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# The ATLAS trigger

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# Outlook

- The LHC and the ATLAS experiment
- The ATLAS trigger system
  - Level-1 Trigger
  - High-Level Trigger
  - Trigger Menu and Configuration
  - Trigger Performance
- Commissioning of the ATLAS trigger
  - "Technical runs"
  - Operation with first beam
  - Trigger performance in cosmic runs

# The LHC and the ATLAS Detector

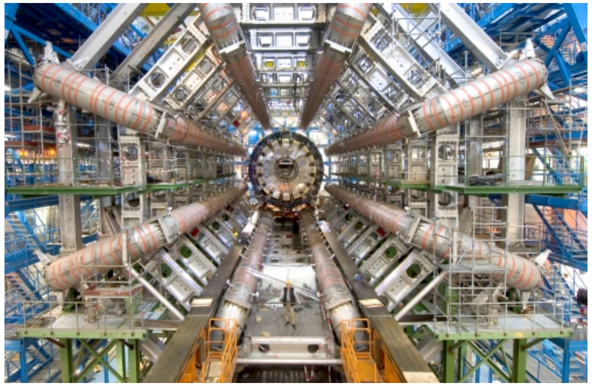
# The Large Hadron Collider

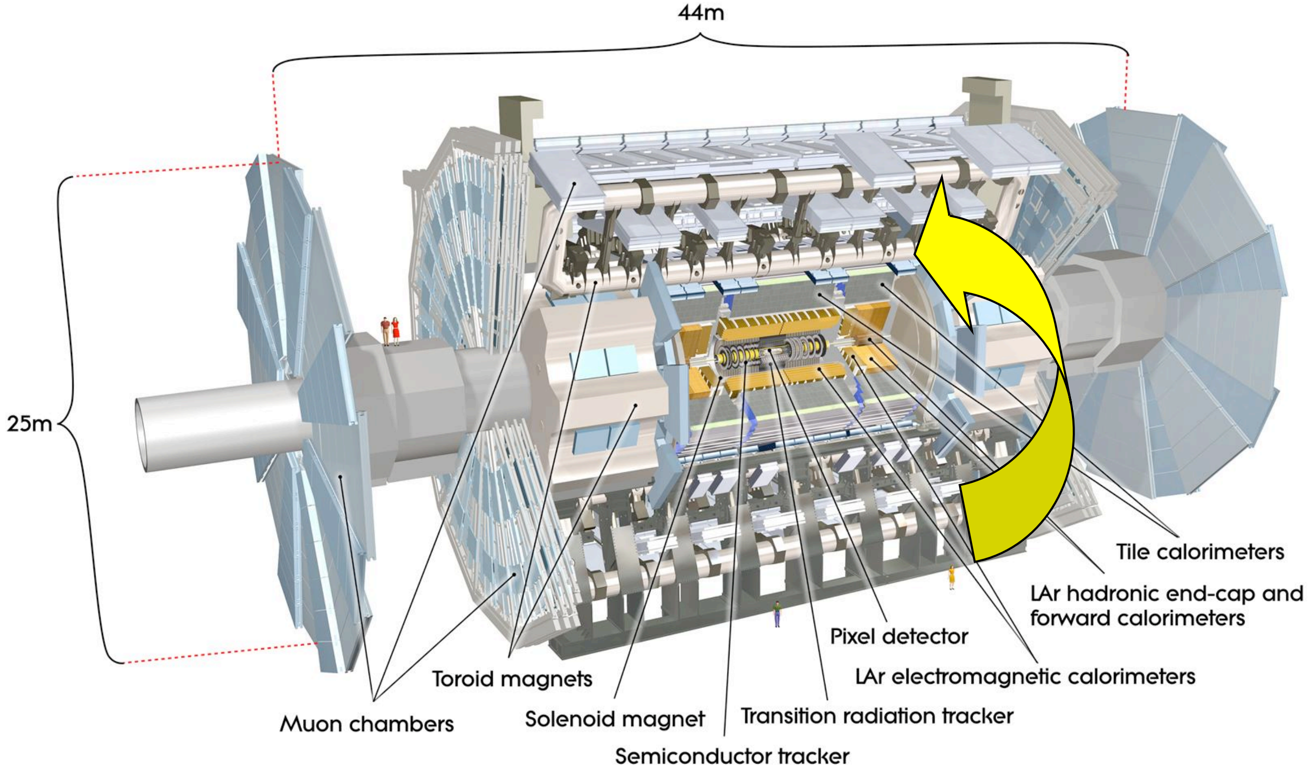
- The LHC started operating on September 10th last and will resume in July/August this year
- Four main experiments:
  - ATLAS and CMS – general-purpose
  - LHCb – B physics
  - ALICE – heavy-ion physics

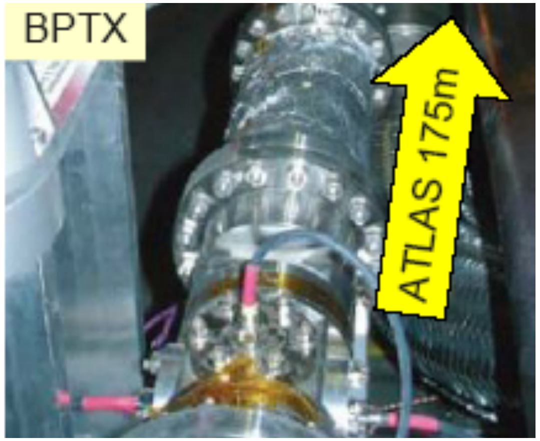
| **CM energy** | **14 TeV (design)** |
|---|---|
| Luminosity ($cm^{-2}s^{-1}$) | Low: $2x10^{33}$<br>High: $10^{34}$ |
| Bunch crossing | 24.95 ns |
| Overlaid events | 23 @ $10^{34}cm^{-2}s^{-1}$ |
| Beam radius | 16.7 µm |
| Particles/bunch | $1.15x10^{11}$ |
| Bunches/beam | 2808 (design) |
| **Stored energy** | 362 MJ/beam |

# The ATLAS Detector

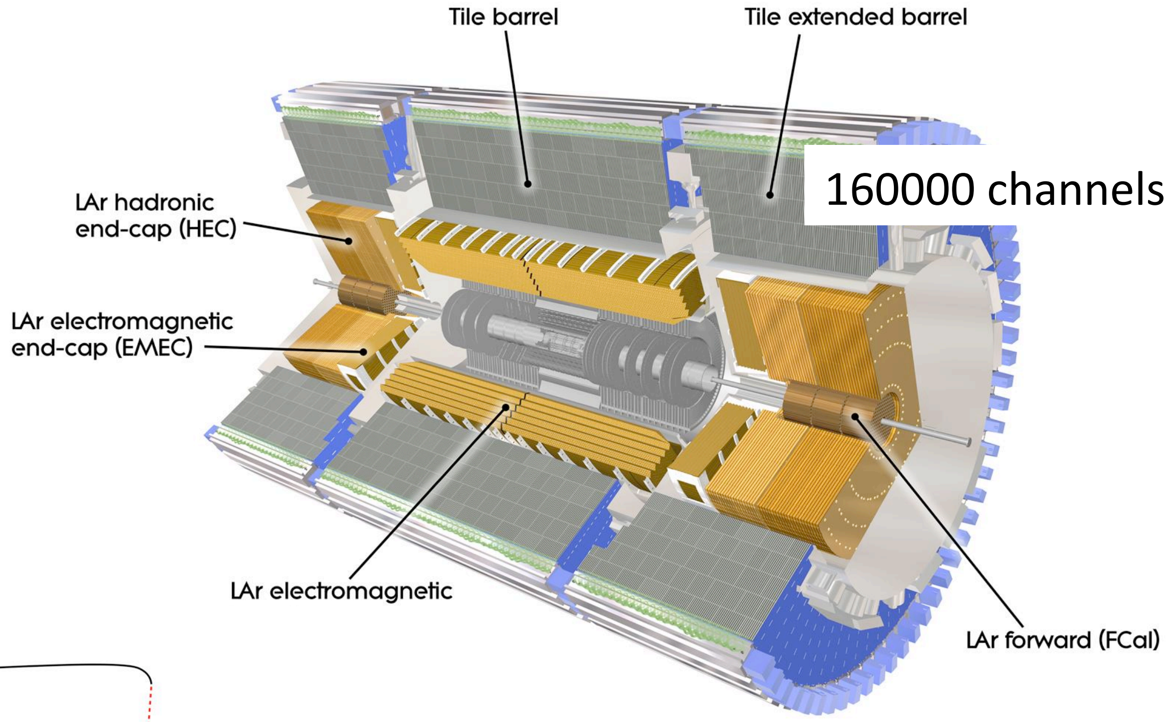
- Large angular coverage: $|\eta|<4.9$; tracking in $|\eta|<2.5$
- Inner detector: pixels, Si-strips and transition Radiation Tracker in for particle identification
- Liquid Argon electromagnetic calorimeter with accordion geometry
- Iron-scintillating tile hadronic calorimeter; tiles placed radially and staggered in depth
- Toroidal magnetic field (peak 4T) in air-core toroids; 2T in solenoid around Inner Detector



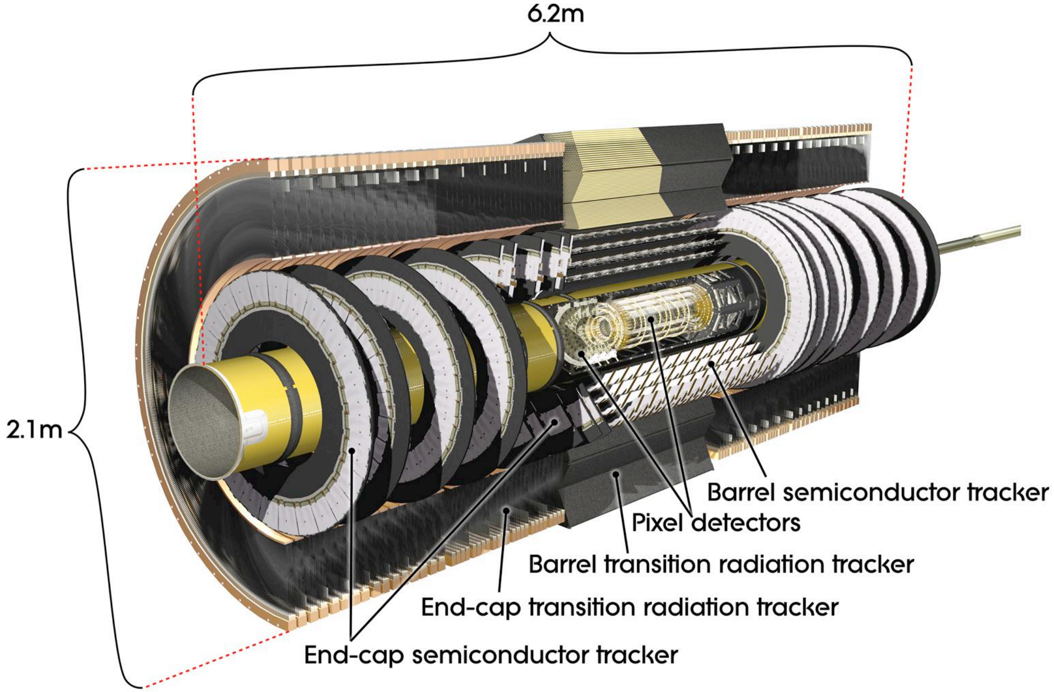




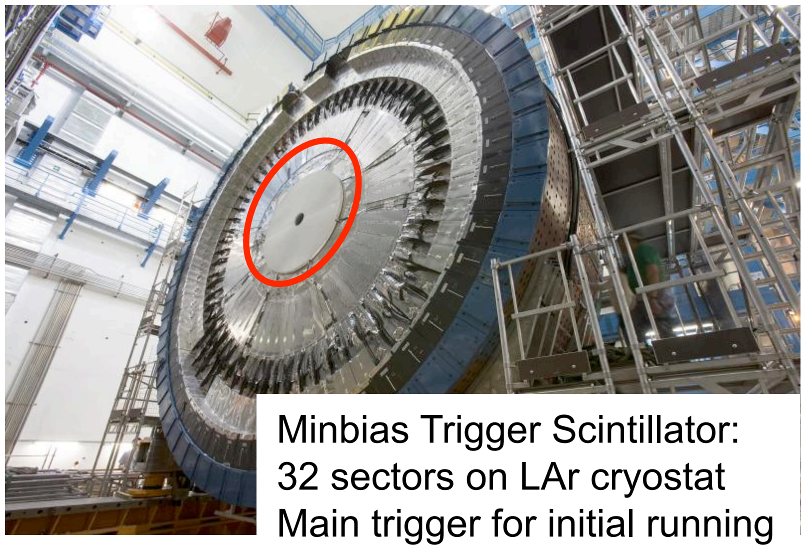

Beam Pickup: at ± 175m from ATLAS
Trigger on filled bunch
Provide the reference timing




160000 channels

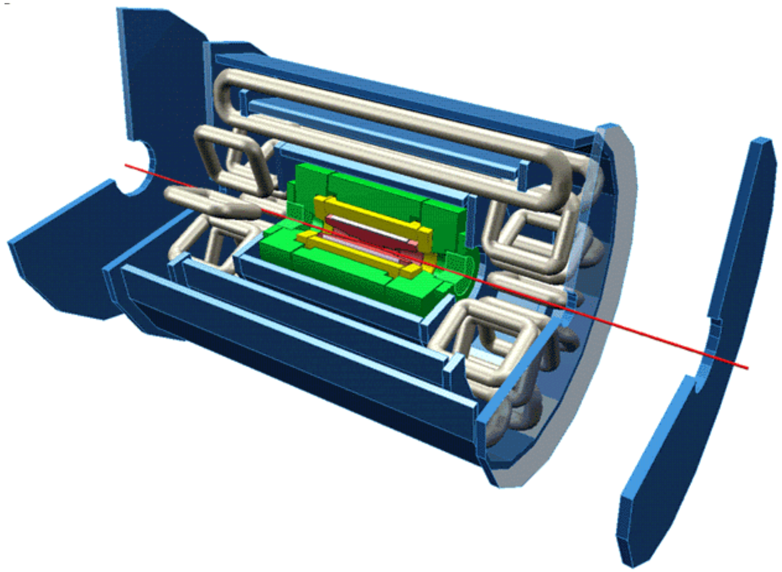


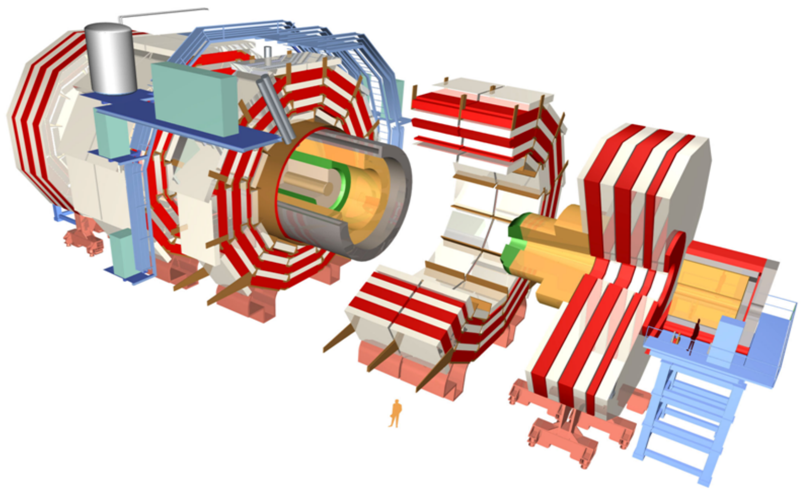

Pixel: 10x100µm; 80 M channels
Strips: 80µm; 6 M channels



Minbias Trigger Scintillator:
32 sectors on LAr cryostat
Main trigger for initial running
$\eta$ coverage 2.1 to 3.8

| | ATLAS | CMS |
|---|---|---|
| Magnetic field | 2 T solenoid + toroid (0.5 T barrel 1 T endcap) | 4 T solenoid + return yoke |
| Tracker | Si pixels, strips + TRT<br>$\sigma/p_T \approx 5x10^{-4} p_T + 0.01$ | Si pixels, strips<br>$\sigma/p_T \approx 1.5x10^{-4} p_T + 0.005$ |
| EM calorimeter | Pb+LAr<br>$\sigma/E \approx 10\%/\sqrt{E} + 0.007$ | PbWO4 crystals<br>$\sigma/E \approx 2\text{-}5\%/\sqrt{E} + 0.005$ |
| Hadronic calorimeter | Fe+scint. / Cu+LAr (10λ)<br>$\sigma/E \approx 50\%/\sqrt{E} + 0.03$ GeV | Cu+scintillator (5.8λ + catcher)<br>$\sigma/E \approx 100\%/\sqrt{E} + 0.05$ GeV |
| Muon | $\sigma/p_T \approx 2\%$ @ 50GeV to 10% @ 1TeV (ID+MS) | $\sigma/p_T \approx 1\%$ @ 50GeV to 5% @ 1TeV (ID+MS) |
| Trigger | L1 + RoI-based HLT (L2+EF) | L1+HLT (L2 + L3) |

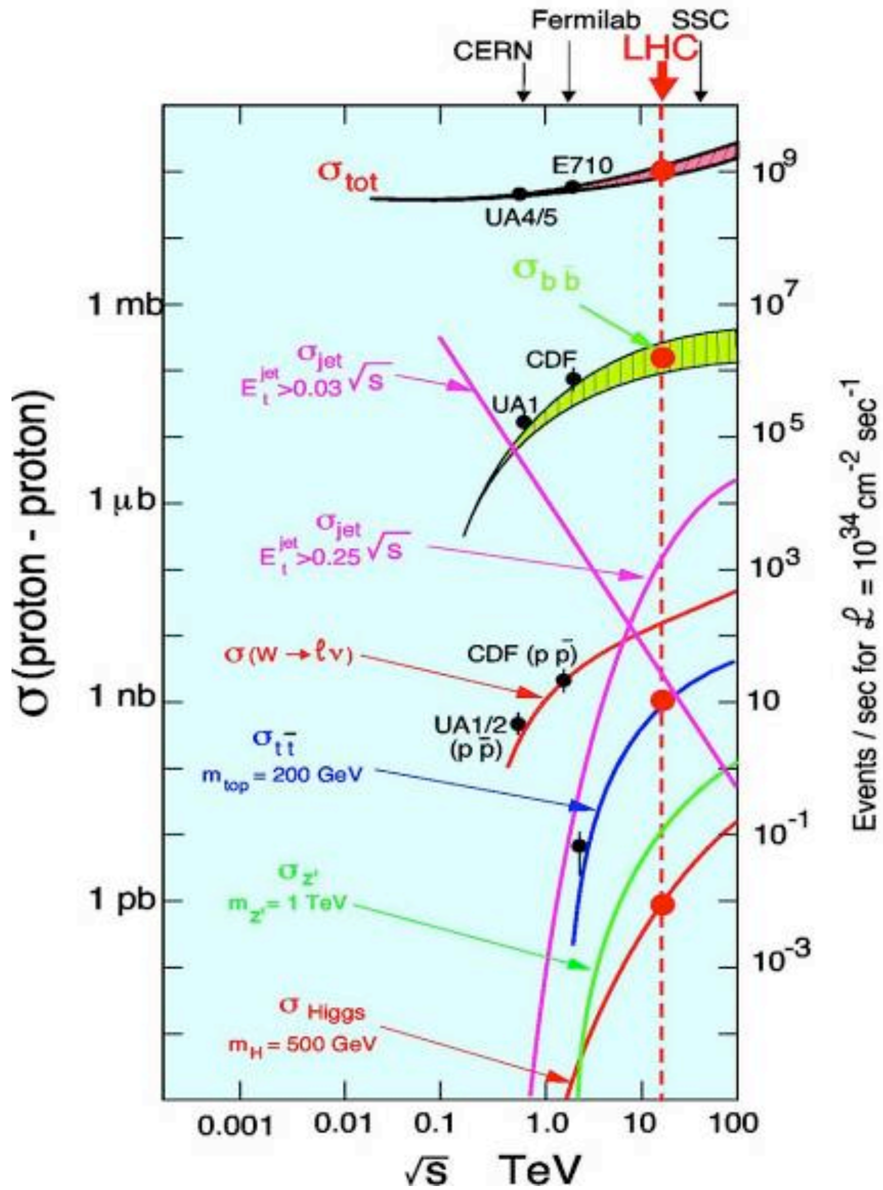




# The ATLAS Trigger

# Challenges faced by the ATLAS trigger

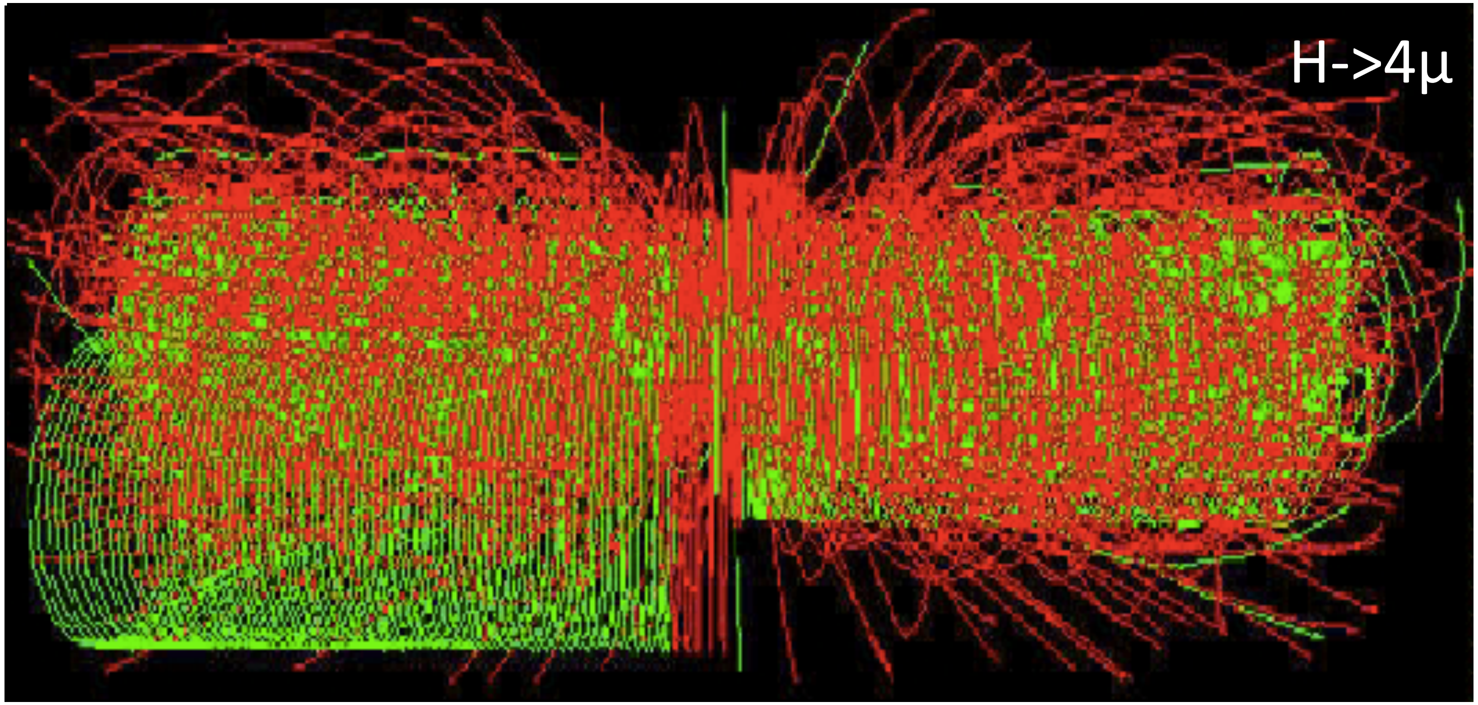
- Much of ATLAS physics means cross sections at least ~$10^6$ times smaller than total cross section
- 25ns bunch crossing interval (40 MHz)
- Event size 1.5 MB (x 40 MHz = 60 TB/s)
- Offline storing/processing: ~200 Hz
  - ~5 events per million crossings!
- In one second at design luminosity:
  - 40 000 000 bunch crossings
  - ~2000 W events
  - ~500 Z events
  - ~10 top events
  - ~0.1 Higgs events?
  - **200 events written out**
- We'd like the right 200 events to be written out!...



- Ok, so we reject background and take only signal events

Maybe not so simple:

  - Bunch spacing is 25ns: not much time to decide! (25ns x $c$ = 7.5m)
  - Put event fragments in memory pipeline to buy time for Level 1 decision
  - Pileup of minimum-bias events means longer reconstruction time and higher occupancy
  - Not only pileup from same bunch crossing! ATLAS sub-detector response varies from a few ns to about 700 ns (= 28 bunch crossings!)
  - Try to rely mostly on high-pT particles

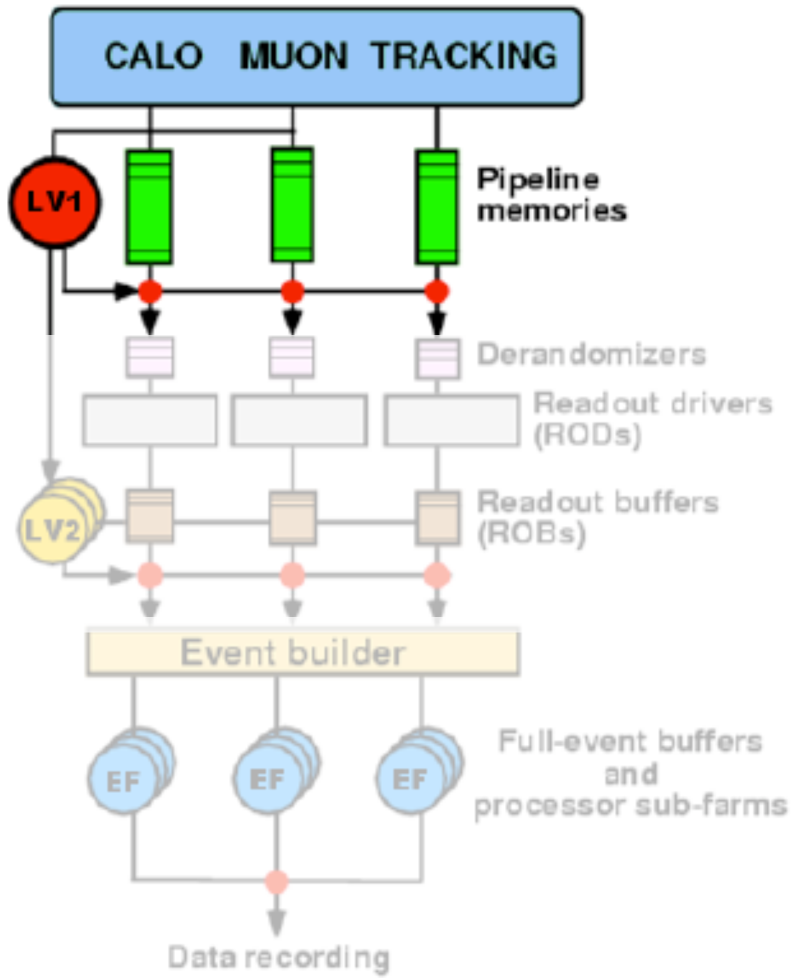


# The ATLAS trigger

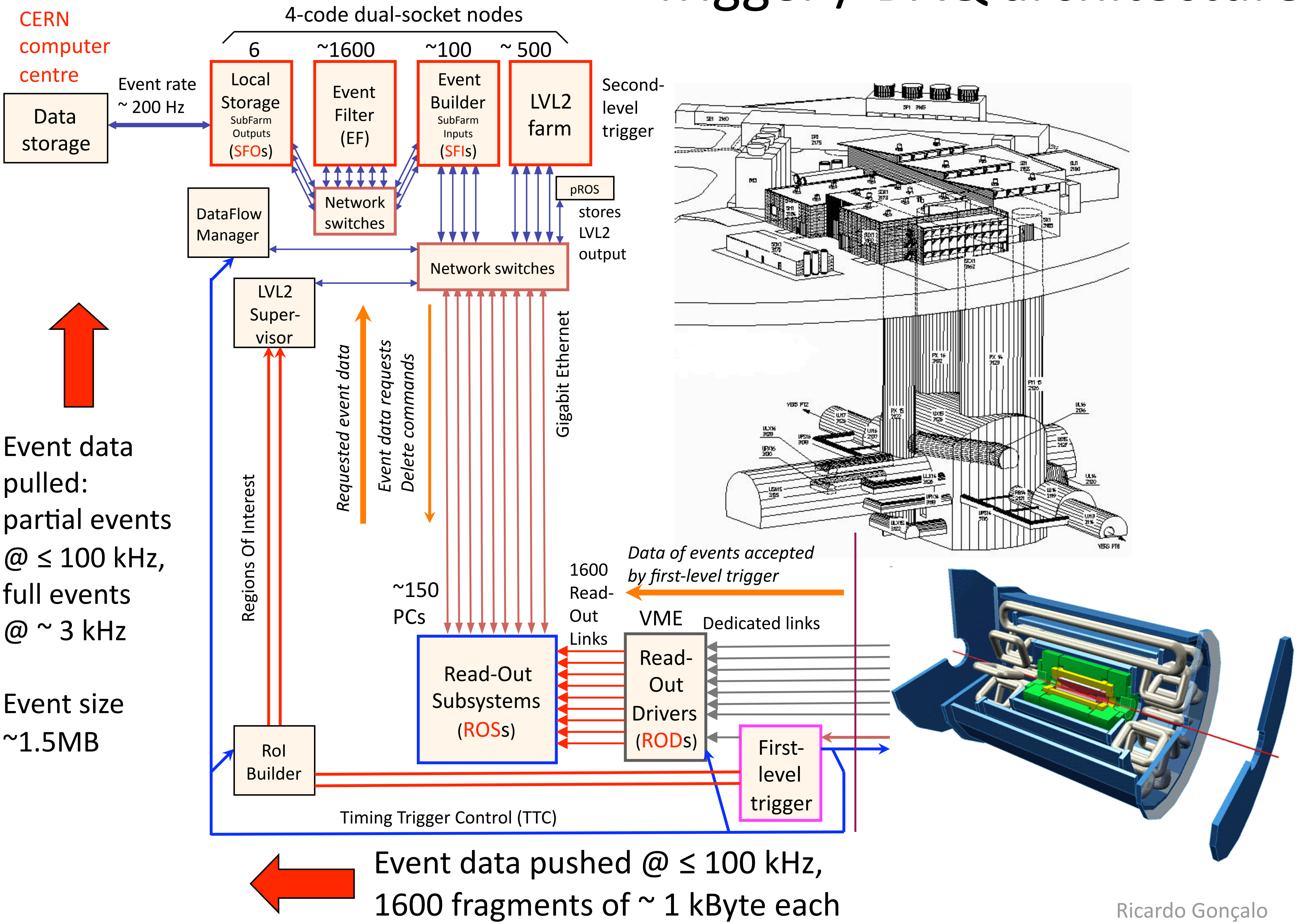
Three trigger levels:

- Level 1:
  - Hardware based (FPGA/ASIC)
  - Coarse granularity detector data
  - Calorimeter and muon spectrometer only
  - Latency 2.5 μs (buffer length)
  - Output rate ~75 kHz (limit ~100 kHz)
- Level 2:
  - Software based
  - Only detector sub-regions processed (**R**egions **o**f **I**nterest) seeded by level 1
  - Full detector granularity in RoIs
  - Fast tracking and calorimetry
  - Average execution time ~40 ms
  - Output rate ~1 kHz
- Event Filter (EF):
  - Seeded by level 2
  - Full detector granularity
  - Potential full event access
  - Offline algorithms
  - Average execution time ~1 s
  - Output rate ~200 Hz

High-Level Trigger



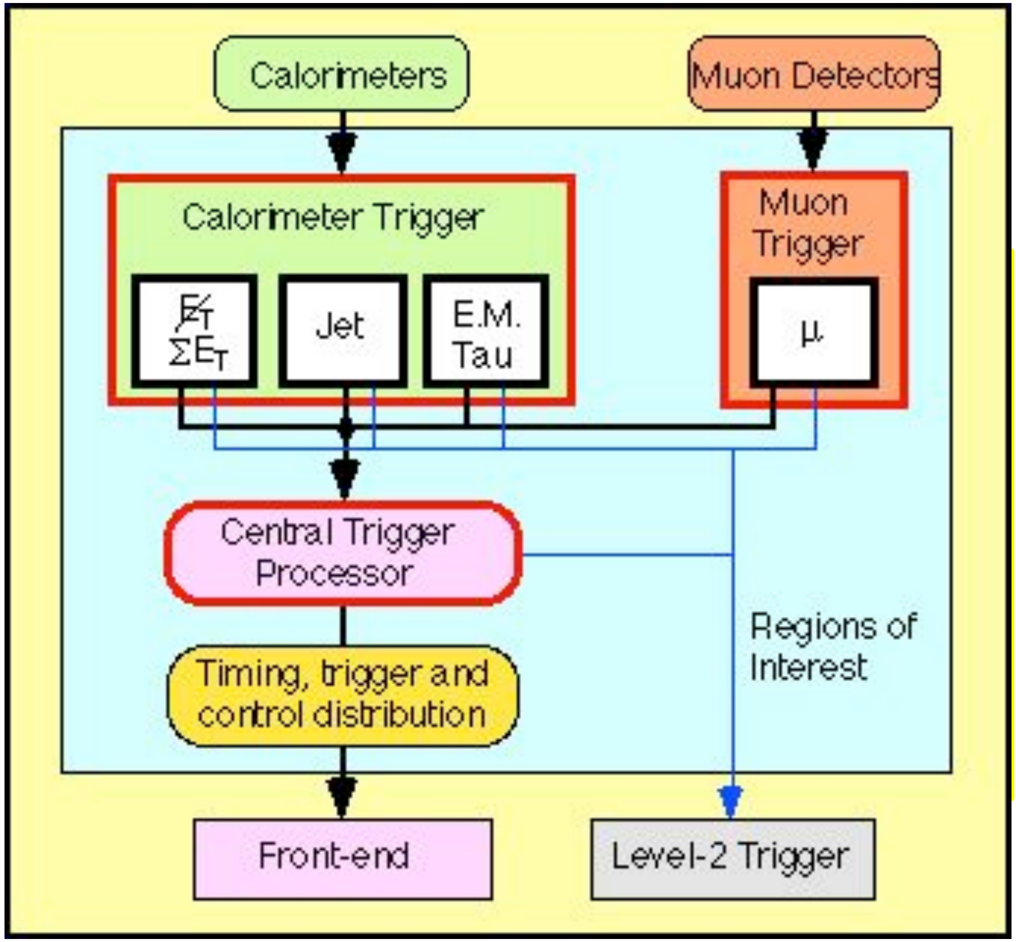
# Trigger / DAQ architecture



# First-Level Trigger

# Level 1 architecture

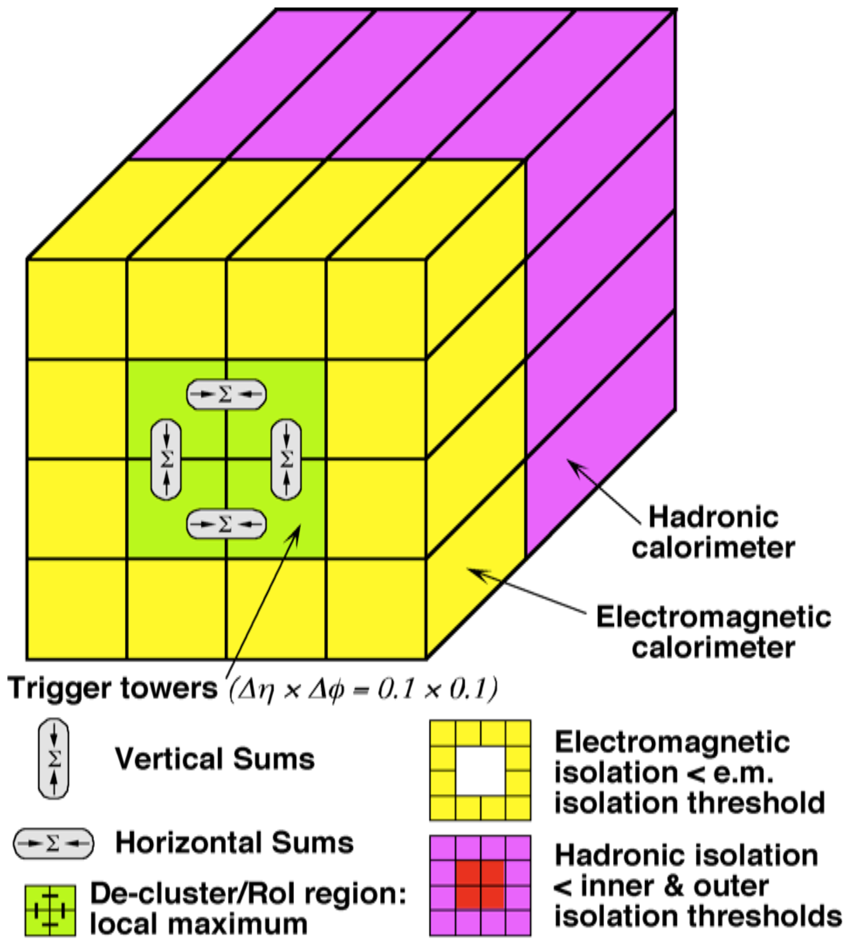
- Level 1 uses calorimeter and muon systems only
- Muon spectrometer:
  - Dedicated (fast) trigger chambers
    - Thin Gap Chambers – TGC
    - Resistive Plate Chambers – RPC
- Calorimeter:
  - Based on Trigger Towers: analog sum of calorimeter cells with coarse granularity
  - Separate from precision readout
- Identify regions of interest (RoI) and classify them as MU, EM/TAU, JET
- On L1 accept, pass to level 2:
  - RoI type
  - $E_T$ threshold passed
  - Location in $\eta$ and $\varphi$



# Level 1: Calorimeter Trigger

- Coarse granularity trigger towers
  - $\Delta\eta\times\Delta\varphi$ = 0.1×0.1 for e, γ, τ up to |η|<2.5
  - $\Delta\eta\times\Delta\varphi$ = 0.2×0.2 for jets, up to |η|<3.2
- Search calorimeter for physical objects (sliding window)
  - e/γ: isolated electromagnetic clusters
  - τ/hadrons: isolated hadronic clusters
  - Jets: local $E_T$ maximum in programmable 2x2, 3x3 or 4x4 tower sliding window
  - Extended to η=4.9 wit low granularity (FCAL)
  - $\Sigma E_T^{em,had}$, $\Sigma E_T^{jets}$ and $E_t^{miss}$ with jet granularity, up to η=4.9
- Analog sum of calorimeter cells; separate from precision readout
  - Separate for EM and hadronic towers

e/γ trigger

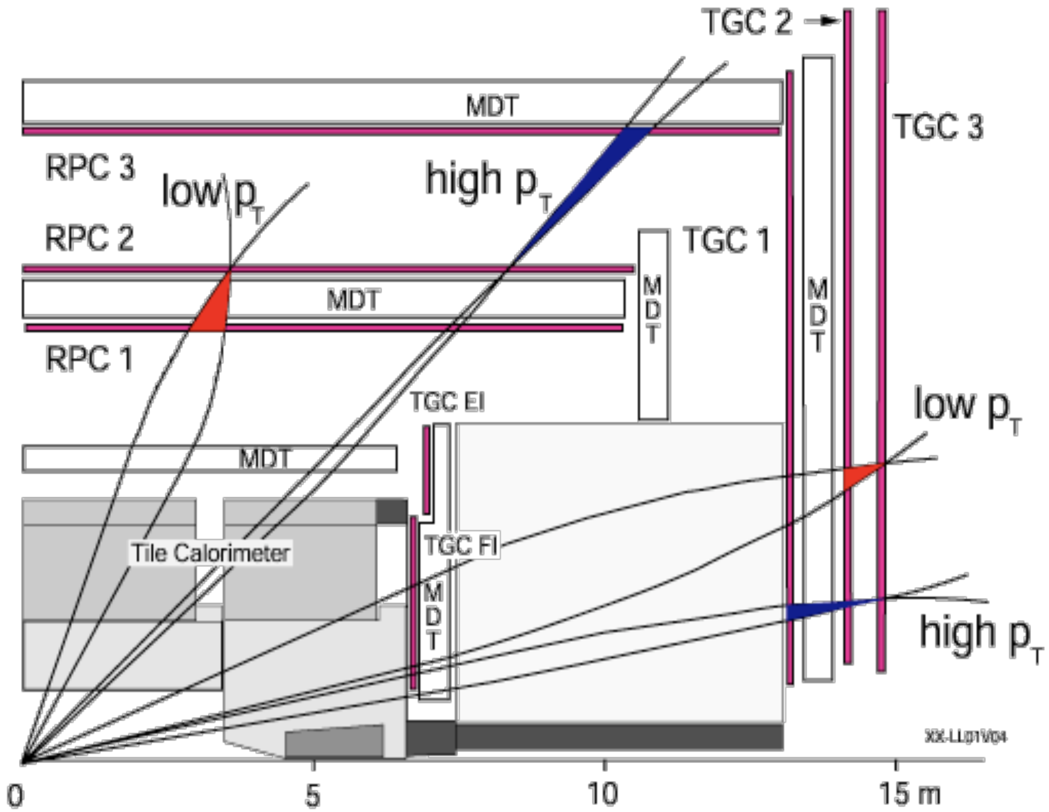


# Level 1: Muon trigger

- Uses dedicated trigger chambers with fast response (RPC, TGC)
- Searches for coincidence hits in different chamber double-layers
  - Starting on pivot plan (RPC2, TGC2)

Example:

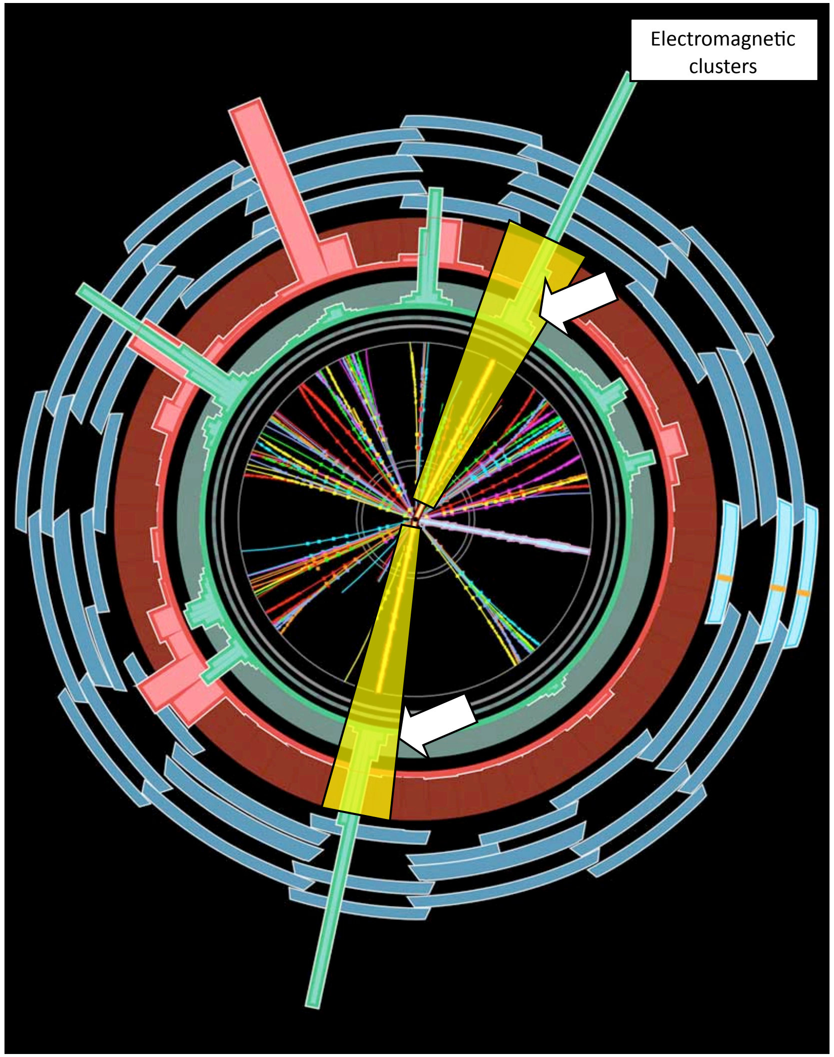
- Low-$p_T$ threshold (>6GeV) look for 3 hits out of 4 planes
- High-$p_T$ threshold (>20GeV) look for 3 hits out of 4 planes + 1 out of 2 in outer layer
- Algorithm is programmable and coincidence window is $p_T$-dependent



# High-Level Trigger

# Selection method

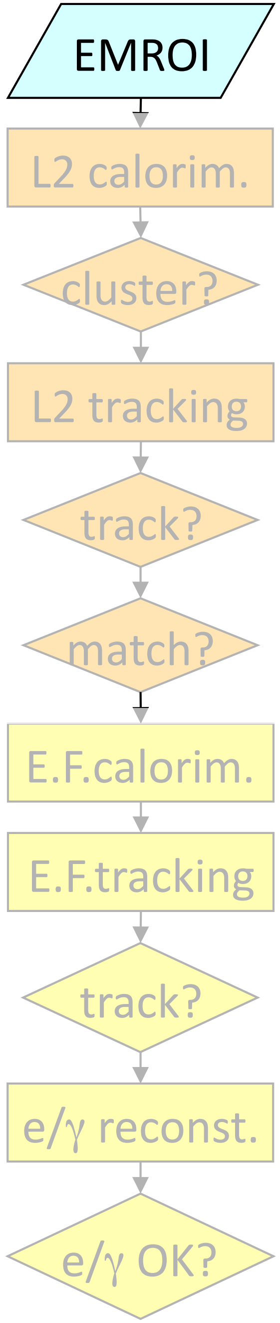
Event rejection possible at each step




Level1 Region of Interest is found and threshold/position in EM calorimeter are passed to Level 2

Level 2 seeded by Level 1
Fast reconstruction algorithms
Reconstruction within RoI

Ev.Filter seeded by Level 2
Offline reconstruction algorithms
Refined alignment and calibration



# High Level Trigger architecture

*Basic idea:*

- ***Seeded*** **and** ***Stepwise*** **Reconstruction**

- Regions of Interest (RoI) *"seed"* trigger reconstruction chains

- Reconstruction ("Feature Extraction") in steps
  - One or more algorithms per step

- Validate step-by-step in "Hypothesis" algorithms
  - Check intermediate signatures

- **Early rejection**: rejects hypotheses as early as possible to save time/resources

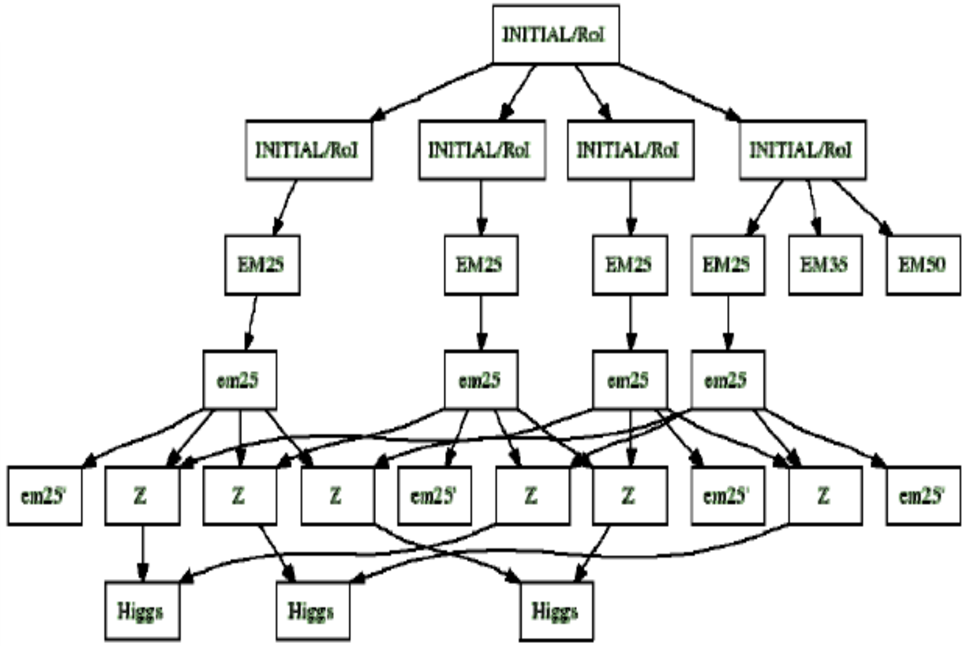
Note:

- Level 2 usually accesses only a small fraction of the full event (about 2%)
  - Depends on number and kind of Level 1 RoI's
  - "Full-scan" is possible but too costly for normal running
- Event Filter runs after event building and may analyse full event
  - But will normally run in seeded mode, with some exceptions (e.g. $E_T^{miss}$ triggers)

# Trigger Algorithm Steering

- One top algorithm (Steering) manages the HLT algorithms:
  - Determines from trigger Menu what chains of algorithms exist
  - Instantiates and calls each of the algorithms in the right sequence
  - Provides a way (the Navigation) for each algorithm to pass data to the next one in the chain

- Feature caching
  - Physical objects (tracks etc) are reconstructed once and cached for repeated use
- Steering applies prescales
  - Take 1 in N accepted events
- And passthrough factors
  - Take 1 in N events
- Possible to re-run prescaled-out chains for accepted events (tricky…for expert studies)



# Trigger algorithms

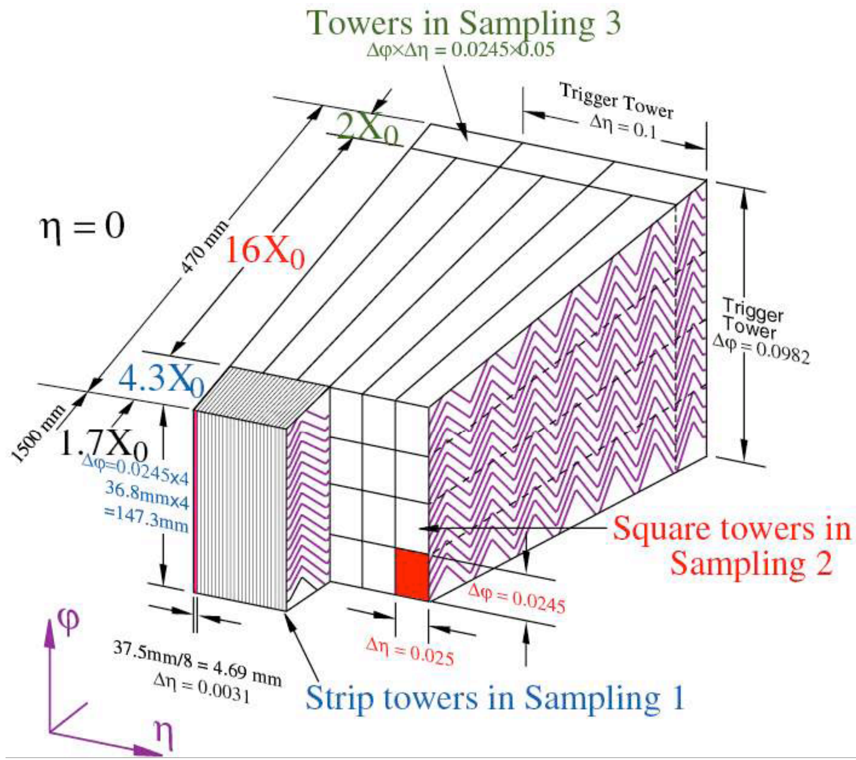
- High-Level Trigger algorithms organised in groups ("slices"):
  - Minimum bias, e/$\gamma$, $\tau$, $\mu$, jets, B physics, B tagging, $E_T^{miss}$, cosmics, plus combined-slice algorithms (e.g. e+$E_t^{miss}$)
- Level 2 algorithms:
  - Fast algorithms – make the best of the available time
  - Minimize data access – to save time and minimize network use
- Event Filter algorithms:
  - Offline reconstruction software wrapped to be run by Steering algorithm in RoI mode
  - More precise and much slower than L2
  - Optimise re-use and maintenability of reconstruction algorithms
  - Ease analysis of trigger data and comparison with offline (same event data model)
  - Downside can be a lower flexibility in software development (different set of people/ requirements)
- Different algorithm instances created for different configurations
  - E.g. track reconstruction may be optimized differently for B-tagging and muon finding
- All algorithms running in ATLAS software framework ATHENA
  - No need to emulate the high-level trigger software
  - In development: run MC production from Trigger configuration database
  - Only Level 1 needs to be emulated

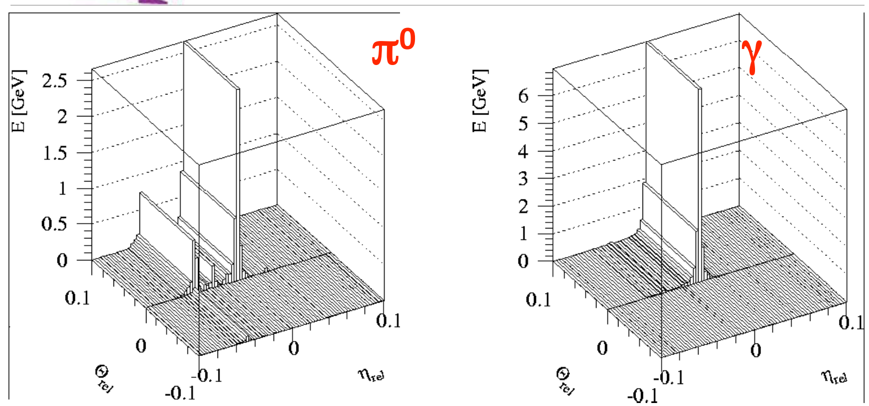
# Example: level 2 e/$\gamma$ calorimeter reconstruction

- Full granularity but short time and only rough calibration

- Reconstruction steps:
  1. LAr sample 2; cluster position and size (E in 3x3 cells/E in 7x7 cells)
  2. LAr sample 1; look for second maxima in strip couples (most likely from $\pi^0 \rightarrow \gamma\gamma$, etc)
  3. Total cluster energy measured in all samplings; include calibration
  4. Longitudinal isolation (leakage into hadronic calorimeter)

- Produce a level 2 EM cluster object

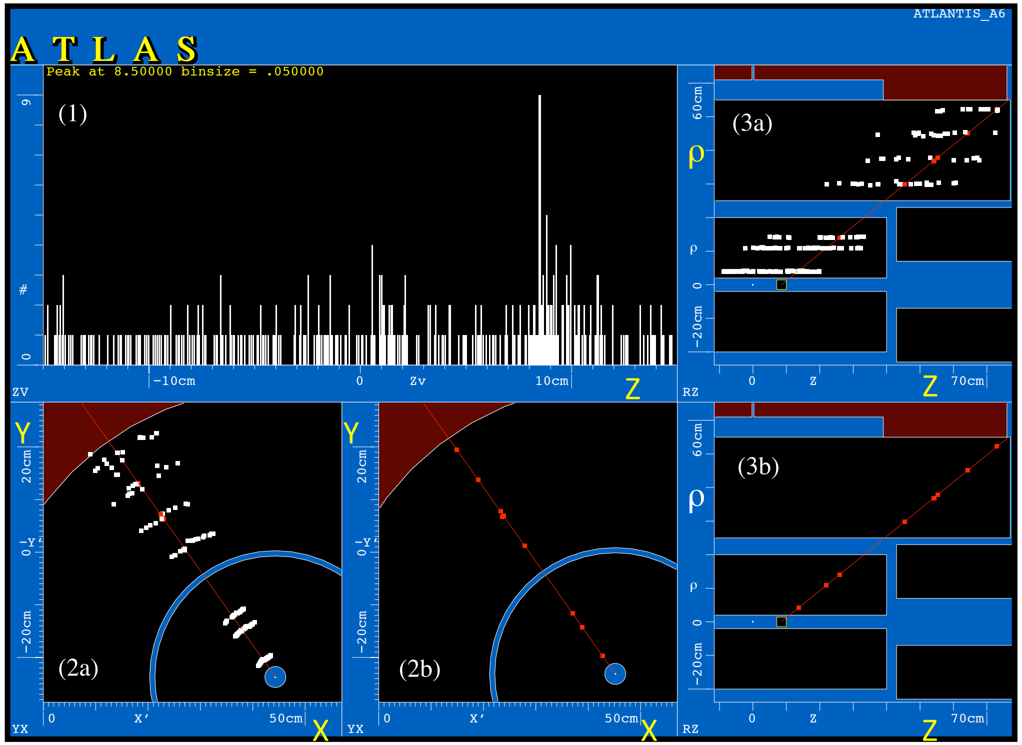


# Example: level 2 tracking algorithm

1. Form pairs of hits in Pixel and SCT in thin ϕ slices;
   - extrapolate inwards to find $Z_{vtx}$ from a 1D histogram
2. Using $Z_{vtx}$, make 2D histogram of hits in η-ϕ plane;
   - remove bins with hits in too few layers
3. Do 2D histogram using space point triplets in $1/p_T$-ϕ plane;
   - Form tracks from bins with hits in >4 layers
4. Use Kalman technique on the space points obtained in previous steps
   - Start from already estimated parameters: $Z_{vtx}$, $1/p_T$, η, ϕ

- Full granularity but short time
- Algorithms optimised for execution speed, including data access time
- Produce level 2 tracks



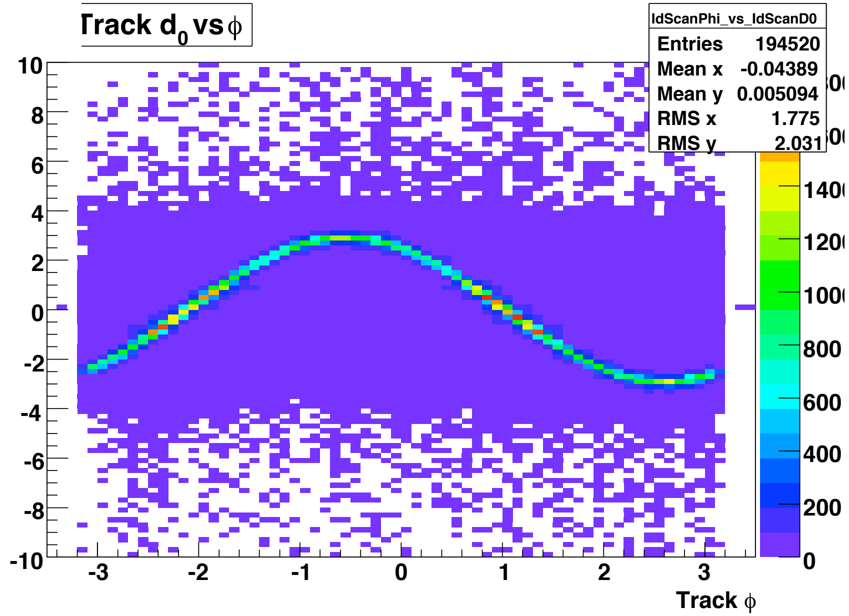
# Trigger algorithm robustness

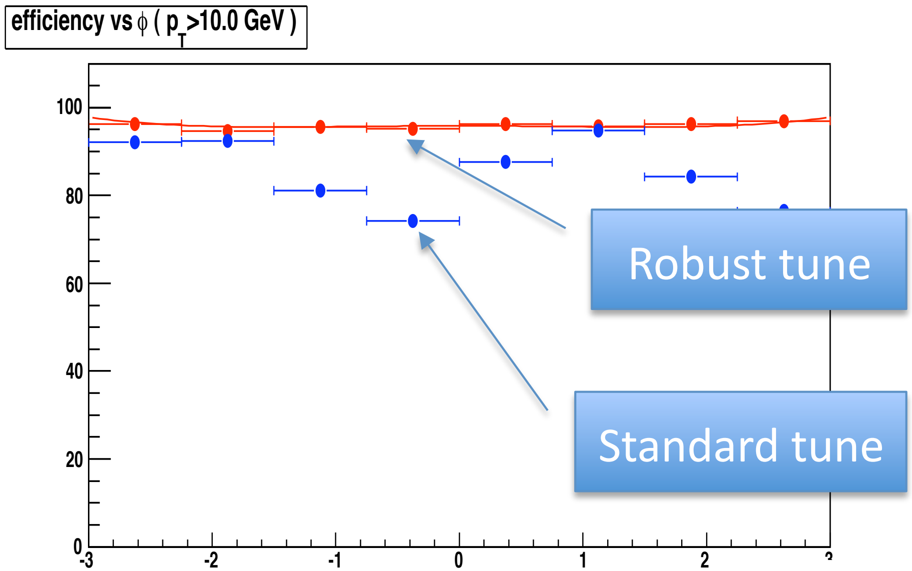
- Work has been devoted to verifying that the trigger is robust against several possible error sources
- Likely sources of error introduced in simulation:
  - Added dead material (up to $1X_0$)
  - Misaligned inner detector, calorimeter and muon spectrometer
  - Displaced beam spot

Example: beam-spot displacement wrt the Atlas reference frame was found to be a possible source of inefficiency

Two aspects:

- Tracking algorithm robustness at L2: robust tune found for the L2 tracking algorithms
- Online determination of beam-spot position (for B-tagging etc)



# Trigger Menu and Configuration

# Trigger Menu

- Complex menu, includes triggers for:
  - Physics
  - Detector calibration
  - Minimum bias
  - Efficiency measurement

- Offline data streams based on trigger

| Trigger Group | Rate (Hz) |
|---|---|
| | |
| Muons | 80 |
| Electrons | 67 |
| Tau+X | 56 |
| BPhys | 37 |
| Jets | 25 |
| Photons | 18 |
| $E_T^{miss}$ | 13 |
| Misc | 13 |
| TOTAL | 310 |

250Hz plus overlaps

Draft e/γ menu for $L=10^{31}cm^{-2}s^{-1}$

| Signature | Level-1 Item | Level-1 Pre-scale | Level-1 Rate [kHz] | Event Filter Sel-ection | Event Filter Pre-scale | Event Filter Rate [Hz] | |
|---|---|---|---|---|---|---|---|
| e5 | EM3 | 60 | 0.7 | medium | 1 | $4.8 \pm 0.2$ | $J/\Psi \to ee, \Upsilon \to ee$, Drell-Yan |
| 2e5 | 2EM3 | 1 | 6.5 | medium | 1 | 6 | $J/\psi \to ee, \Upsilon \to ee$, Drell-Yan |
| Jpsiee | 2EM3 | 1 | 6.5 | medium | 1 | 1 | $J/\psi \to ee, \Upsilon \to ee$ |
| e10 | EM7 | 1 | 5.0 | medium | 1 | 21 | $e^{\pm}$ from b,c decays, E/p studies |
| γ10 | EM7 | 1 | 5.0 | medium | 100 | $0.6 \pm 0.1$ | $e^{\pm}$ direct photon cross-section, e-no-track trigger |
| e10_xe30 | EM7_XE30 | 1 | 0.2 | medium | 1 | $0.3 \pm 0.3$ | access low $p_T$-range for $W \to e\nu$ |
| 2γ10 | 2EM7 | 1 | 0.5 | loose | 1 | $< 0.1$ | di-photon cross-section |
| 2e10 | 2EM7 | 1 | 0.5 | loose | 1 | $0.4 \pm 0.2$ | $Z \to e^+e^-$ |
| Zee | 2EM7 | 1 | 0.5 | loose | 1 | $< 0.1$ | $Z \to e^+e^-$ |
| 2e12i_L33 | 2EM7 | 1 | 0.5 | tight | 1 | $< 0.1$ | trigger for $L \sim 10^{33}$ cm$^{-2}$ s$^{-1}$ |
| γ15 | EM13 | 1 | 0.7 | medium | 10 | $1.3 \pm 0.1$ | $e^{\pm}$ direct photon cross-section |
| e15_xe20 | EM13_XE20 | 1 | 0.2 | loose | 1 | $1.0 \pm 0.4$ | access low $p_T$-range for $W \to e\nu$ |
| 2g17i_L33 | 2EM13I | 1 | 0.1 | tight | 1 | $< 0.1$ | trigger for $L \sim 10^{33}$ cm$^{-2}$ s$^{-1}$ |
| γ20 | EM18 | 1 | 0.3 | loose | 1 | $5.4 \pm 0.2$ | direct photons, jet calibration using γ-jet events, high-$p_T$ physics,check tracking eff. |
| e20_passL2 | EM18 | 1 | 0.3 | loose | 200 | $< 0.1$ | check L2EF performance |
| e20 passEF | EM18 | 1 | 0.3 | | 125 | 0.1 | check L2EF performance |
| em20_passEF | EM18 | 1 | 0.3 | | 750 | $0.5 \pm 0.1$ | check HLT performance |
| em20i_passEF | EM18I | 1 | 0.1 | | 300 | $0.5 \pm 0.1$ | check L1 isolation |
| e22i_L33 | EM18I | 1 | 0.1 | tight | 1 | $1.2 \pm 0.1$ | trigger for $L \sim 10^{33}$ cm$^{-2}$ s$^{-1}$ |
| γ55_L33 | EM18 | 1 | 0.3 | tight | 1 | $1.2 \pm 0.1$ | trigger for $L \sim 10^{33}$ cm$^{-2}$ s$^{-1}$ |
| em105_passHLT | EM100 | 1 | 1 | | 1 | $1.0 \pm 0.1$ | New physics, check for possible problems |
| γ150_passHLT | EM100 | 1 | 1 | | 1 | $< 0.1$ | check for possible problems in express stream |

Table 12: Summary of triggers for the first physics run assuming a luminosity of $L \sim 10^{31}$ cm$^{-2}$ s$^{-1}$. For each signature rates and the motivation for this trigger are given.

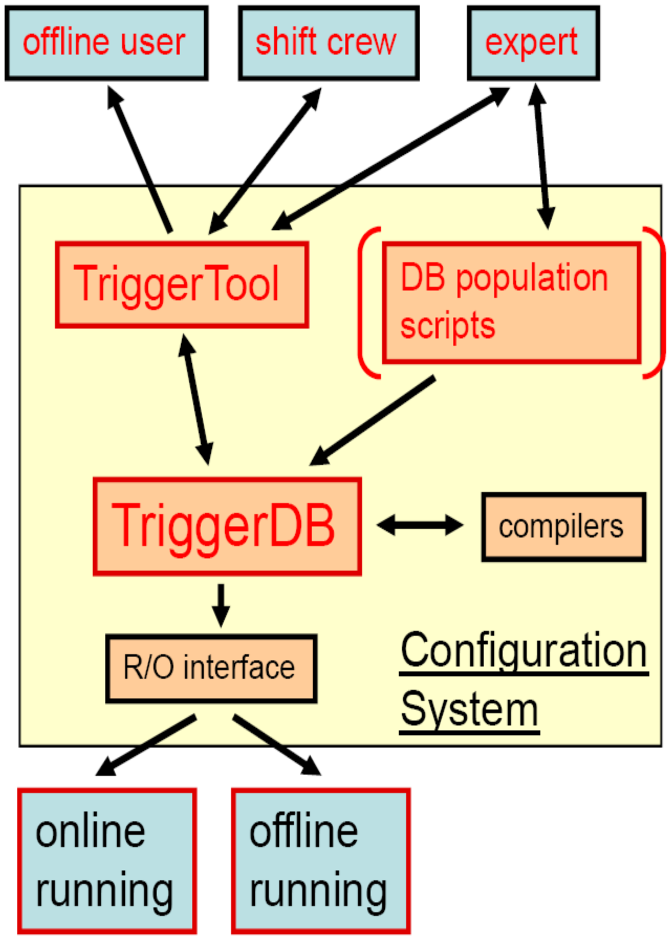
# Configuration

- Trigger configuration:
  - Active triggers
  - Their parameters
  - Prescale factors
  - Passthrough fractions
  - Consistent over three trigger levels

- Needed for:
  - Online running
  - Event simulation
  - Offline analysis

- Relational Database (TriggerDB) for online running
  - User interface (TriggerTool)
  - Browse trigger list (menu) through key
  - Read and write menu into XML format
  - Menu consistency checks

- After run, configuration becomes conditions data (Conditions Database)
  - For use in simulation & analysis



# Configuration Data Flow

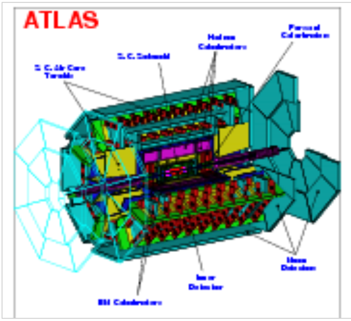
**Preparation**

**TriggerDB**
**All configuration data**

Configures

Stores decoded Trigger Menu

**Data taking**




**Online Conditions Database**

**Encoded trigger decision (trigger result from all 3 levels )**

**Decoded Trigger Menu**

**Reconstruction/ Trigger aware analysis**

**Trigger Result**

- passed?, passed through?, prescaled?, last successful step in trigger execution?

**Trigger EDM**

- Trigger objects for trigger selection studies

**Trigger Configuration**

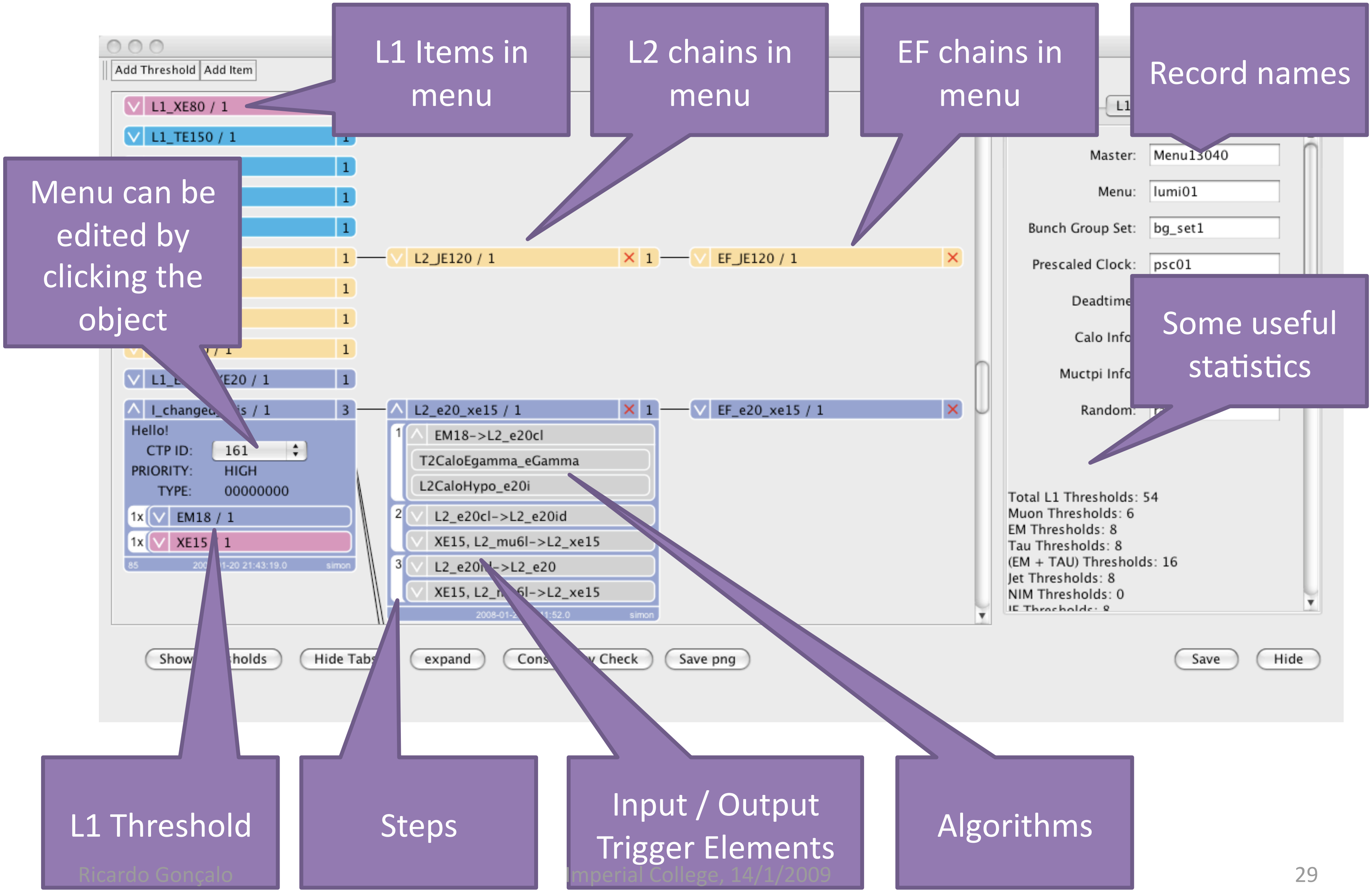
- Trigger names (version), prescales, pass throughs

Data formats:

- ESD
- AOD
- DPD
- TAG

With decreasing amount of detail

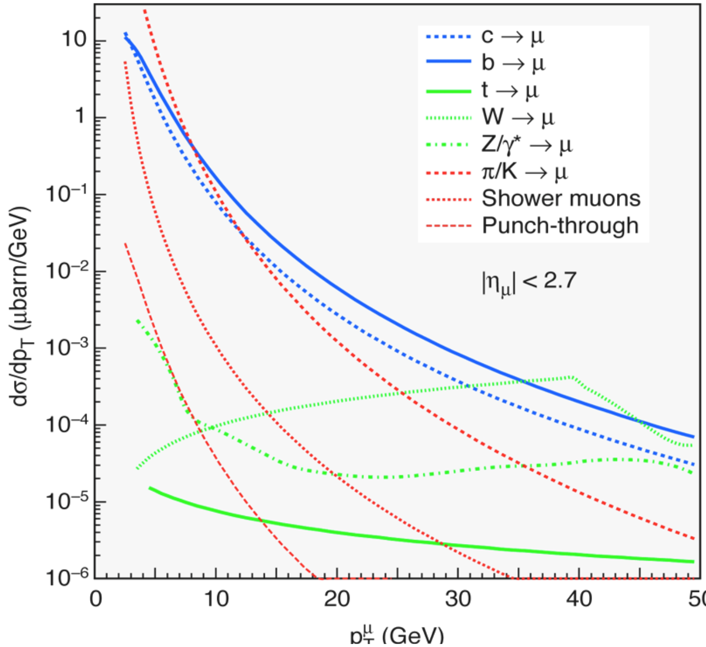
# Viewing and Modifying a Menu



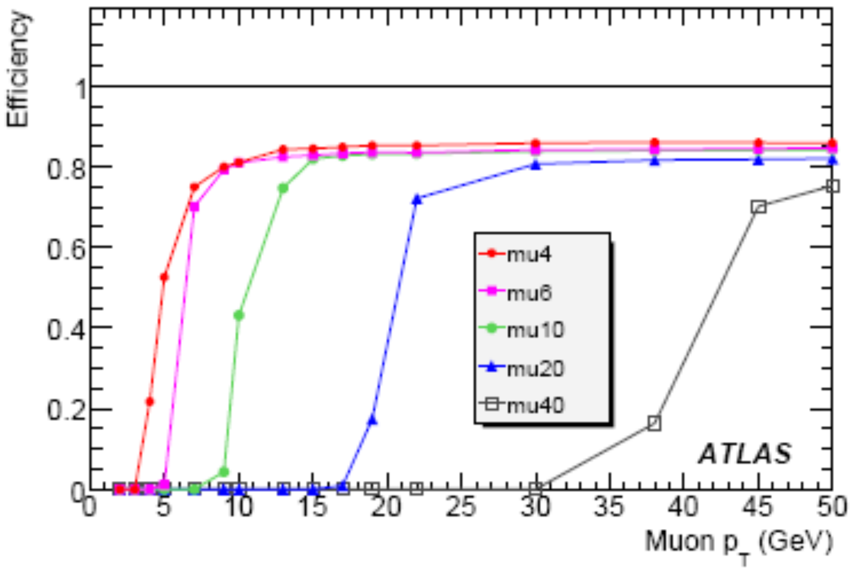
# Performance of the ATLAS Trigger

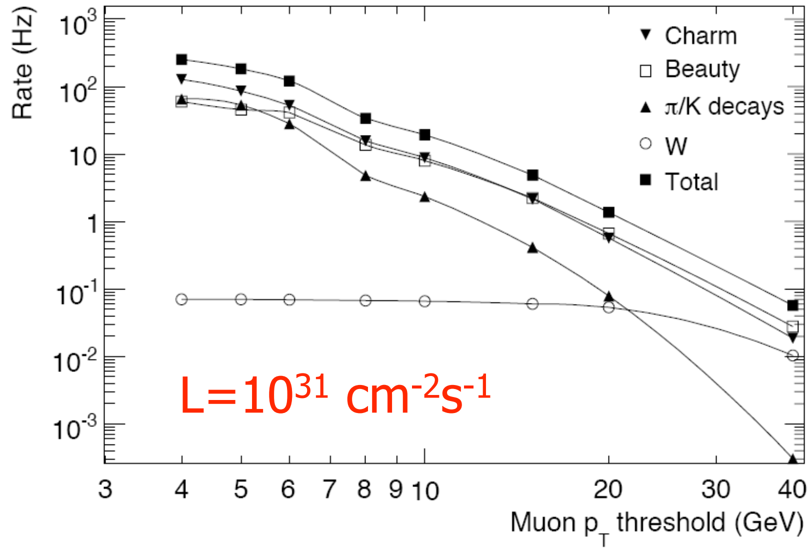
# Muon trigger performance

- Rapidly falling backgound cross section means a sharp efficiency turn on is essential
- Uncertainty in modeling of π, K decays in flight add to rate uncertainty
- Absolute efficiency limited by geometrical acceptance (MS feet)
  Efficiency: 80% (barrel), 94% (endcap)



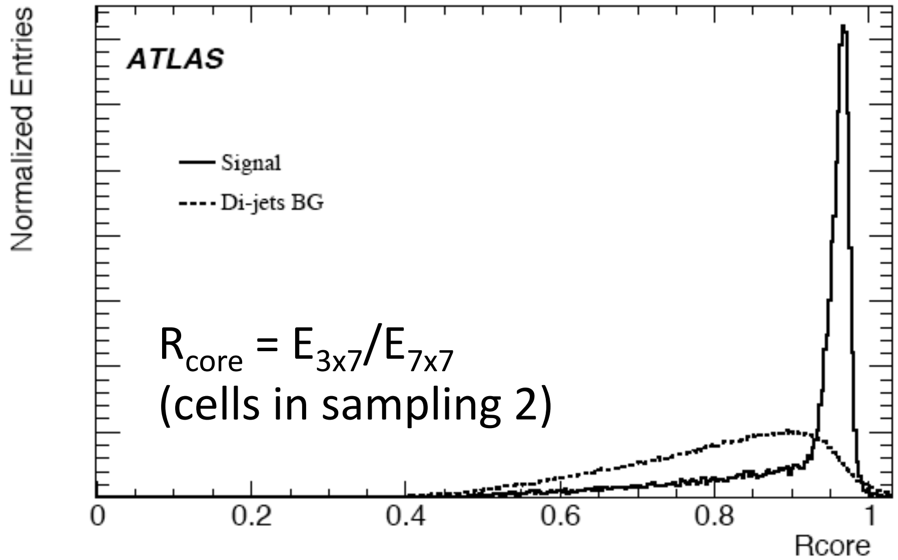

muon inclusive cross sections

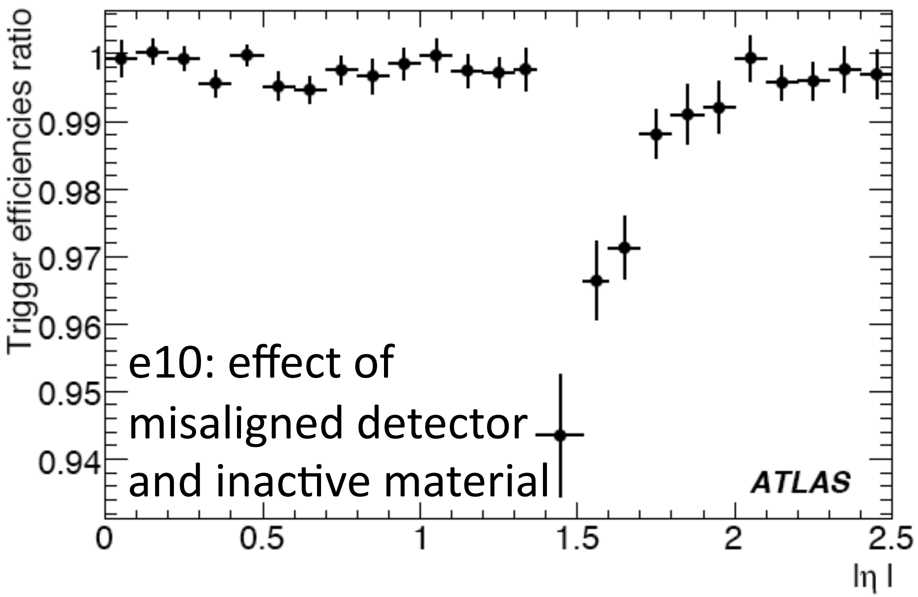


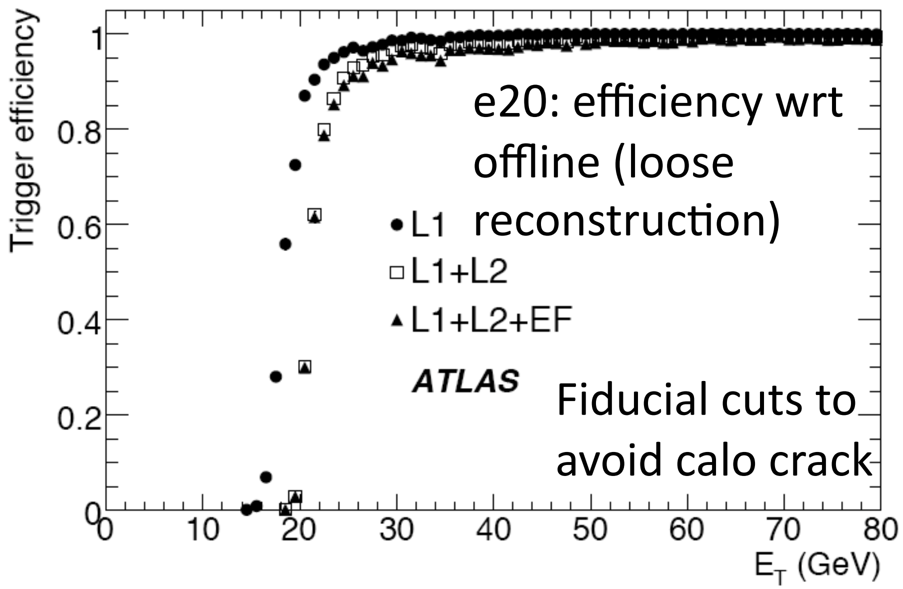



# Electron and photon triggers

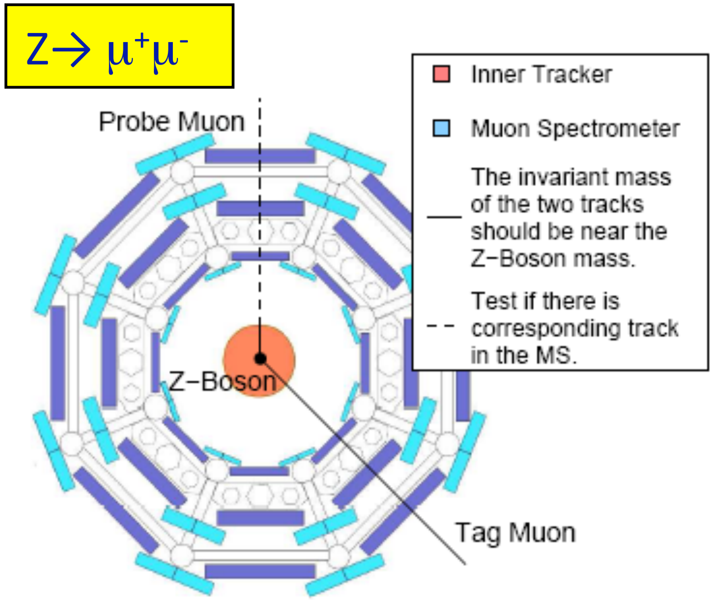
- e/γ triggers use features of LAr calorimeter to calculate discriminating variables ("shower shapes")
  – E.g.: $R_{core} = E_{3x7}/E_{7x7}$ gives width of shower, while accounting for bremstrahlung
- Robustness studied in several ways
  – Effect of additional inactive material, misalignment, beamspot displacement, pileup



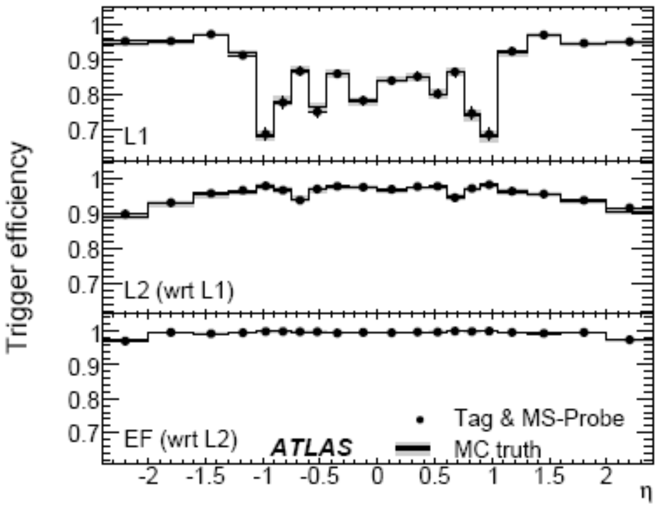



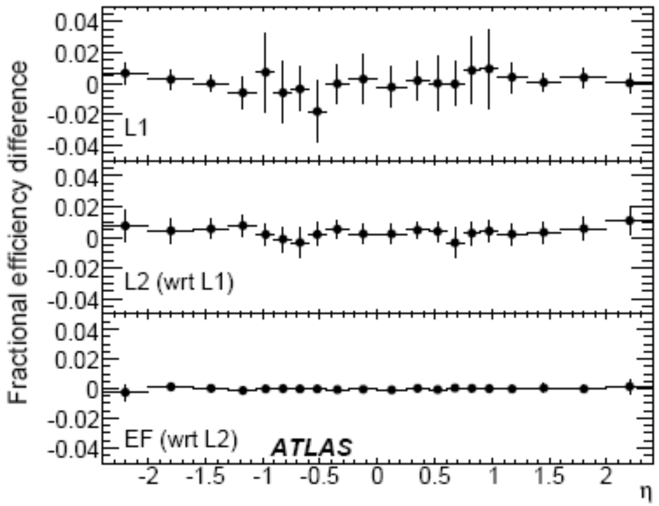
# Trigger Efficiency from data




- Try to rely on simulated data as little as possible
- For electrons and muons the "Tag & Probe" method can be used
  - Use clean signal sample (Z, J/ψ → $l^+l^-$)
  - Select track that triggered the event ("Tag")
  - Find other track using offline reconstruction ("Probe")
  - Determine efficiency by applying trigger selection to Probe
- Applicability of these efficiencies to more busy events also being studied

mu20

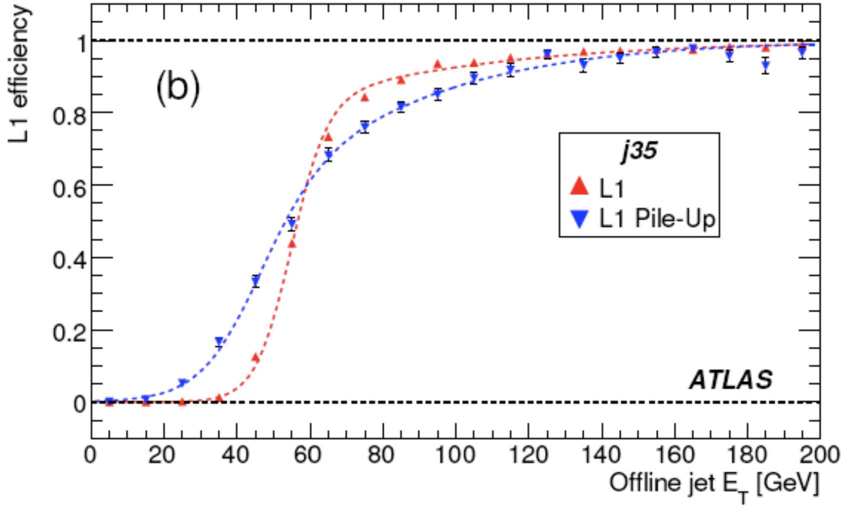


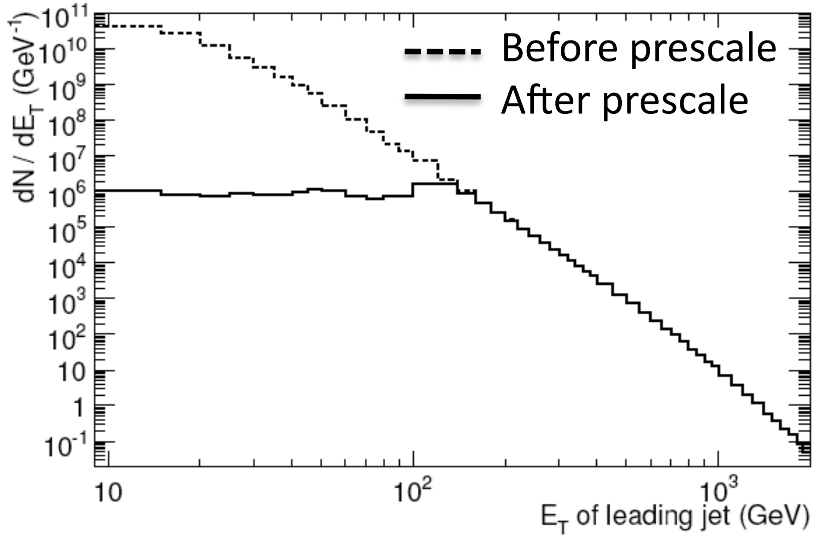



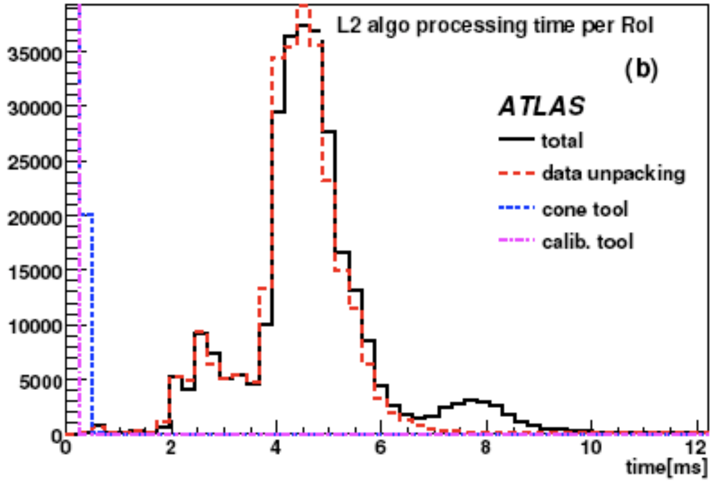

- Study with ~50 $pb^{-1}$
- Overall efficiency (77.4%±0.4)
- Very good agreement between Tag&Probe and MC truth

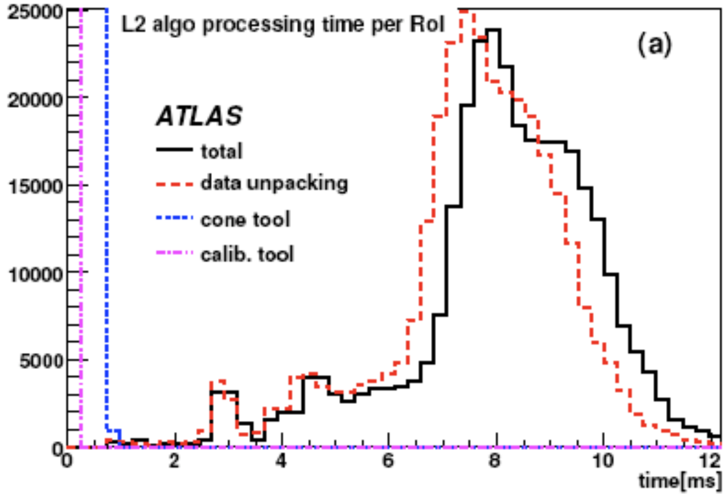
# Jet trigger performance

- Jet trigger efficiency turn on affected by pileup
- Low-$E_T$ jet rate too high: prescale low-$E_T$ triggers to have constant rave vs $E_T$



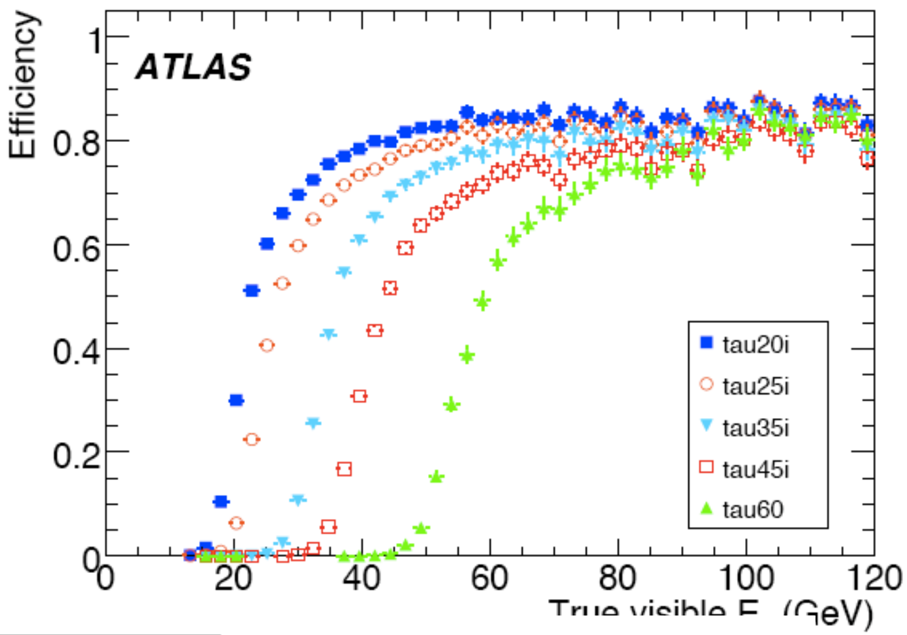



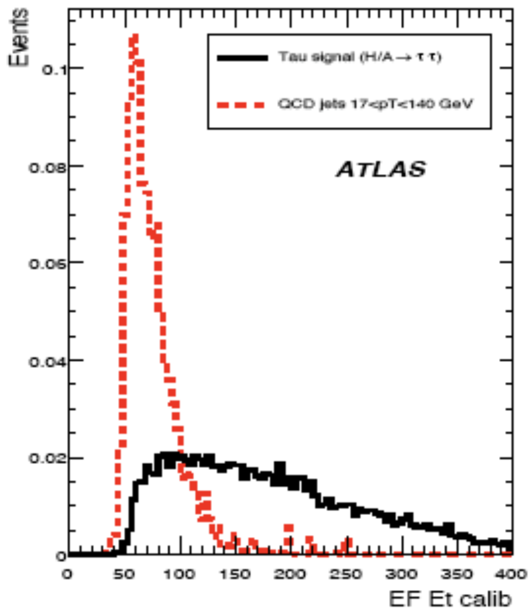



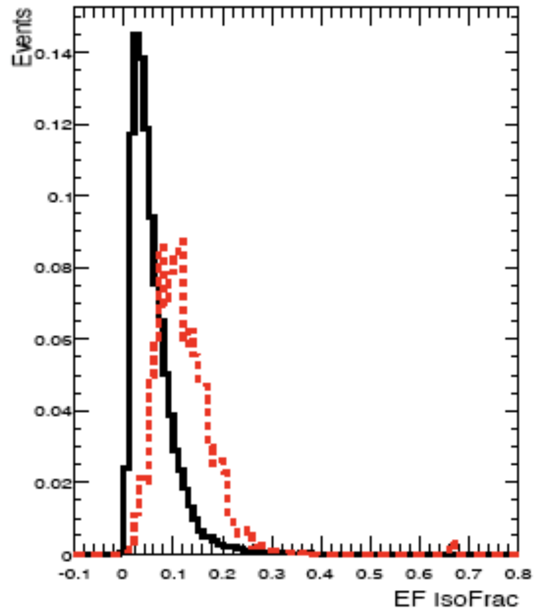

- Level 2: possible to use pre-calculated tower energy components (Ex,Ey,Ez) from front-end boards (FEB)
  - Saves unpacking time but has coarser granularity and resolution; studies ongoing

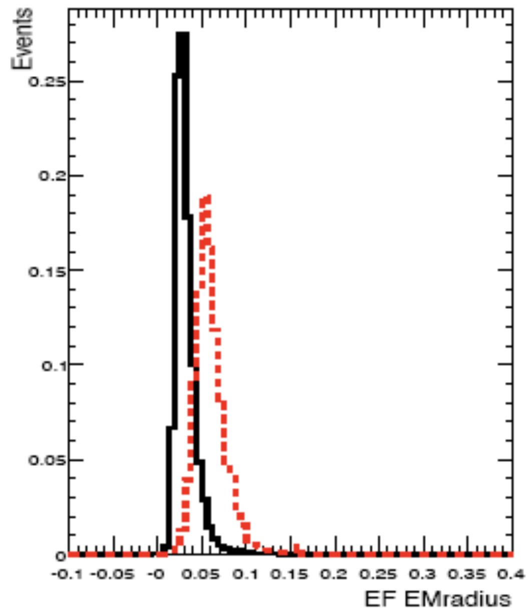
# Tau trigger performance

- As the electron trigger, taus rely on shower shapes in the calorimeter and finding a number of matching tracks
- Turn on curve dominated by the level 1 energy resolution
- At the Event Filter, offline reconstruction is used
  - Track-initiated tau identification to complement an older calorimeter-initiated algorithm



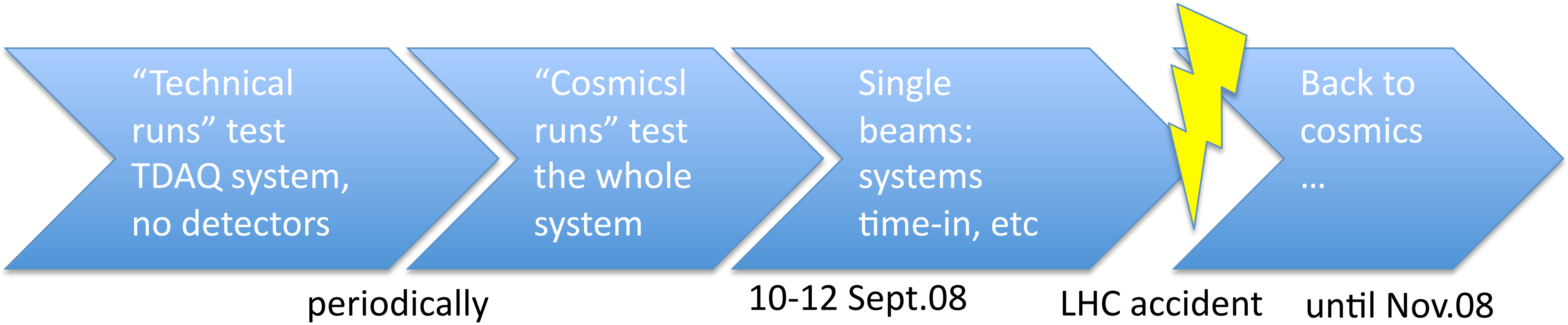



# Commissioning the ATLAS Trigger

# Timeline

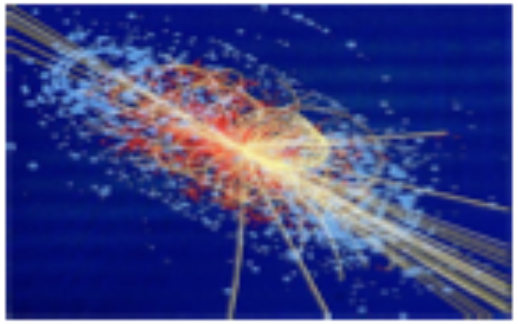
- Commissioning has been going on for more than a year with a gradually more complete system
- The TDAQ system (but not Level 1) was exercised in “Technical runs”
  - Learned how to deal with a large HLT farm
  - Correct estimates of processing time
  - Helped develop configuration and monitoring tools
- Cosmics runs use Level 1 and detectors
  - Need special menu: triggers that are efficient in selecting cosmic ray events
  - Very hard to test physics triggers meaningfully
  - Can collect charged tracks useful e.g. to constrain some detector alignment degrees of freedom
- Single beam:
  - Allowed to time-in some detectors: properly assign detector signals to bunch-crossing
  - Started to find dead channels, correlate problems between detectors etc



# Technical and cosmics runs

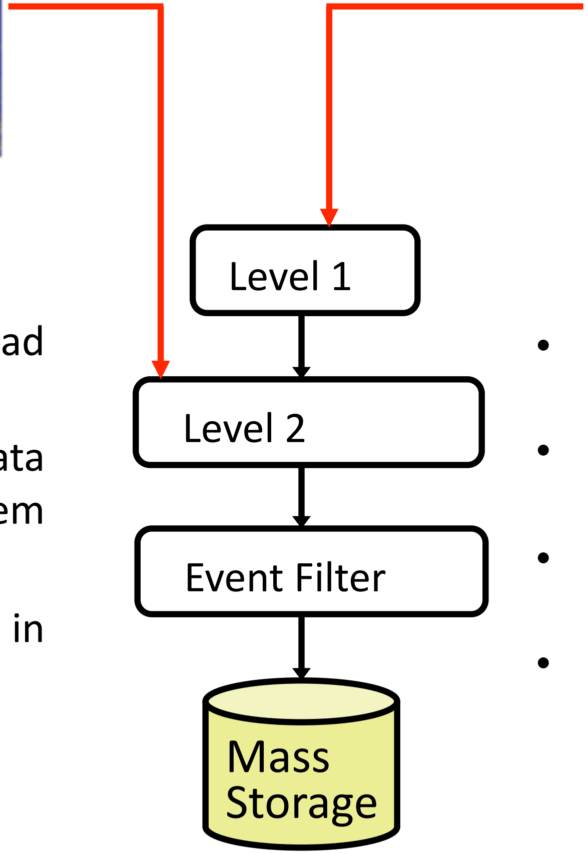
## Technical runs

Monte Carlo Events



Playback mode

- Data is pre-loaded into the Read Out System
- DAQ/HLT plays back the data through the whole system except Level 1
- Allows testing the system in realistic environment




## Cosmics runs

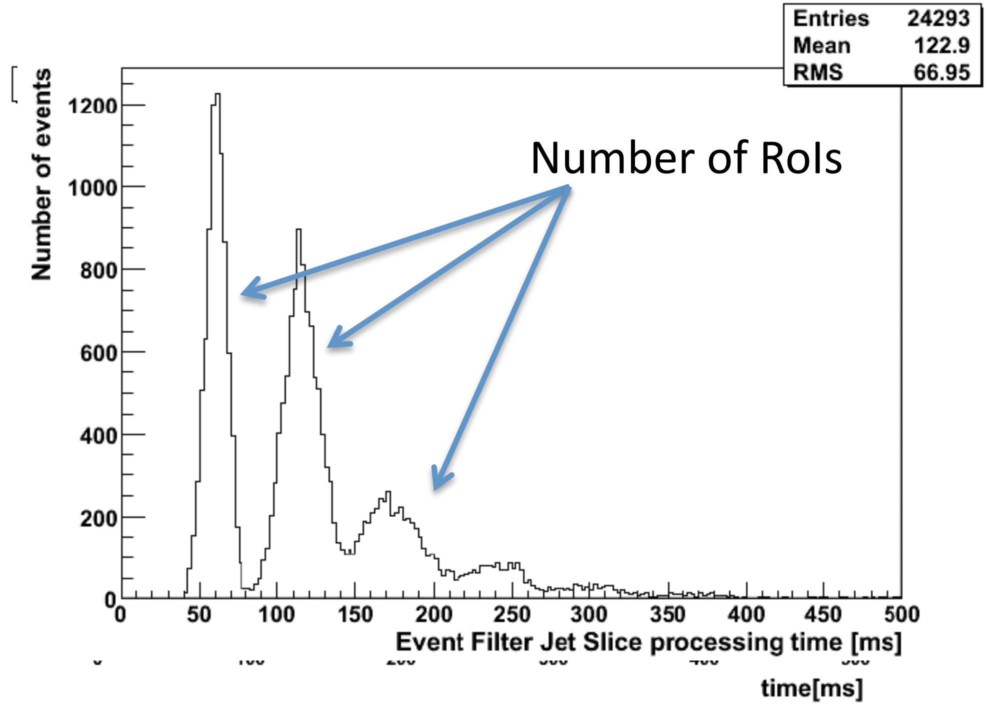
Cosmic Real Events

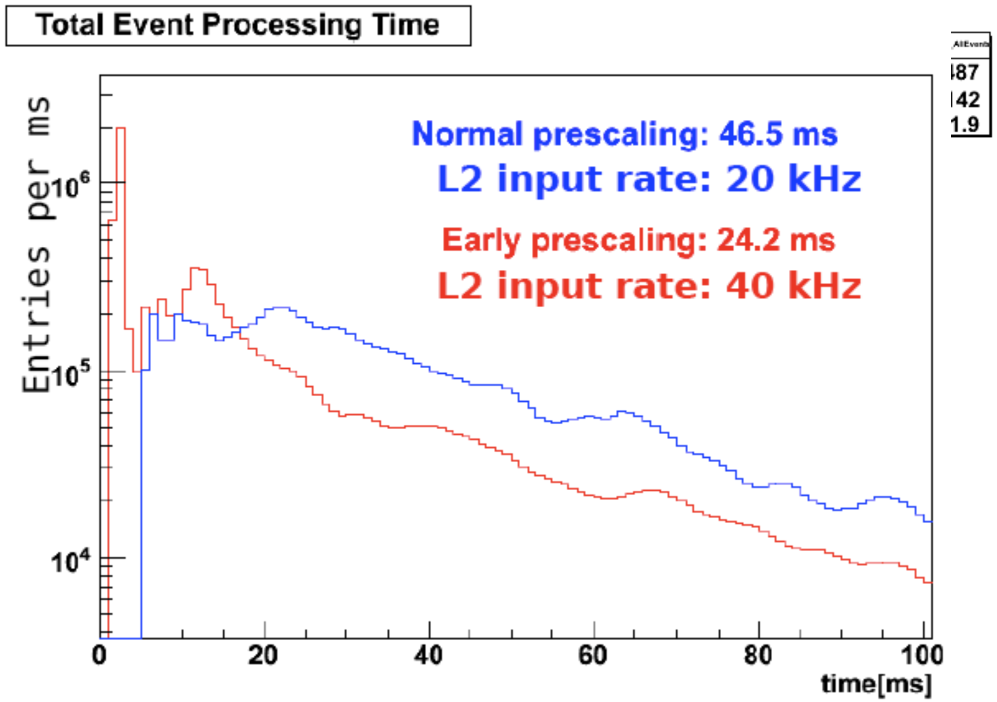
Real mode

- Real data comes from the detectors
- Allows testing the whole system including Level 1
- Tests the software with real “imperfect” data
- Limited to cosmic-ray events

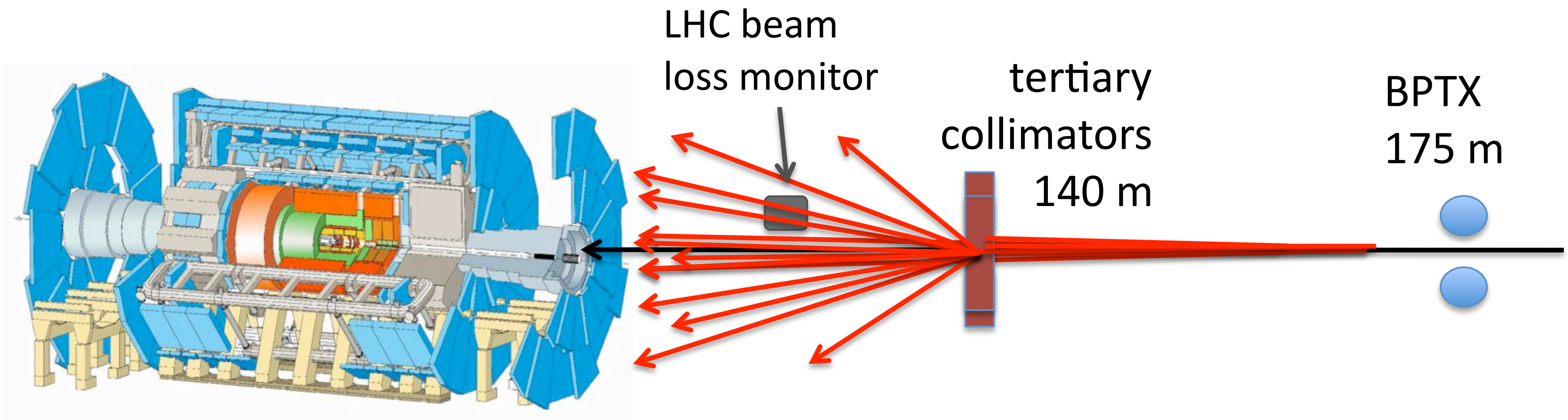
# MC Event playback

- Very useful to test system and estimate e.g. processing time
- $10^{31}$ trigger menu on L1-accepted minimum bias sample:
  - **33 ms @ L2** (40 ms nominal)
  - **142 ms @ EF** (1 s nominal)
- Algorithm timing
- Study: prescales applied before/after each level
  - Gains for early prescaling, but menu dependent



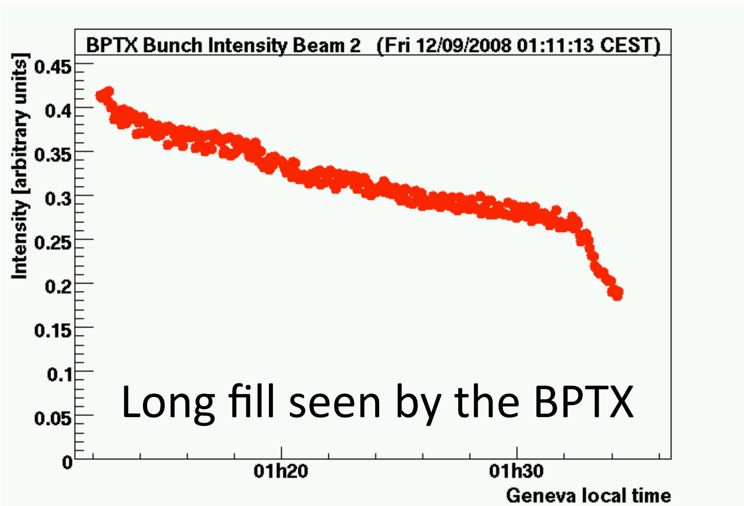
# First experience with LHC beams

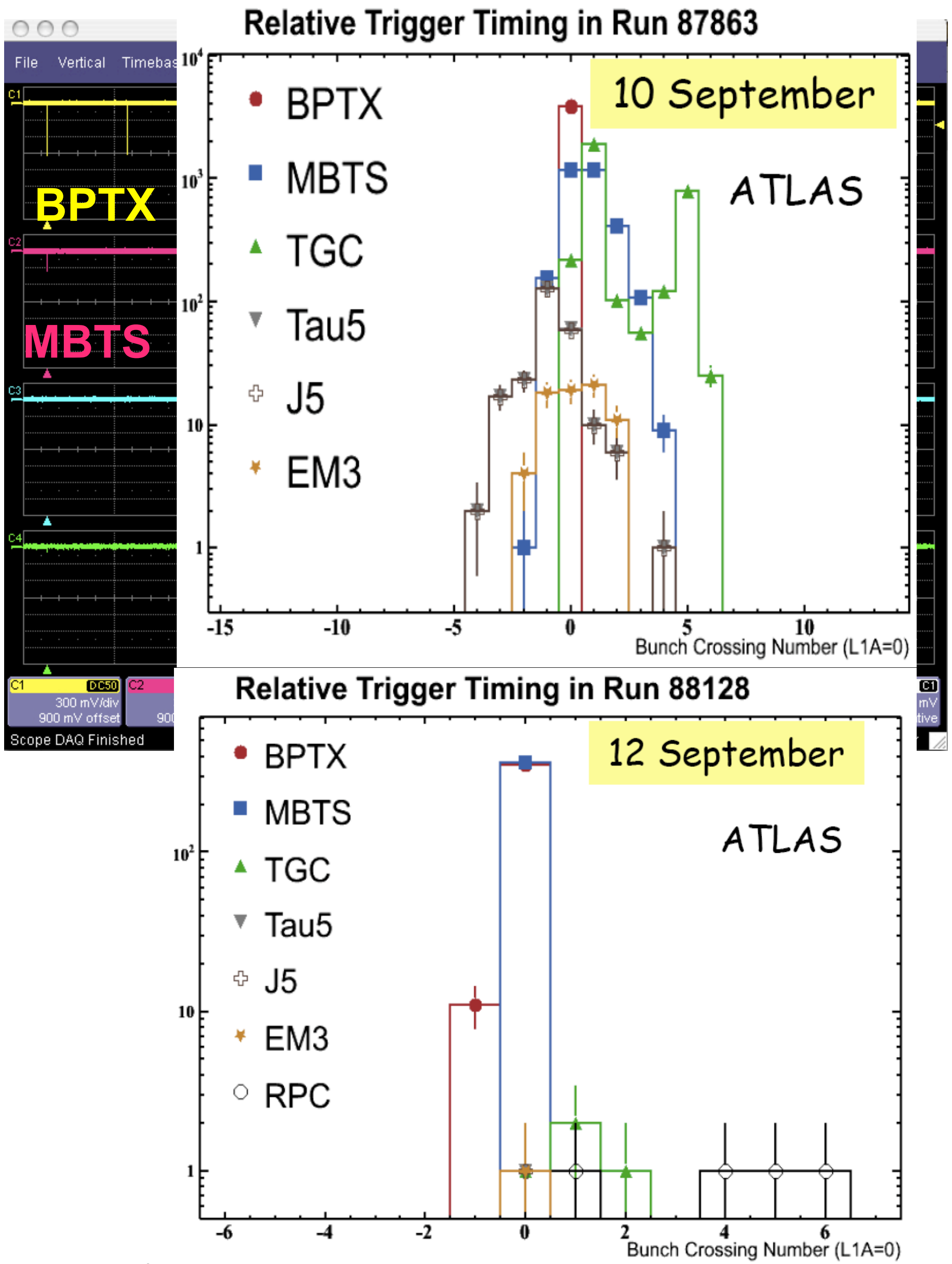



**ATLAS was ready for first beam:**

- Muon system (MDT, RPC, TGC) on at reduced HV
- LAr (-FCAL HV), Tile on
- TRT on, SCT reduced HV, Pixel off
- BCM, LUCID, MinBias Scintillators (MBTS), Beam pickups (BPTX)
- L1 trigger processor, DAQ up and running, HLT available (but used for streaming only)

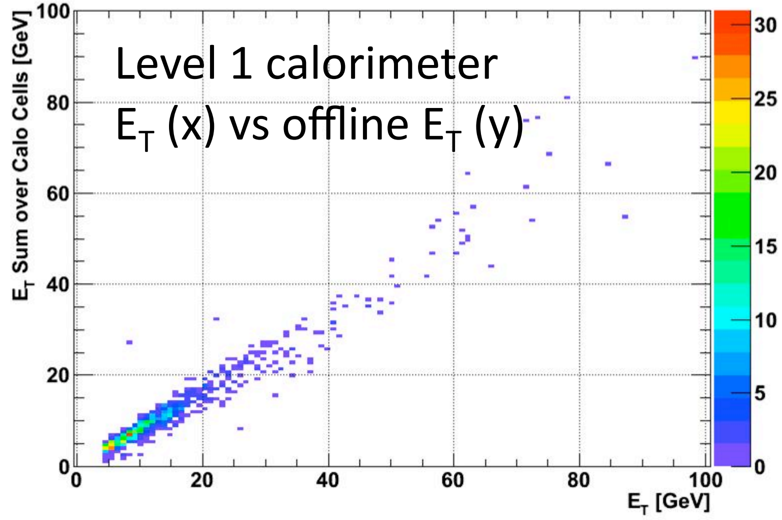
- Atlas relied on the MBTS and the L1 calorimeter triggers to record the first events
- Later used BPTX (beam pickup) as timing reference
- Defines time when bunch crosses interaction point
- Used this to adjust time of other detectors
  - See TGC time difference as beam crosses detector

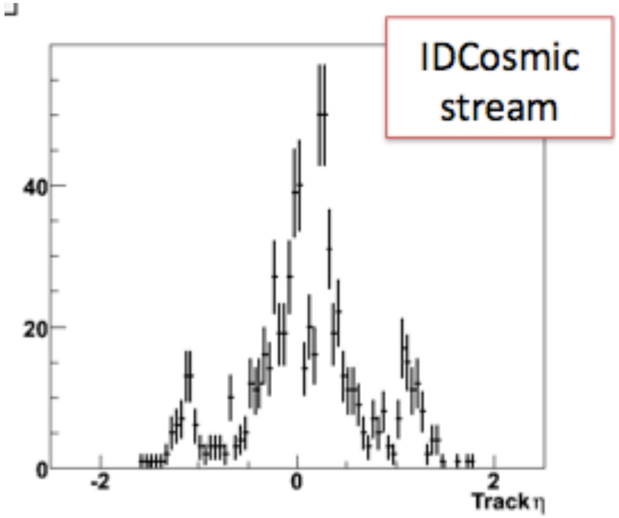


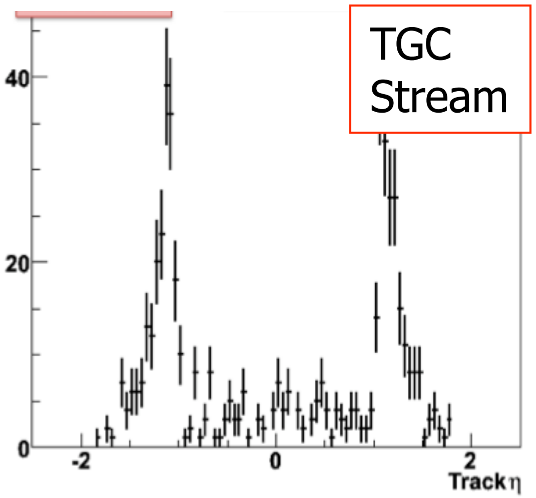



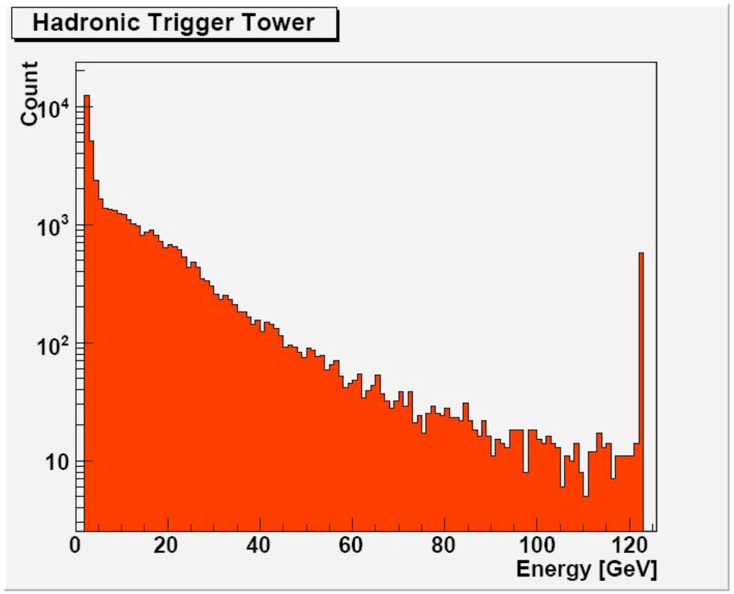
# Cosmic run after LHC incident

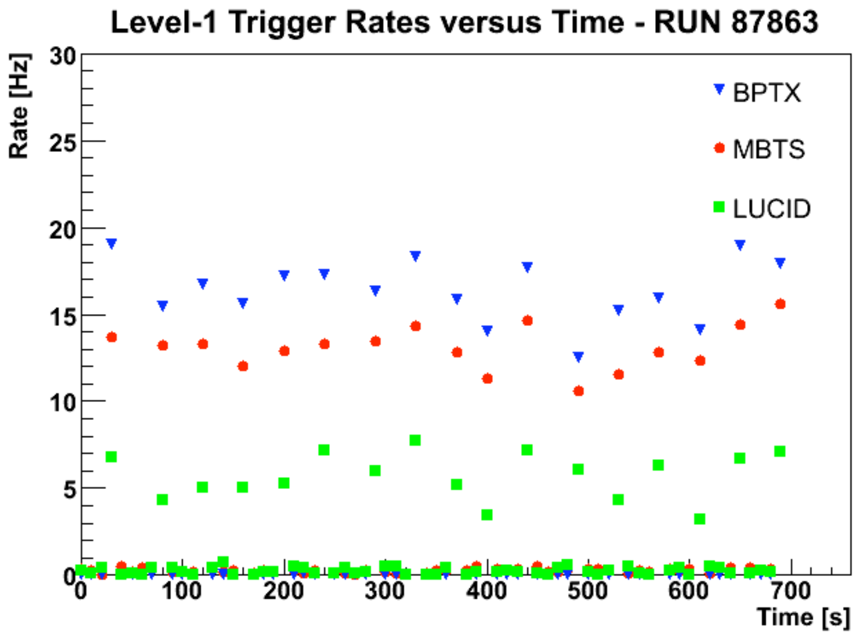
- Combined cosmic run (all sub-detectors) from 17th September to 23rd October
- Aim was to debug the system further and to calorimeter signals and muon tracks for alignment and calibration
- HLT running in "flagging mode" used only to send events to streams, but this allowed plenty of validation
- Also did high-rate tests of Level 1 and HLT with good results

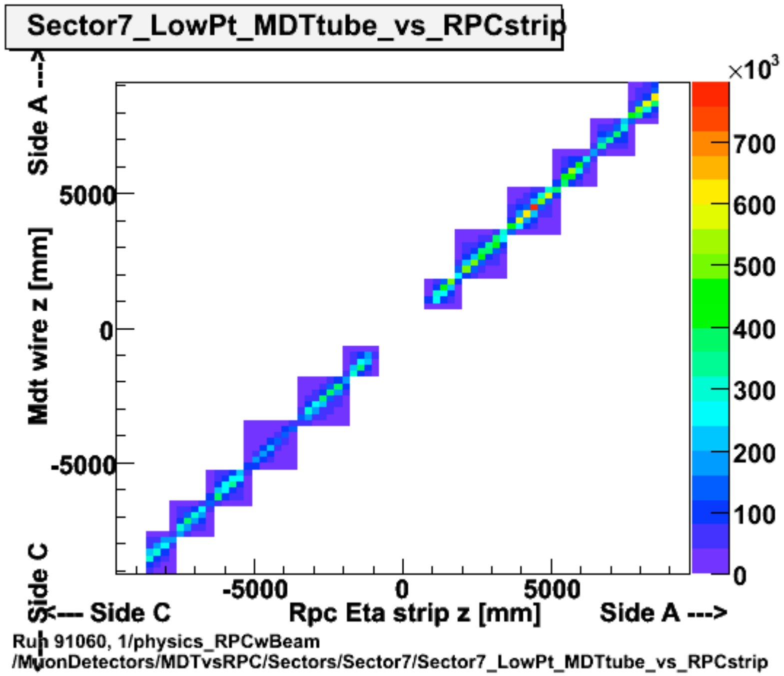


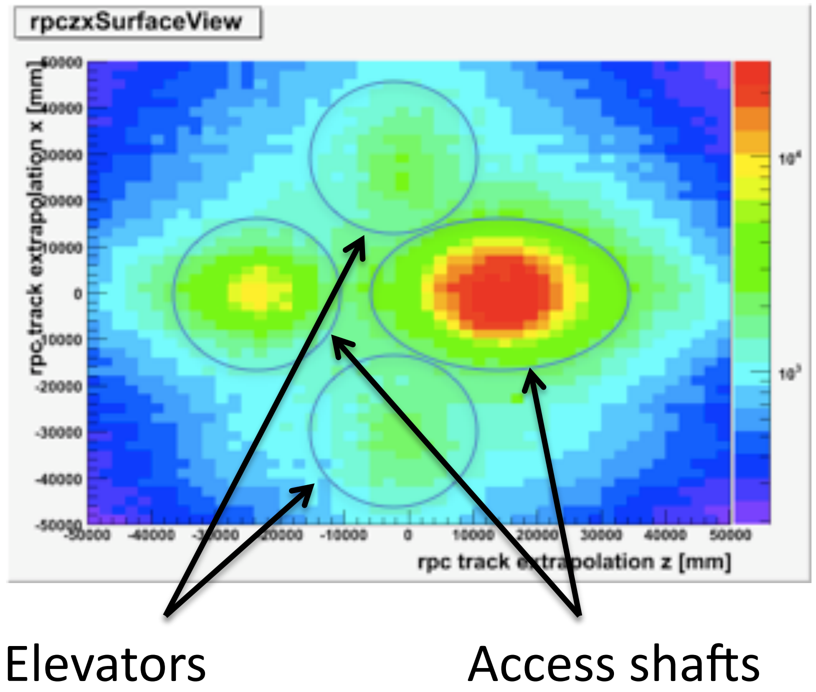





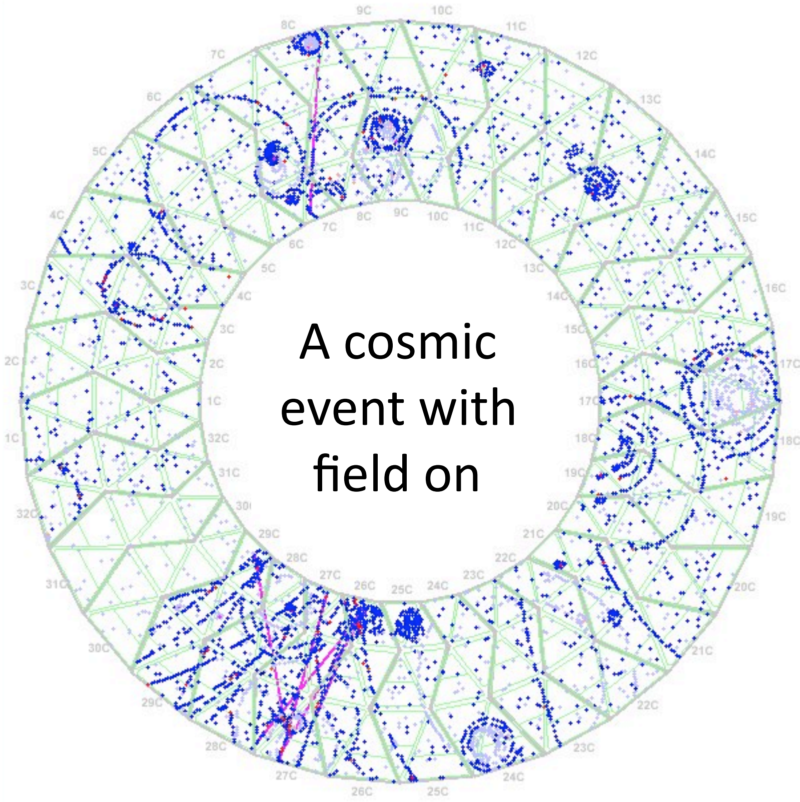

X-ray of the ATLAS cavern with cosmic muons




Very good correlation between RPC (trigger chambers) and MDT (precision chambers) hits

# Conclusions

# Conclusions



A cosmic event with field on

- The ATLAS Trigger is now becoming mature
- Both level 1 and the High Level Trigger used with real data from the LHC and with cosmic rays
- Important progress was made!
- Trigger algorithms have been developed with good timing performance, basically robust, and good efficiency
- Some work remains to be done, but mostly we need collisions data to progress further
- Eagerly awayting LHC data later this year!

# The first has been delivered to the