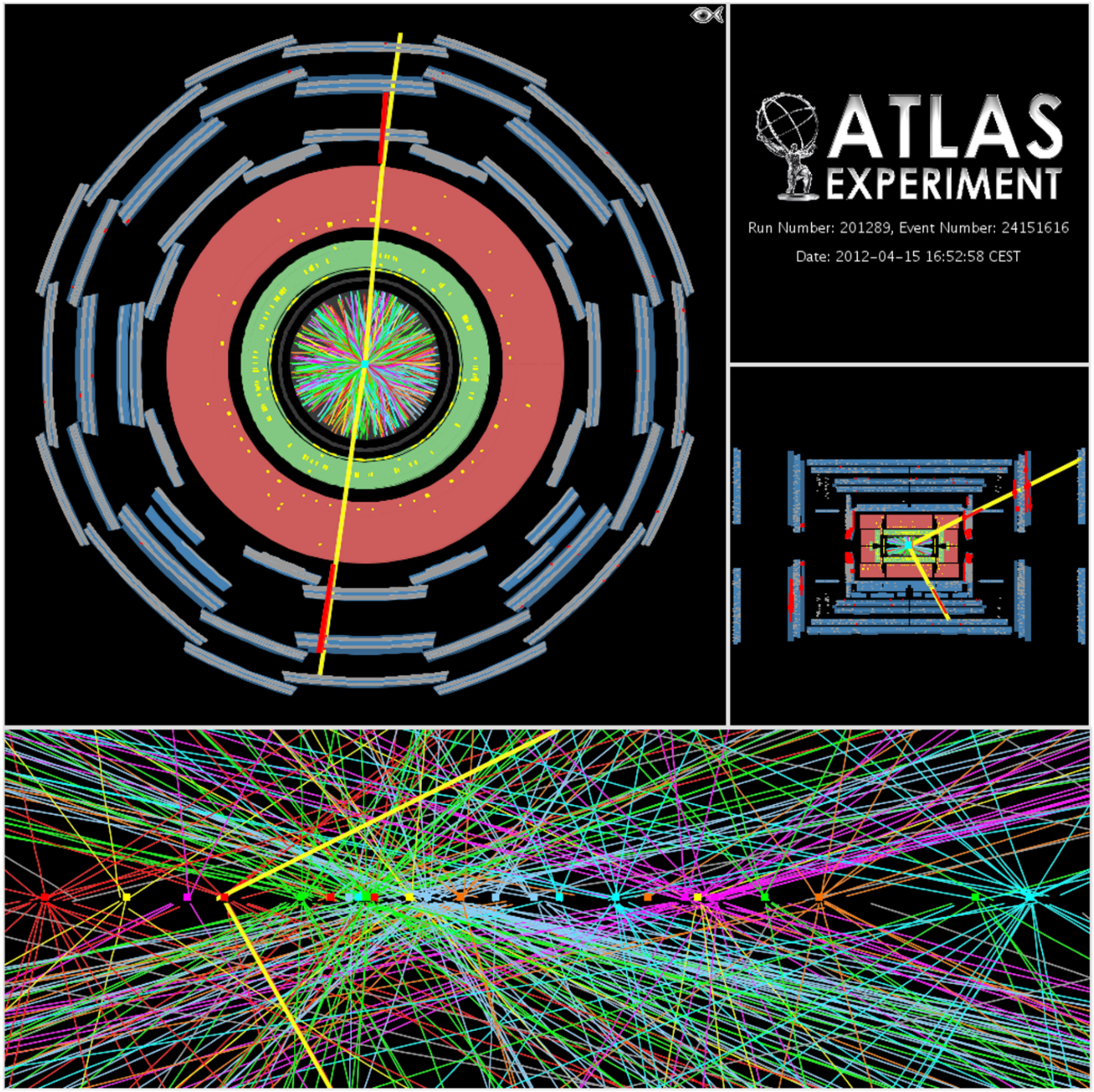
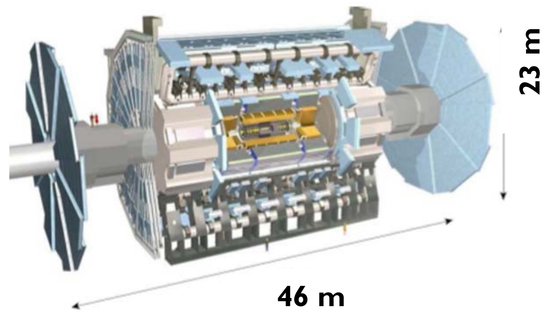
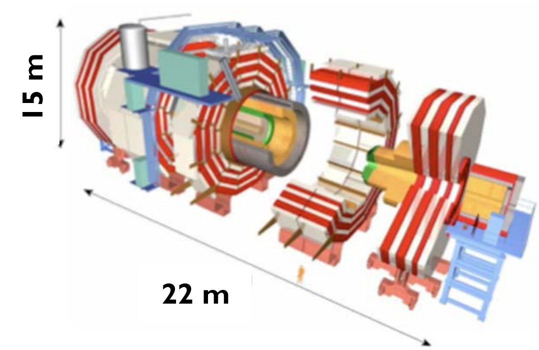
Life at LHC in 2012



Candidate Z boson event 25 reconstructed vertices

ATLAS and CMS Comparison

Subsystem	ATLAS	CMS
Overview		
Magnet System	Solenoid 2T – Calorimeters outside Three air-core toroid magnets	Solenoid 3.8T Calorimeters inside
Inner Tracker	Pixels/Si-strip/TRT - Part ID dE/dx $\sigma_{pT}/p_T \sim 5X10^{-4}p_T \oplus 0.01$	Pixel & Si strips - Part. ID dE/dx $\sigma_{pT}/p_T \sim 1.5X10^{-4}p_T \oplus 0.005$
EM CAL	Pb-LAr Sampl. – longitudinal seg. $\sigma_E/E \sim 10\%/\sqrt{E} \oplus 0.7\%$	Pb Tungstate Cryst. – no long. seg. $\sigma_E/E \sim 3\%/\sqrt{E} \oplus 0.5\%$
HCAL	Fe-Scint & Cu-LAr fwd $\geq 11\lambda_0$ $\sigma_E/E \sim 50\%/\sqrt{E} \oplus 3\%$	Brass-Scint. $\geq 11\lambda_0$ tail catcher $\sigma_E/E \sim 100\%/\sqrt{E} \oplus 5\%$
Muon Spectrometer ATLAS to η = 2.7 CMS to η = 2.4	Air Core – drift tubes (stand alone) σ_{pT}/p_T ~ 4% (at 50 GeV) ~ 11% (at 1 TeV)	Instrumented Fe return σ_{pT}/p_T ~ 1% (at 50 GeV) ~ 10% (at 1 TeV)

ATLAS and CMS Comparison

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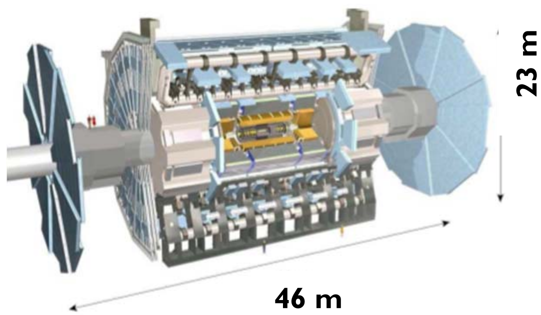
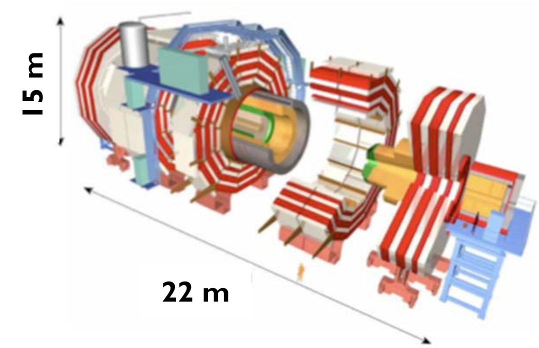
<tr><td>Overview</td><td></td><td></td></tr>
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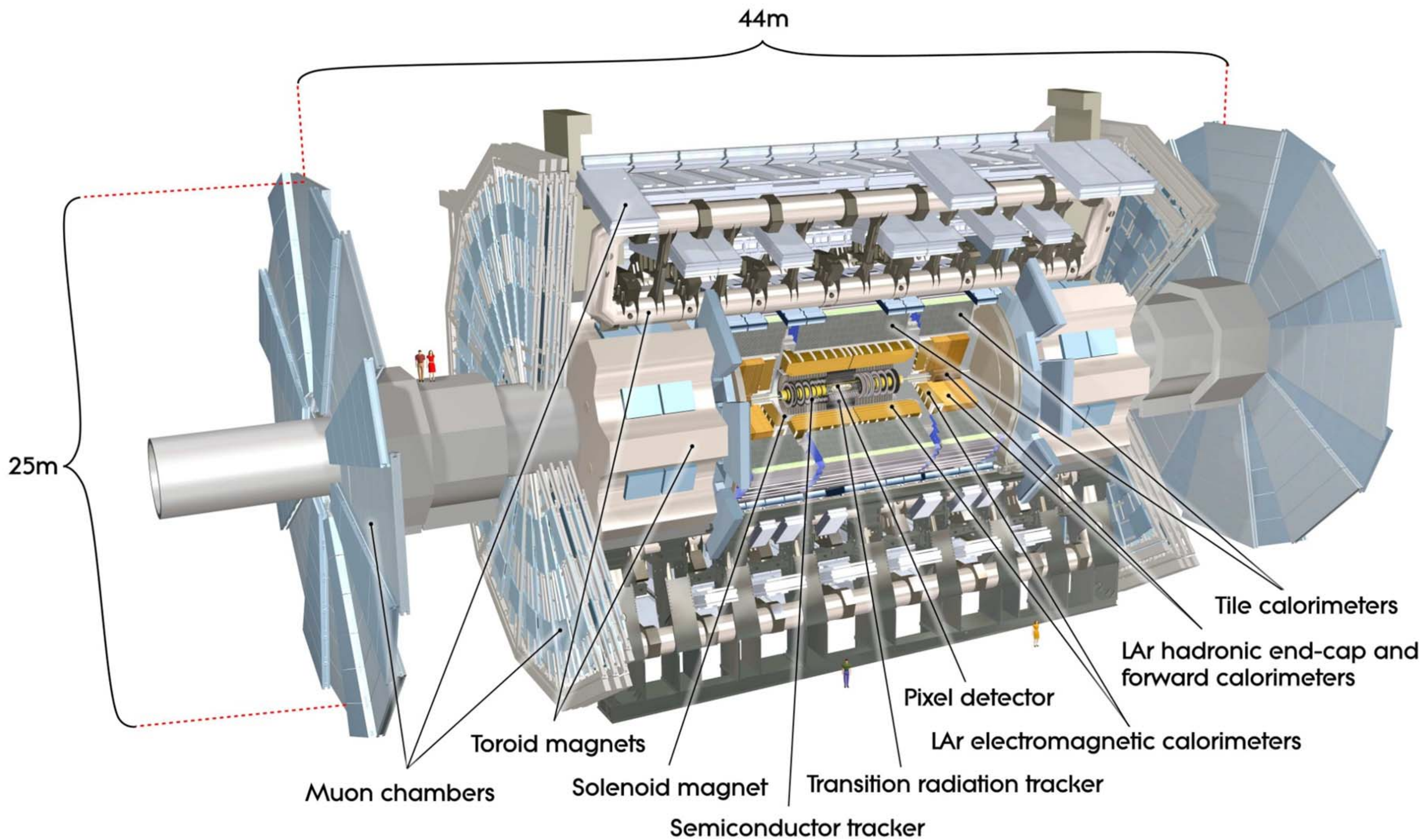
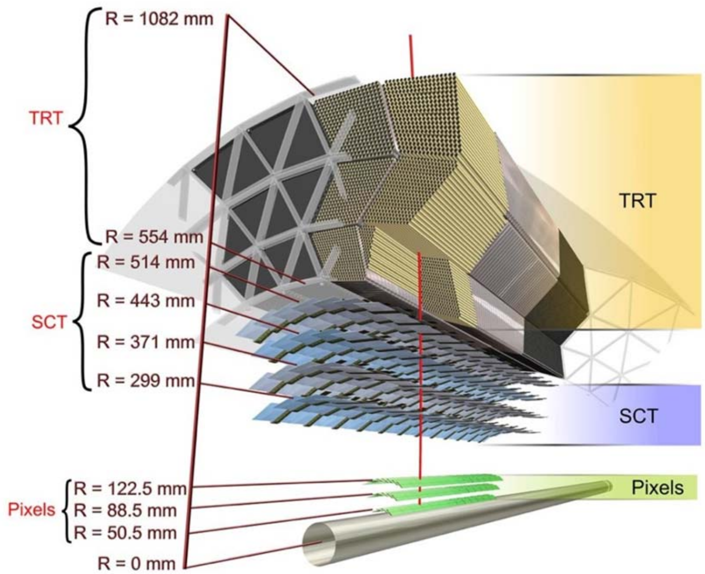
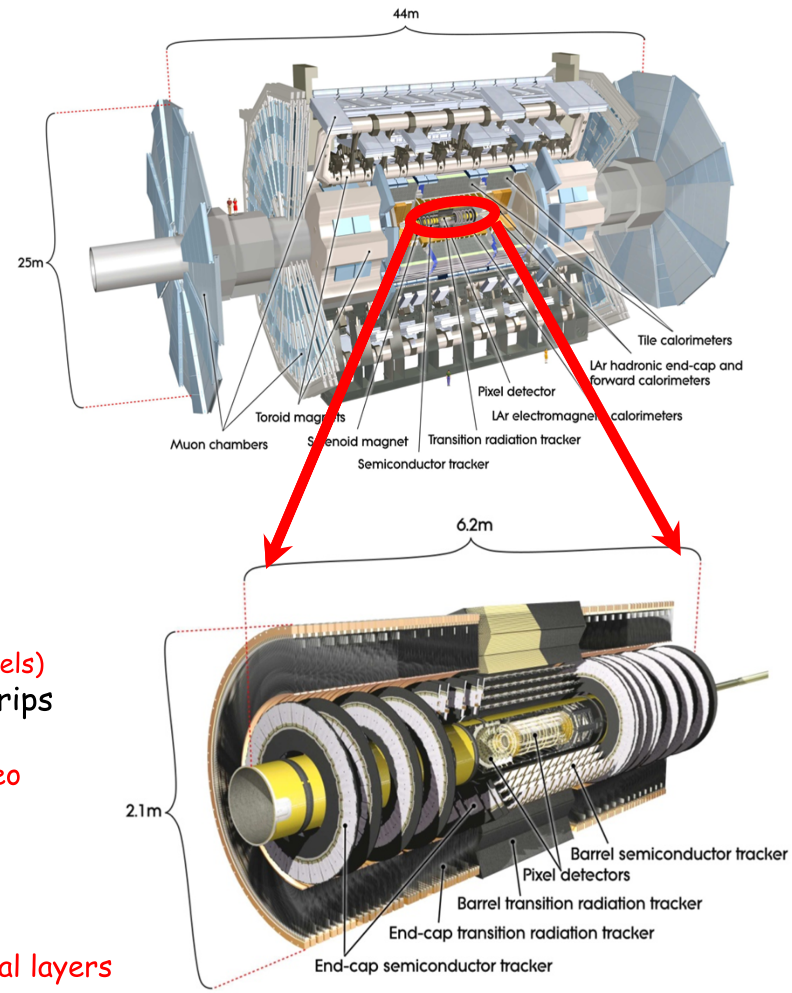
ATLAS Detector



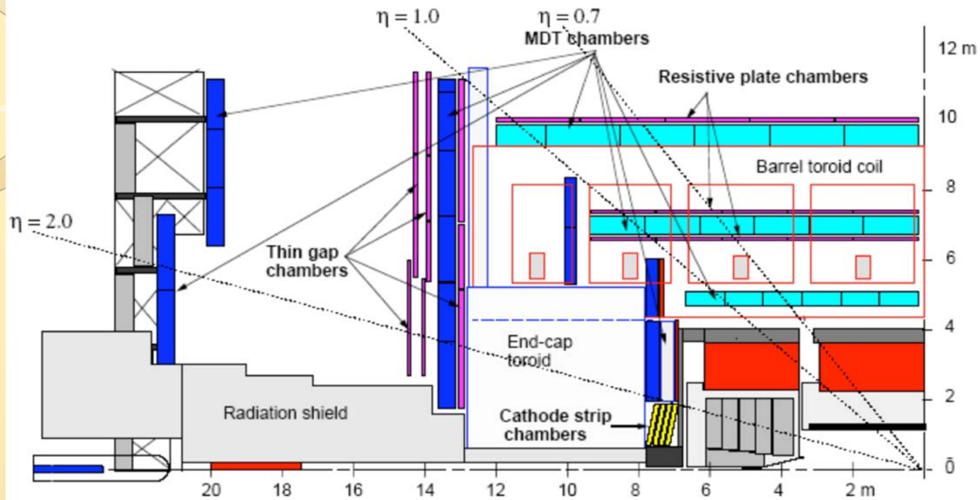
ATLAS Inner Detector (ID)





- 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/π 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



- *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

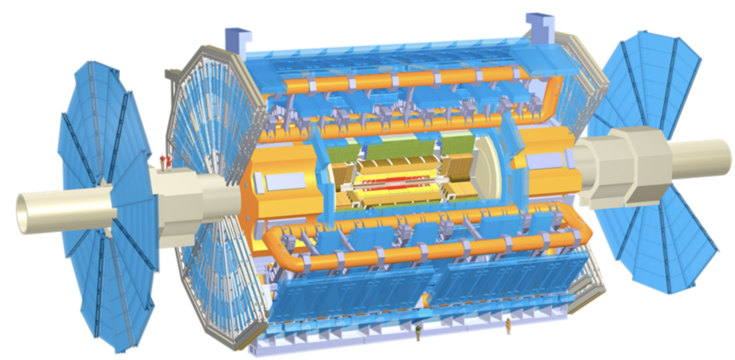
Precision Chambers

- 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

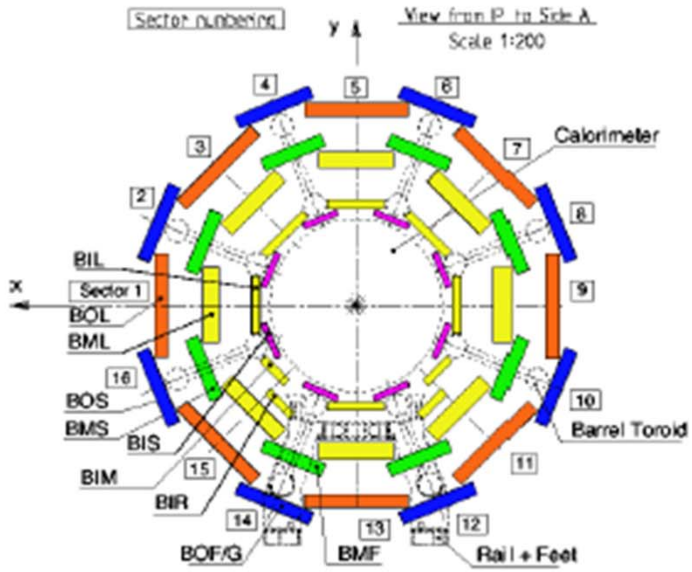
Cathode Strip Chambers (CSC's) for $2.0 < \eta < 2.7$

- **Resolution**

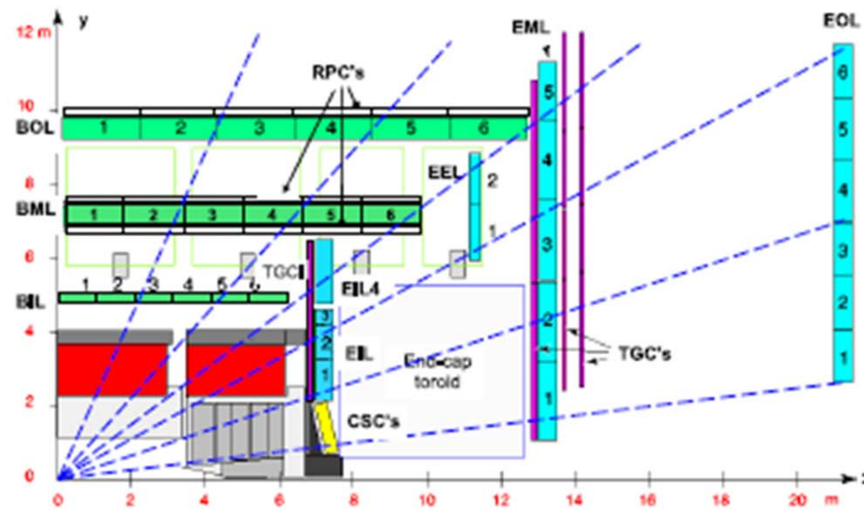
σ_{p_T}/p_T ~ 4% at 50 GeV
~ 11% at 1 TeV



Muon Spectrometer



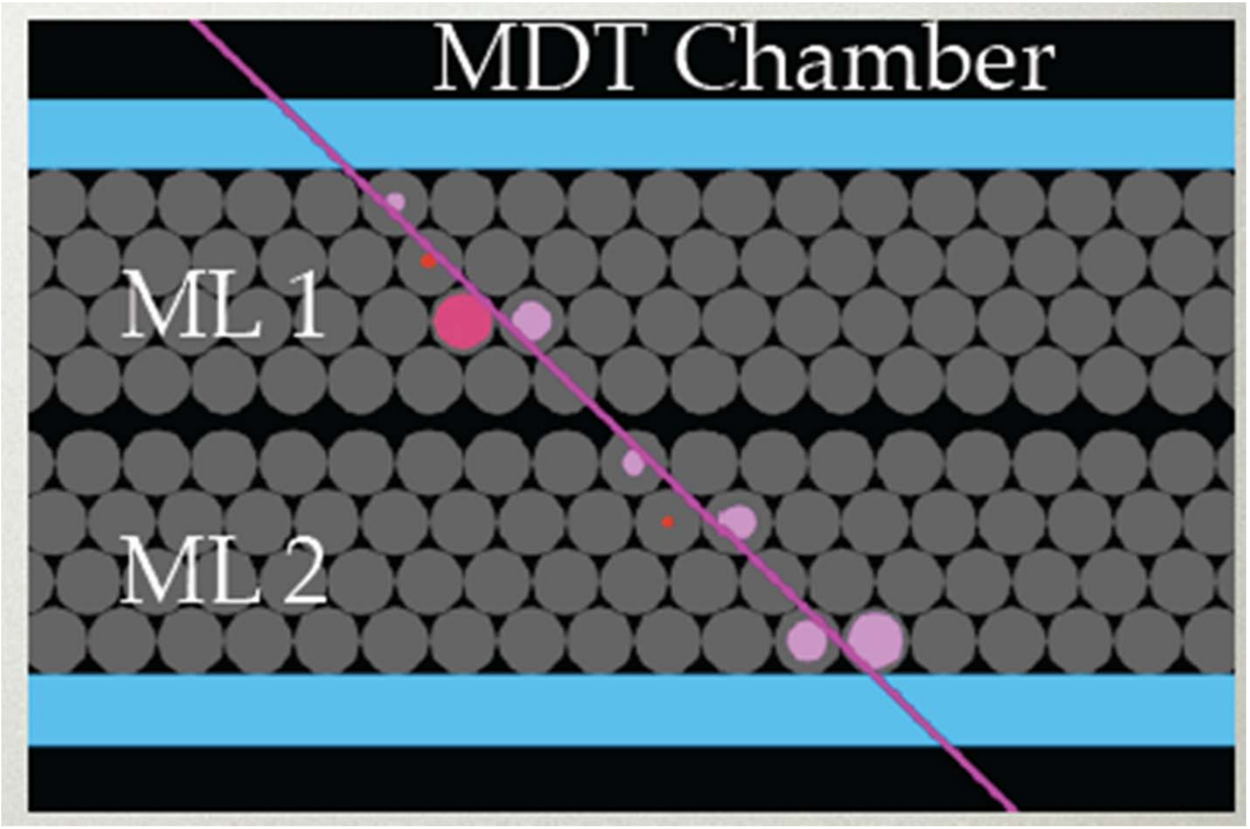
Cross-section of the barrel MS (non-bending plane), showing the three concentric cylindrical layers of eight large and eight small chambers. OD is about 20 m



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

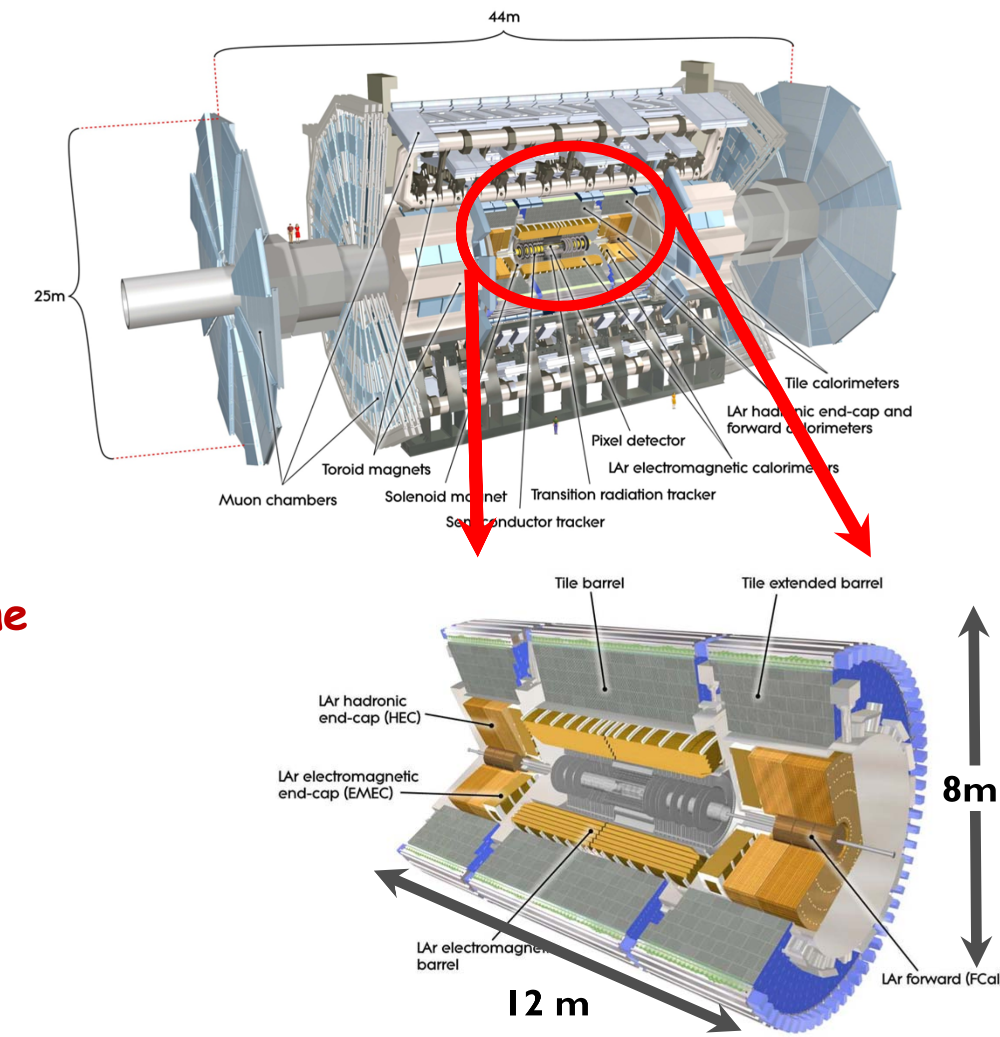
MDT Chambers

- MDT Chamber has two multilayers with three or four layers of drift tubes
- Tubes 30 mm diameter operating at 3 bar absolute



Calorimeters

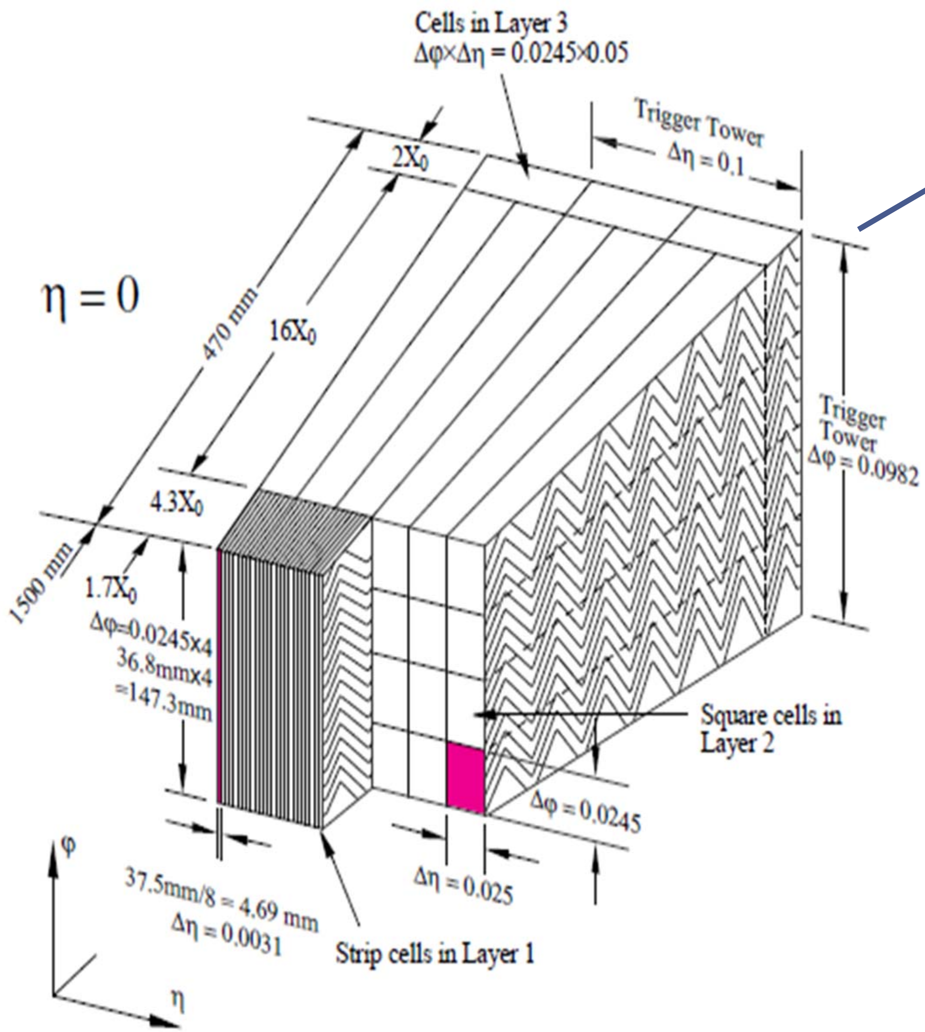
- Electromagnetic Calorimeter (ECAL)
  - Lead accordion with liquid argon -uniform
  - Three longitudinal segments
- Hadronic Calorimeter (HCAL)
  - Barrel Fe Scintillator plates with polystyrene
  - Forward Cu Liquid Ar
- Barrel Dimensions
  - ECAL 1.1m < r < 2.25m
  - HCAL 2.25m < r < 4.25m



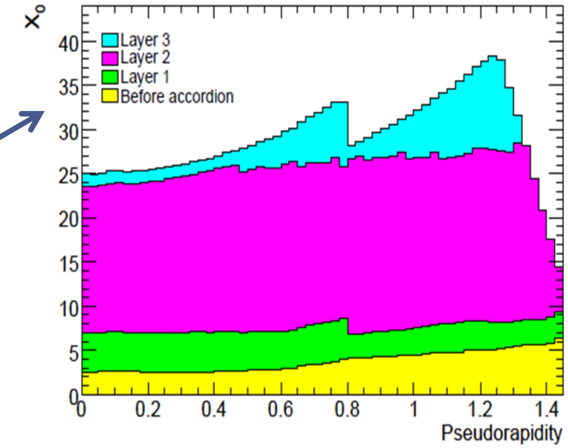
Features of Atlas Calorimeter

- 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.
- More later in the talk

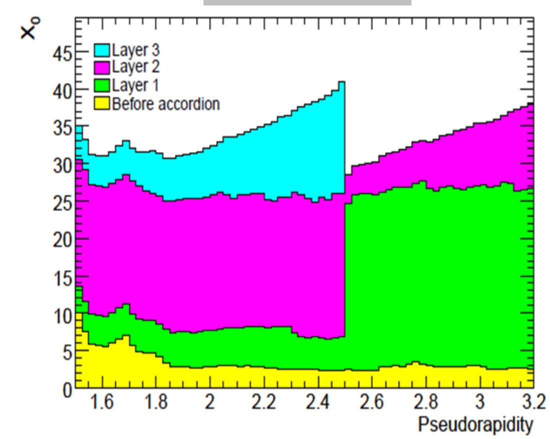
EM Calorimeter



Barrel



Forward

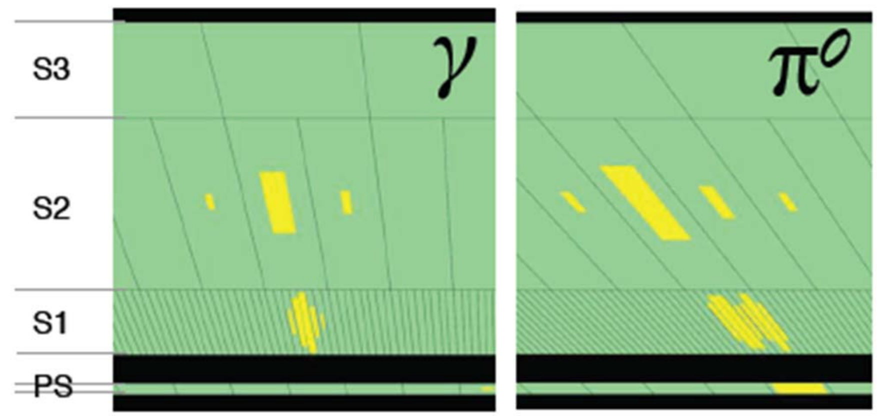


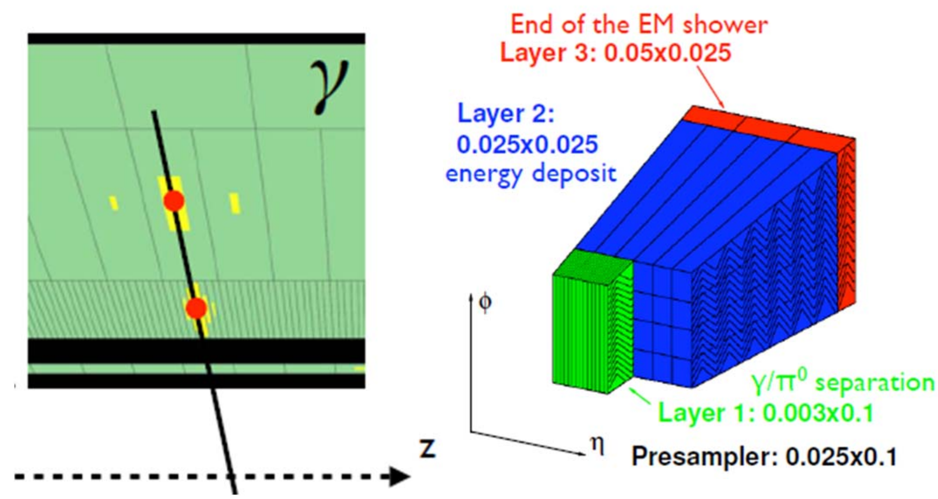
Barrel Segmentation

Cumulative Material in units of X_0

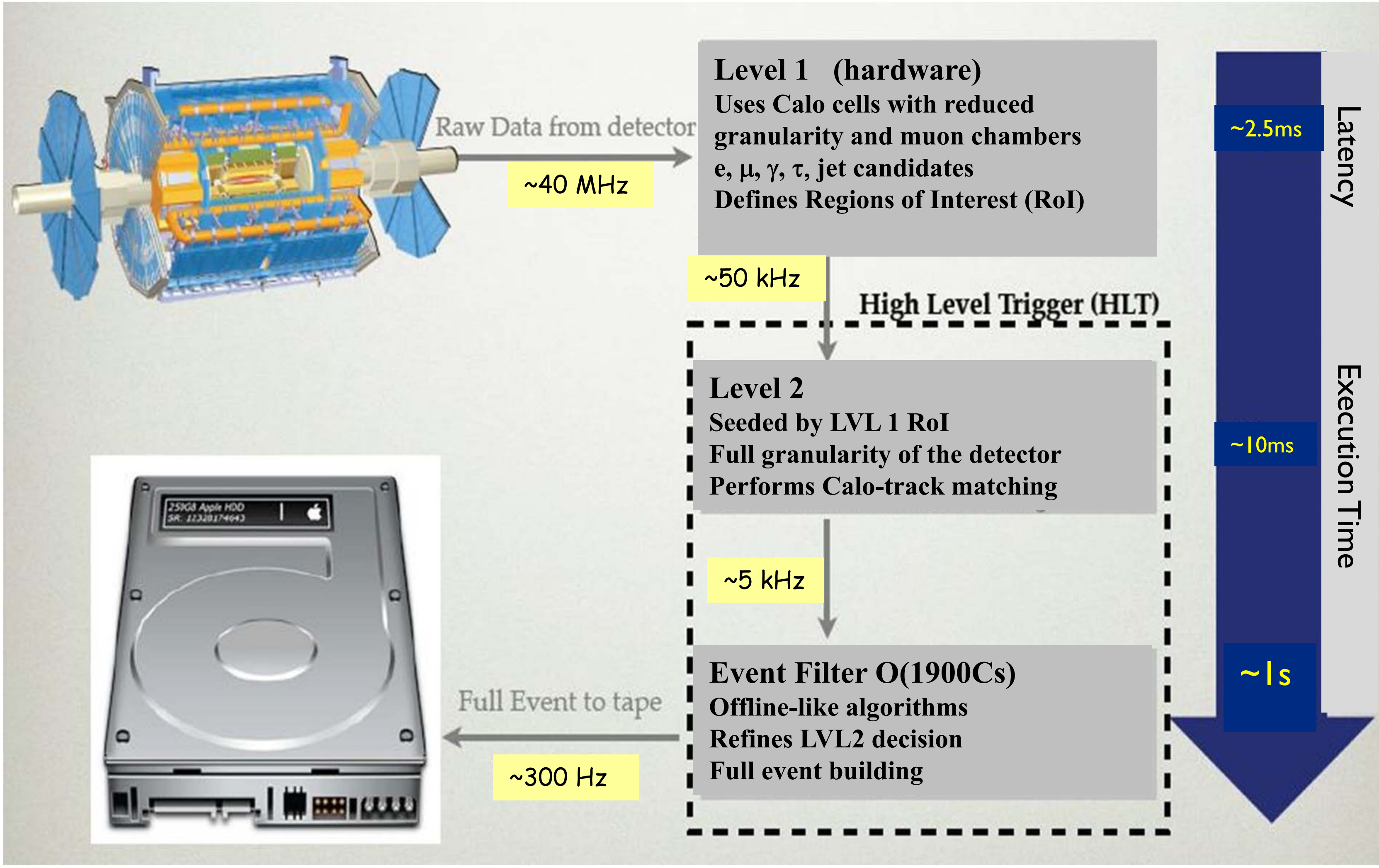
EM Calorimeter

- Photon ID based on longitudinal and lateral segmentation of the ECAL (shower shapes)
- High granularity in S1 results in good rejection efficiency for $\pi^0 \longrightarrow \gamma\gamma$
- 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 and get z find z of primary vertex (IP).
- Vertex with pointing ~1.6-1.8 cm (without 5.6 cm)





Triggers

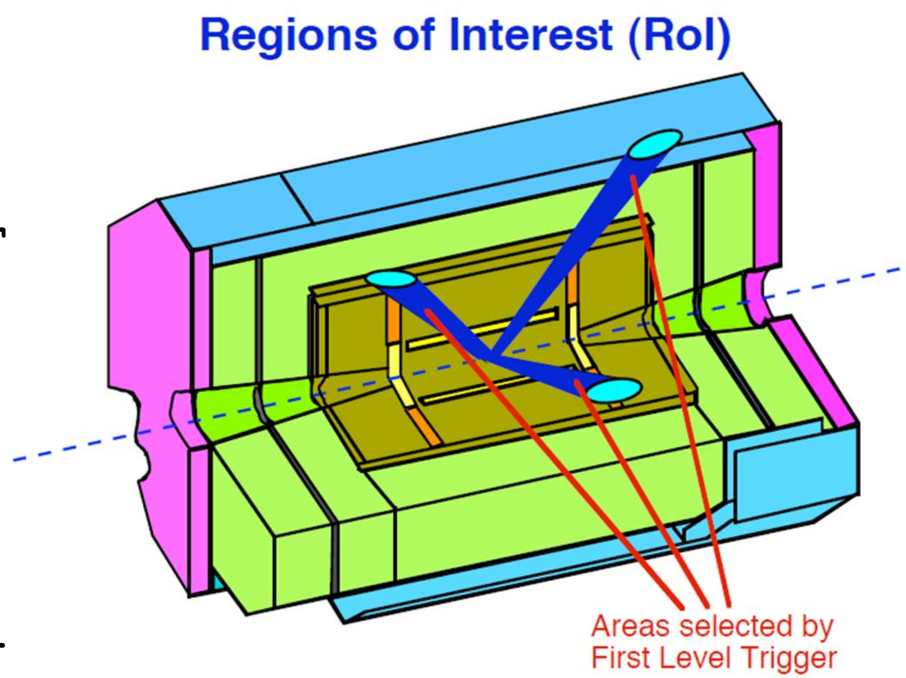


Raw Data from detector
~40 MHz
Level 1 (hardware)
Uses Calo cells with reduced granularity and muon chambers
e, μ, γ, τ, jet candidates
Defines Regions of Interest (RoI)
~50 kHz
High Level Trigger (HLT)
Level 2
Seeded by LVL 1 RoI
Full granularity of the detector
Performs Calo-track matching
~5 kHz
Event 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

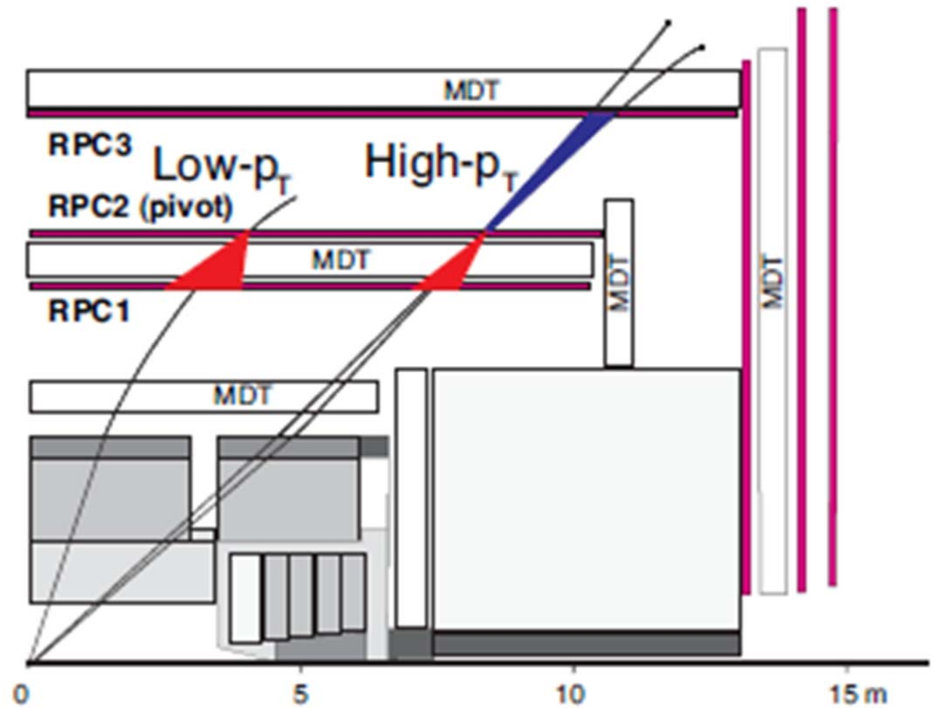
- **Level 1**
  - Corse CAL & Muon Spectrometer granularity and no ID tracking
  - Identifies **R**egions **o**f **I**nterest (**RoI**) for further processing at Level 2

- **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

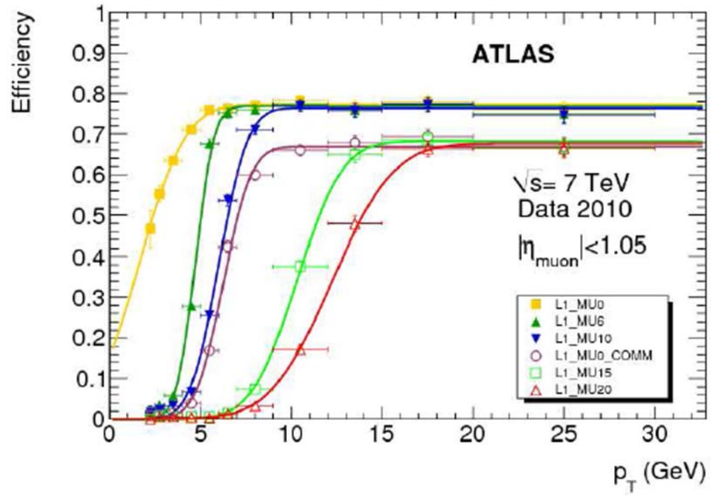


Muon Level1 Trigger

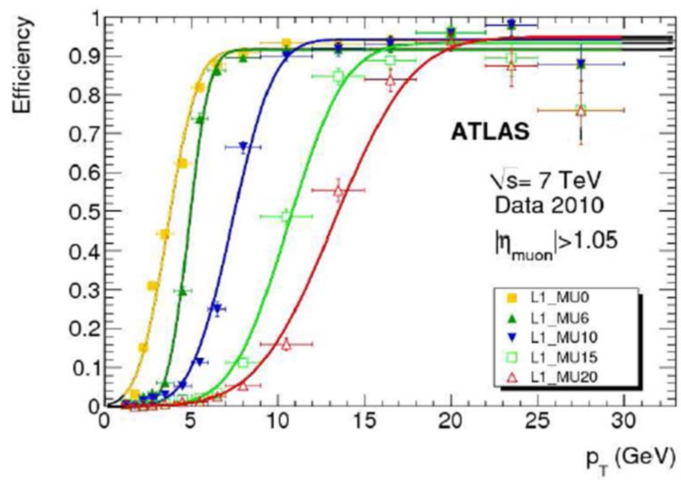
- based on three trigger stations
- The algorithm requires a coincidence of hits in the different trigger stations
- Defines a road: tracks the path of a muon from the interaction point through the detector.
- Width of the road depends on the p_T threshold.



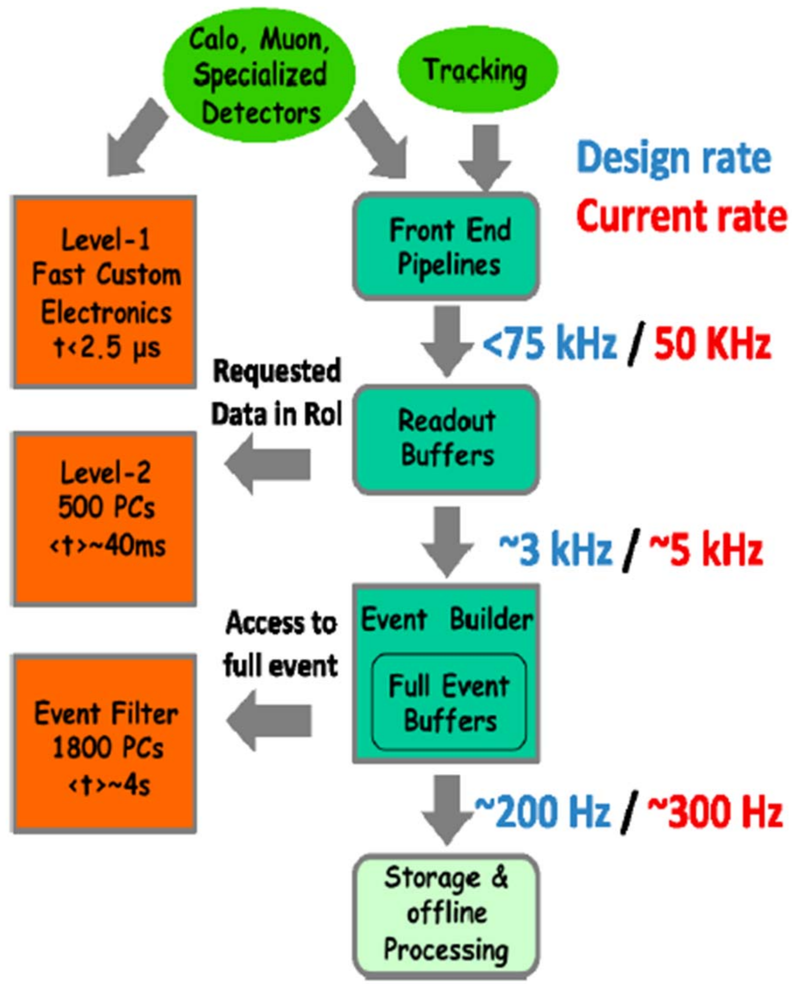
L1 Muon Trigger Efficiency



L1 muon trigger efficiency - Barrel

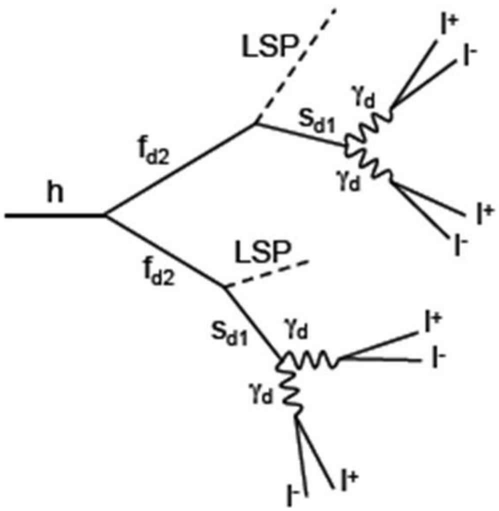


L1 muon trigger efficiency - Forward



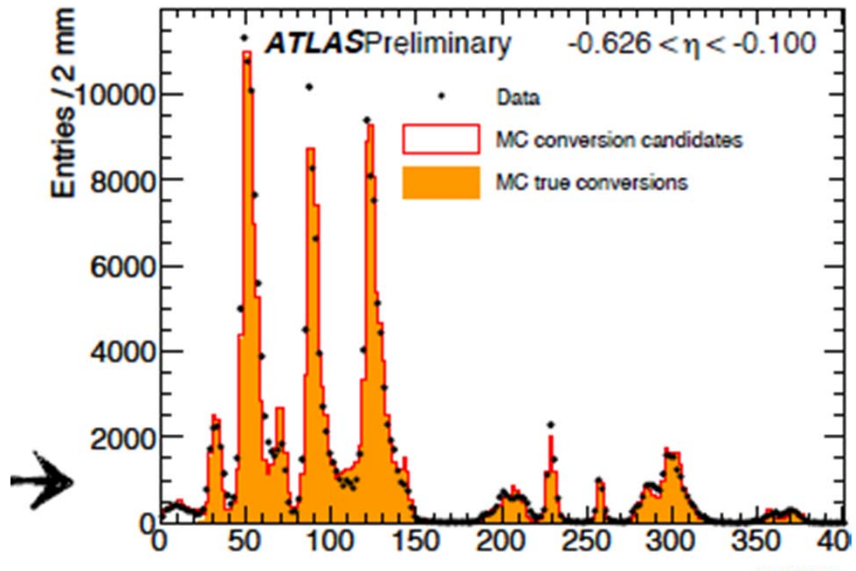
Level2 Triggers

- Both_ IP centric and muon stand alone triggers
- MSonly triggers (Muon stand alone triggers)
- Used in many analyses including long-lived decays of dark photons to lepton-jets
  - 3mu6_MSonly used to select decays to long-lived muon jets
  - 2mu6_MSonly_g10_loose used for selection of displaced decays to lepton jets (electrons/muons)
- Hidden Valley triggers
  - Select decays of neutral particles to hadron jets

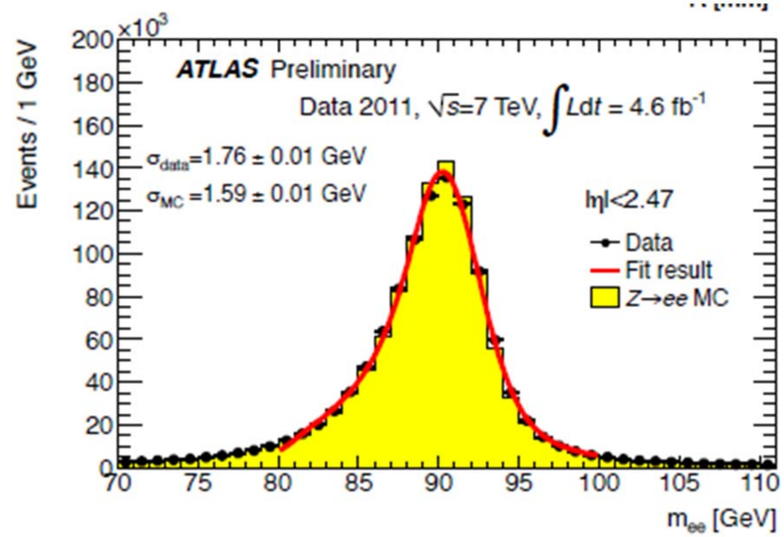


2011 Accomplishments

- Good understanding of material distribution from γ conversions



- Photon energy scale calibration from global fit to the 2011 data $Z \rightarrow e^+e^-$

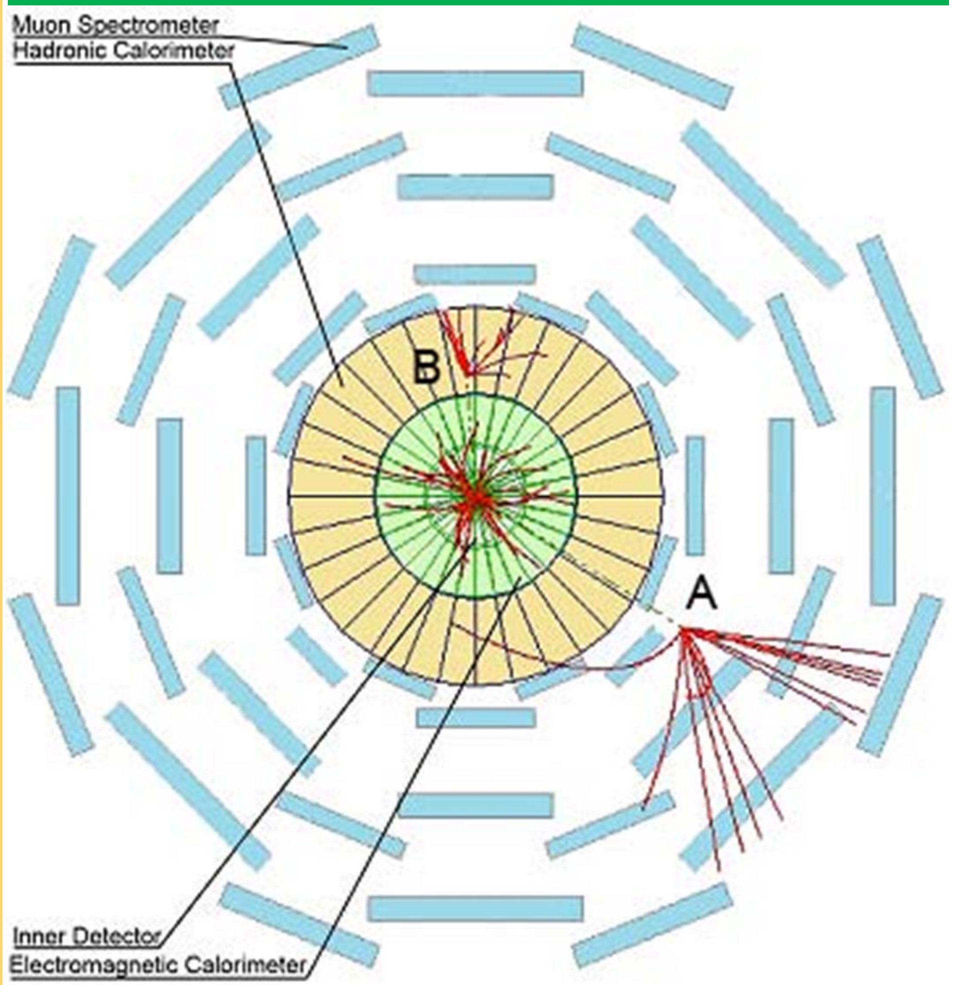


Triggers

- ATLAS triggers were designed to be IP centric and generally require a connection to the IP (b-tagging an exception)
- But many extensions of the SM models have suggested the possibility of long-lived neutral particles with a wide range of lifetimes, final states and production mechanism*
- New triggers needed to select such events

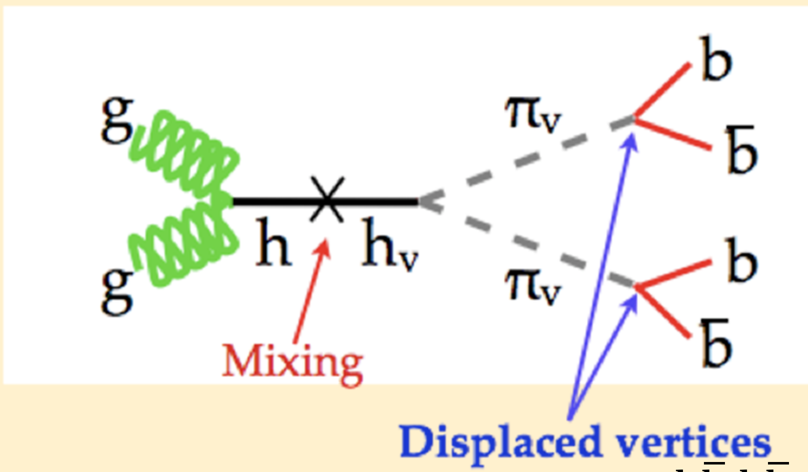
* S. Chang, R. Dermisek, J. F. Gunion and N. Weiner Ann. Rev. Nucl. Part. Sci. 58 (2008) for nice introduction

Neutral particles decaying to b-jets

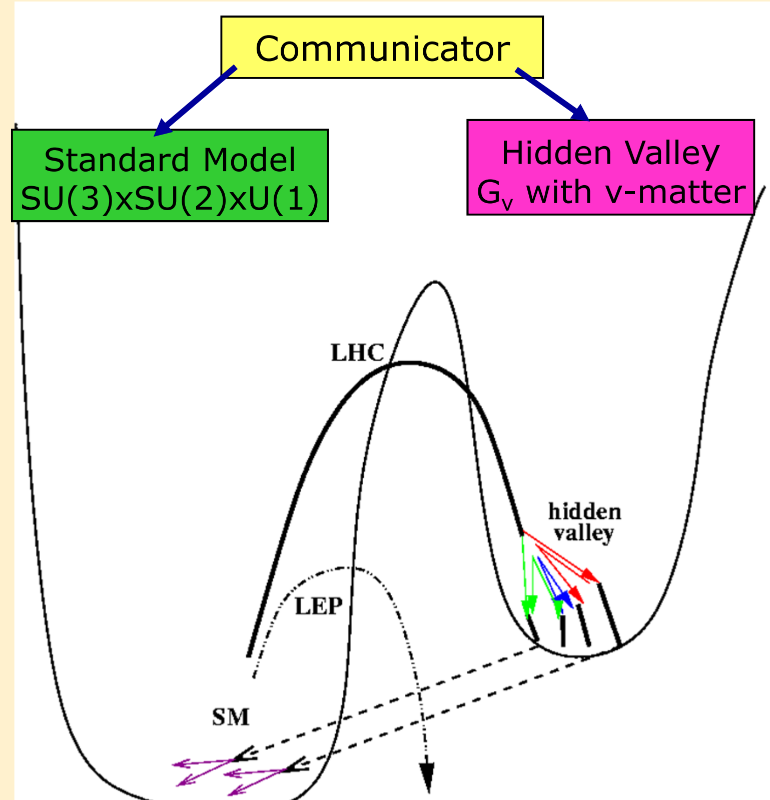


Long-lived Decays

- Hidden Valley (HV) Scenarios in which a new, hidden sector is weakly coupled to the Standard Model through a communicator(Higgs, Z', ...) used to bench mark triggers and for first search
- mixing between the SM and hidden sector Higgs boson



- Long-lived particles $h_v \rightarrow \pi_v \pi_v \rightarrow b\bar{b}\, b\bar{b}$
- Life-time of π_v unspecified by model
- First analysis searched for two displaced decays at end of H_{CAL} or in MS

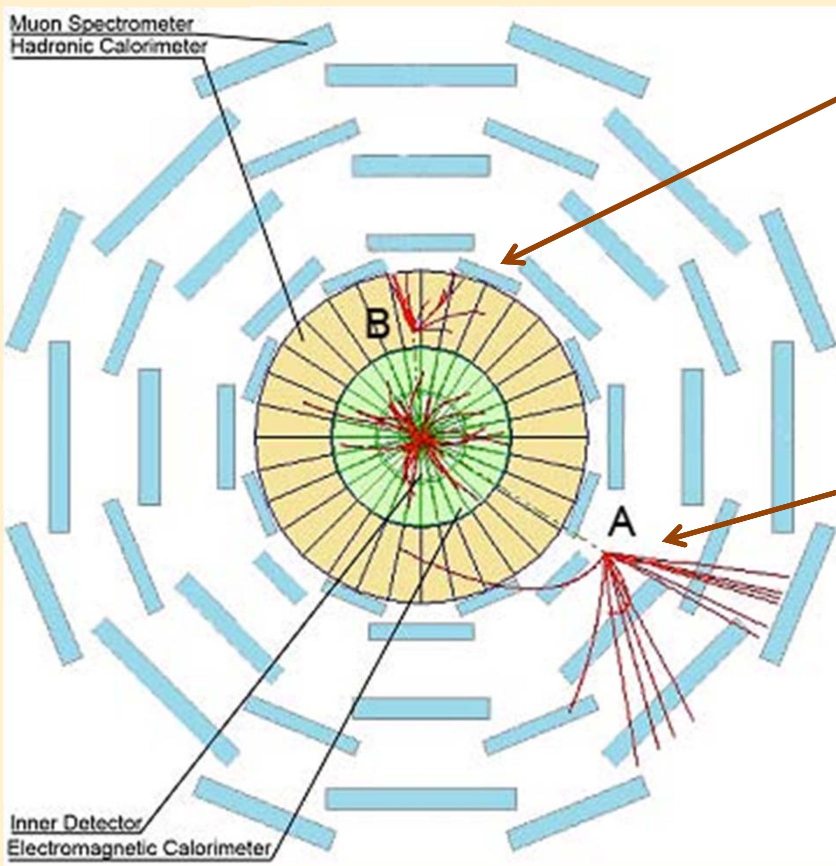


M. J. Strassler and K. M. Zurek Phys. Lett. B 661 (2008) 263-267.

Long-lived Particle Triggers

Signatures for displaced decays of neutral particles to $q\bar{q}$

MC event



Decays in or beyond ECAL gives E_{HAD}/E_{EM} ratio larger than observed for jets originating at IP

L2 Trigger Object

Decays near end of HCAL & before 1st muon trigger plane give hadron clusters in small $\Delta R(\eta,\phi)$ region of muon spectrometer and L1 muon trigger returns multiple RoIs in this small ΔR region

L2 Trigger Object

Long-lived Particle Triggers

Signature driven triggers

Increasing proper decay length

- Muon Spectrometer RoI cluster trigger — 4 – 7 m
  - Selects decays inside of MS (only active in barrel)
  - Events with at least 3 muon RoI's in $\Delta R < 0.4$ cone
  - Isolation
    - Jets with $E_T > 35$ GEV in $\Delta R < 0.4$ around cluster center
    - ID tracks ($p_T > 5$ GeV) in $\Delta\eta \times \Delta\phi = 0.2 \times 0.2$
- Calorimeter energy ratio trigger (E_{HAD}/E_{EM}) — 2 – 3 m
  - Selects decays at end of E_{CAL} or in H_{CAL}
  - $\text{Log}[E_{HAD}/E_{EM}] > 1.2$
  - Isolation
    - No tracks > 1 GeV in $\Delta R = 0.2$ cone around the jet axis
- Trackless jet trigger (decays in ID…) — 0.5 – 3 m
  - μ-jet matching in $\Delta R = 0.4$
  - Isolation: No tracks > 0.8 GeV in $\Delta R = 0.2$ around jet axis

Long-lived Particle Triggers

Signature driven triggers

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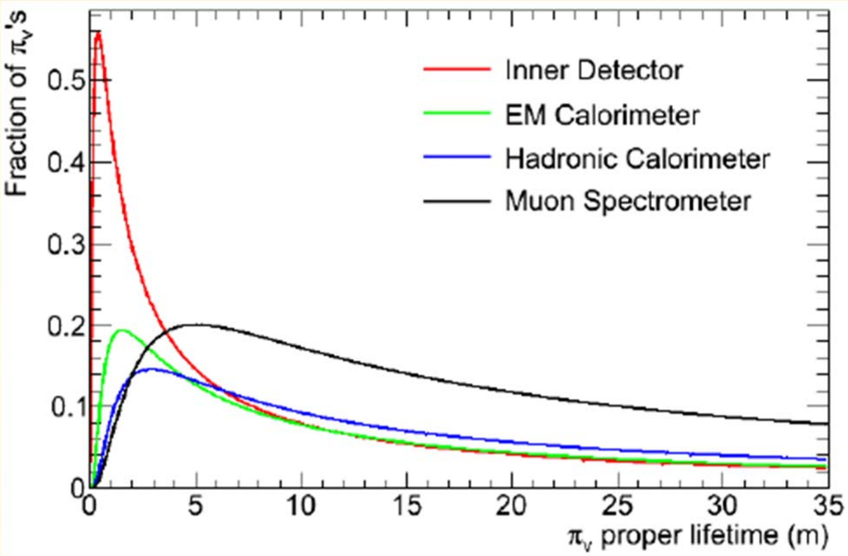
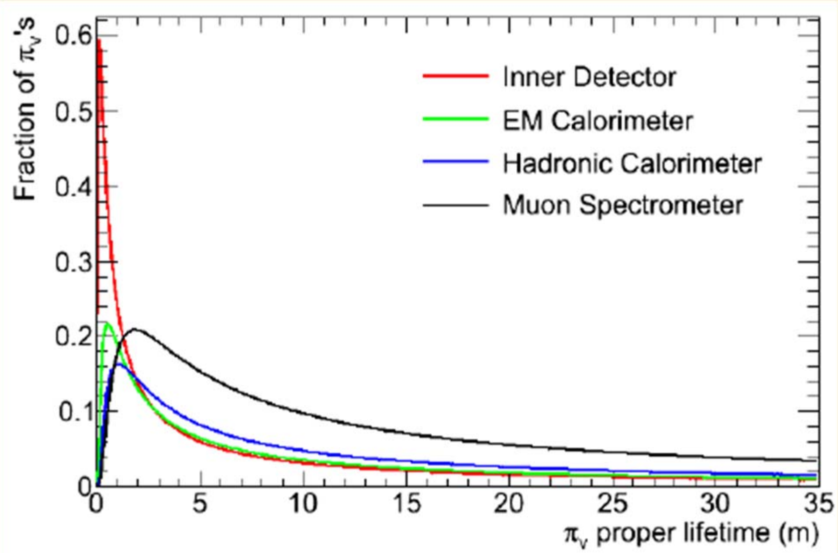
Decay probabilities

- Probability for a π_v to decay in each of the detector regions as a function of the π_v proper decay length
- Depends on boost (masses of decaying particles)
- Generator level simulation of $h_v \rightarrow \pi_v \pi_v \rightarrow b\bar{b}\, b\bar{b}$



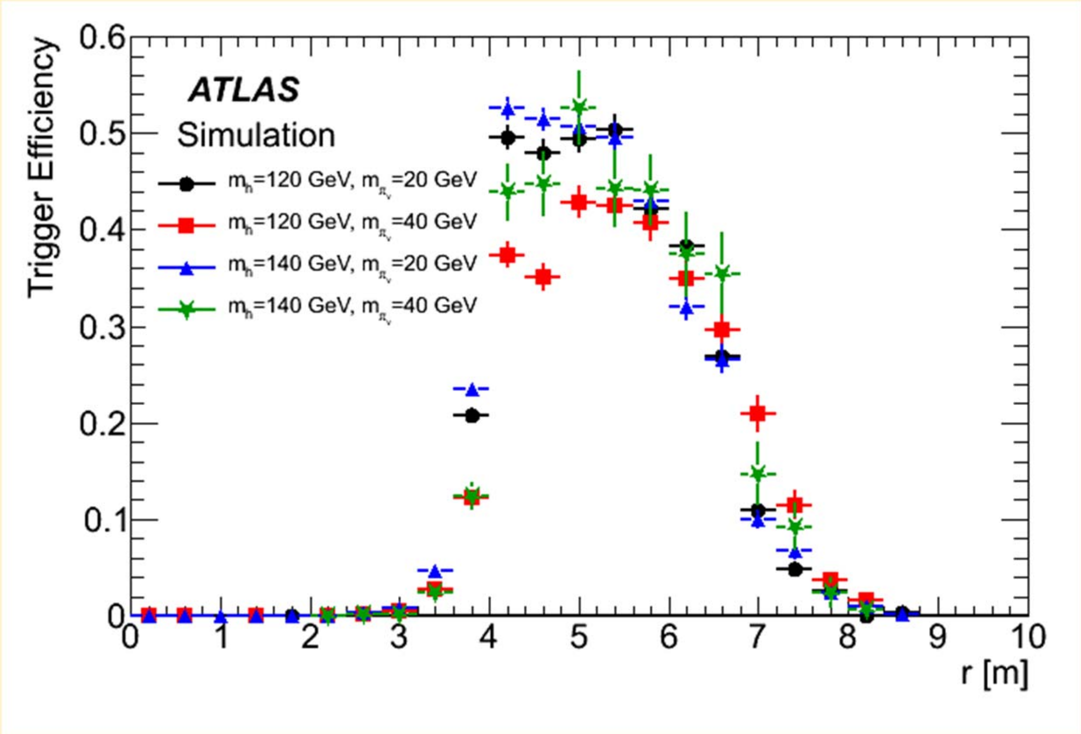
m_h = 120 GeV/c^2, $m_{\pi v}$ = 40 GeV/c^2



m_h = 140 GeV/c^2, $m_{\pi v}$ = 20 GeV/c^2

- Probability for decay in barrel and forward detectors ($|\eta| \leq 2.5$)

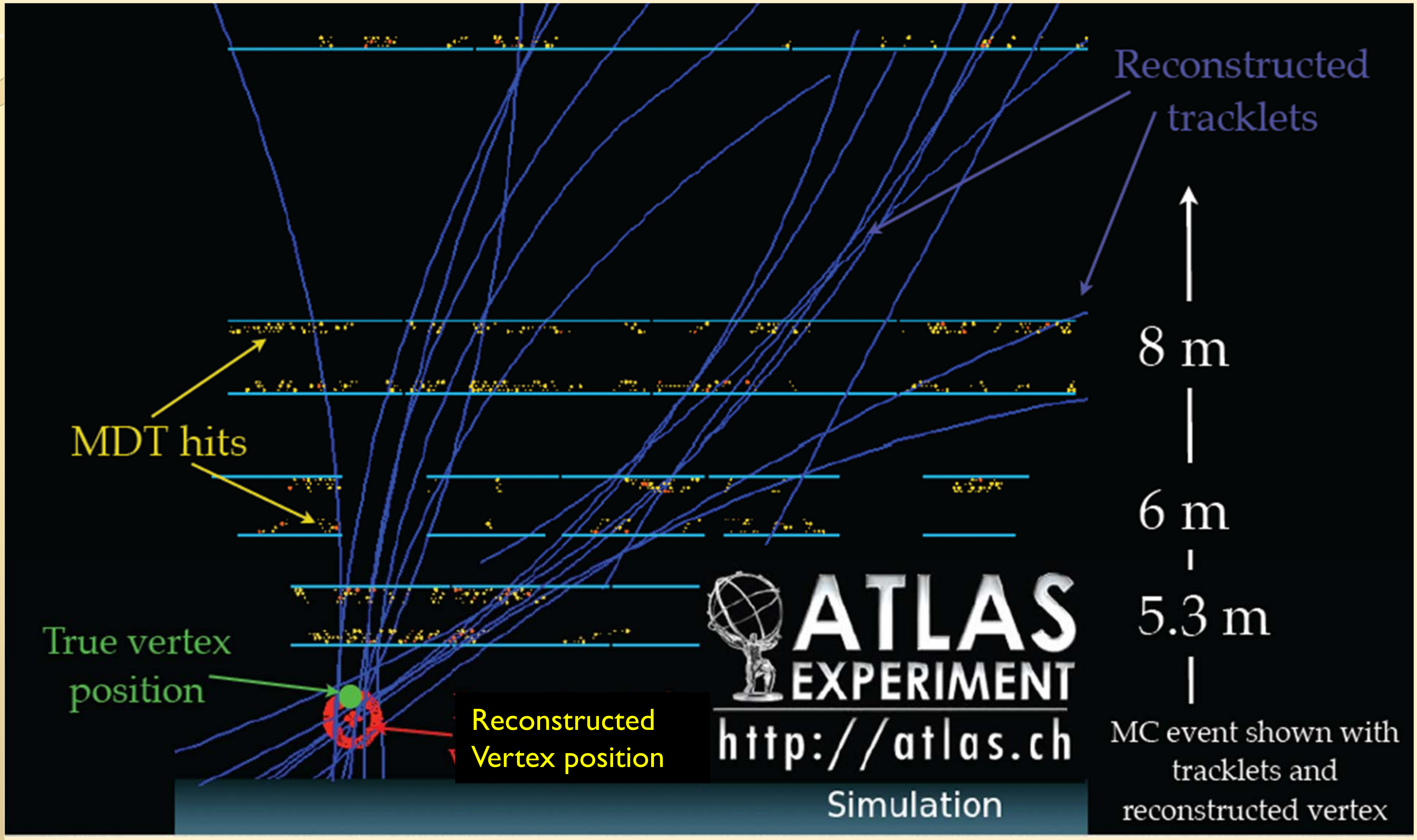
Trigger efficiency – MS Decays



- Fraction of π_v's that decay at a given radius that result in a trigger
- Trigger is 40 – 50% efficient in barrel MS
- Lower efficiency for m_h = 120 GeV/c, $m_{\pi v}$ = 40 GeV result of kinematics and trigger timing (π_v arrives in next BC)

Search for Long-lived Particle s in MS

Standalone MS vertex routine developed for displaced vertices in the MS

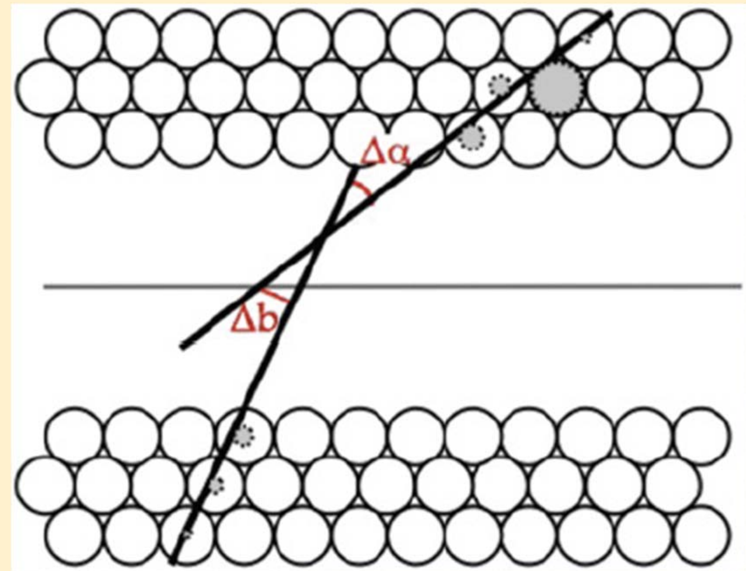


Vertex Reconstruction in MS

New

Dedicated

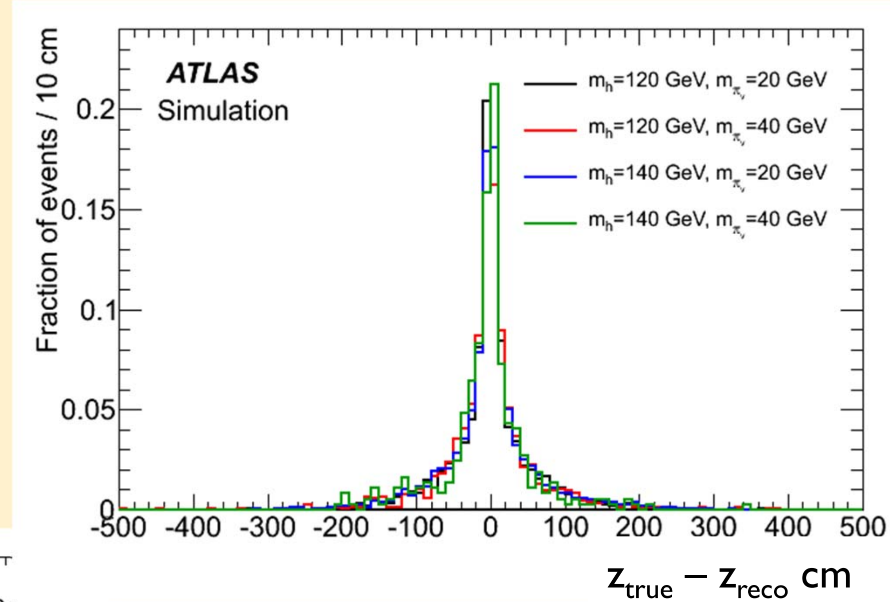
- Reconstruct single segments from ≥ 3 MDT hits
  - Segments pointing to second ML kept if χ^2 > 5%
  - No ϕ information (too many hits in RPC's)
- ML separation gives powerful handle for pattern recognition

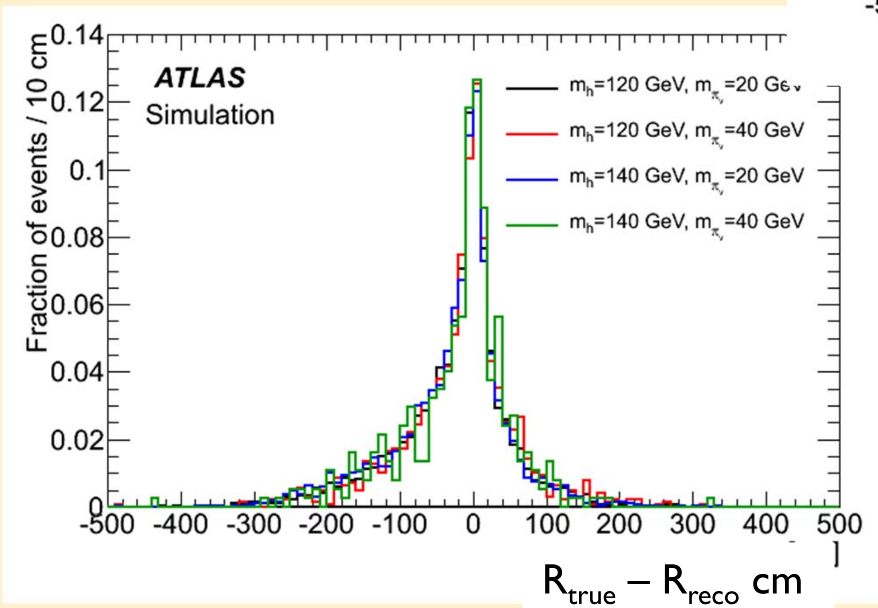


- Tracklets reconstructed by matching segments using the two parameters Δb and $\Delta\alpha$
- Δb is distance of closest approach at the mid-plane of MDT chamber
- $\Delta\alpha$ is amount of bending in the chamber and combined with the average magnetic field gives a measure of the tracklet momentum with uncertainty $\Delta p/p \approx [0.06 - 0.08]p$

Long-lived Particle Triggers

- Vertex resolution in the barrel MS is approximately 20 cm in z and 30 cm in R
- Reconstruction efficiency
  - 40 % in barrel MS
  - 50% in forward MS



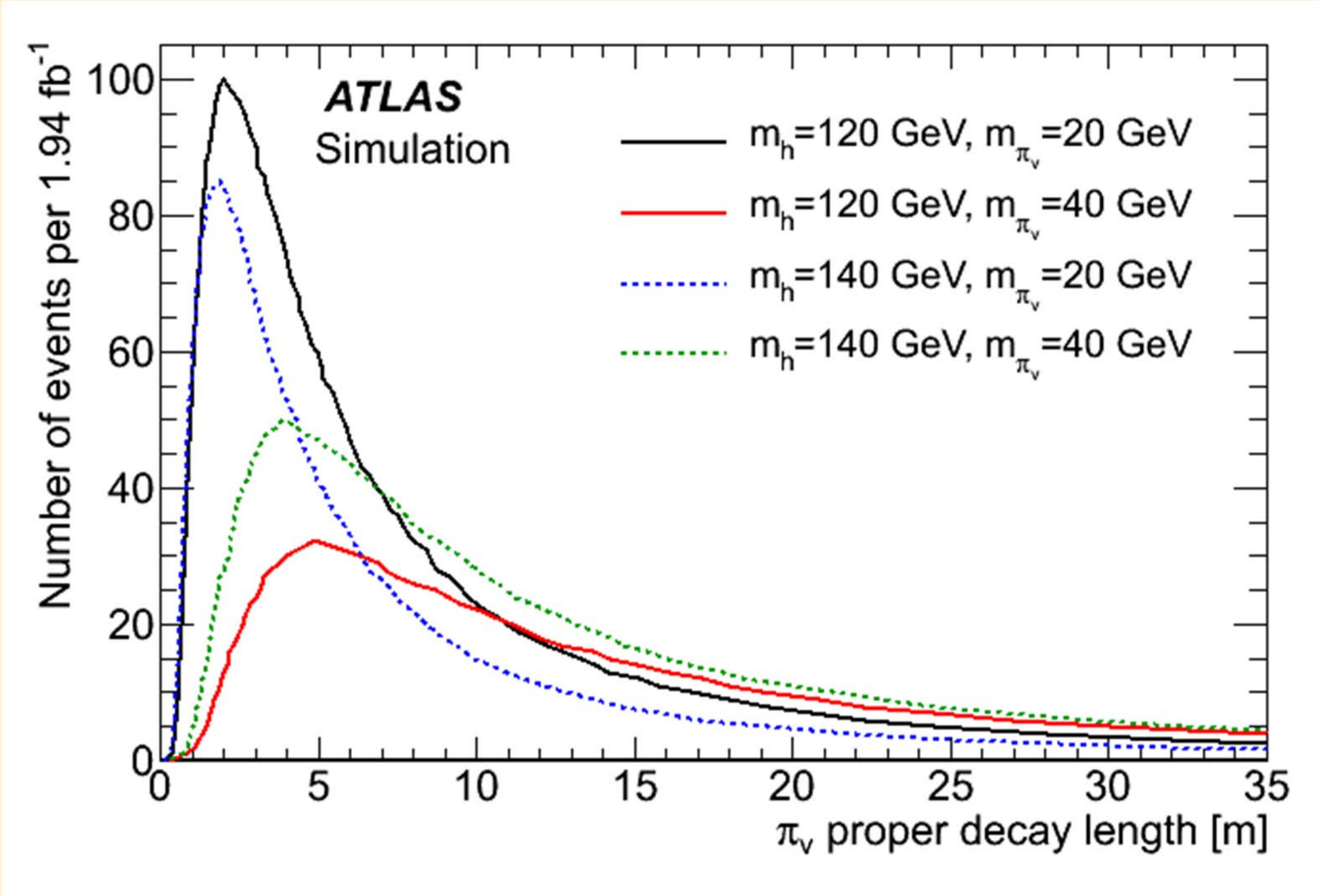


Powerful tool for rejecting QCD jets punch through backgrounds

Analysis Strategy

- Search for events where two decays occur in the MS where one decays in the barrel
- Only events passing the Muon RoI cluster trigger
- Final event selection requires two good MS vertices separated by $\Delta R>2$ (back-to back)
- Each vertex required to
  - Point to the IP (sum of tracklet p_z points to IP)
  - MDT and RPC/TGC hits in cone centered on vertex be in the range $200 \leq N_{MDT} \leq 3000$ and $N_{RPC/TGC} \geq 100$
  - Isolation: jets with $E_T \geq 15$ GeV and $\log_{10}[E_{HAD}/E_{EM}] \leq 0.5$
  - Vertex in the ID tracking volume - $|\eta_{vx}| < 2.2$
  - Isolation: ID tracks with $p_T \geq 5$ GeV

Expected decays



Expected number of $h^0 \rightarrow \pi_v \pi_v$ events, with two isolated MS vertices for an integrated luminosity of 1.94 fb^{-1}, as a function of the π_v lifetime assuming 100% branching ratio for $h^0 \rightarrow \pi_v \pi_v$

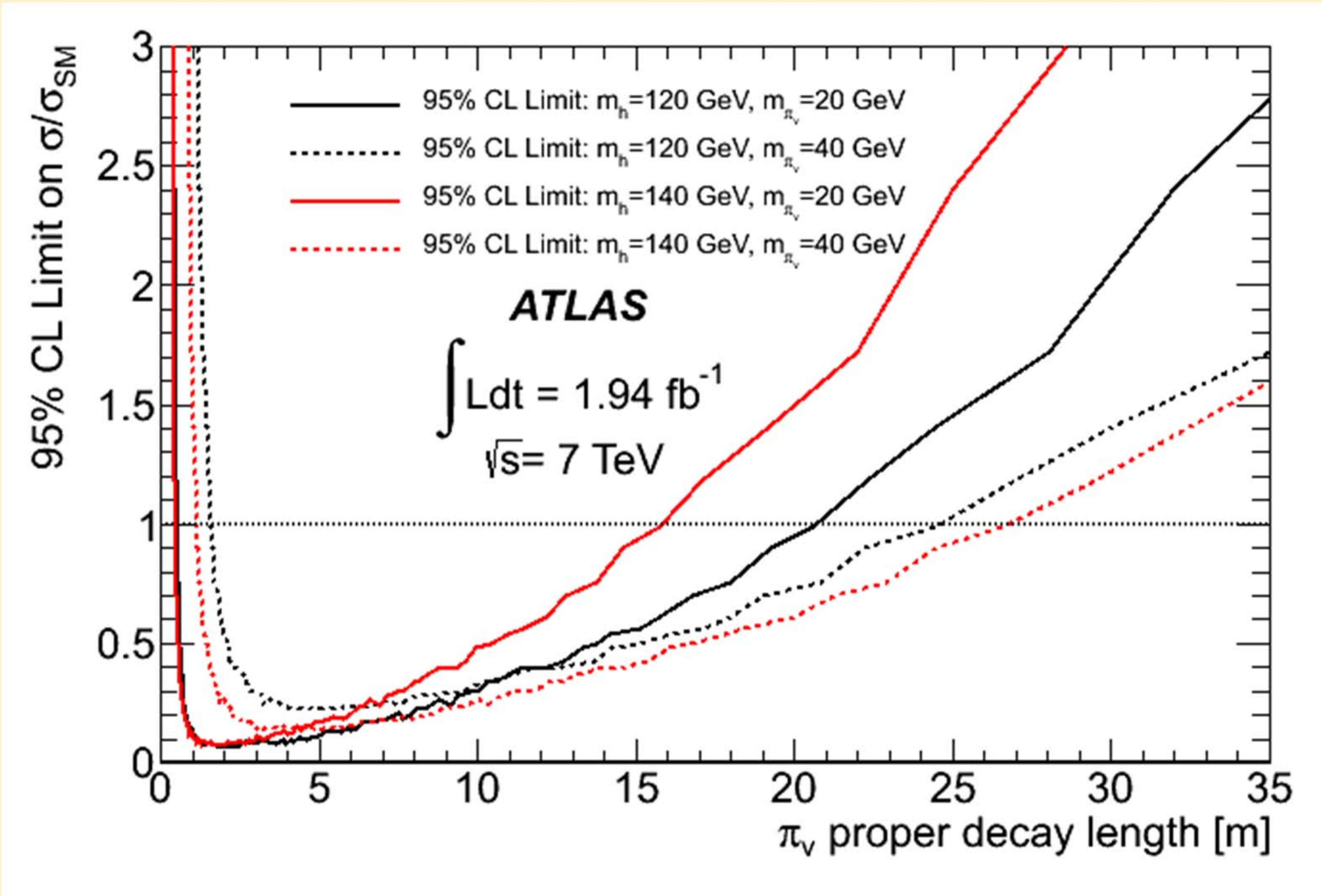
Results

- No events in 1.94 fb^{-1} of 2011 LHC data pass the selection criteria requiring two back-to-back vertices in MS
- Expected background determined by data driven method: 0.03 ± 0.02 events
- Limits
  - Expected number of signal events determined from trigger and reconstruction efficiencies
  - In essence, a counting experiment that is repeated for each π_V lifetime.
  - Take gluon fusion Higgs cross section (σ_{SM}) from LHC Higgs Cross Section Working Group, S Dittmaier, C. Mariotti, G. Passarino and R. Tanaka (Eds.) - CERN 2011-022

Limits

New

arXiv:1203.1303v2 accepted PRL



Limits - summary

- Observed no events in 1.94 fb^{-1} with back-to-back vertices in muon spectrometer
- Stringent exclusion limits obtained for $\sigma_h \times BR(h^0 \rightarrow \pi_v \pi_v) / \sigma_{SM}$
- Assuming 100% $h^0 \rightarrow \pi_v \pi_v$ branching ratio we exclude π_v proper decay lengths in a broad range

m_{h^0} (GeV)	m_{π_v} (GeV)	Excluded Region
120	20	$0.50 < c\tau < 20.65$ m
120	40	$1.60 < c\tau < 24.65$ m
140	20	$0.45 < c\tau < 15.8$ m
140	40	$1.10 < c\tau < 26.75$ m

- Model independent limits on $\sigma \times A \times \varepsilon_{trig} \times \varepsilon_{reco} < 3.6$ fb, where A is acceptance, ε_{trig} and ε_{reco} the trigger and reconstruction efficiencies

Contributors to first result

- University of Washington
  - HL, **Dan Ventura***, A. Policicchio*, G. Watts
- University of Rome (La Sapienza)
  - G. Ciapetti, S. Giagu
- Matt Strassler (during initial stage)

*** PhD thesis, now at U. Mass. Amherst**

* Now at Università della Calabria (Italy)

Long-lived Particle II

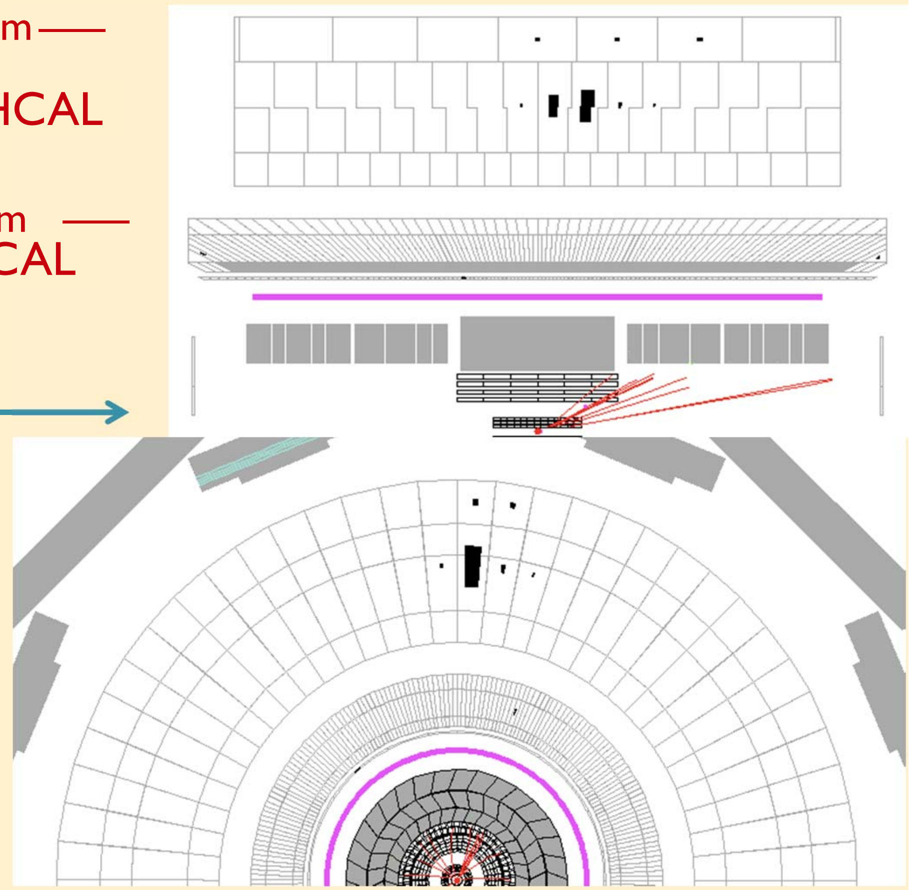
- Currently working on search for decays at end of ECAL or in HCAL

4 m

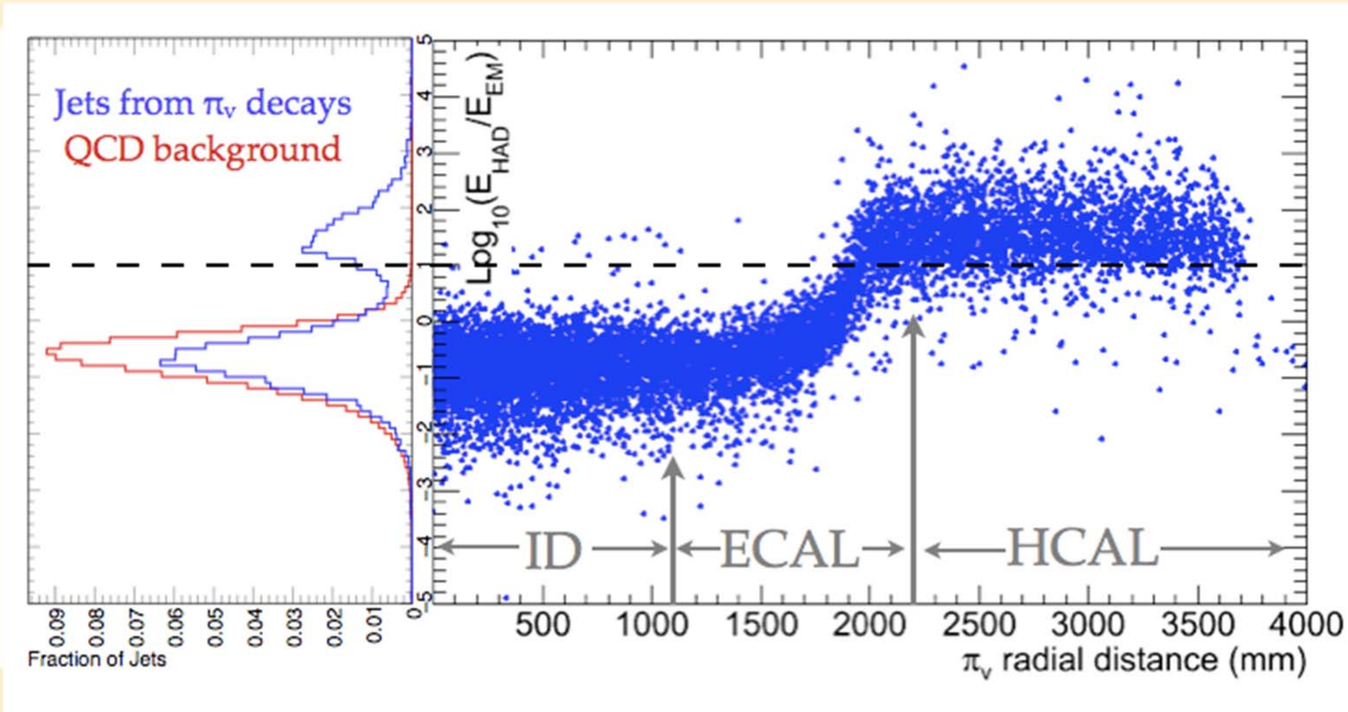
- Large energy deposition in HCAL → HCAL

2 m

- Little or no energy in ECAL → ECAL
- Jets with no tracks reconstructed in ID with $p_T > 1$ GeV
- Suggests ratio E_{HCAL}/E_{ECAL} may be good trigger object



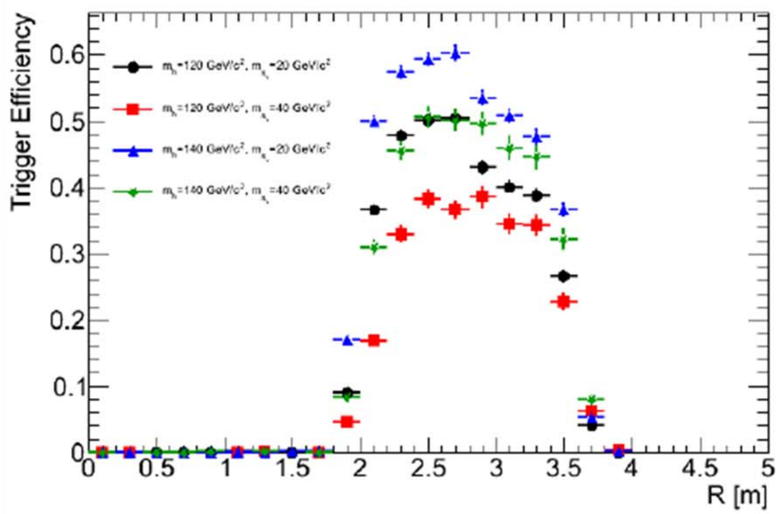
$Log_{10}[E_{HAD}/E_{EM}]$

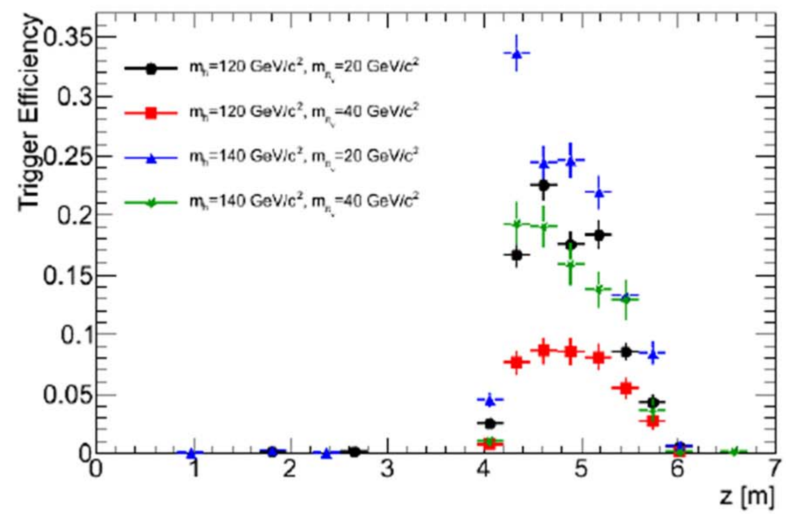


- Normal Low p_T b-jets from IP or ID loose nost of energy in E_{CAL} - $Log_{10}[E_{HAD}/E_{EM}]$ ~ -1
- BUT jets from π_v decays at end of E_{CAL} and beyond have $Log_{10}[E_{HAD}/E_{EM}]$ ~ 1.5 – Trigger object at Level 2

Efficiency

- Efficiency 40 to 50% in barrel
- In Forward region about 15 - 20%

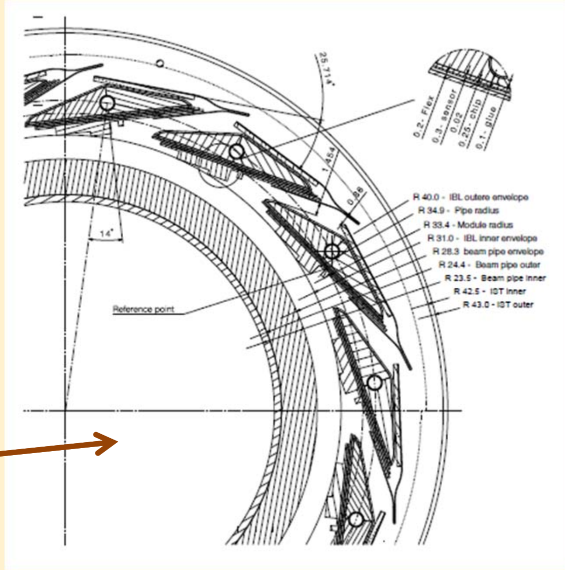




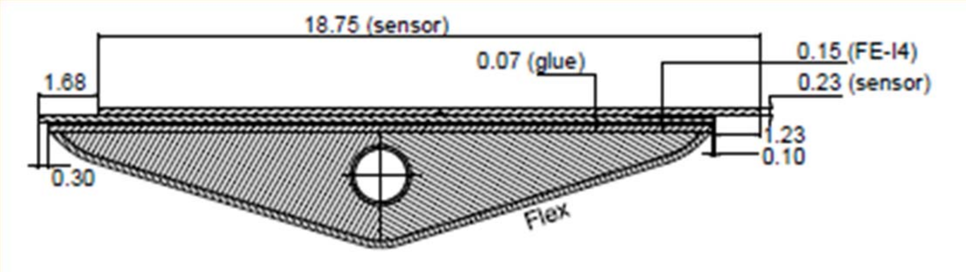
Decays in H_{CAL}

- Currently completing this analysis on the full 2011 data set ~ 4.6 fb^{-1}
- Do not have vertex handle to reduce backgrounds from QCD jets
- Require coincidence of two Cal Ratio triggers or one Cal Ratio trigger and a "trackless jet"
- Data driven background estimates

ATLAS Upgrades and LHC Shutdowns



- Shutdown ~ 1 December 2012
  - Ends 31st July 2014 (about 20 months)
  - Machine development (13-14 TeV) operation to end 2014
- Phase 0 ATLAS upgrades
  - **IBL** (Isertable B Layer)
    - 14 staves, located at r ~ 33.4 mm loaded with silicon sensors new front-end (IC) FE-I4 *
    - Current pixels layer 1 at 50.5 mm (cf slide 5); nominal insertion clearance is about 2 mm radially



Individual stave

* M. Karagounis et al., Development of the ATLAS FE-I4 pixel readout IC for the b-layer upgrade and 844 Super-LHC, Proceedings of Topical Workshop on Electronics for Particle Physics TWEPP 2008, 845 Naxos, Greece, 15-19 Sep 2008, CERN-2009-006, 70-75 .

Phase 0 Upgrade 2013-14

- Phase 0 activities

Be Beam pipe
AL VA, VT beam pipes
IBL INSERTABLE B-LAYER
nSQP/Pixel
new diamont det. for monitors
new evaporative cooling plant
new CO2 IBL cooling plant
remove MB scint, restore tiles readout
new LVPS for LAr
new LVPS for Tiles
repair several Tiles drawers (connectors)
finish EE installation
RPC feet chambers electronics installation
MDT+RPC chambers in sect 13 elevators
substitute few TGC chambers in the BW
new He dryer for magnet main refrigerator
new redundant compressor for the main refrig.
new He tank for Solenoid transfer line
various electrical, vacuum and mechanical magnet consolidation
new neutron shielding on the toroid endcap
new neutron shielding wall UX15/USA15
various access platforms (permanent, temporary,movement system,..)
new visitors passage(cage)
tool for removing at once the lower part of the JF
interface FTK- SCT-PIXEL (Fast TracKer)

The longer term

- Shutdown ~ 2018
  - Upgrade for luminosities of >$10^{34}cm^{-2}s^{-1}$
- **Phase 1** ATLAS upgrades – active discussion and planning currently (examples)
  - New muon small wheel to replace CSCs
  - Target is to implement full digital read-out of the calorimeter at 40 MHz
- Phase 2 (2022-2023)
  - Major changes to tracking system $5\times10^{34}cm^{-2}s^{-1}$ operation
  - Replace the complete strip detector system
    - electronics and sensors with finer granularity
    - greater radiation tolerance.
    - Project has such a large lead-time that it already is taking considerable R&D resources