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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

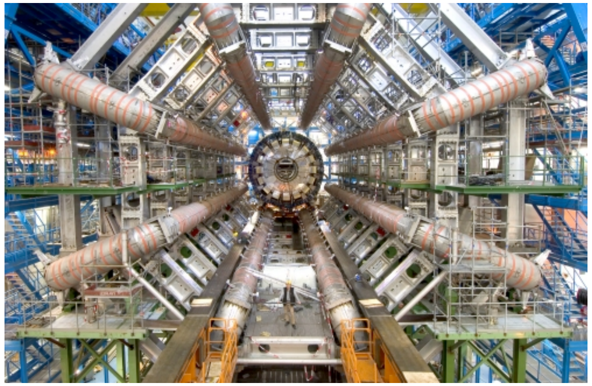
- The LHC started operating on September 10th last and will resume in July/August this year

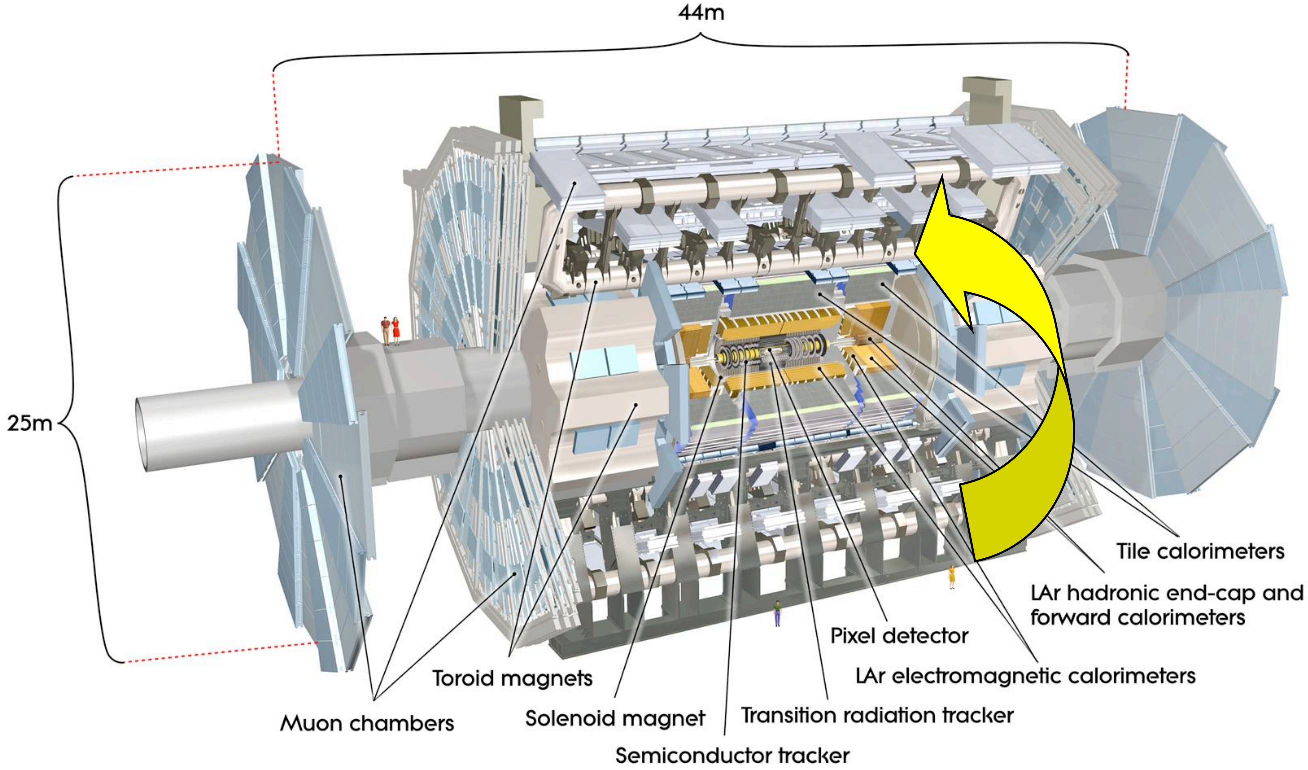
- Four main experiments:
  - ATLAS and CMS – general-purpose
  - LHCb – B physics
  - ALICE – heavy-ion physics

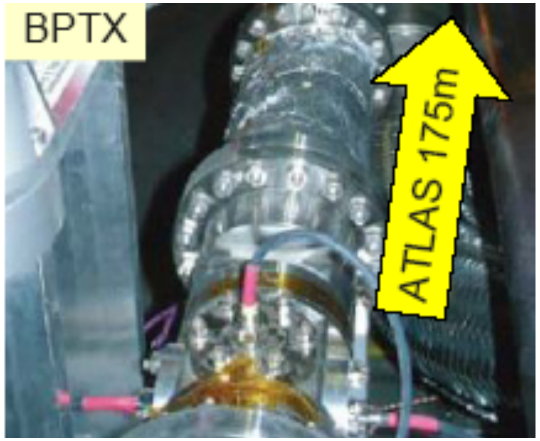
CM energy	**14 TeV (design)**
Luminosity ($cm^{-2}s^{-1}$)	Low: $2x10^{33}$ High: 10^{34}
Bunch crossing	24.95 ns
Overlaid events	23 @ $10^{34}cm^{-2}s^{-1}$
Beam radius	16.7 μm
Particles/bunch	$1.15x10^{11}$
Bunches/beam	2808 (design)
Stored energy	362 MJ/beam

The ATLAS Detector

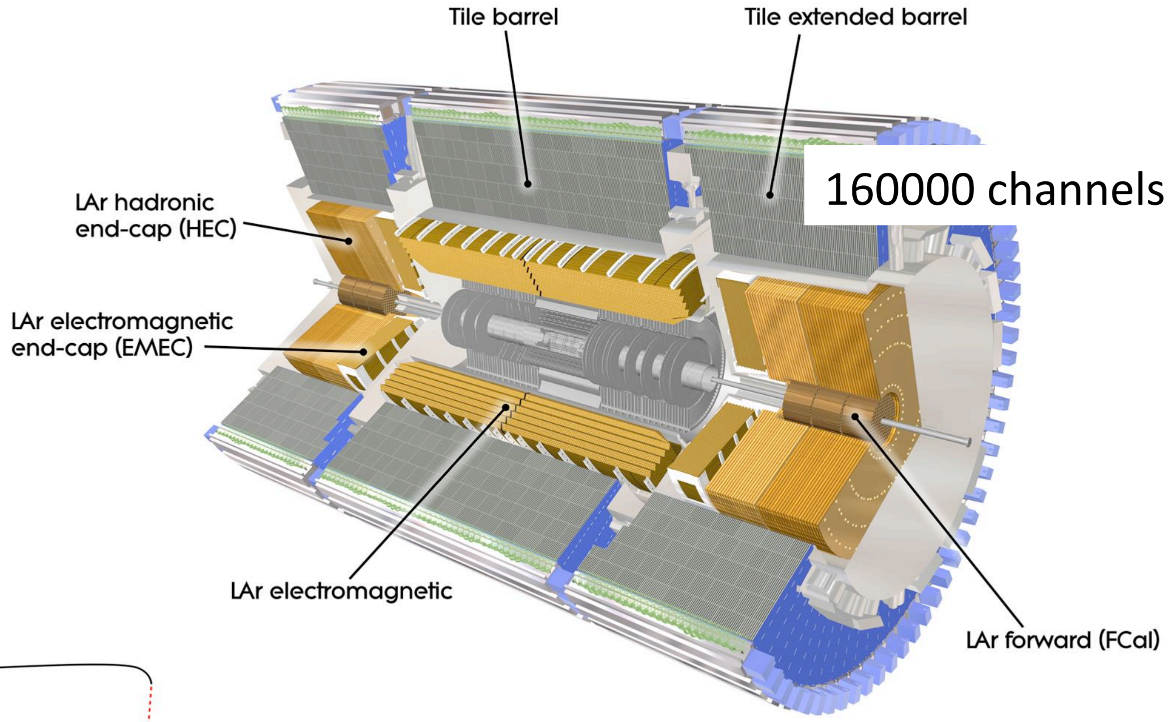
- Large angular coverage: $|\eta|<4.9$; tracking in $|\eta|<2.5$
- Inner detector: pixels, Si-strips and transition Radiation Tracker in for particle identification
- Liquid Argon electromagnetic calorimeter with accordion geometry
- Iron-scintillating tile hadronic calorimeter; tiles placed radially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

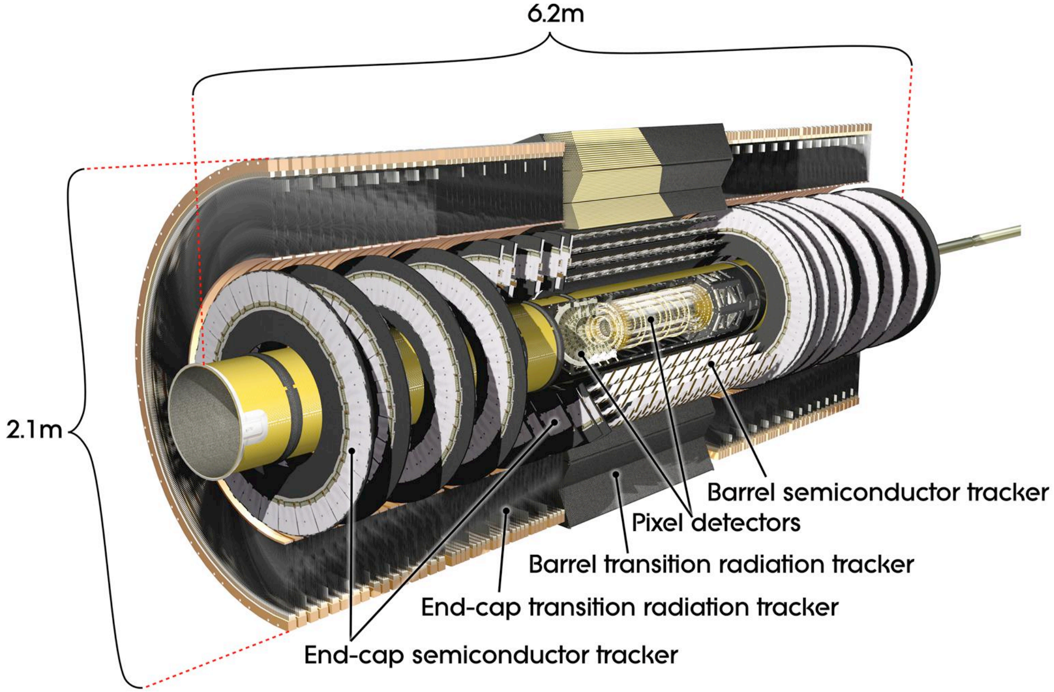






Beam Pickup: at ± 175m from ATLAS
Trigger on filled bunch
Provide the reference timing

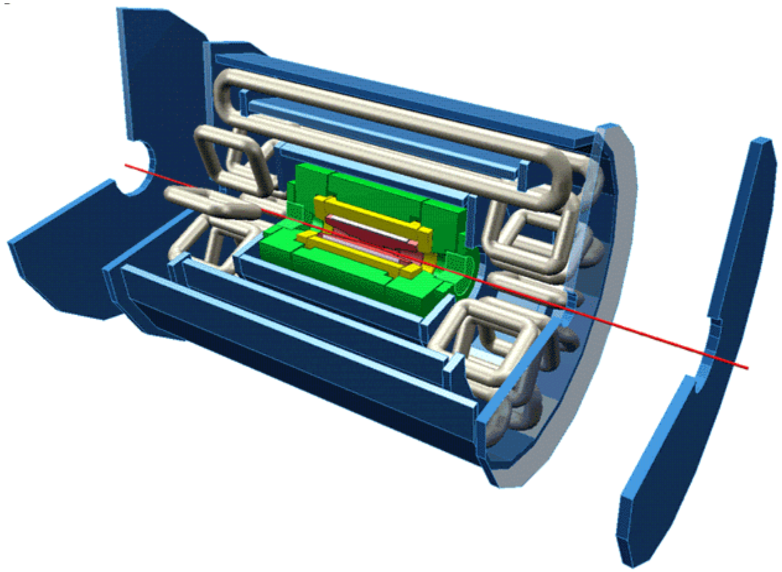


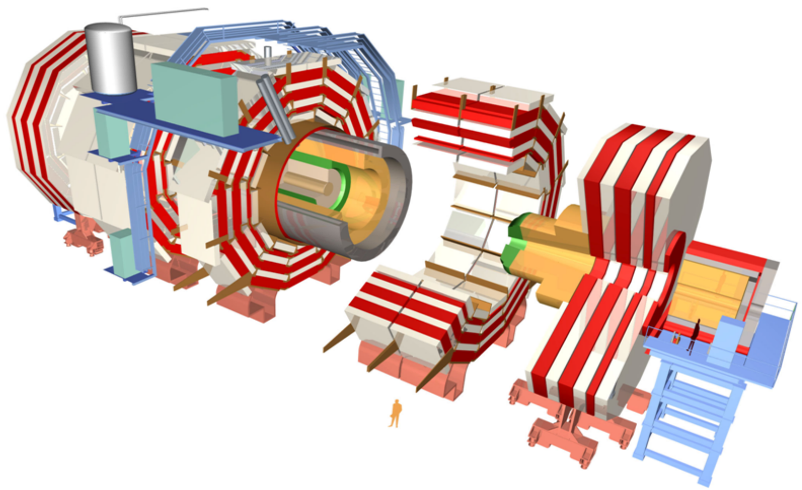


Minbias Trigger Scintillator:
32 sectors on LAr cryostat
Main trigger for initial running
η coverage 2.1 to 3.8

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

	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 $\sigma/p_T \approx 5\text{x}10^{-4} p_T + 0.01$	Si pixels, strips $\sigma/p_T \approx 1.5\text{x}10^{-4} p_T + 0.005$
EM calorimeter	Pb+LAr $\sigma/E \approx 10\%/\sqrt{E} + 0.007$	PbWO4 crystals $\sigma/E \approx 2\text{-}5\%/\sqrt{E} + 0.005$
Hadronic calorimeter	Fe+scint. / Cu+LAr (10λ) $\sigma/E \approx 50\%/\sqrt{E} + 0.03$ GeV	Cu+scintillator (5.8λ + catcher) $\sigma/E \approx 100\%/\sqrt{E} + 0.05$ 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)

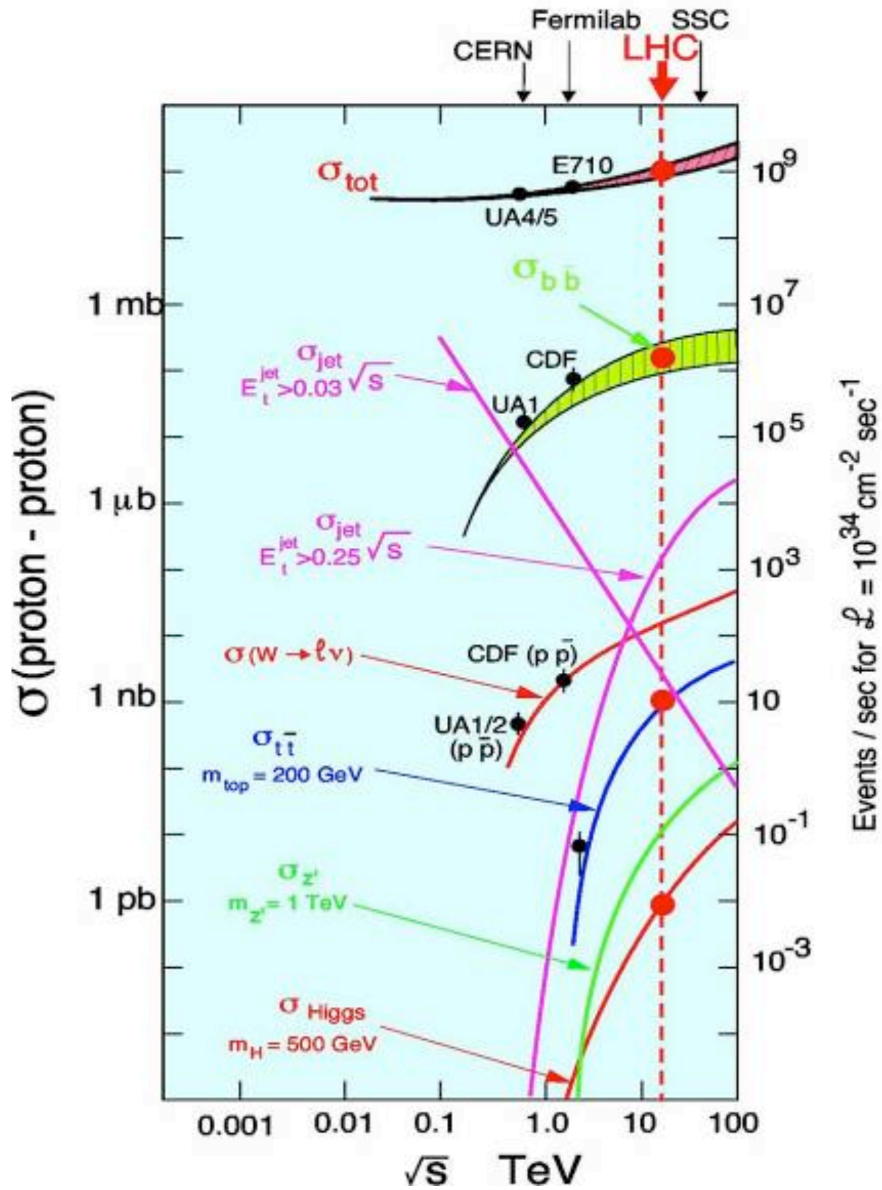




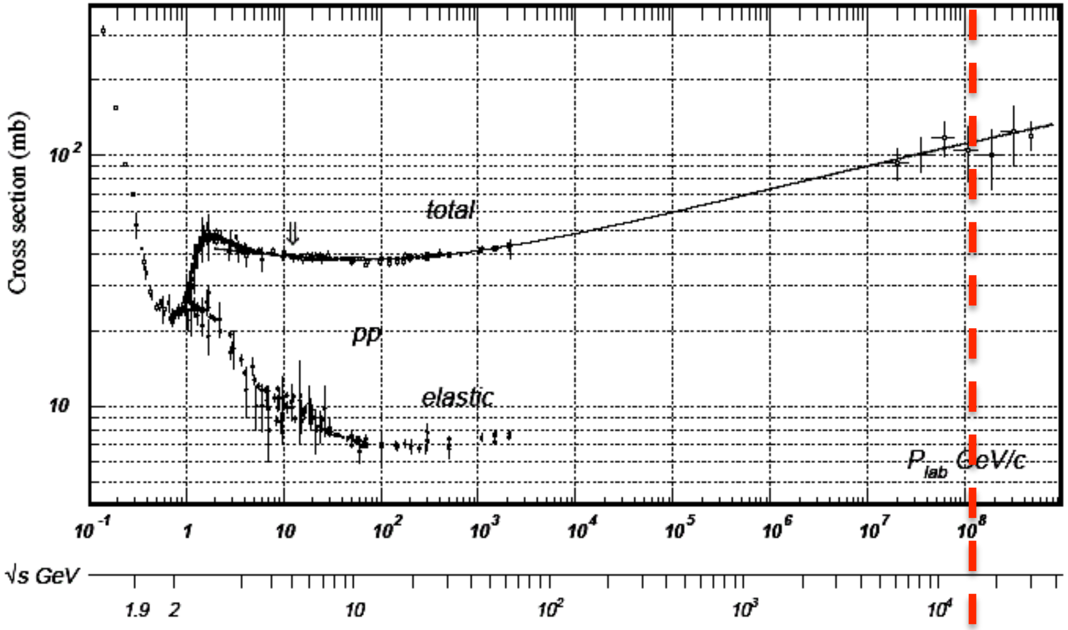
The ATLAS Trigger

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!...



Challenges faced by the ATLAS trigger



- $L = 10^{34}\ cm^{-2}s^{-1} = 10^{7} mb^{-1}Hz$
- $\sigma = 70$ mb

=> Rate = 70×10^{7}Hz

- $\Delta t = 25ns = 25 \times 10^{-9}\ Hz^{-1}$

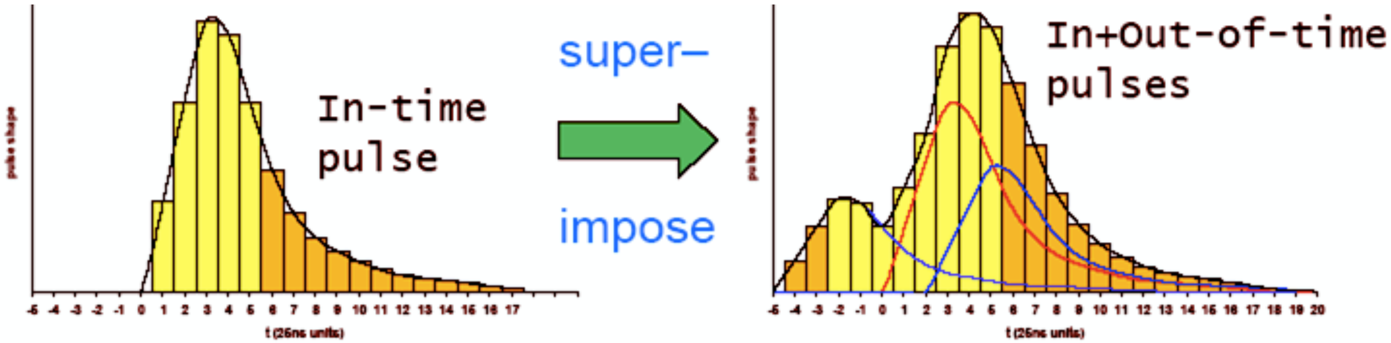
=> Events/25ns = $70 \times 25 \times 10^{-2} = 17.5$

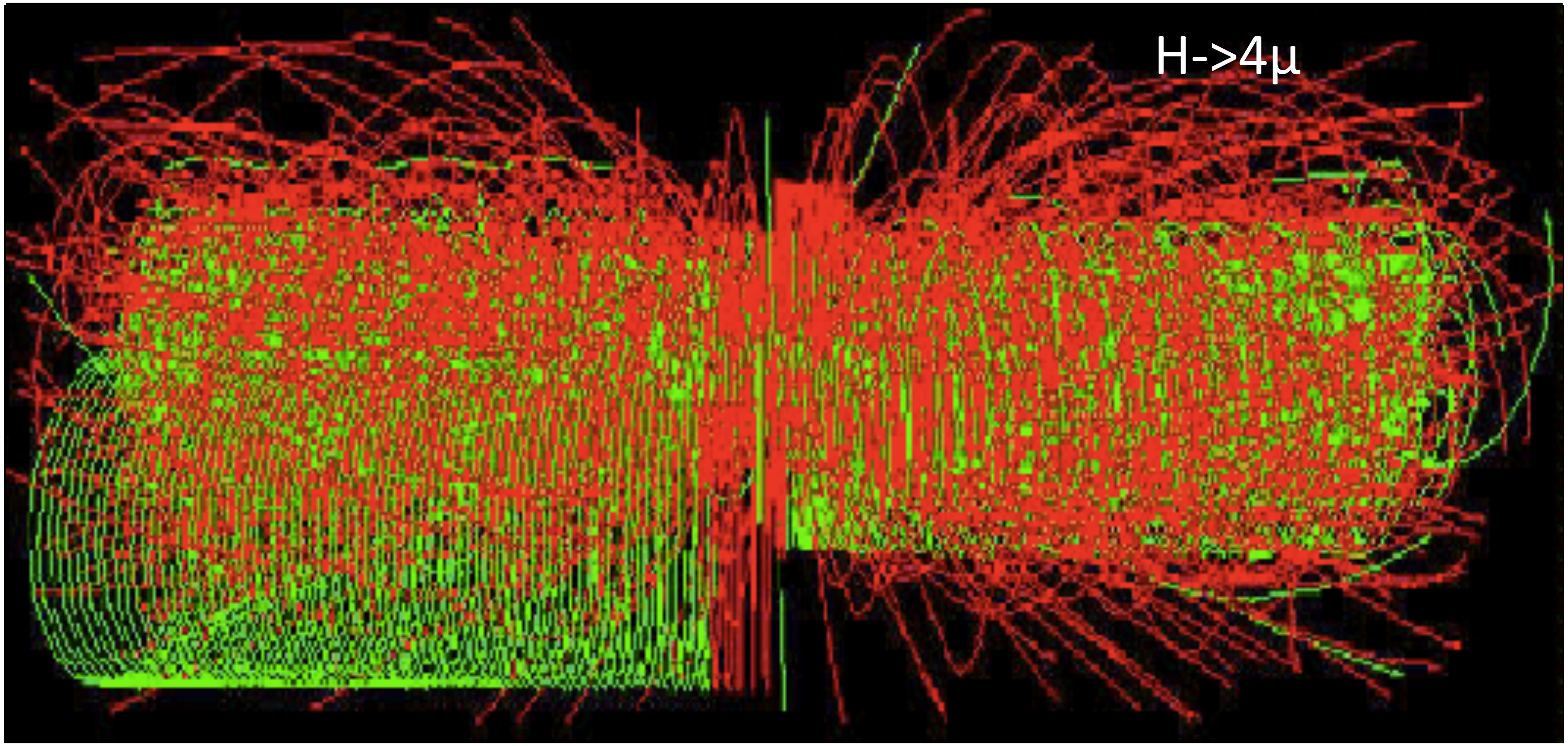
- Not all bunches full (2835/3564)

⇒ 22 events/crossing

- Detector response time varies from a few ns to e.g. ~700 ns for MDT chambers

=> Pileup not only from the same crossing




H->4μ

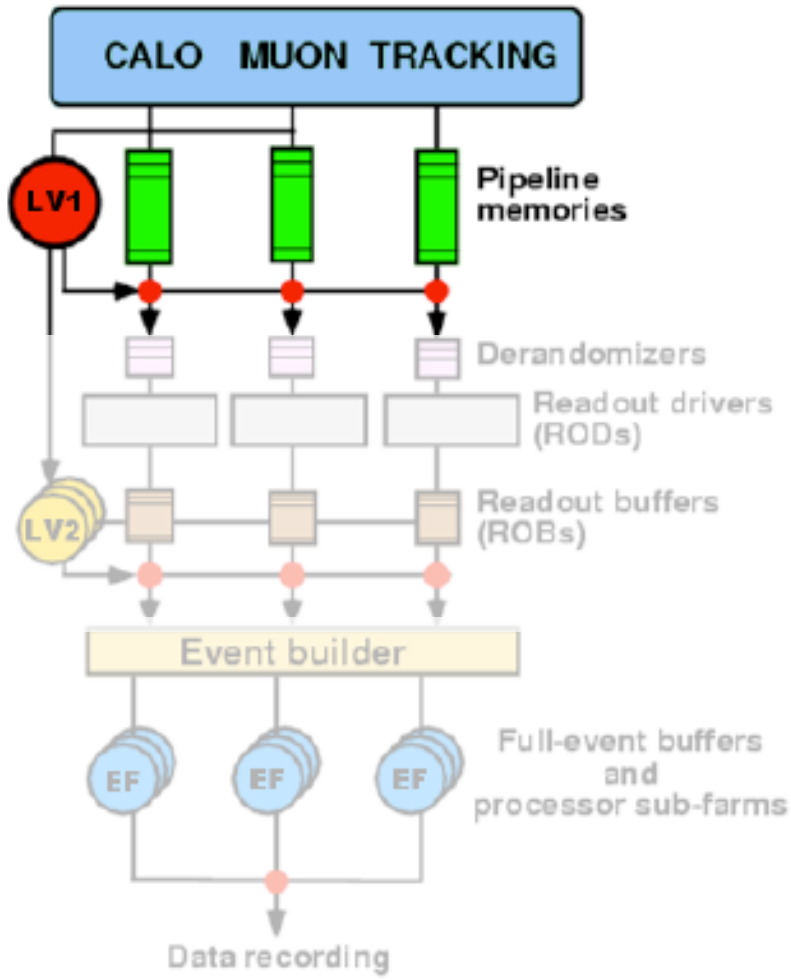
The ATLAS trigger

Three trigger levels:

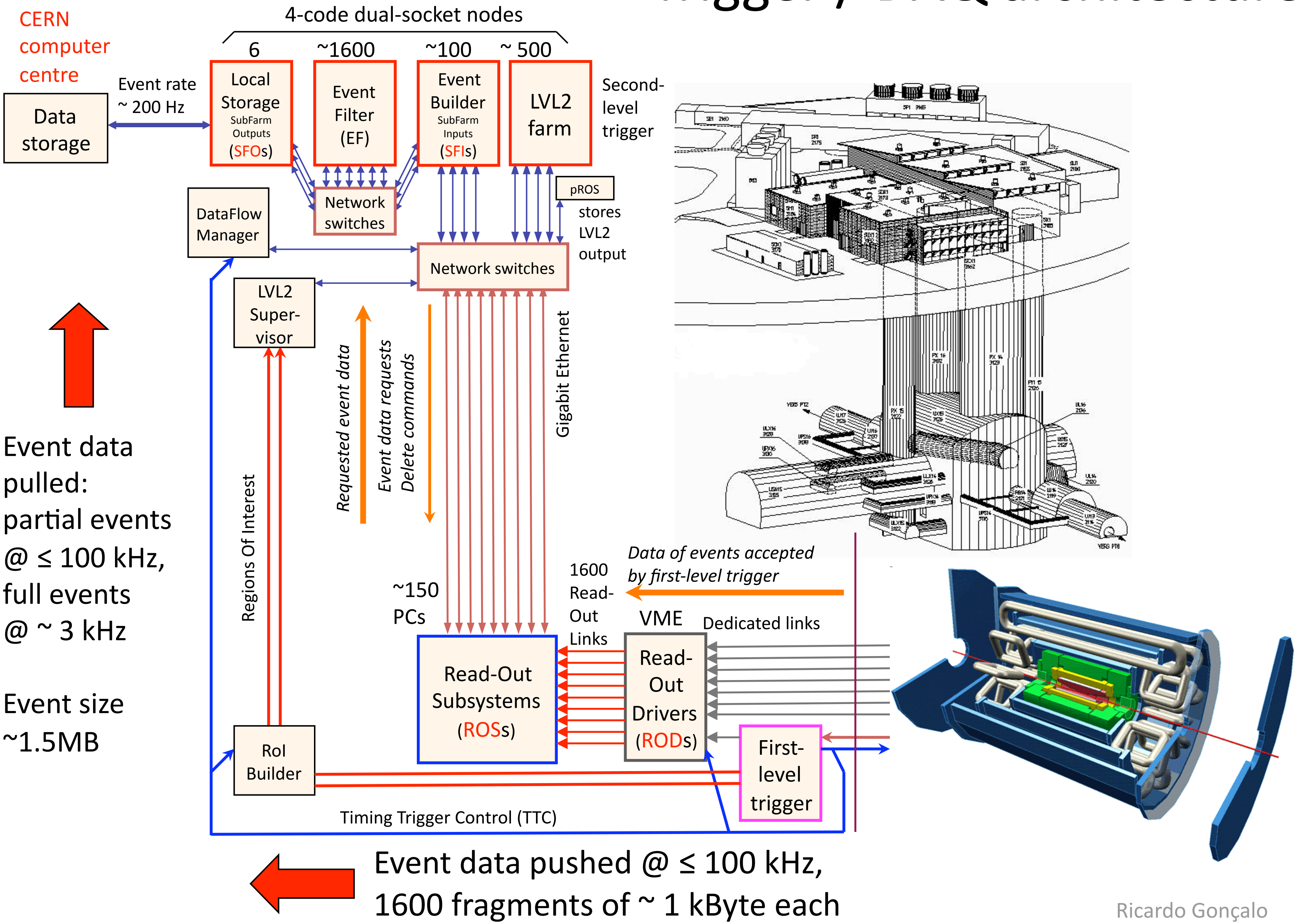
- Level 1:
  - Hardware based (FPGA/ASIC)
  - Coarse granularity detector data
  - Calorimeter and muon spectrometer only
  - Latency 2.5 μs (buffer length)
  - Output rate ~75 kHz (limit ~100 kHz)

High-Level Trigger

- 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



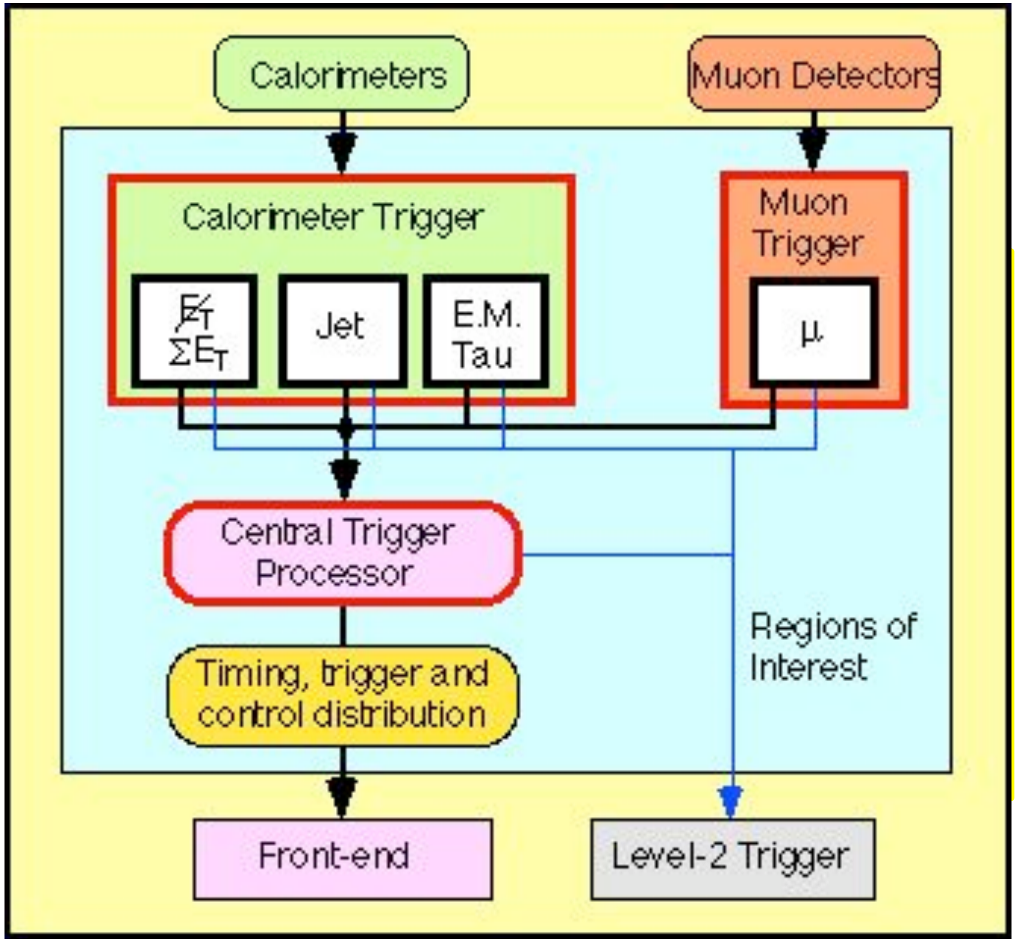
Trigger / DAQ architecture



First-Level Trigger

Level 1 architecture

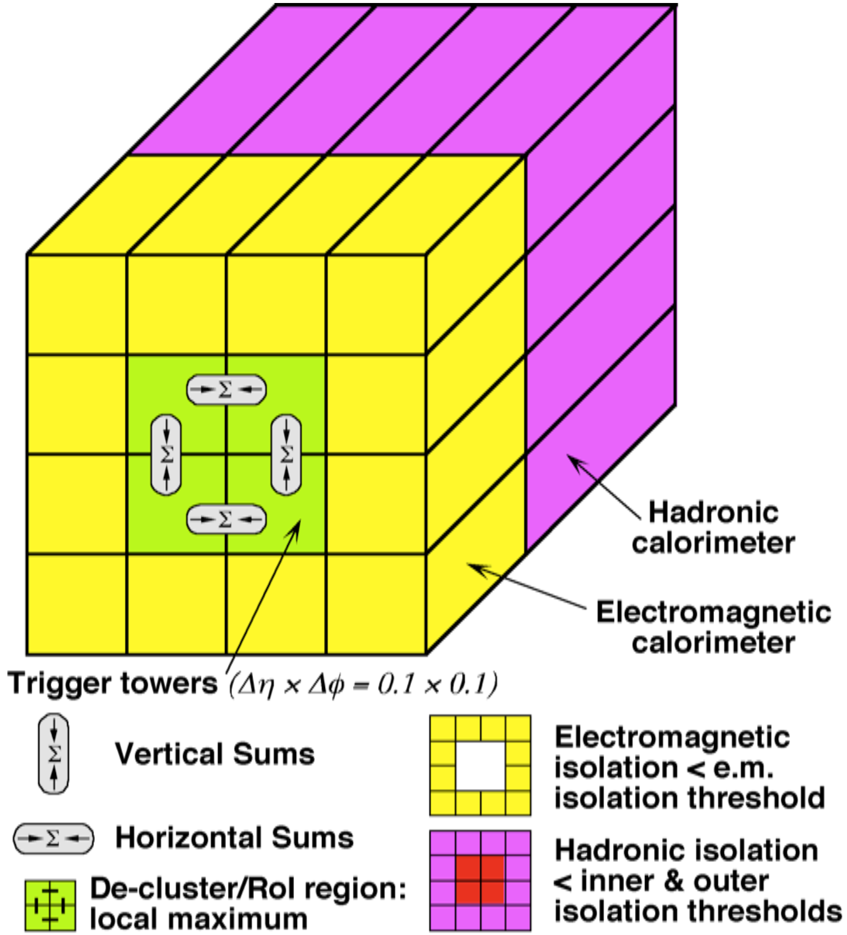
- Level 1 uses calorimeter and muon systems only
- Muon spectrometer:
  - Dedicated (fast) trigger chambers
    - Thin Gap Chambers – TGC
    - Resistive Plate Chambers – RPC
- Calorimeter:
  - Based on Trigger Towers: analog sum of calorimeter cells with coarse granularity
  - Separate from precision 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 η and φ



Level 1: Calorimeter Trigger

- Coarse granularity trigger towers
  - $\Delta\eta\times\Delta\varphi$ = 0.1×0.1 for e, γ, τ up to $|\eta|<2.5$
  - $\Delta\eta\times\Delta\varphi$ = 0.2×0.2 for jets, up to $|\eta|<3.2$
- 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)
  - $\Sigma E_T^{em,had}$, ΣE_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

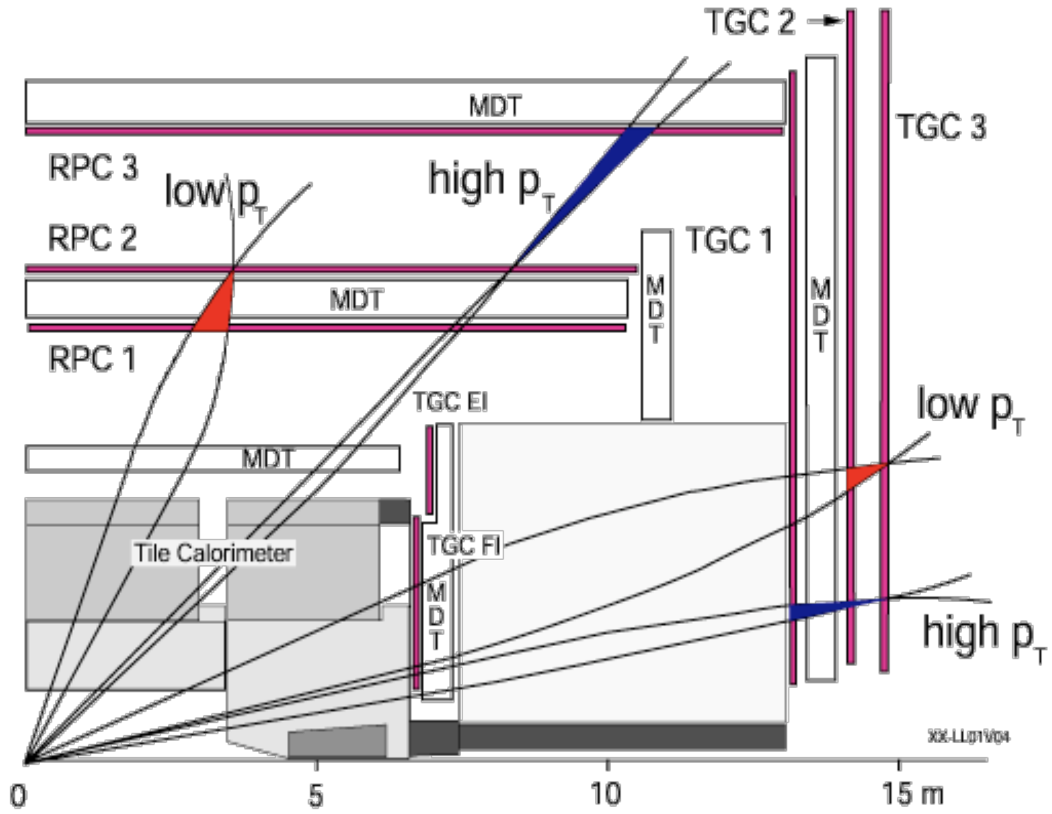


Level 1: Muon trigger

- 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:

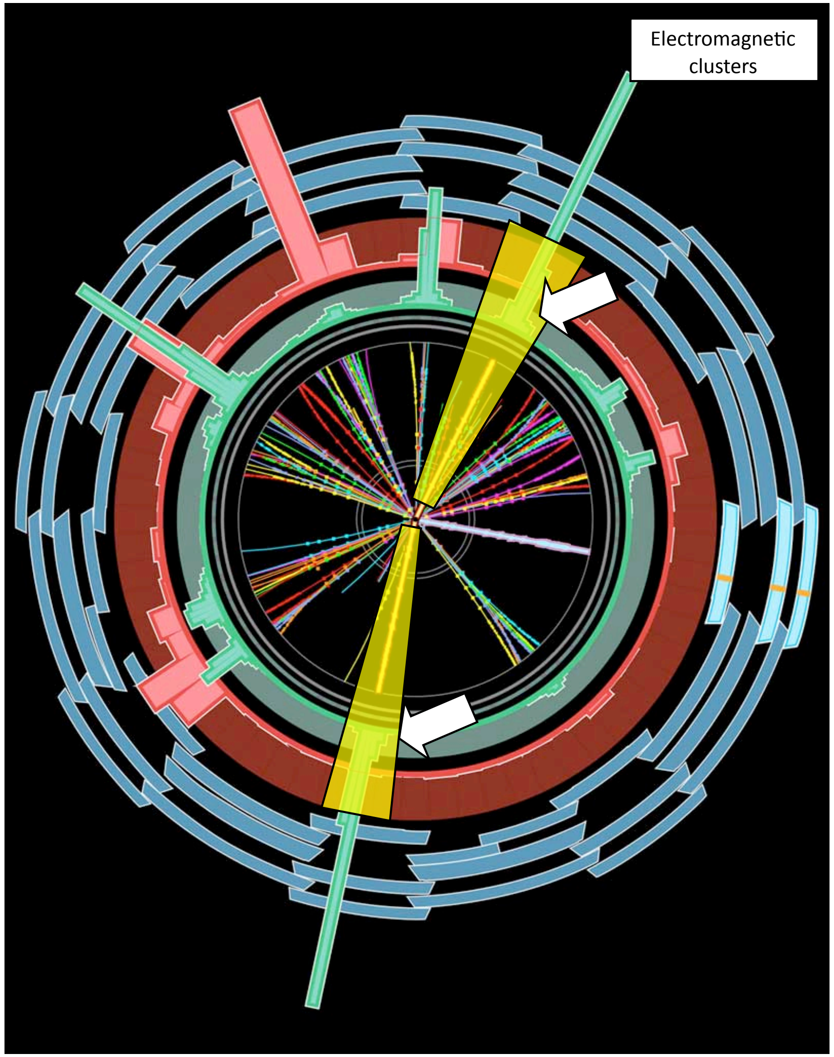
- Low-p_T threshold (>6GeV) look for 3 hits out of 4 planes
- High-p_T threshold (>20GeV) look for 3 hits out of 4 planes + 1 out of 2 in outer layer
- Algorithm is programmable and coincidence window is p_T-dependent



High-Level Trigger

Selection method

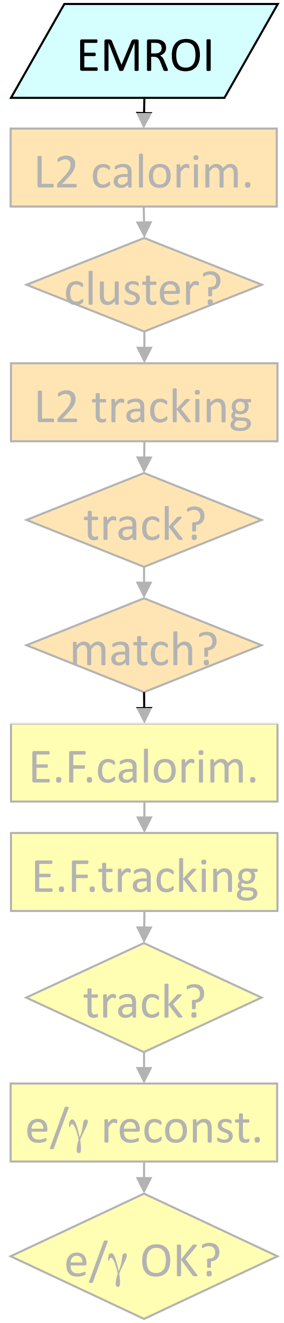
Event rejection possible at each step



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

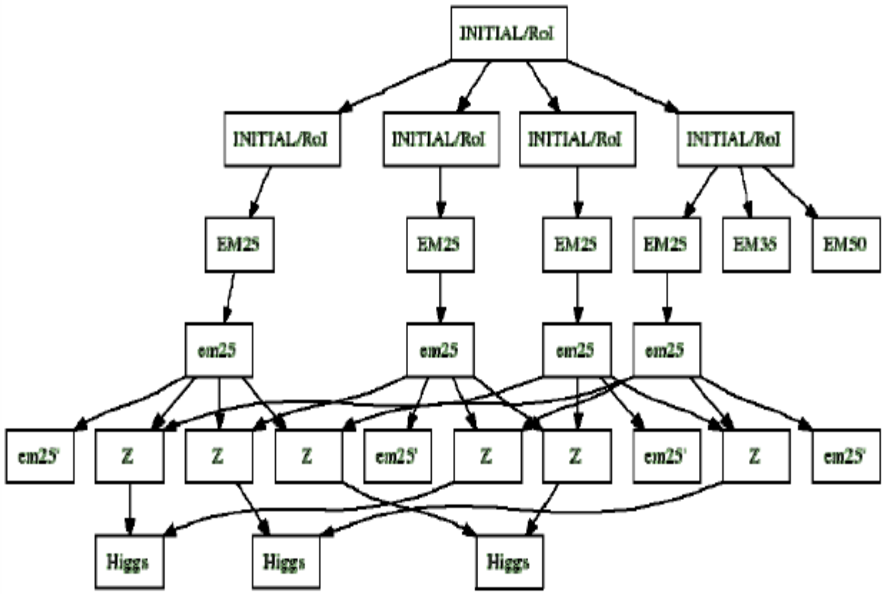
Note:

- 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
- More technical details:
  - Possible to re-run hypothesis algorithms offline – study working point for each trigger
  - Possible to re-run prescaled-out chains for accepted events (tricky…for expert studies)

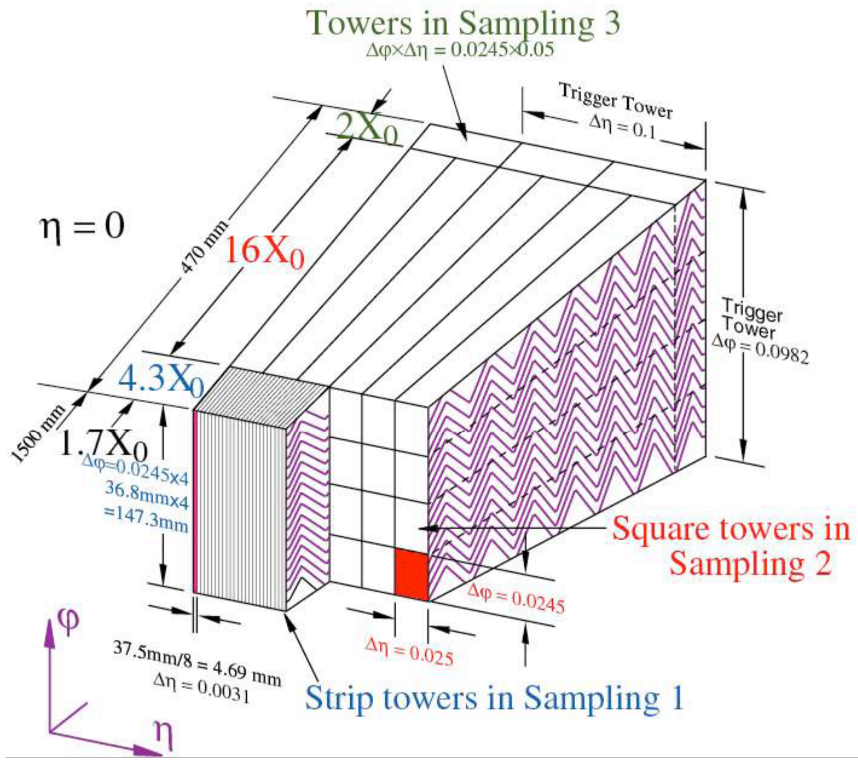


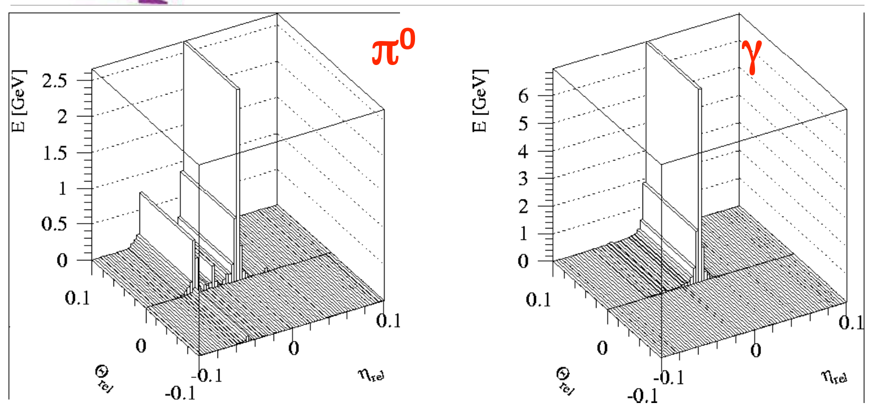
Trigger algorithms

- High-Level Trigger algorithms organised in groups ("slices"):
  - Minimum bias, e/γ, τ, μ, 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/γ 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

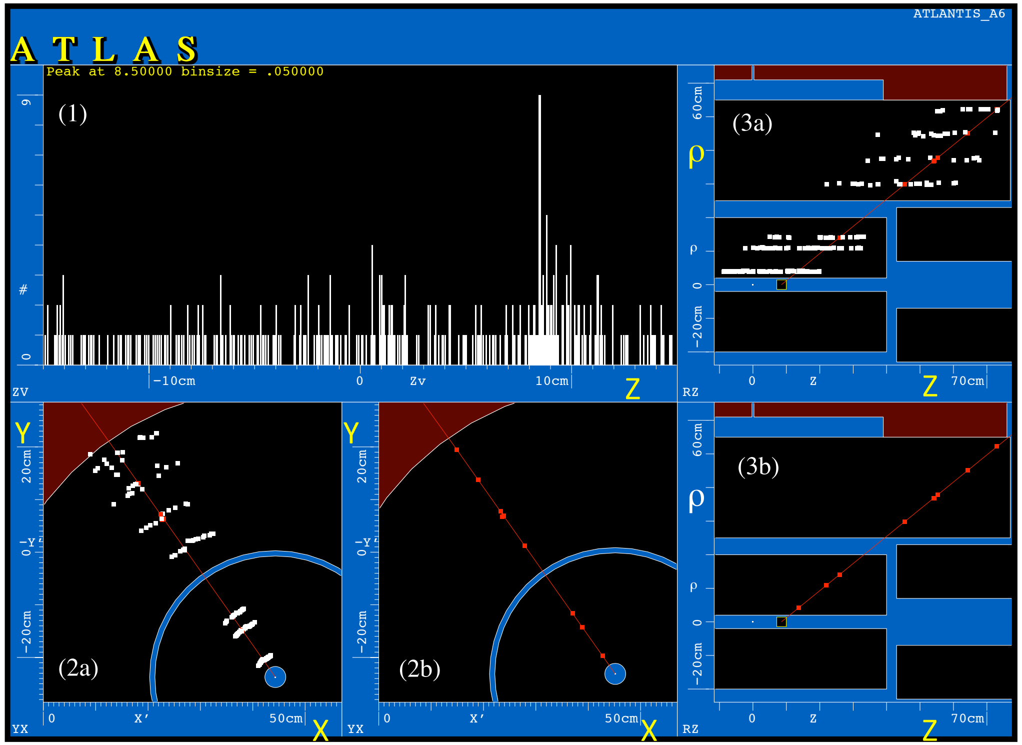




Example: level 2 tracking algorithm

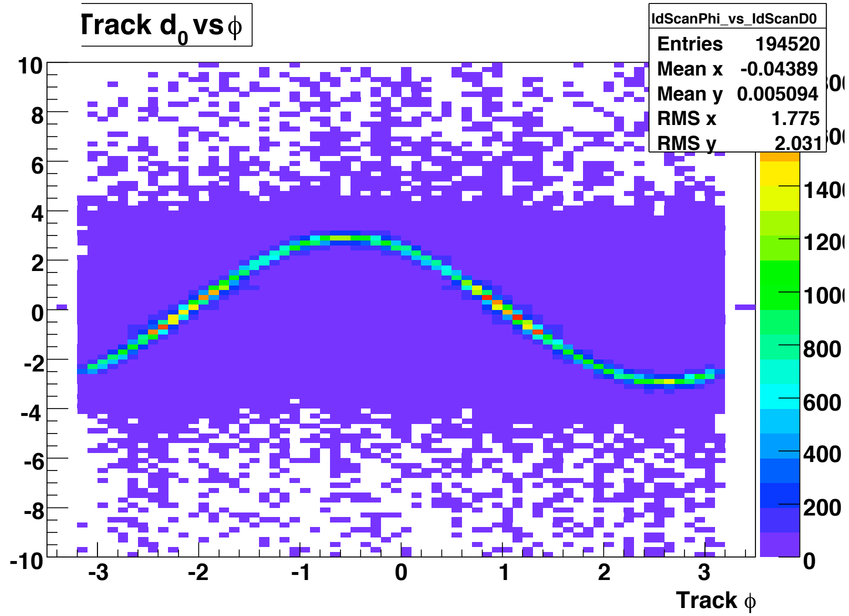
1. Form pairs of hits in Pixel and SCT in thin ϕ slices;
   - extrapolate inwards to find Z_{vtx} from a 1D histogram
2. Using Z_{vtx}, make 2D histogram of hits in η-ϕ plane;
   - remove bins with hits in too few layers
3. Do 2D histogram using space point triplets in $1/p_T$-ϕ plane;
   - Form tracks 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

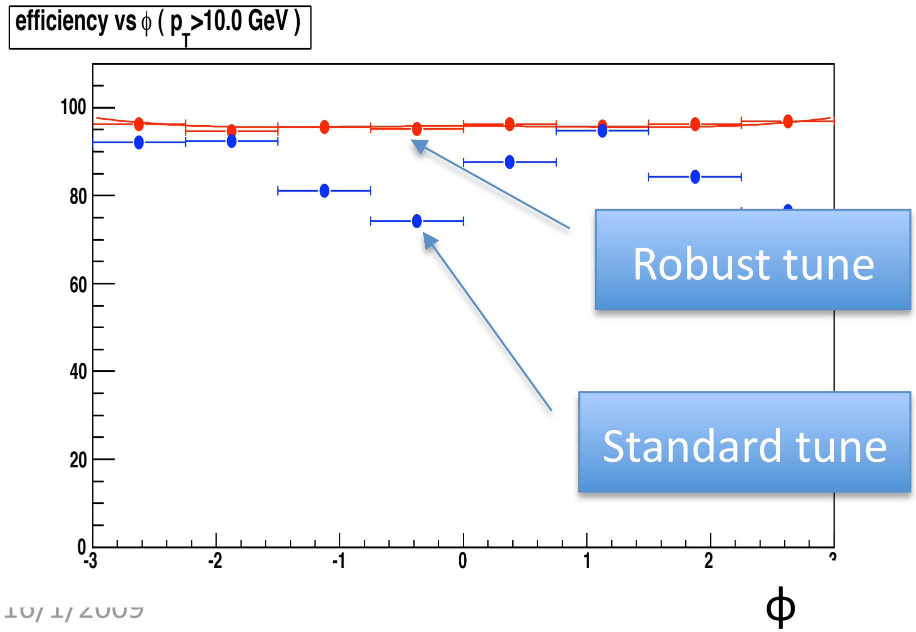
- Work has been devoted to verifying that the trigger is robust against several possible error sources
- Likely sources of error introduced in simulation:
  - Added dead material (up to $1X_0$)
  - Misaligned inner detector, calorimeter and muon spectrometer
  - Displaced beam spot



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 ± 0.2	$J/\Psi \to ee, Y \to ee$, Drell-Yan
2e5	2EM3	1	6.5	medium	1	6	$J/\psi \to ee, Y \to ee$, Drell-Yan
Jpsiee	2EM3	1	6.5	medium	1	1	$J/\psi \to ee, Y \to ee$
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 ± 0.1	$e^\pm$ direct photon cross-section, e-no-track trigger
e10_xe30	EM7_XE30	1	0.2	medium	1	0.3 ± 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 ± 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$\sim10^{33}$ cm^{-2} s^{-1}
γ15	EM13	1	0.7	medium	10	1.3 ± 0.1	$e^\pm$ direct photon cross-section
e15_xe20	EM13_XE20	1	0.2	loose	1	1.0 ± 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$\sim10^{33}$ cm^{-2} s^{-1}
γ20	EM18	1	0.3	loose	1	5.4 ± 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 ± 0.1	check HLT performance
em20i_passEF	EM18I	1	0.1		300	0.5 ± 0.1	check L1 isolation
e22i_L33	EM18I	1	0.1	tight	1	1.2 ± 0.1	trigger for L$\sim10^{33}$ cm^{-2} s^{-1}
γ55_L33	EM18	1	0.3	tight	1	1.2 ± 0.1	trigger for L$\sim10^{33}$ cm^{-2} s^{-1}
em105_passHLT	EM100	1	1		1	1.0 ± 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$\sim10^{31}$ cm^{-2} s^{-1}. For each signature rates and the motivation for this trigger are given.

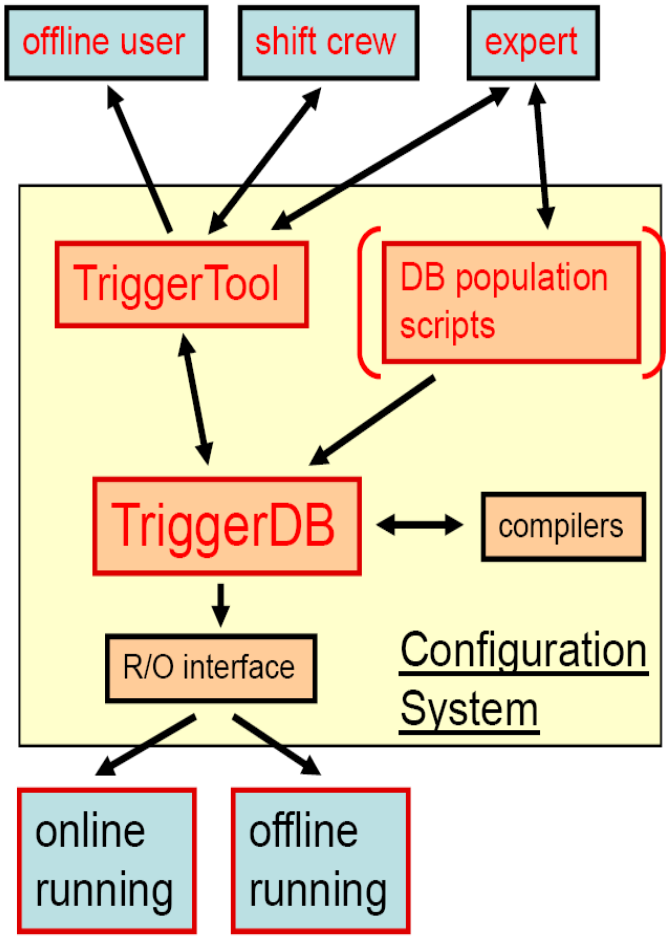
Configuration

- 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

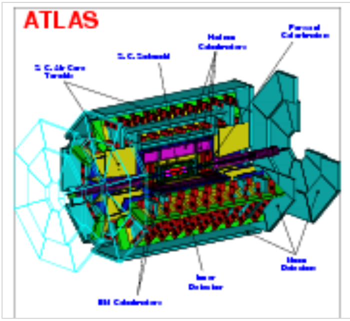
Preparation

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

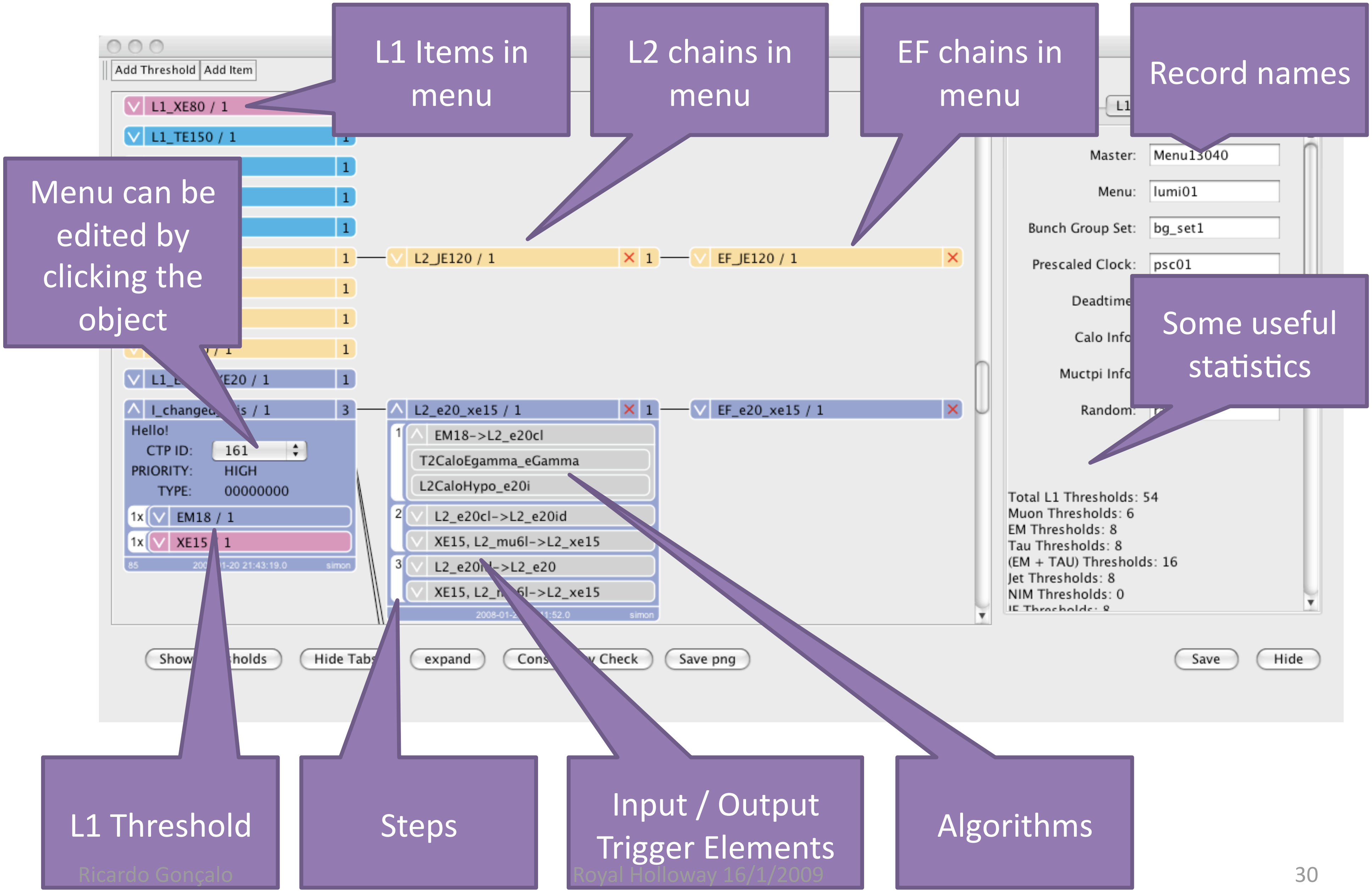
- Trigger names (version), prescales, pass throughs

Data formats:

ESD
AOD
DPD
TAG

With decreasing amount of detail

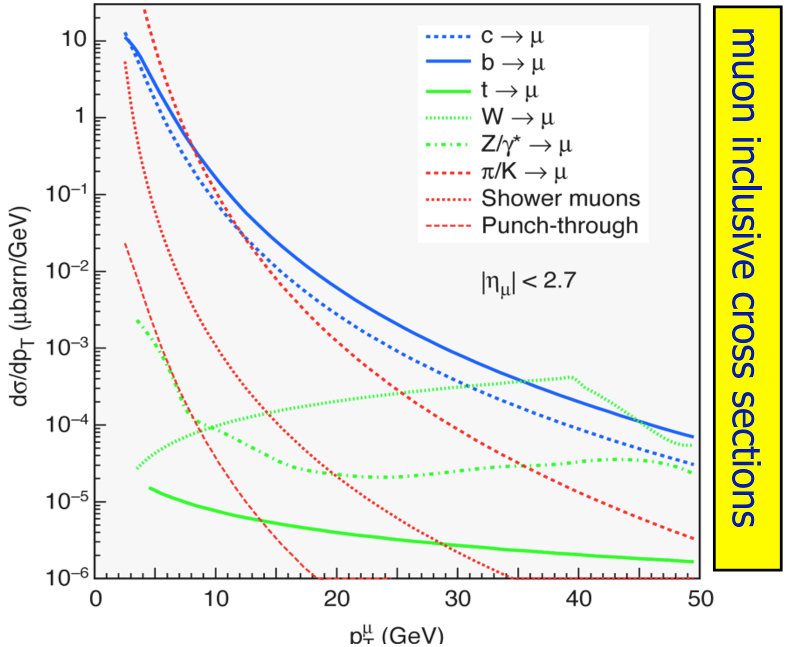
Viewing and Modifying a Menu

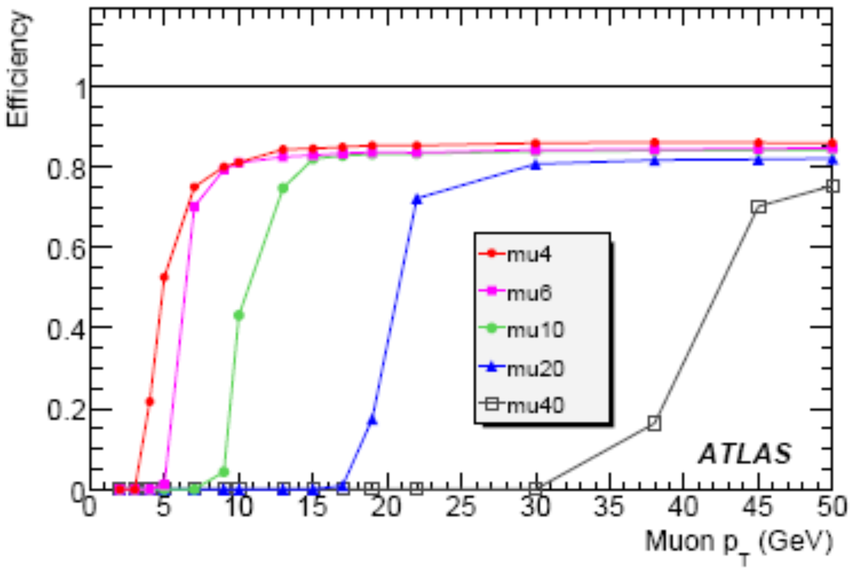


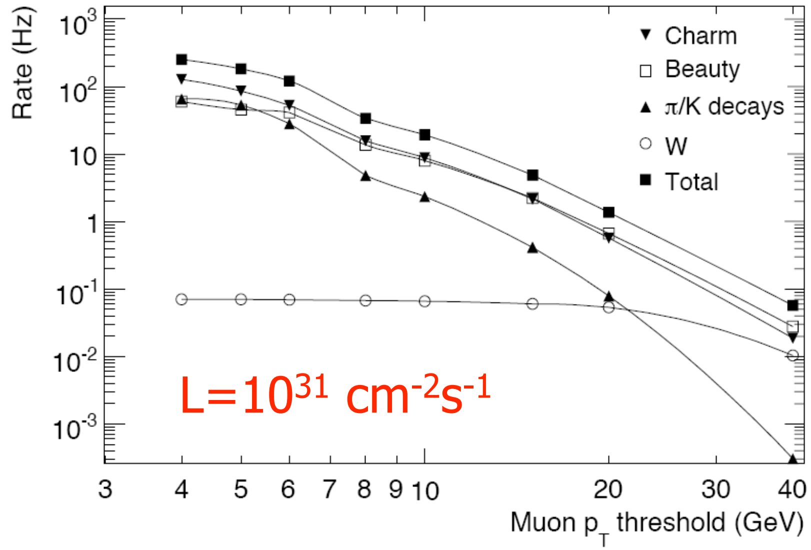
Performance of the ATLAS Trigger

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)

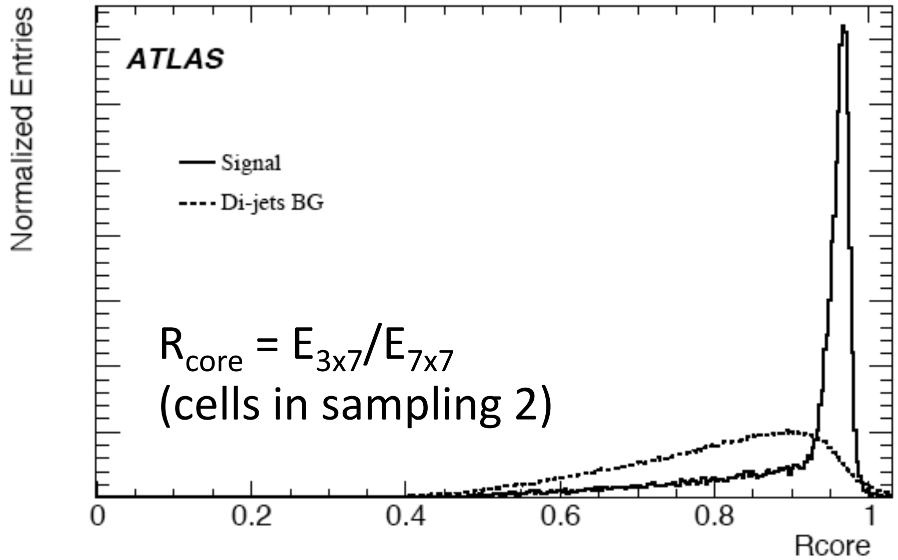


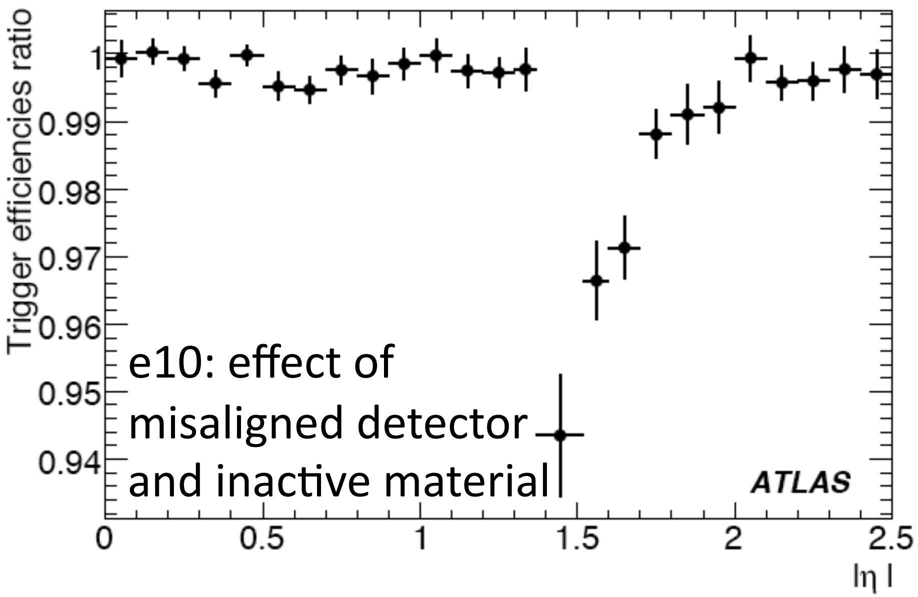


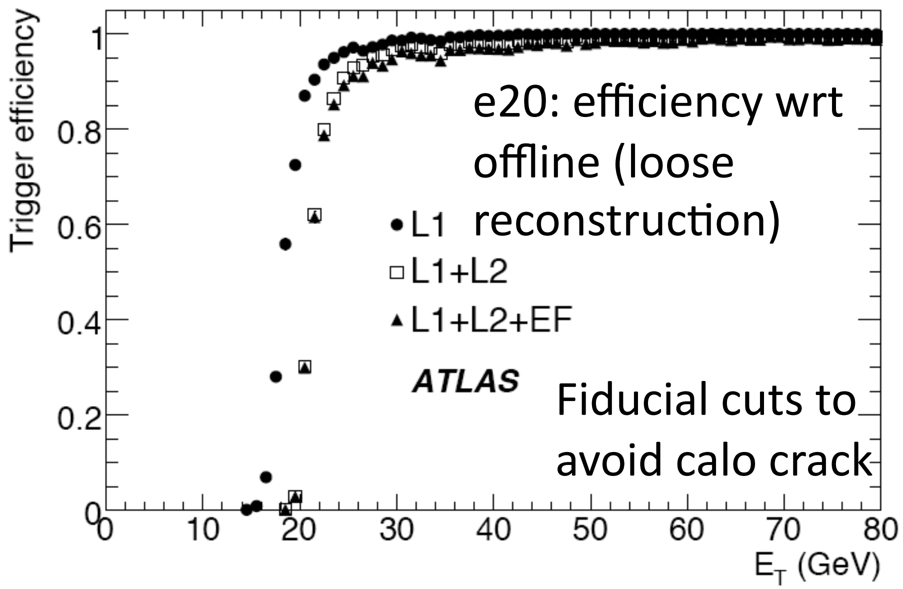


Electron and photon triggers

- 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



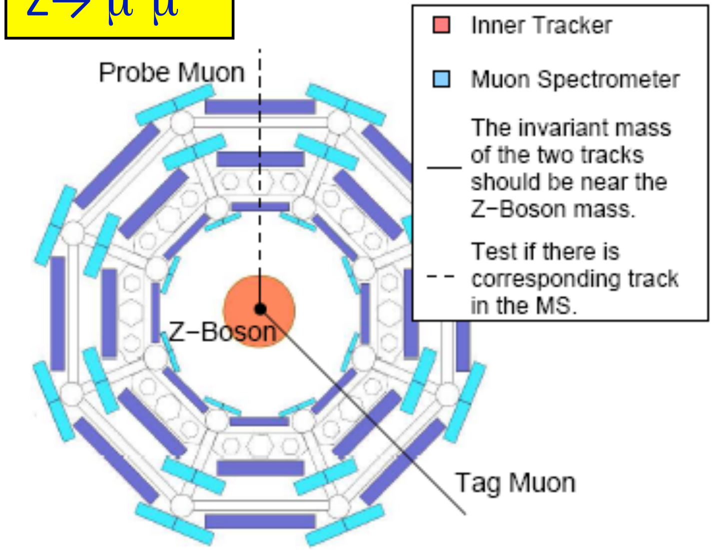




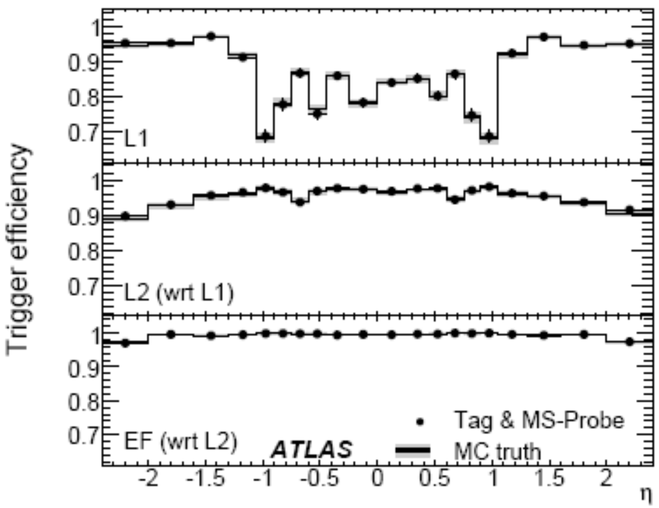
Trigger Efficiency from data

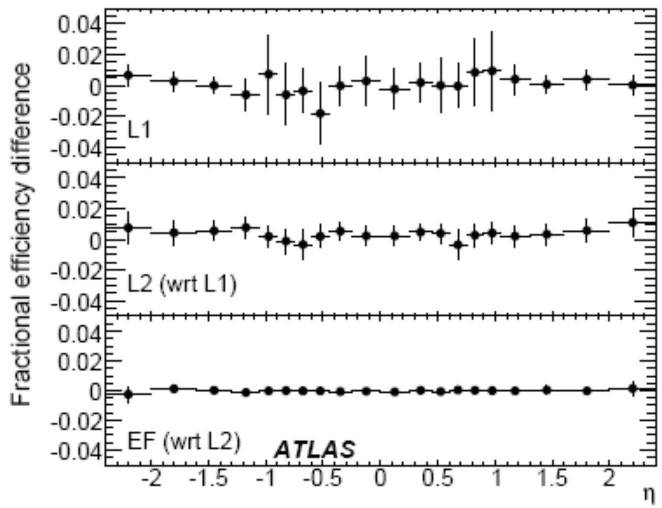
- Try to rely on simulated data as little as possible
- For electrons and muons the "Tag & Probe" method can be used
  - Use clean signal sample (Z, J/ψ → l^+l^-)
  - Select track that triggered the event ("Tag")
  - Find other track using offline reconstruction ("Probe")
  - Determine efficiency by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

$Z \rightarrow \mu^+\mu^-$



mu20

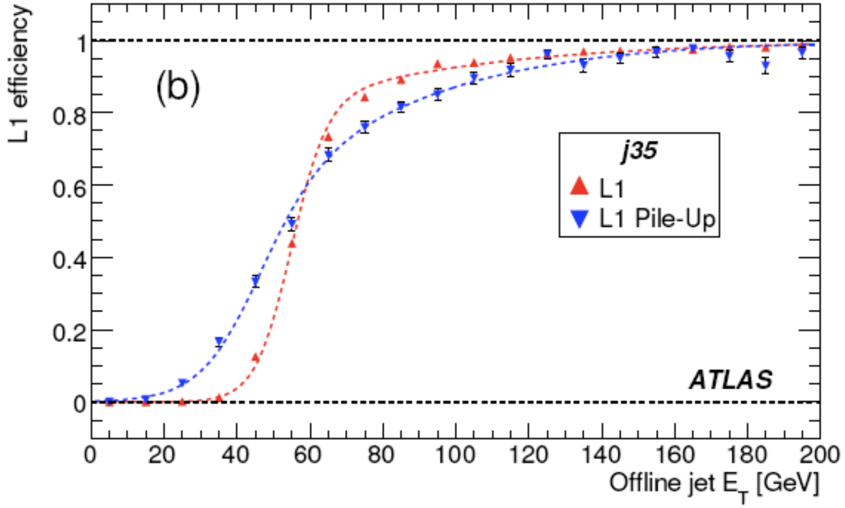


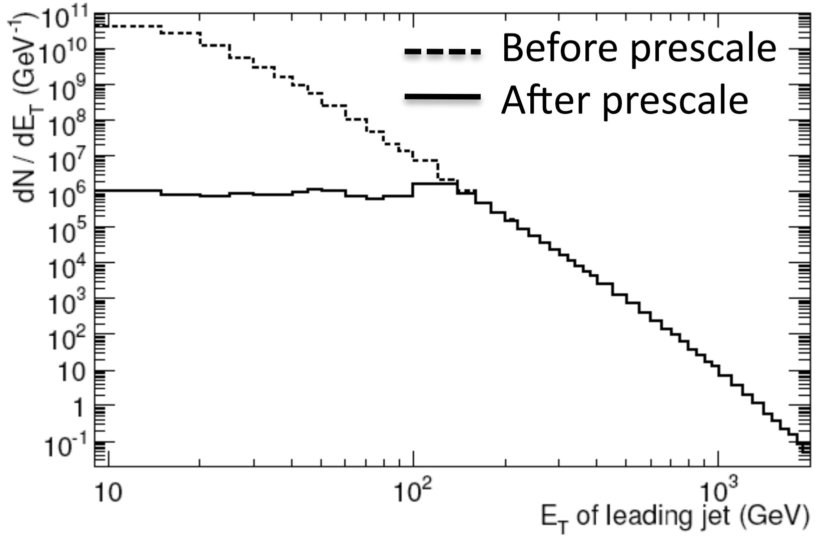


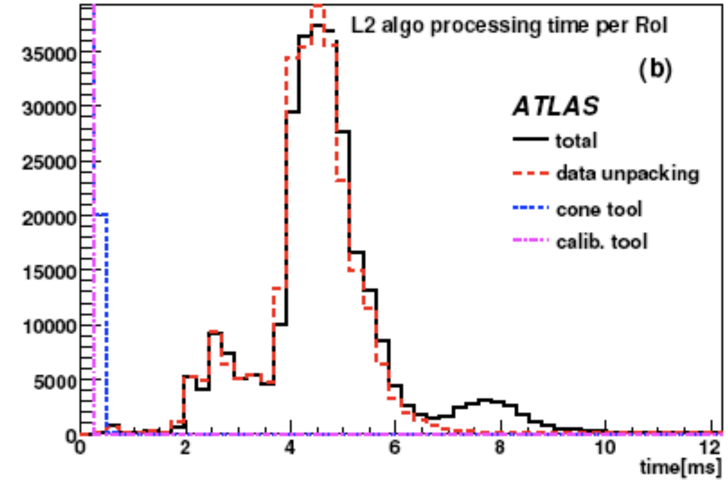
- Study with ~50 pb^{-1}
- Overall efficiency (77.4%±0.4)
- Very good agreement between Tag&Probe and MC truth

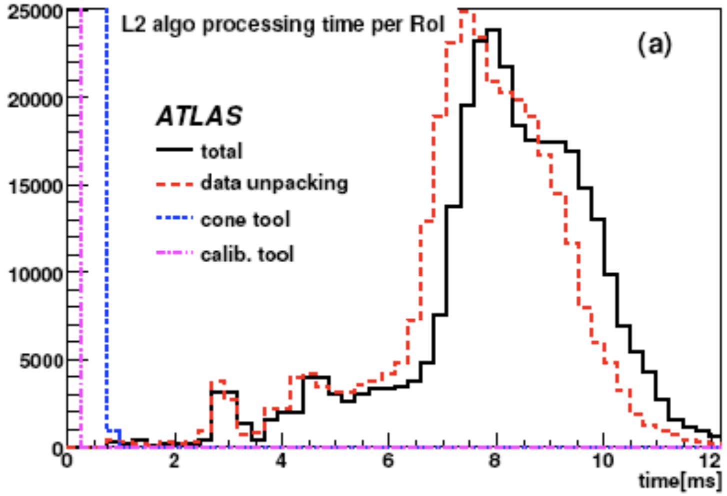
Jet trigger performance

- 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





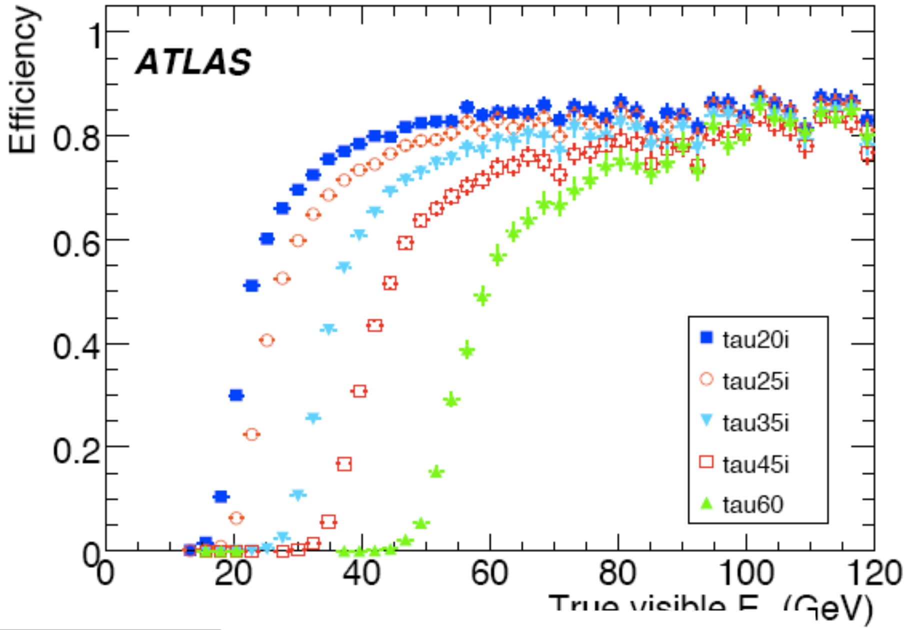


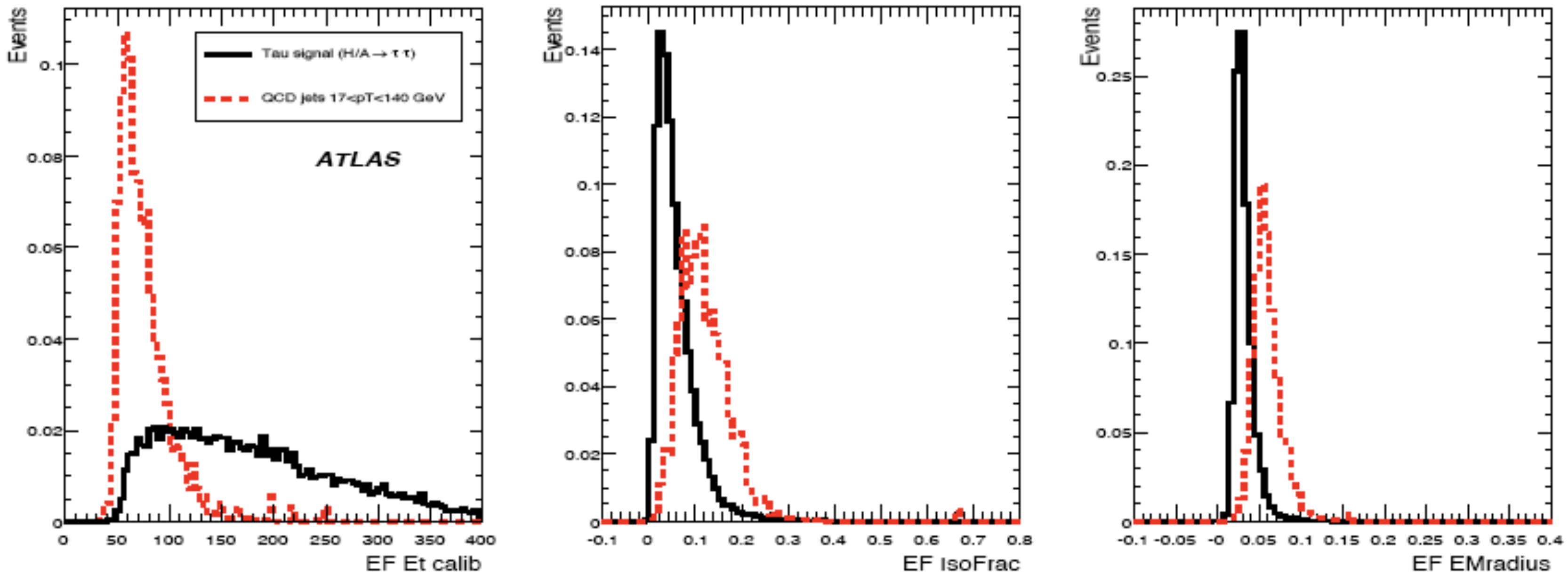


- Level 2: possible to use pre-calculated tower energy components (Ex,Ey,Ez) from front-end boards (FEB)
  - Saves unpacking time but has coarser granularity and resolution; studies ongoing

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

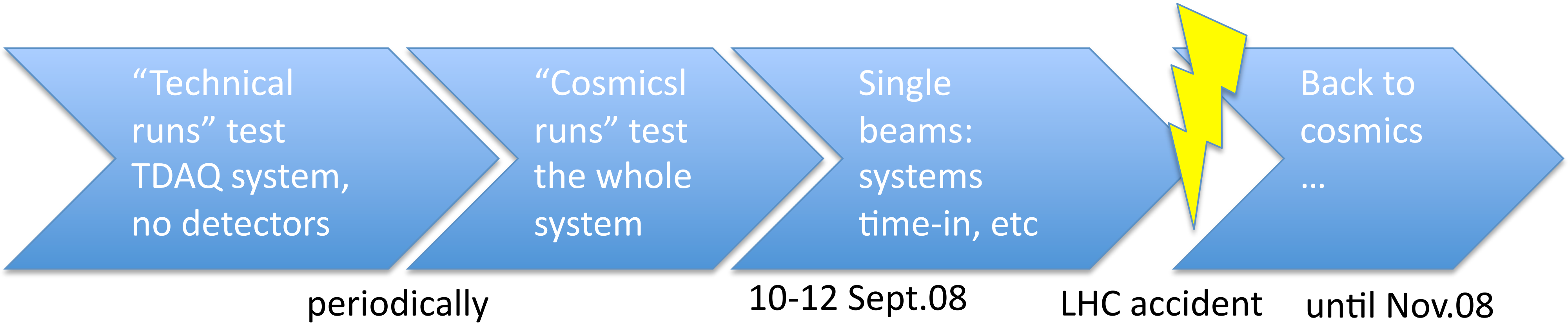




Commissioning the ATLAS Trigger

Timeline

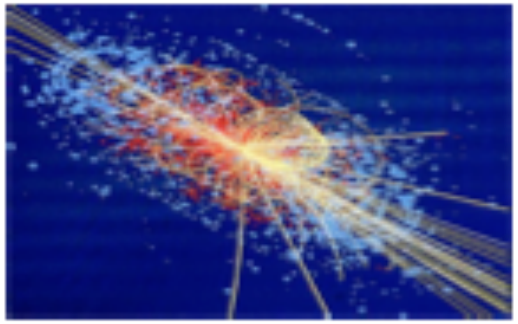
- Commissioning has been going on for more than a year with a gradually more complete system
- The TDAQ system (but not Level 1) was exercised in “Technical runs”
  - Learned how to deal with a large HLT farm
  - Correct estimates of processing time
  - Helped develop configuration and monitoring tools
- 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

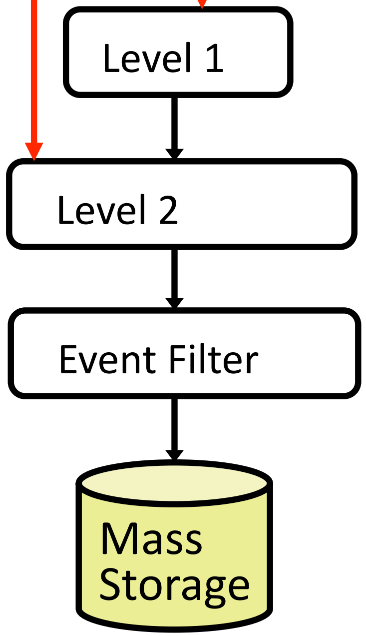
- Data is pre-loaded into the Read Out System
- DAQ/HLT plays back the data through the whole system except Level 1
- Allows testing the system in realistic environment

Cosmics runs

Cosmic Real Events

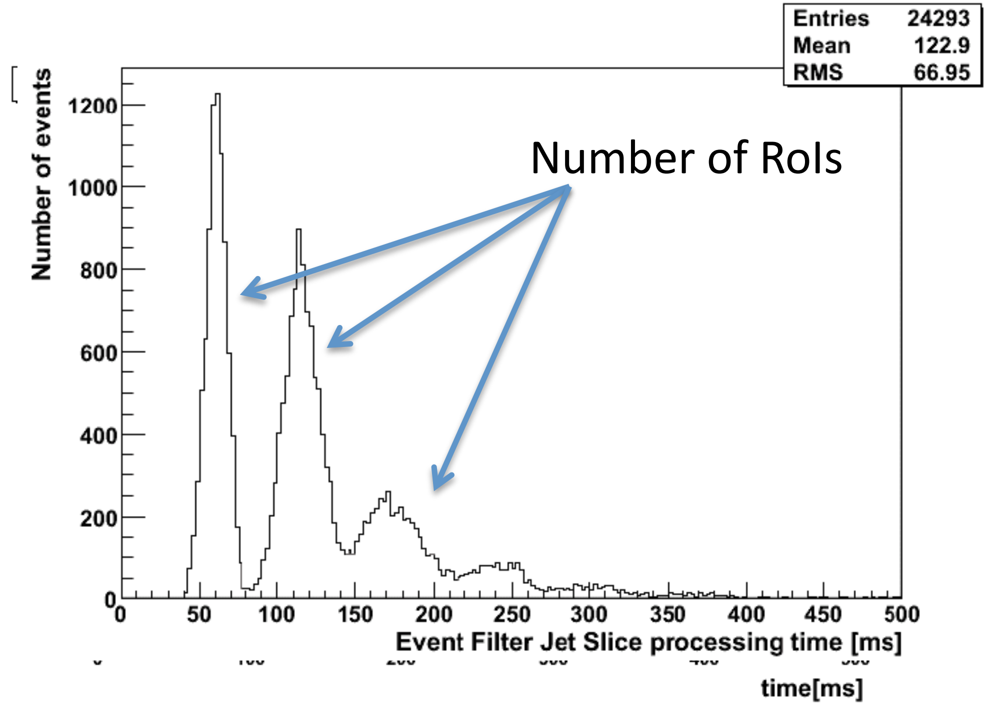
Real mode

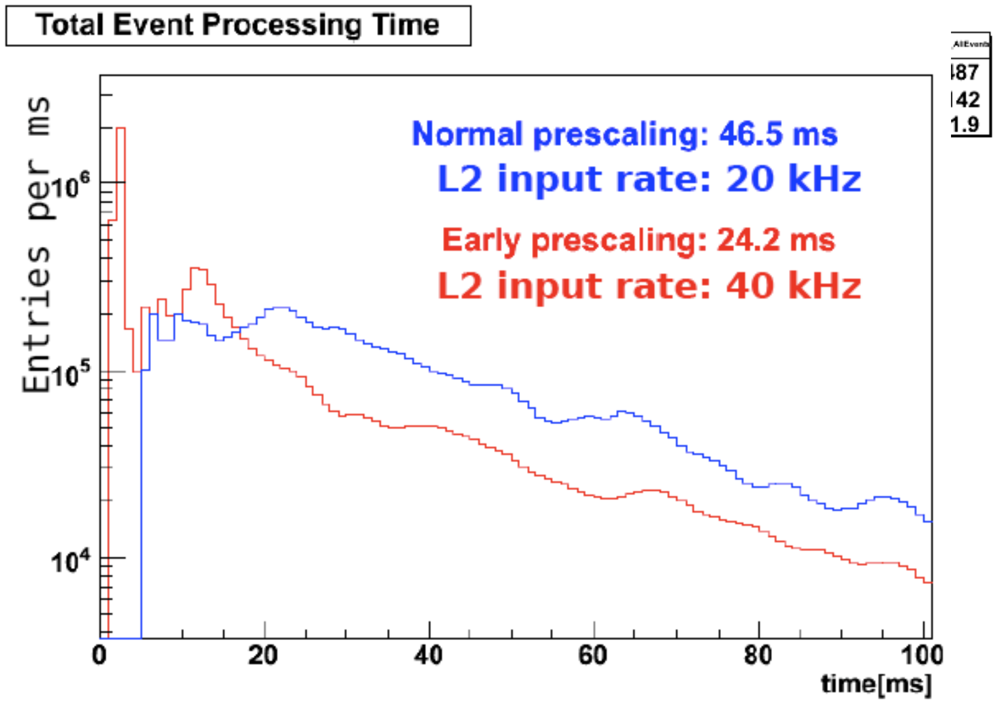
- Real data comes from the detectors
- Allows testing the whole system including Level 1
- Tests the software with real “imperfect” data
- Limited to cosmic-ray events



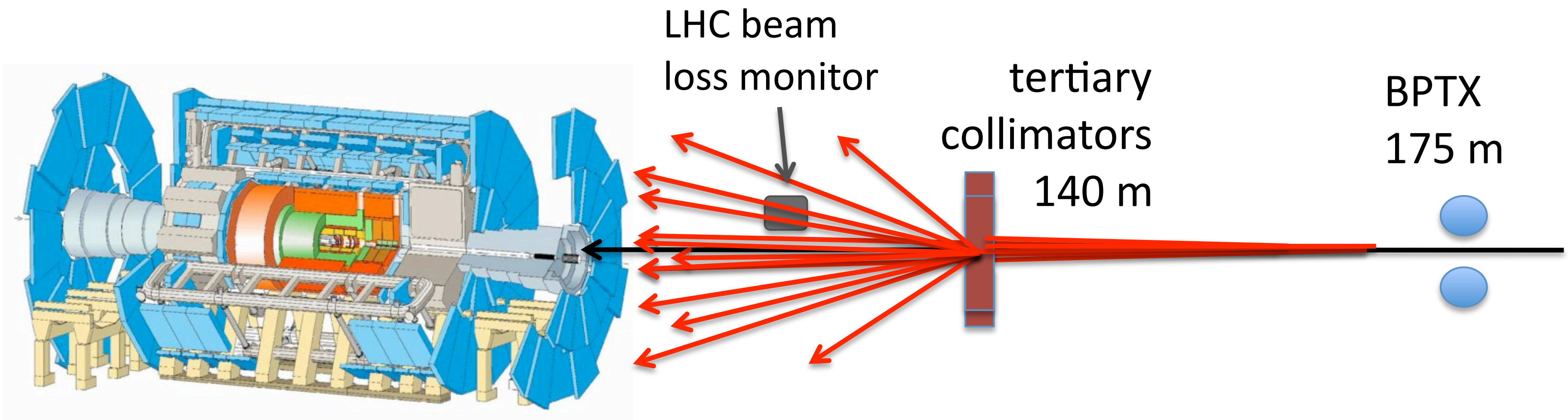
MC Event playback

- 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





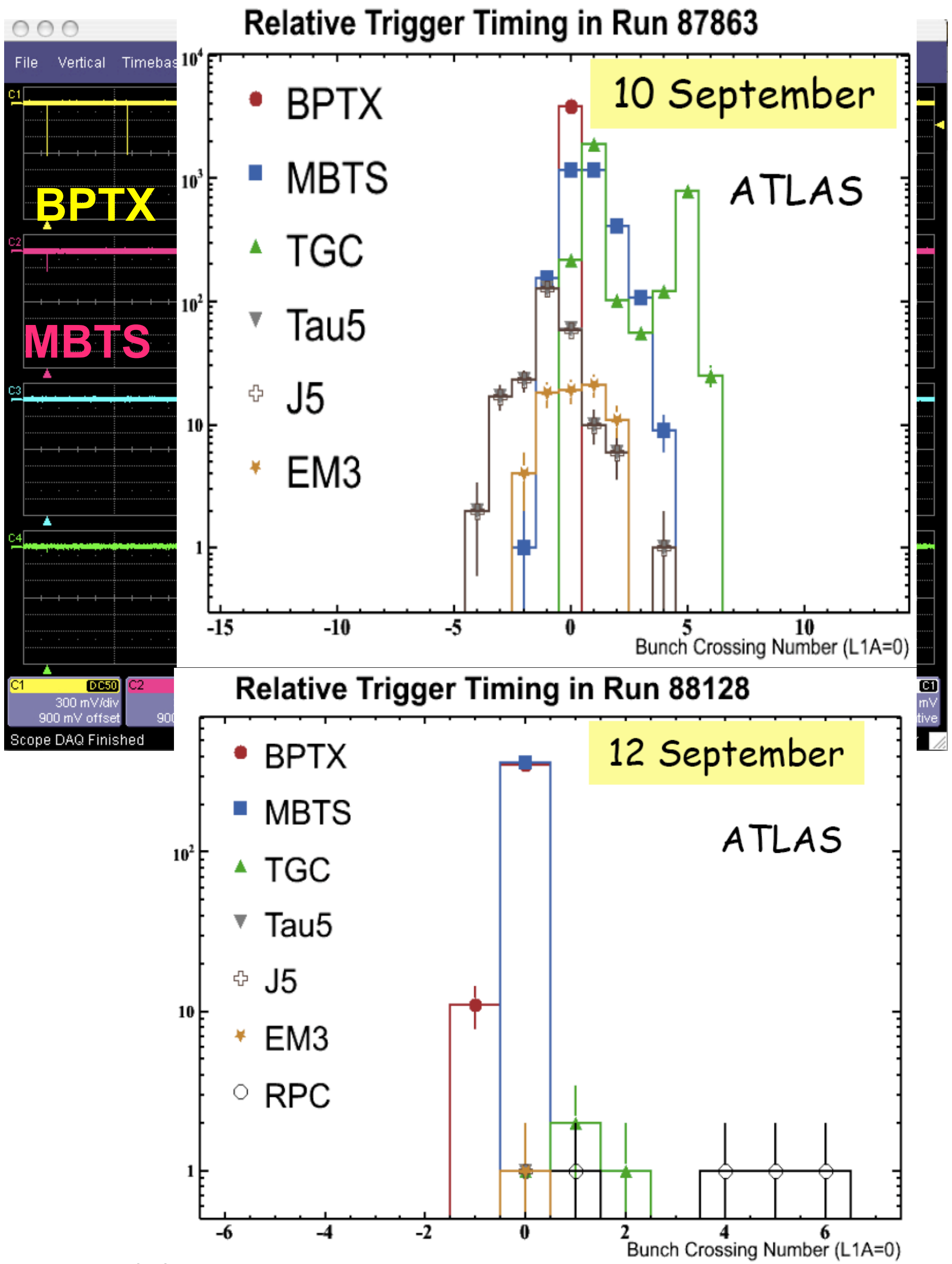
First experience with LHC beams

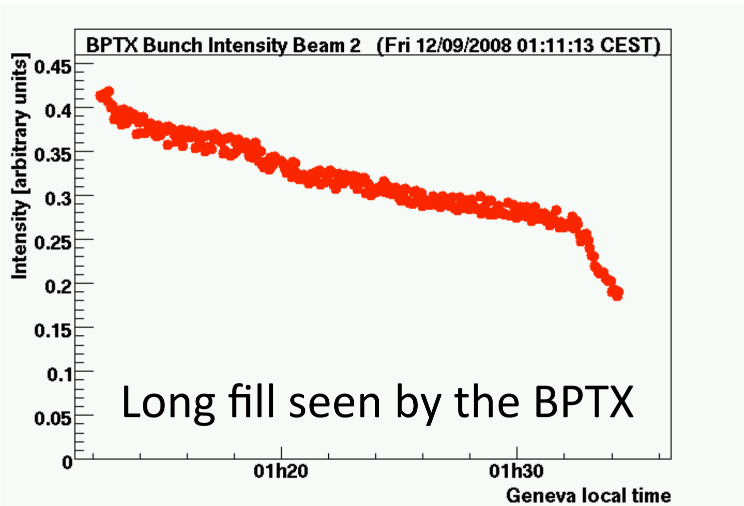


ATLAS was ready for first beam:

- 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)

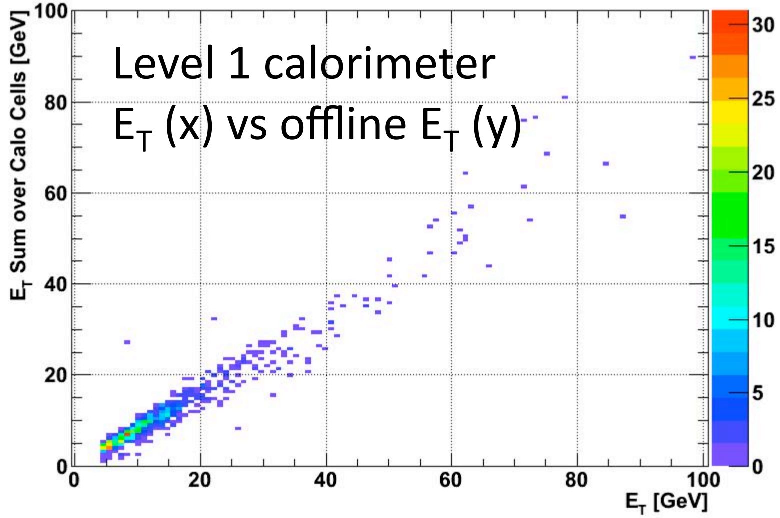
- Atlas relied on the MBTS and the L1 calorimeter triggers to record the first events
- Later used BPTX (beam pickup) as timing reference
- Defines time when bunch crosses interaction point
- Used this to adjust time of other detectors
  - See TGC time difference as beam crosses detector

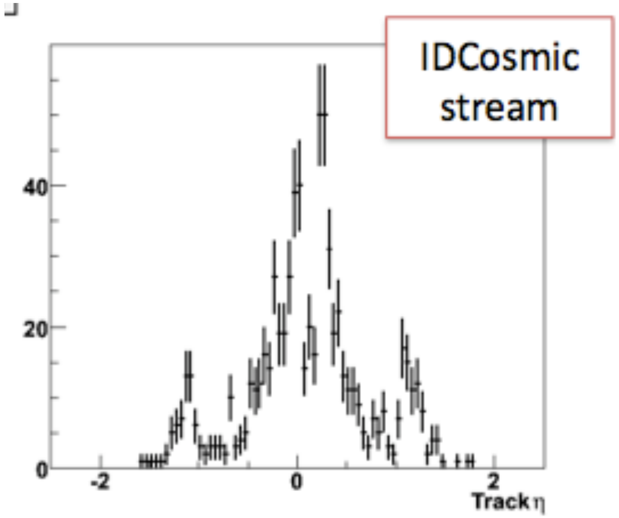


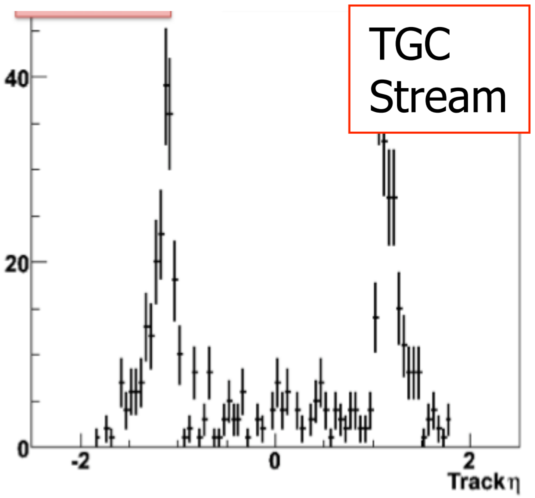


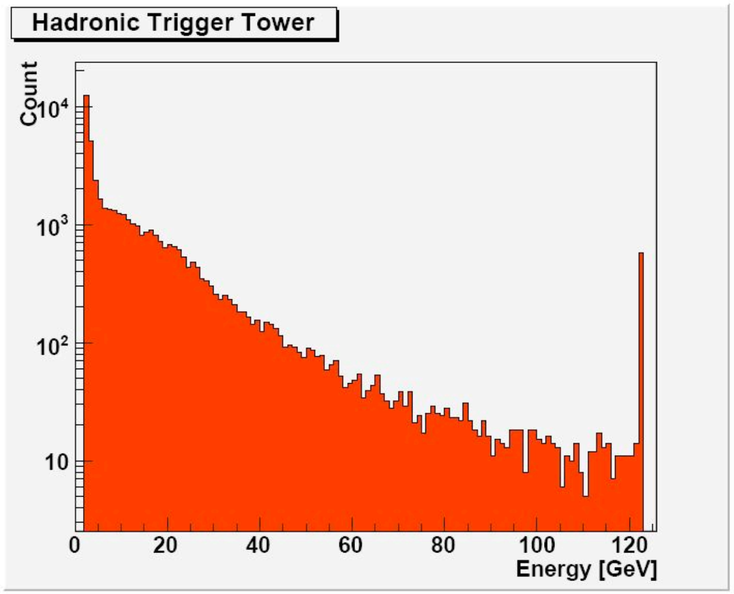
Cosmic run after LHC incident

- 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

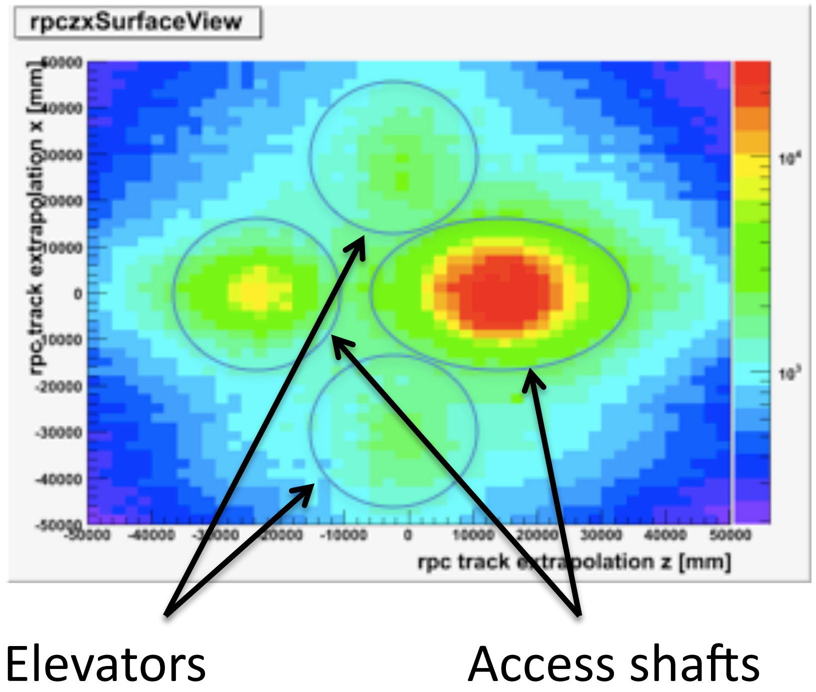


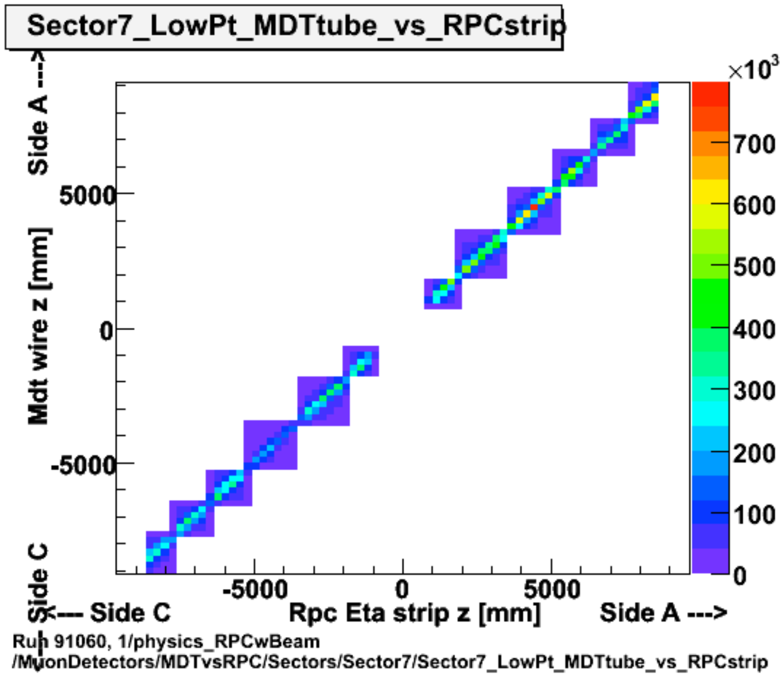






X-ray of the ATLAS cavern with cosmic muons

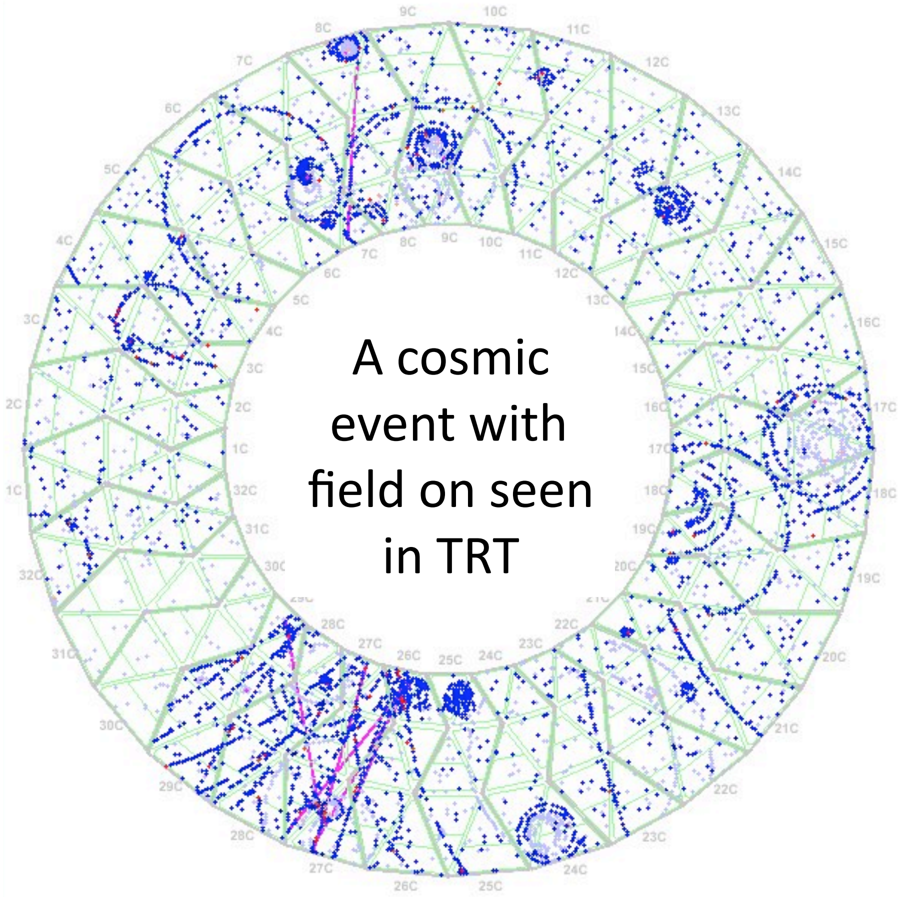




Very good correlation between RPC (trigger chambers) and MDT (precision chambers) hits

Conclusions

Conclusions



A cosmic event with field on seen in TRT

The ATLAS Trigger is now mature:

- Both level 1 and the High Level Trigger used with real data from the LHC and with cosmic rays
- Important progress was made!

Plans for this year:

- Trigger workshop in February:
  - Review the 2008 run: what went wrong? What went right? What do we need to change for the next run period?
  - Plan ahead for 2009: trigger menu; monitoring; data quality; physics analysis support; configuration…
- Start taking cosmics early before new run starts
- Eagerly awaiting LHC data later thi: year!

The first has been delivered to the