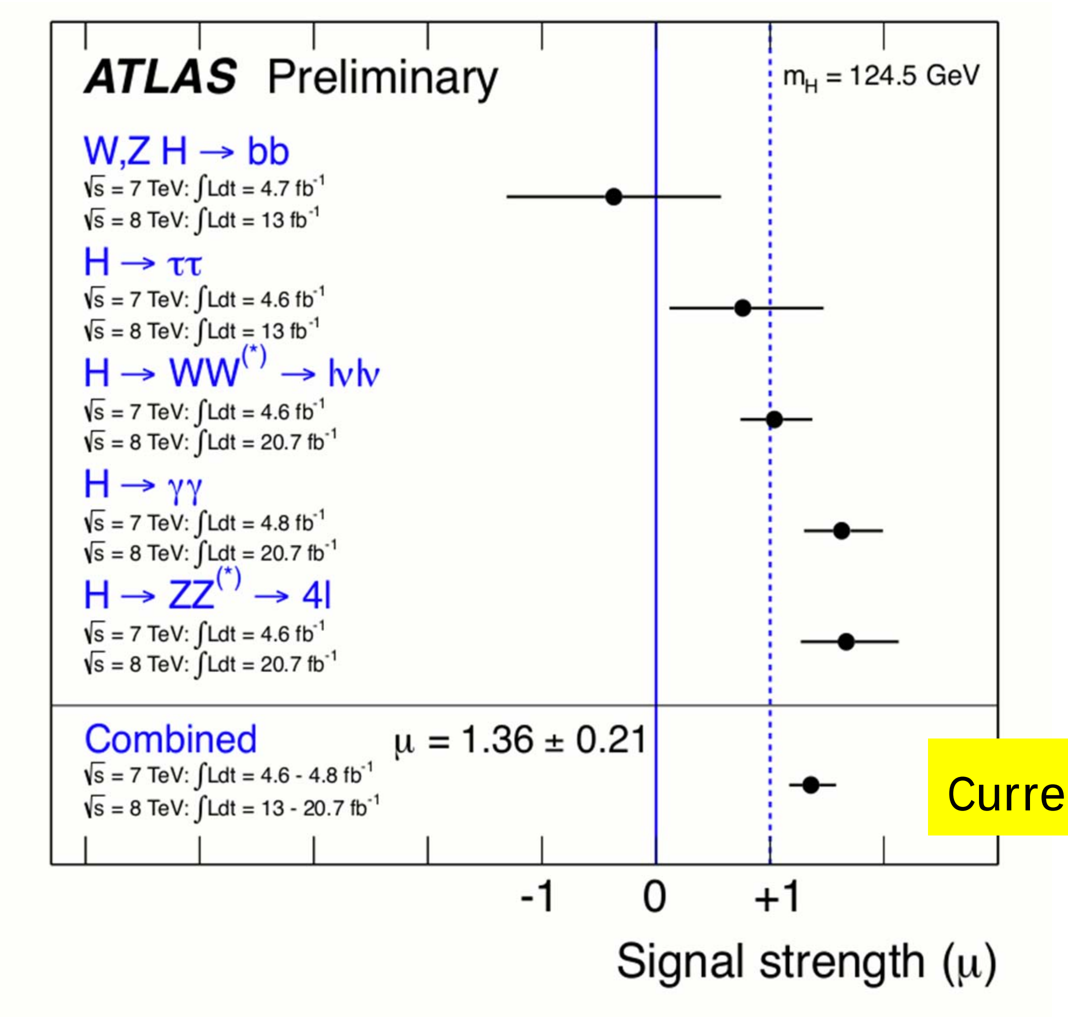






Combination of All Channels

Assuming a single narrow resonance at a mass m_X ~ 125 GeV/c^2



ATLAS-CONF-2013-034

Summary of the signal strength in all SM Higgs search channels

$$\hat{\mu} = 1.30 \pm 0.13\ (stat) \pm 0.14\ (syst)$$

Overall agreement with the SM Higgs boson hypothesis
(5 channels w/SM ~8%)

From m_H = 124.5 GeV to m_H = 126.5 GeV

Current observed significance : ~10σ

OUR Contributions to Muon System

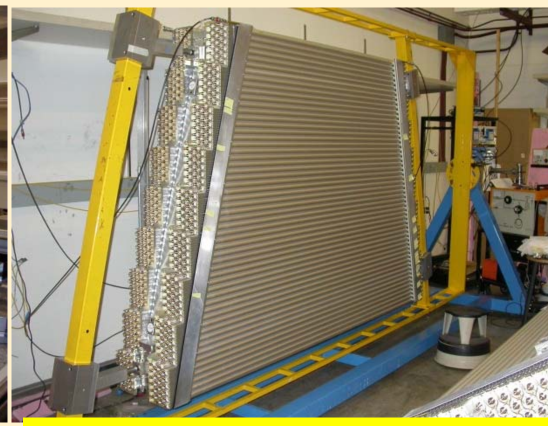
- Designed for all of ATLAS muon chambers the basic support structures for muon chambers (Colin Daly ME faculty, Bill Kuykendall,(ME), Dick Davisson, Tianchi Zhou, me
  - How to support muon drift tubes to define a chamber
  - Kinematic mounts
  - Built all of these items for the ATLAS muon chambers built in US
- Defined drift tube assembly line used by all of the US ATLAS muon chamber builders
- Fabricated 32,000 muon drift tubes and QA each one (lots of UG help)
  - The 32,000 tubes used for assembling 82 ATLAs forward muon chambers (1/3 of US production)
- Chamber assembly (Paul Mockett, Dave Forbush ME)
  - Assembly on large, flat Granit slab
  - To install slab required cutting large opening in load-bearing wall of lab currently occupied by muon g-2 group (NB PAB did not collapse ☺)
- Optical alignment system for endcap MDT chambers (Joe Rothberg)
  - Controls/archiving software and the lower level Linux code.
  - developed software to retrieve data from the database for monitoring and for use by the global endcaps alignment software.
  - Major architectural changes to the alignment readout and data storage procedure fro 2015 run in progress

ATLAS Muon UW Contributions

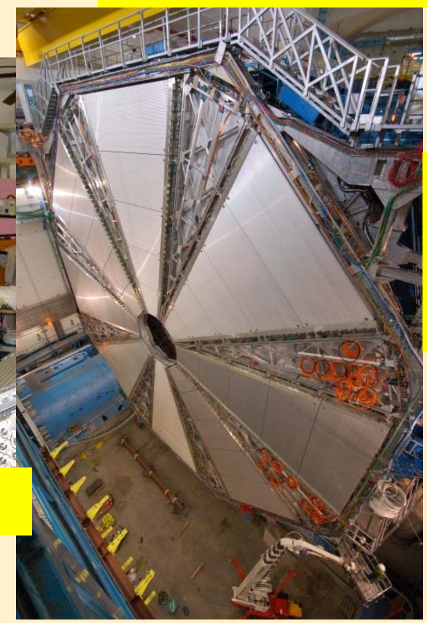
Tube Assembly room – Bill Kuykendall at work

Quality control Dick Davisson

Chamber Assembly Room



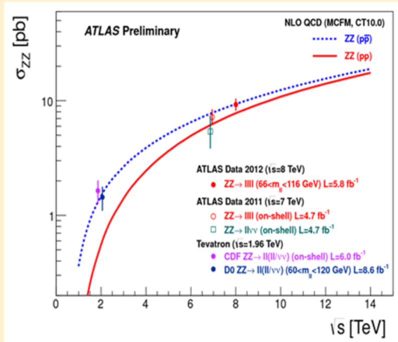
Completed endcap chamber



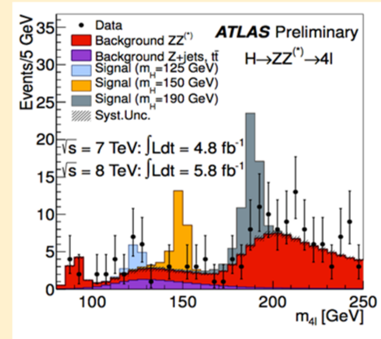
Mounting Chambers for installation at CERN

UW contributions

- Determination of ZZ → 4l background to H→ ZZ* → 4l **Shih-Chieh Hsu** led ATLAS effort



Main Background



- Central contributions to identifying a bottom quark jet, **Gordon Watts**

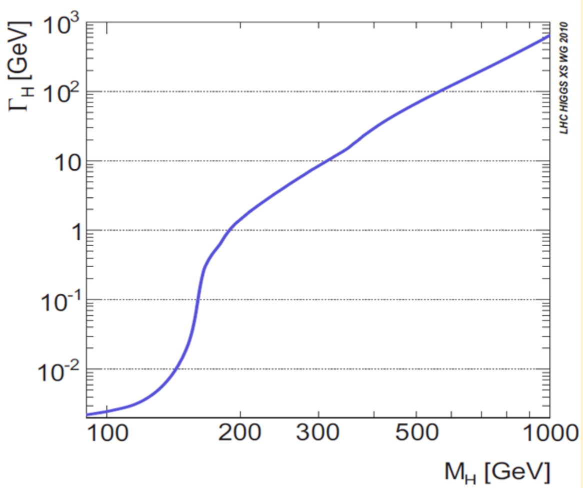
- **Detecton of $H \to b\bar{b}$ necessary understand relative coupling to bottom quark. - requires identifying a bottom quark jet.**
- **Efficiencies to detect a b typically 70% and fake rates about 1%**
- **Systematic uncertainties on b-tagging are largest contributing error to the analysis**

- Central contributions to H → t t measurements, **Anna Goussiou**

- **Detection of $H \to \tau\tau$ necessary understand relative couplings**
- **Requires identifying a tau decays.**
- **H → ττ very sensitive to beyond standard model searches (MSSM).**

Higgs sensitive to exotica

SM 125 GeVhiggs width small and decays relatively rare



Total decay width of the SM Higgs boson

$\Gamma_h/m_h \approx 2\text{-}3 \times 10^{-5}$

Whereas ……

$\Gamma_Z/m_Z \approx 3 \times 10^{-2}$, $\Gamma_W/m_W \approx 3 \times 10^{-2}$

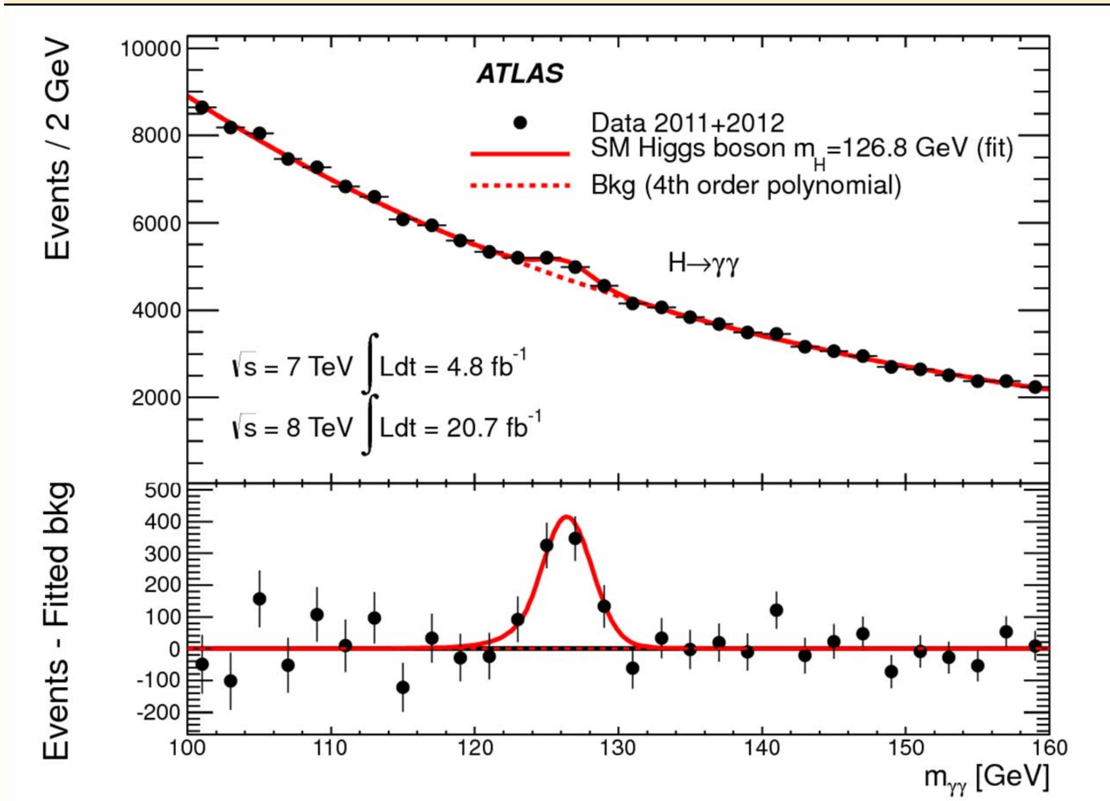
$\Gamma_t/m_t \approx 3 \times 10^{-3}$

125 GeV Higgs candidate for coupling to 'hidden sectors'

Can result in long-lived particles ???

EPE group pioneered search for long-lived particles in ATLAS (Henry Lubatti and Gordon Watts)

Backup Slides



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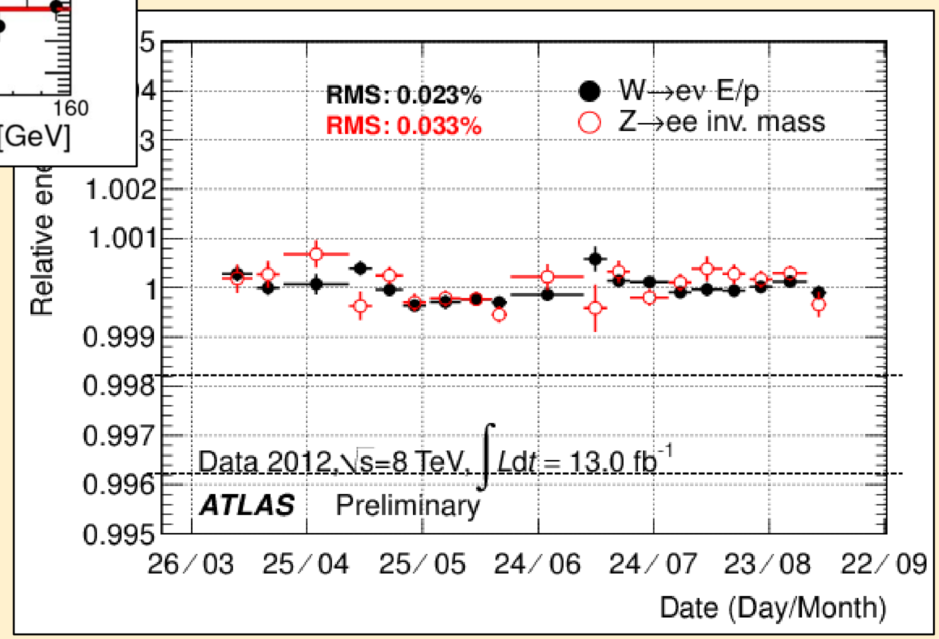
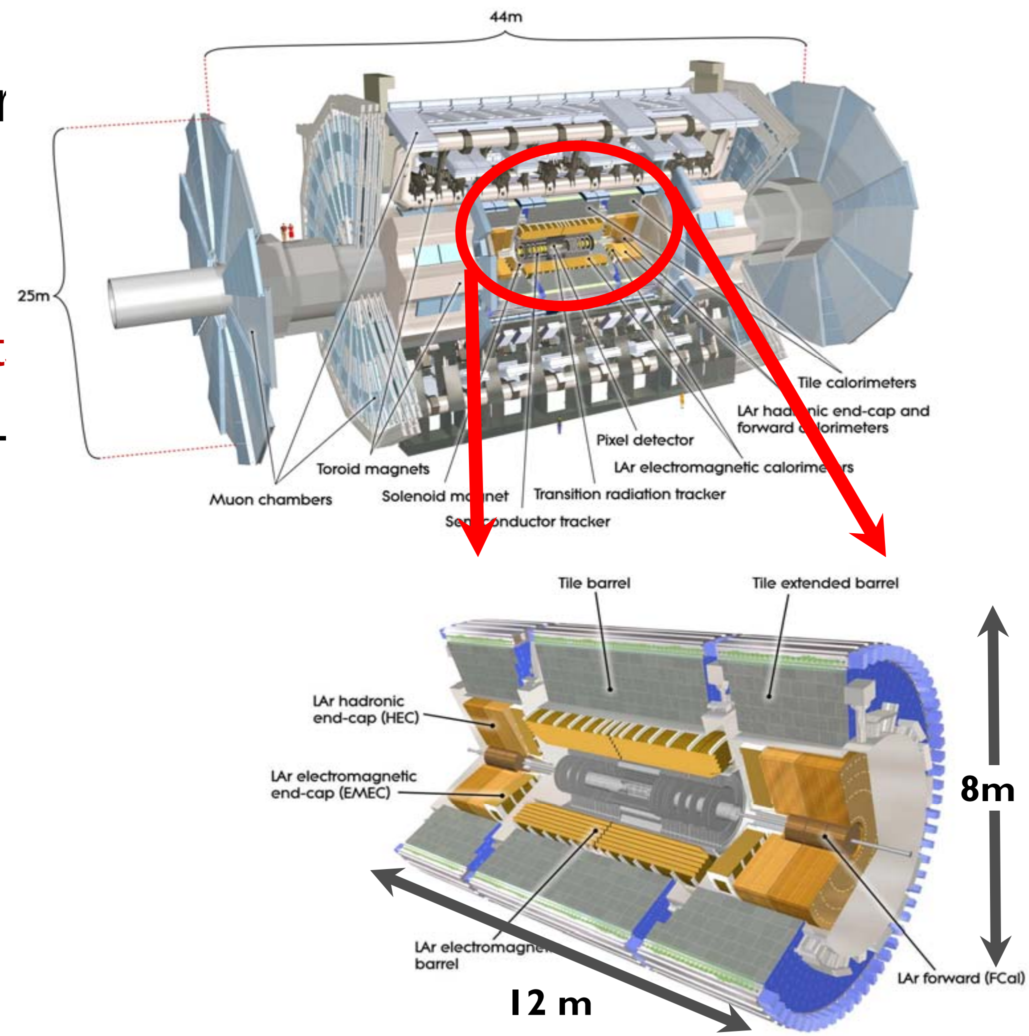


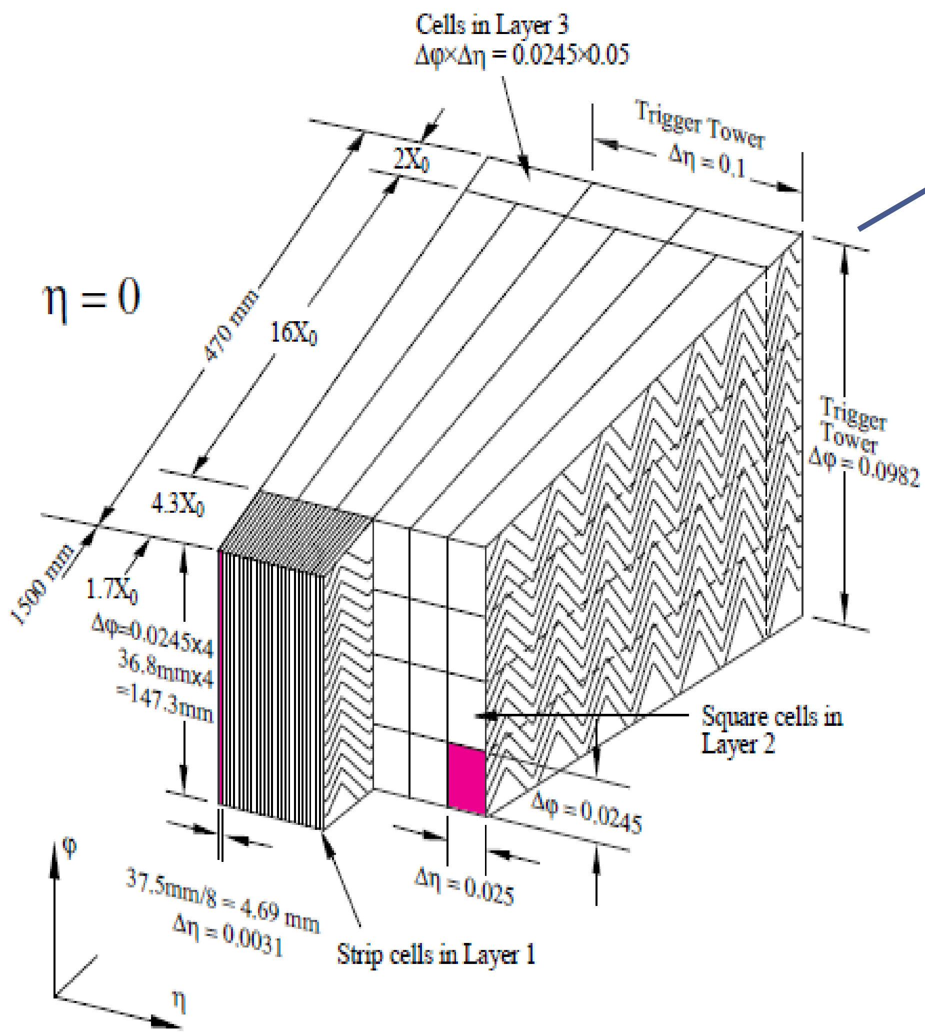
Stability of EM calorimeter vs time during 2012 run better than 0.1%

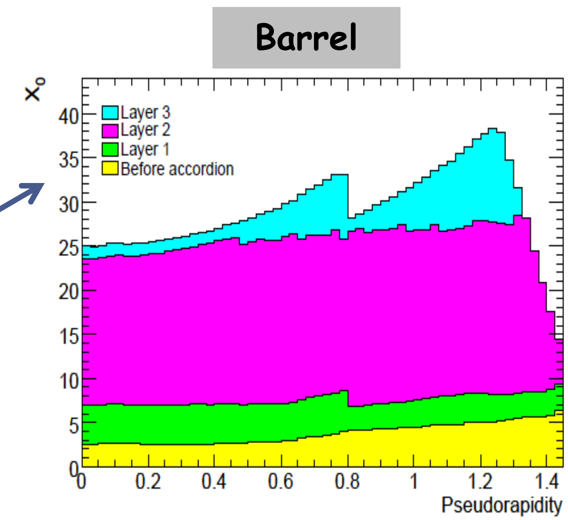
Calorimeters

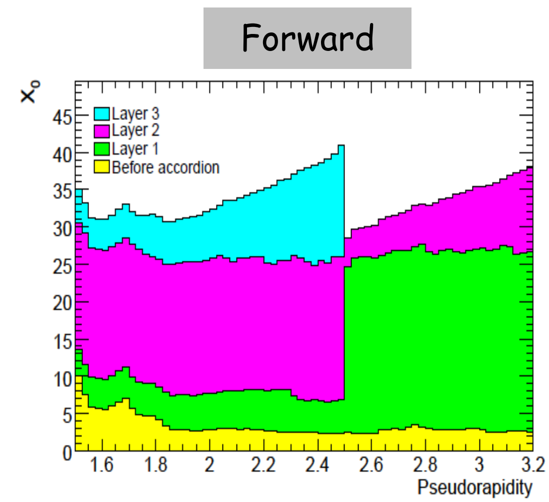
- Electromagnetic Calorimeter (ECAL)
  - Lead accordion with liquid argon -uniform
  - Three longitudinal segment
- Hadronic Calorimeter (HCAL
  - Barrel Fe Scintillator plates with polystyrene
  - Forward – Cu/Liquid Ar
- Barrel Dimensions
  - ECAL 1.1m < r < 2.25m
  - HCAL 2.25m < r < 4.25m



EM Calorimeter



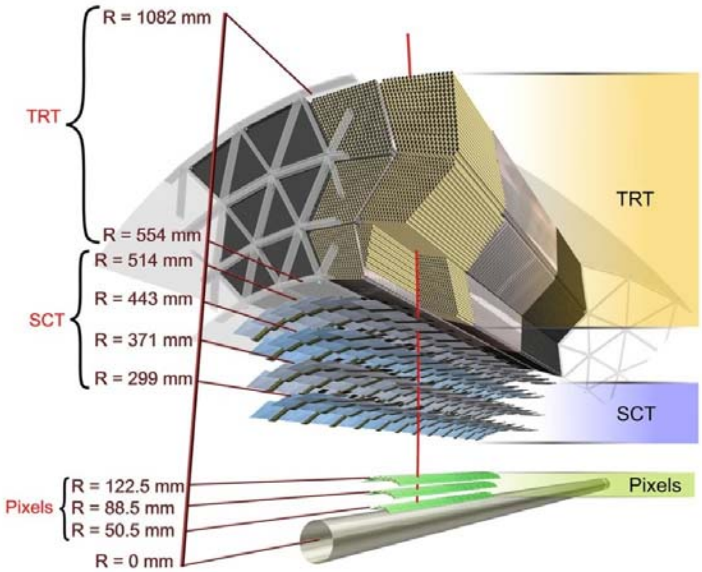


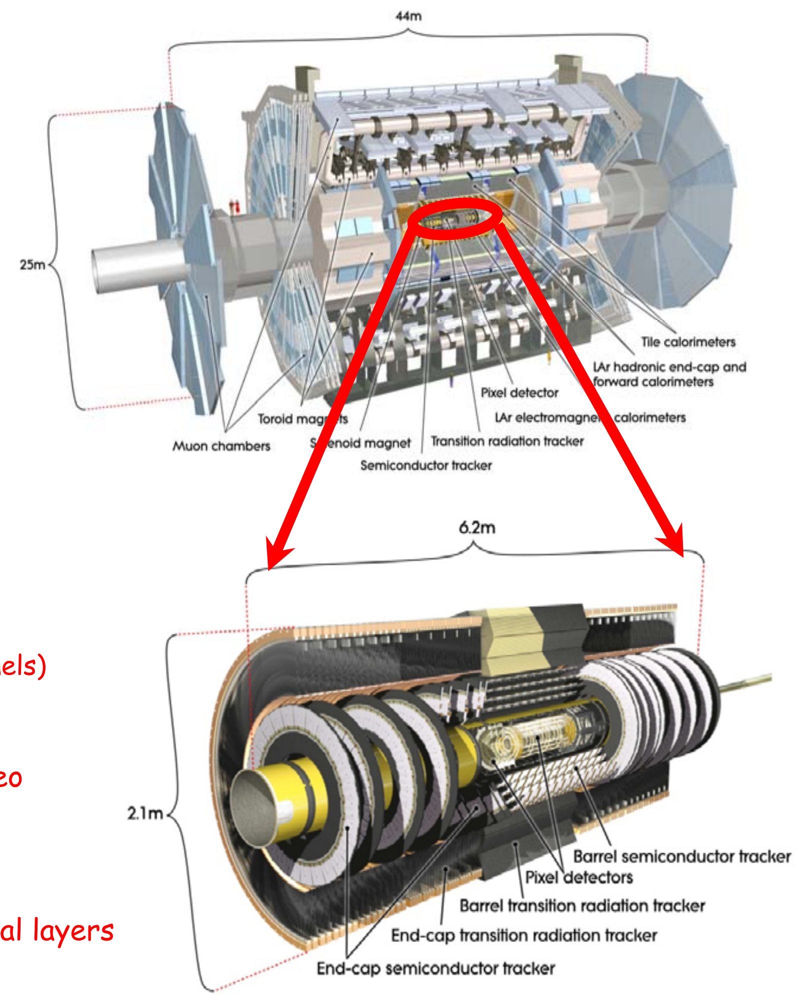


Barrel Segmentation

Cumulative Material in units of X_0

ATLAS Inner Detector (ID)

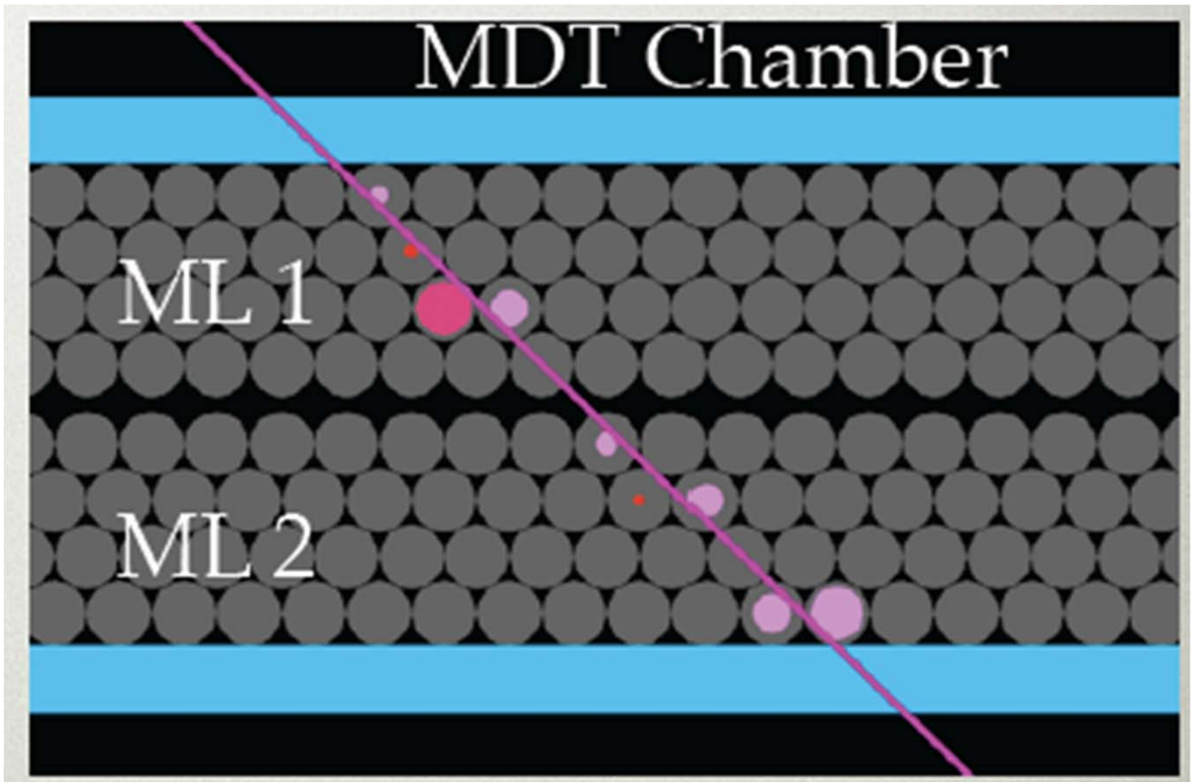




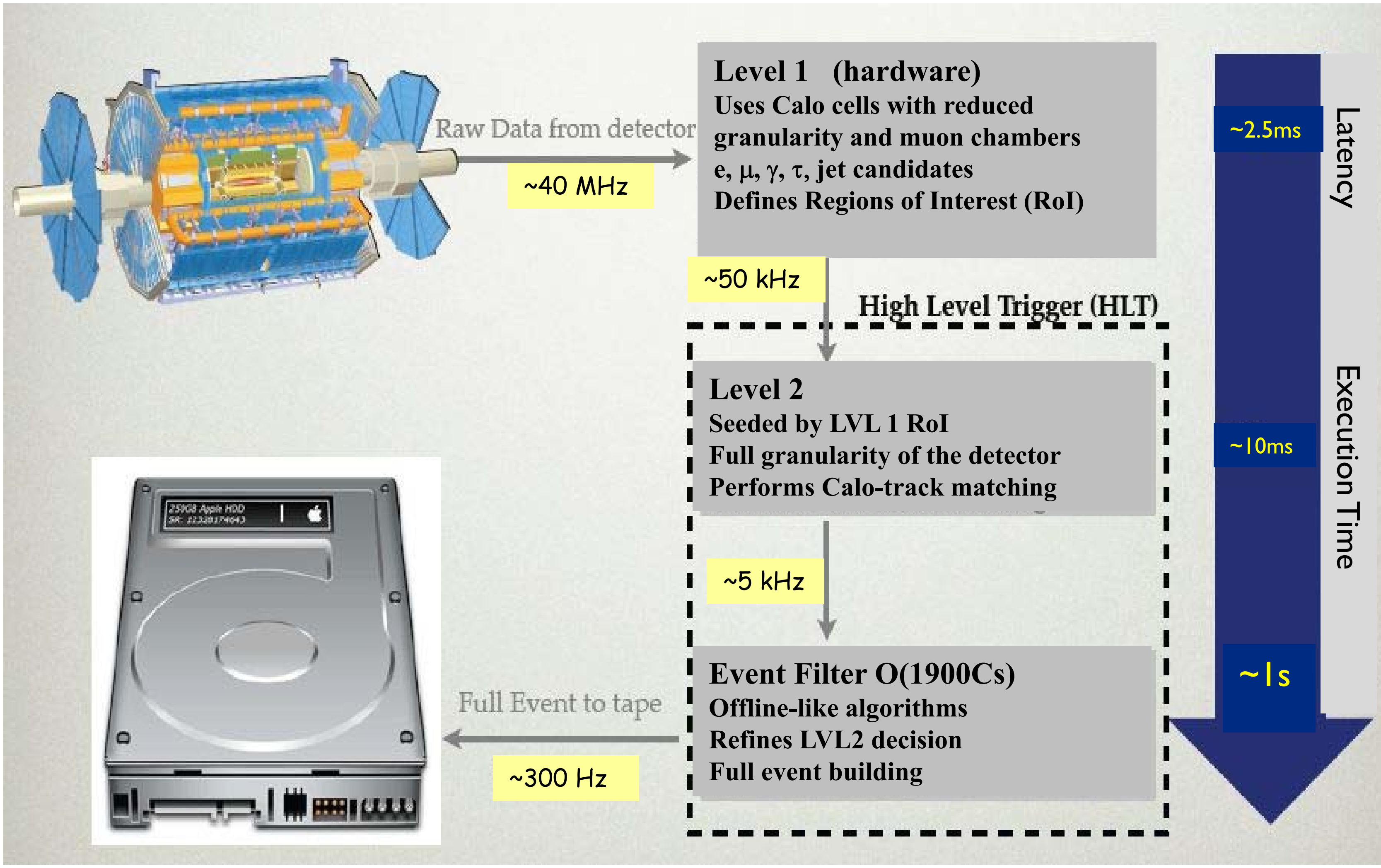
- Pixel Detector (Three layers - double sided)
  - $|\eta| < 2.5$ with $\sigma_{\rho\phi} \sim 10\ \mu m$, $\sigma_z \sim 115\ \mu m$ (80M channels)
- Semiconductor Tracker (SCT): single sided Si strips
  - stereo pairs
  - Four barrel layers and 2x9 end-cap disks stereo
  - $|\eta| < 2.5$ with $\sigma_{r\phi} \sim 17\ \mu m$, $\sigma_z \sim 580\ \mu m$ (6.3M channels)
- Transition Radiation Tracker (tracking and e/p separation)
  - 73 barrel straw layers and 2x160 end-cap radial layers
  - $|\eta| < 2.0$ with $\sigma_{r\phi} \sim 130\ \mu m$ (350k channels)
  - Average of 32 hits/track
- The ID is inside a 2 Tesla solenoidal magnetic field

Muon Spectrometer MDT Chambers

- MDT Chamber has two multilayers with three or four layers of drift tubes 82 chambers built in our physics department
- Tubes 30 mm diameter, 0.4 mm wall thickness operate $ArCO_2$ at 3 bar absolute - 32,000 built in our physics department
- Multilayer separation can be up to 32 cm.

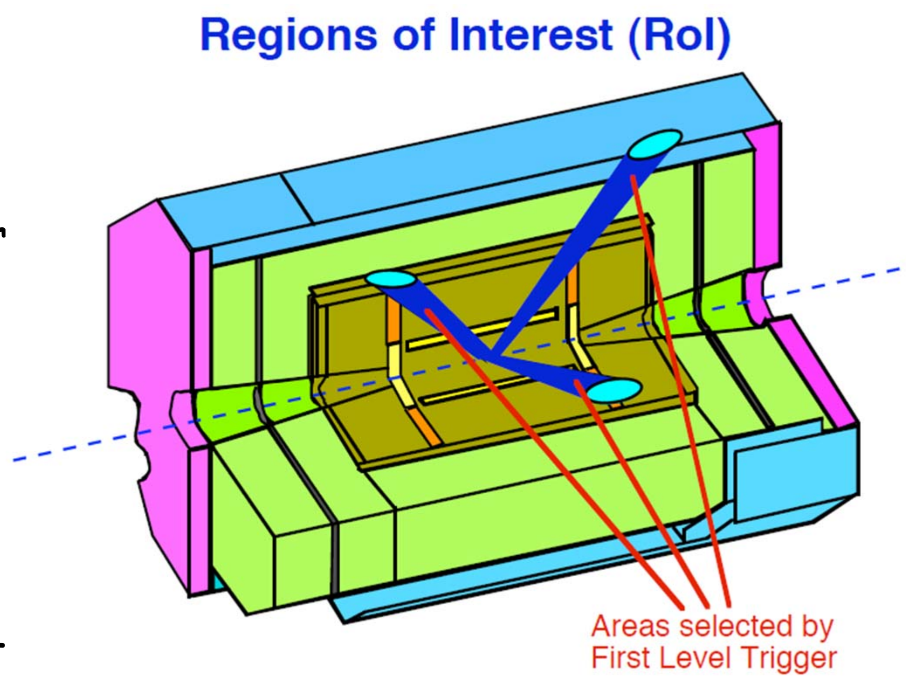


Triggers


Raw Data from detector
~40 MHz
Level 1 (hardware)
Uses Calo cells with reduced granularity and muon chambers
e, μ, γ, τ, jet candidates
Defines Regions of Interest (RoI)
~50 kHz
High Level Trigger (HLT)
Level 2
Seeded by LVL 1 RoI
Full granularity of the detector
Performs Calo-track matching
~5 kHz
Event Filter O(1900Cs)
Offline-like algorithms
Refines LVL2 decision
Full event building
Full Event to tape
~300 Hz
~2.5ms
~10ms
~1s
Latency
Execution Time

Triggers

- **Level 1**
  - Corse CAL & Muon Spectrometer granularity and no ID tracking
  - Identifies **R**egions **o**f **I**nterest (**RoI**) for further processing at Level 2
- **Level 2**
  - The full detector granularity in RoI region
  - Full tracking in RoI and all tracks required to connect to the **I**nteraction **P**oint
  - Only one muon per RoI is reconstructed

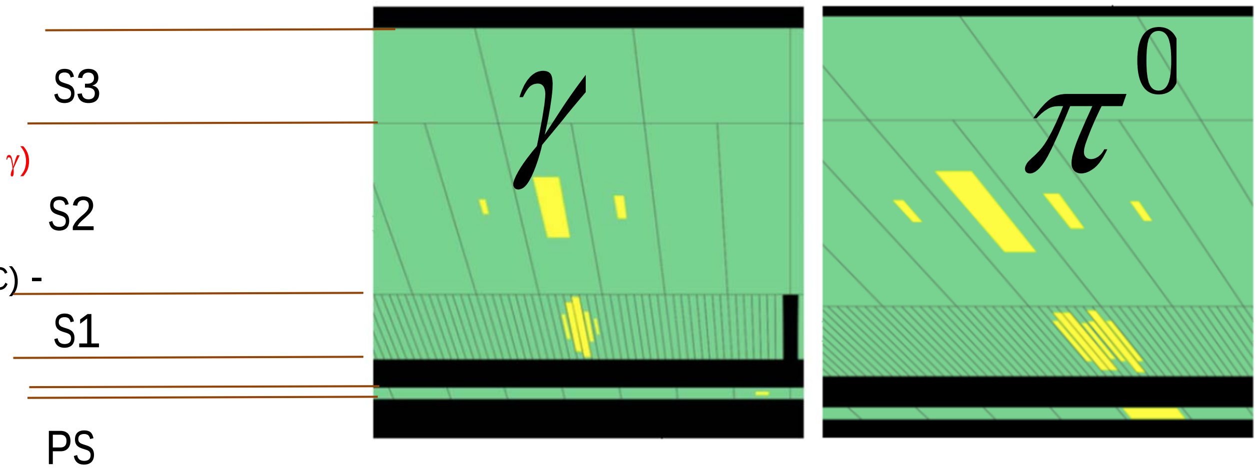


Reconstruction of Isolated photons

π^0-γ Rejection

Photon Cluster
based on 3x5 (unconverted γ)
and 3x7 (converted γ)

- for barrel photons (5x5 EC) -



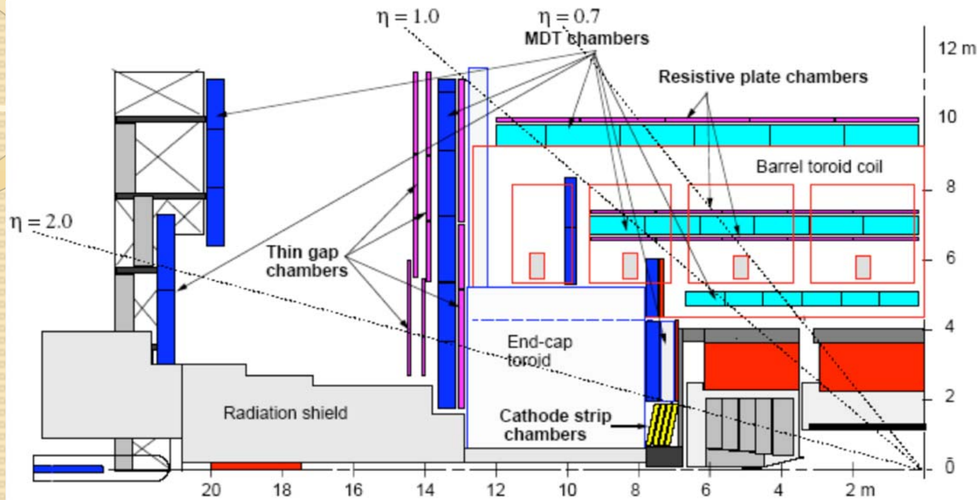
Longitudinal and Lateral segmentation

- Shower shape variable in S2
- Fine S1 granularity ~0.003 in pseudo rapidity
- Excellent γ-π^0 rejection
- Simple cuts technique

Photon isolation :

- Track Isolation
- Calorimeter based (0.4 cone)
- Out-of-(inner)-cone leakage corrections
- Underlying event and pile-up (PU) correction event based (using a Jet-Area type of algorithm)

Muon Spectrometer



- Air core toroidal magnetic field allows - stand-alone momentum measurements

Trigger Chambers

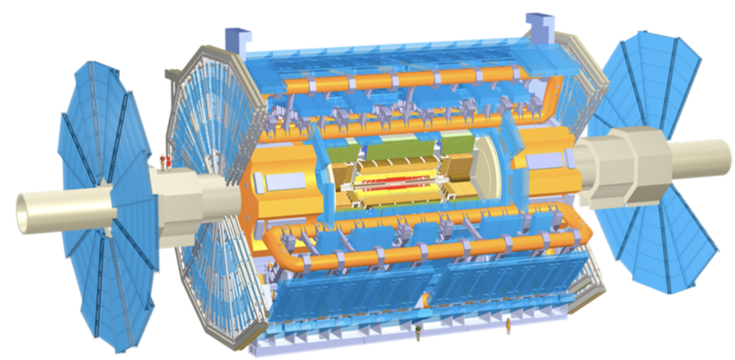
- RPC's in barrel region $|\eta|<2.4$ andTGC's in Forward region $2.0 < |\eta| < 2.7$
- Trigger chambers provide second coordinate (ϕ) for track reconstruction

Precision Chambers

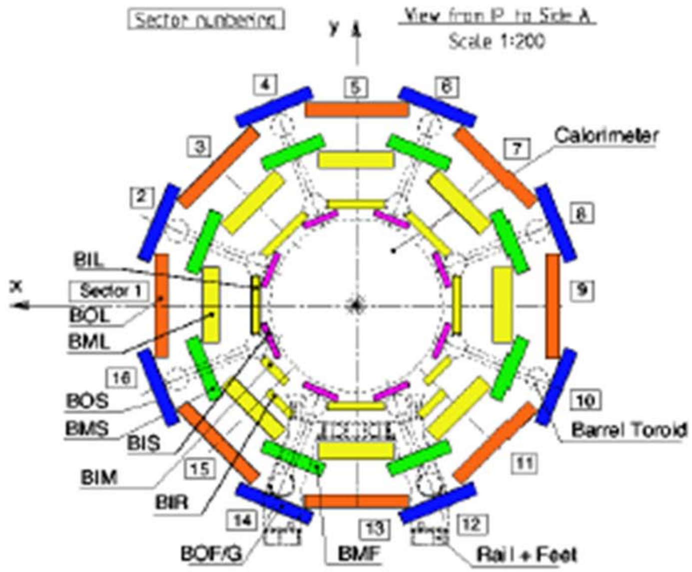
- Monitored Drift Tube (MDT) chambers in barrel and most of forward spectrometer
  - Barrel MDTs ~ 4.5, 7 and 10 m
  - Forward MDTs ~ 7.5 and 14 m
- MDT chamber has two multilayers (ML) with 3 or 4 layers of MDT tubes
- Multilayers separated: up to 32 cm

Cathode Strip Chambers (CSC's) for $2.0 < \eta < 2.7$

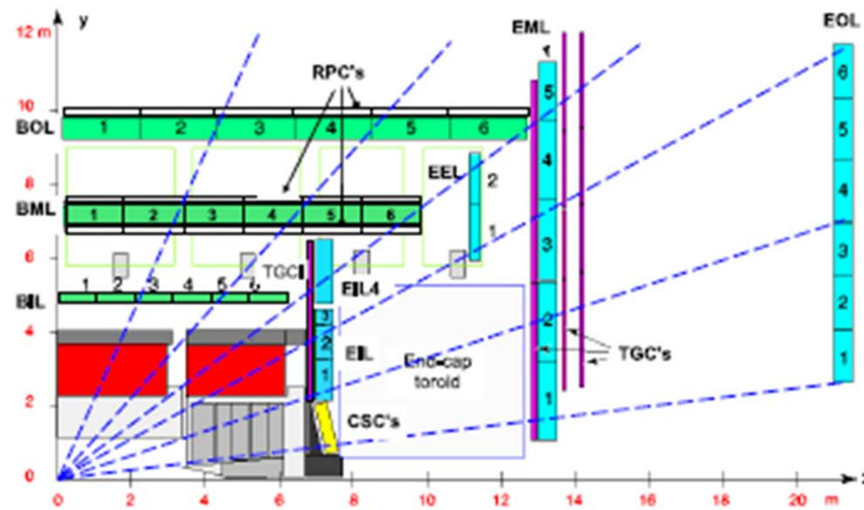
- **Resolution**
  σ_{p_T}/p_T ~ 4% at 50 GeV
  ~ 11% at 1 TeV



Muon Spectrometer



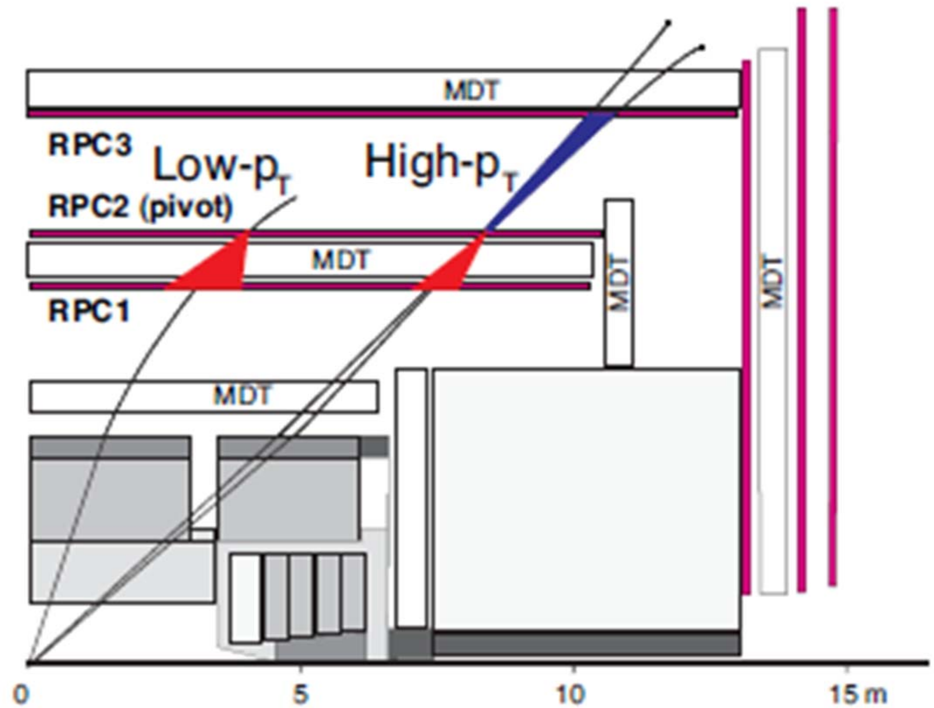
Cross-section of the barrel MS (non-bending plane), showing the three concentric cylindrical layers of eight large and eight small chambers. OD is about 20 m

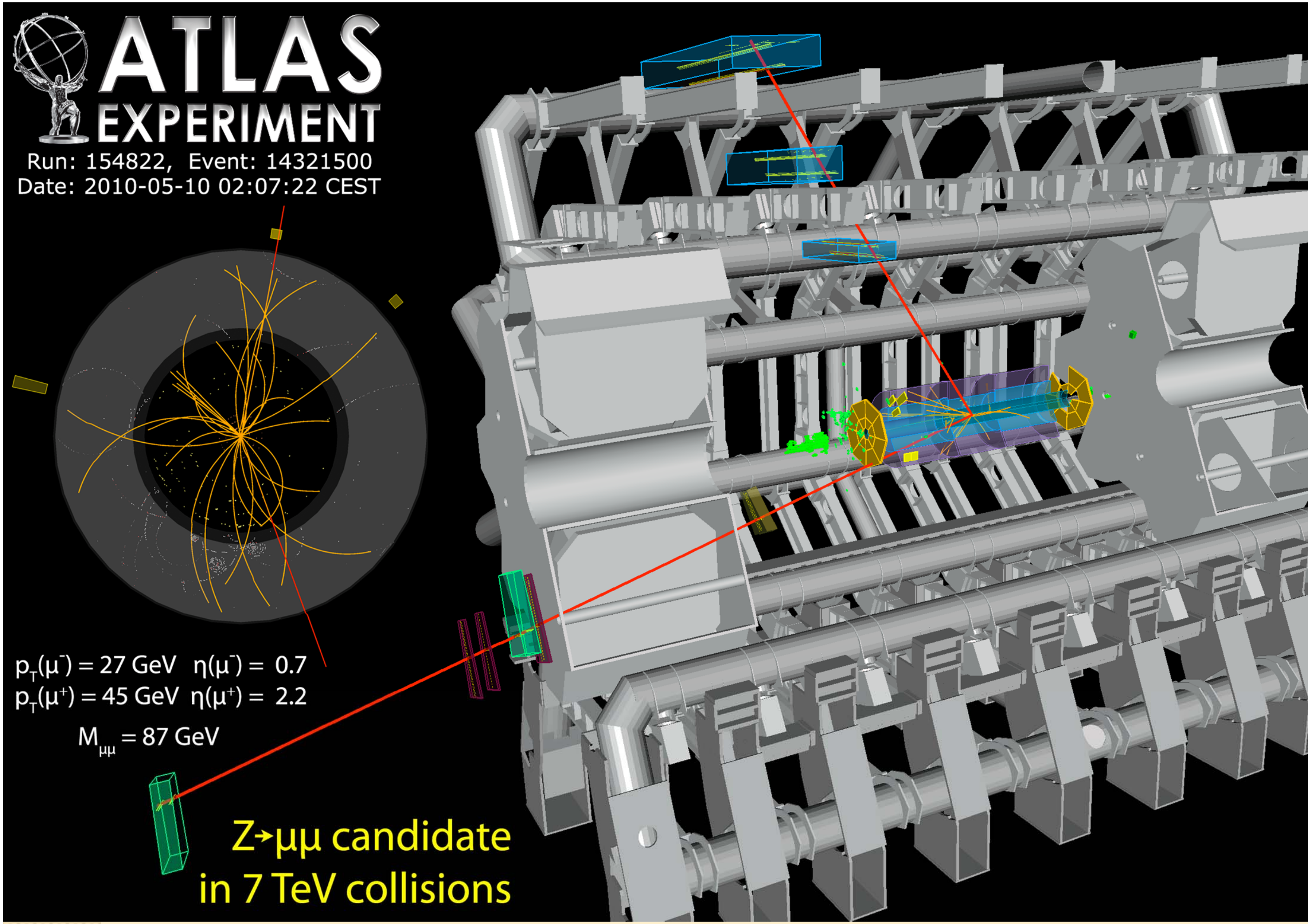


Cross-section MS in bend plane showing the three muon stations.

Muon Level1 Trigger

- based on three trigger stations
- The algorithm requires a coincidence of hits in the different trigger stations
- Defines a road: tracks the path of a muon from the interaction point through the detector.
- Width of the road depends on the p_T threshold.




ATLAS
EXPERIMENT
Run: 154822, Event: 14321500
Date: 2010-05-10 02:07:22 CEST
$p_T(\mu^-) = 27$ GeV $\eta(\mu^-) = 0.7$
$p_T(\mu^+) = 45$ GeV $\eta(\mu^+) = 2.2$
$M_{\mu\mu} = 87$ GeV
Z→μμ candidate
in 7 TeV collisions

Back-up Slides