The ATLAS Trigger System

Graduate School 1504
Autumn Block Course October 2011

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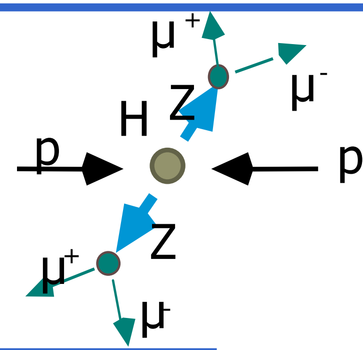
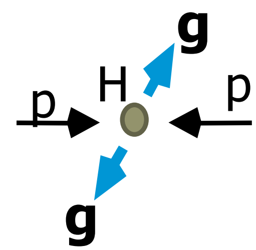
Content

- ATLAS trigger requirements and concepts
- first level trigger
- central trigger processor
- bunch structure
- higher level trigger
- streaming and data acquisition
- trigger configurations
- data taking and prescale strategy
- trigger analysis

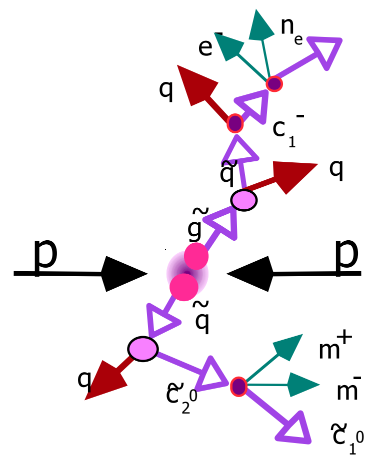
Physics Goals at the LHC

EW symmetry breaking:
search for the Higgs Boson





extensions of the Standard Model:
search for SUSY or other BSM physics



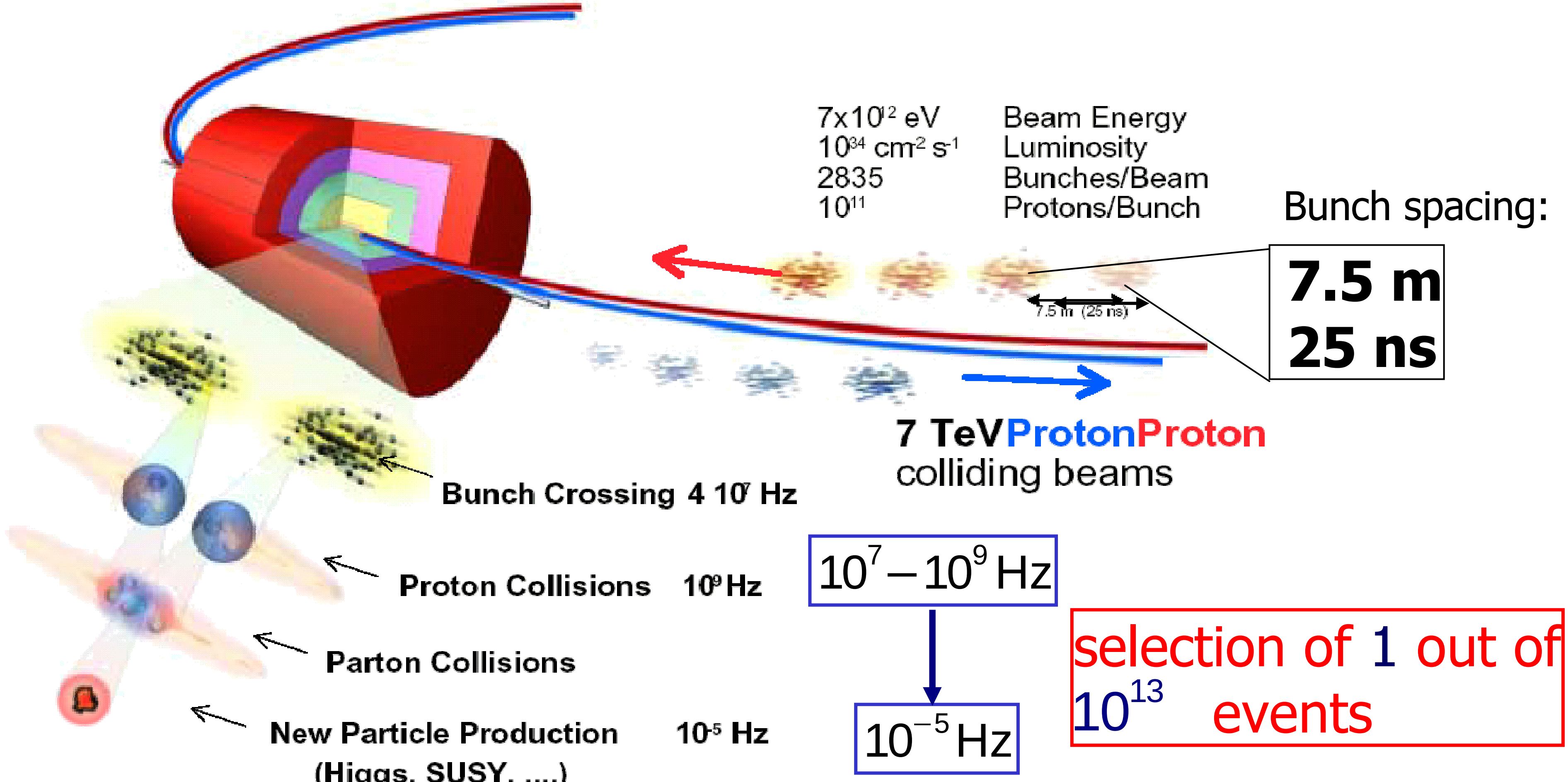
other topics: **top, EW, QCD, B-physics**

trigger question:

What events do we need to take?

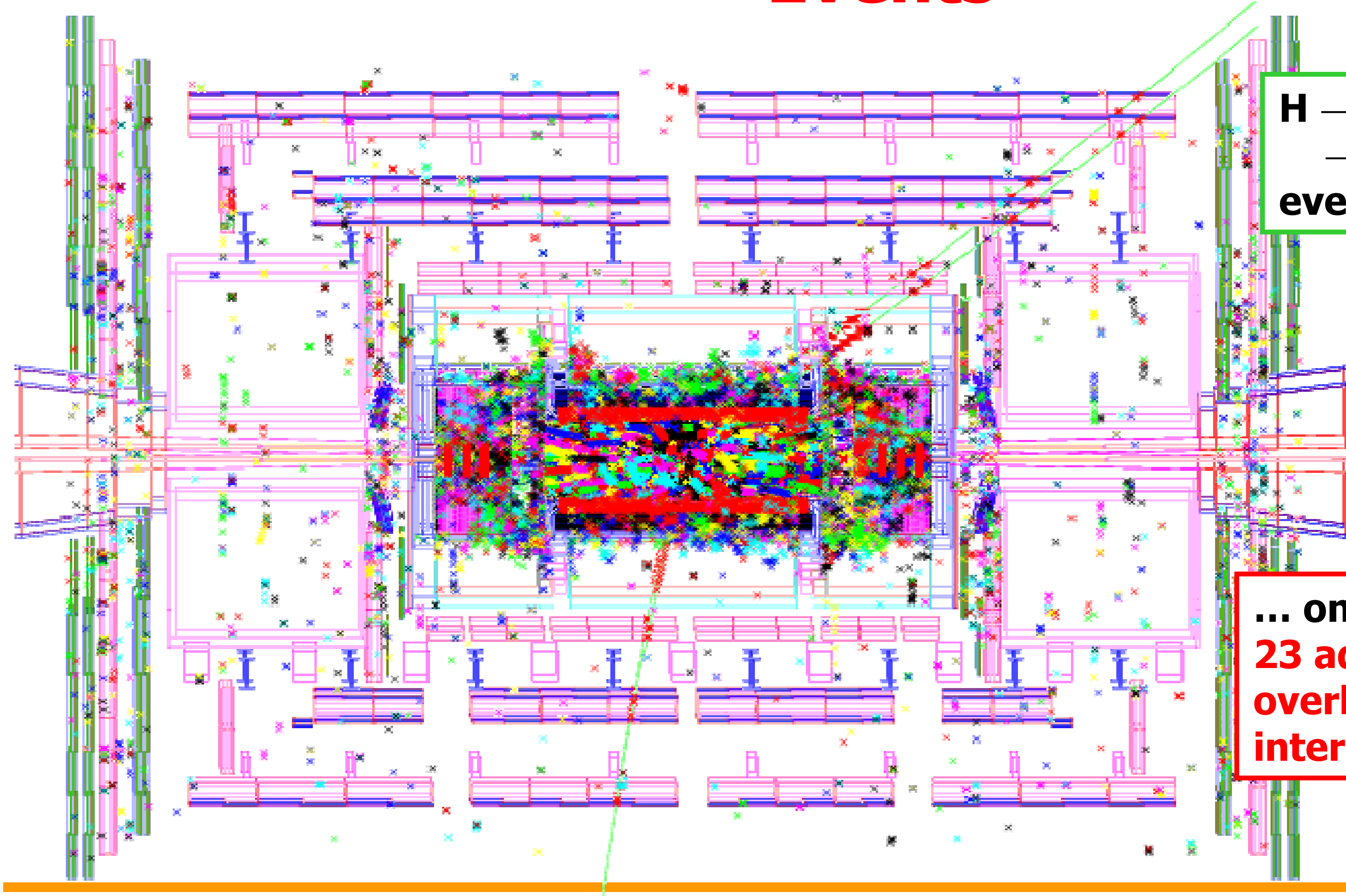
- **physics objects: μ, γ, e, τ, jets, b-jets, $E_{T,miss}$**
  - -high p_T objects (un-pre-scaled)
  - -low p_T objects (pre-scaled or in exclusive selection)
- monitor and calibrations events

Particle Collisions at LHC and Selection



highly selective and efficient trigger system needed

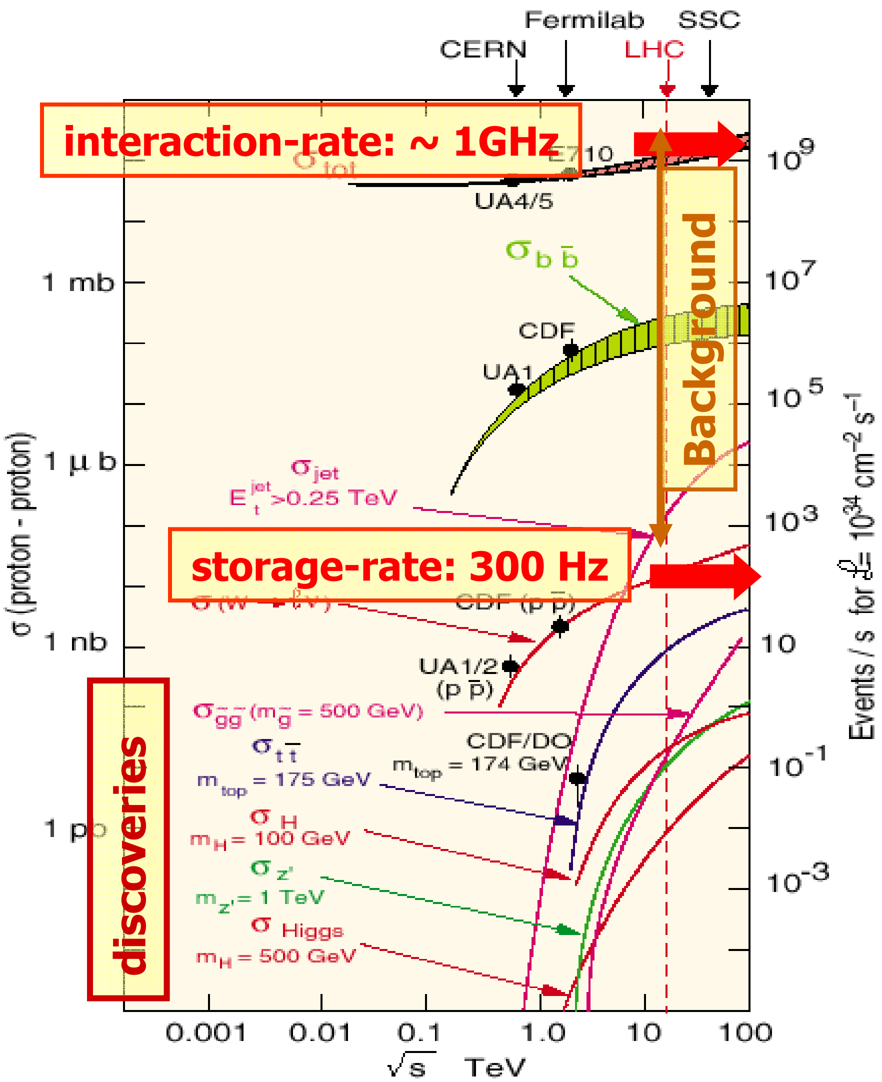
Looking for Interesting Events



H → ZZ
→ μμee
event …

… on top of
23 additional overlaid interactions

Overview Trigger System



Selection of **rare events ($R \approx 10^{-5}$ Hz)** out of extremely **high background ($R = 10^{9}$ Hz)**

Realized in a **multi level trigger:**

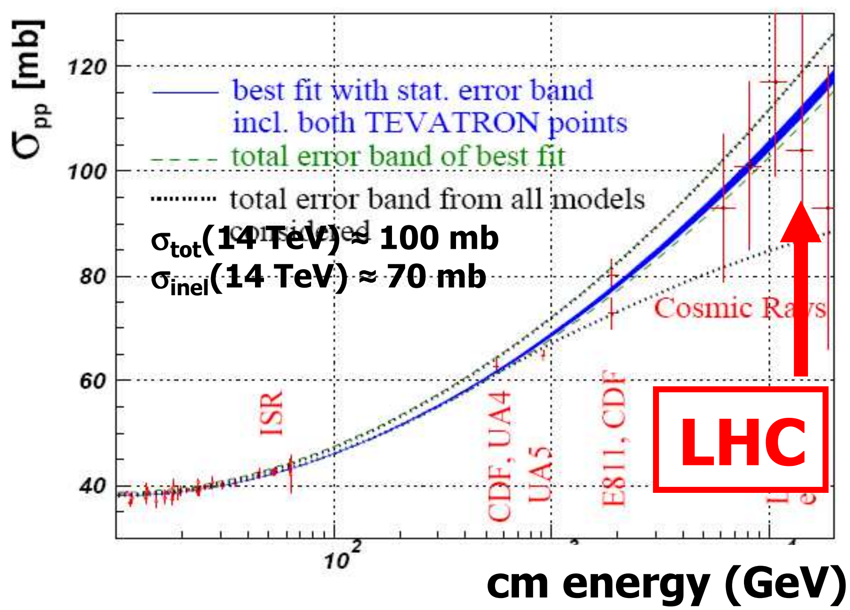
LVL1: muon and calorimeter signals used for "Regions of Interest"
stop data acquisition (75 kHz)

LVL2: LVL1 candidates used to find physics objects as **e**, **γ**, **μ**, **τ**, **jet**, **b-jet** or **E_T^{miss}** with reduced event information within Region of Interest
starts the read-out (2-3 kHz)

EF: full event information, fast data analysis
storage after filtering (300 Hz)

Event Rates and Multiplicities

cross section of p-p collisions



R = event rate

Λ = luminosity = 10^{34} cm^{-2} s^{-1}

σ_{inel} = inel. Cross section = 70 mb

N = interactions / bunch crossing

Dt = bunch crossing interval = 25 ns

$R = \Lambda * \sigma_{inel} = 10^{34} cm^{-2}\, s^{-1} * 70mb = 7 \cdot 10^{8}$ Hz

N = R / Dt

= $7 \cdot 10^{8}\, s^{-1} * 25 \cdot 10^{-9}$ s = 17.5

= 17.5 x 3564 / 2808 (not all bunches filled)

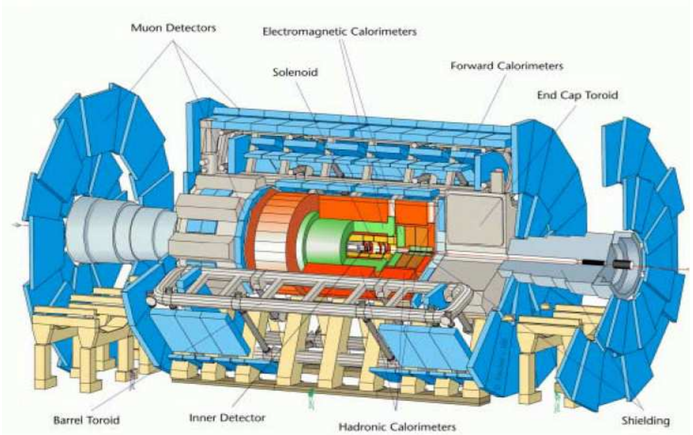
= 23 interactions / bunch crossing (pileup)

n_{ch} = charged particles / interaction
N_{ch} = charged particles / BC
N_{tot} = all particles / BC

with every bunch crossing
23 Minimum Bias events
with ~1725 particles produced

n_{ch} ≈ 50
N_{ch}= n_{ch} x 23 = ~ 1150
N_{to}= N_{ch} x 1.5 = ~ 1725

ATLAS Event Size



pile-up, adequate precision
→need small granularity detectors

Detector	Channels	Fragment size [KB]
Pixels	$1.4*10^8$	60
SCT	$6.2*10^6$	110
TRT	$3.7*10^5$	307
LAr	$1.8*10^5$	576
Tile	10^4	48
MDT	$3.7*10^5$	154
CSC	$6.7*10^4$	256
RPC	$3.5*10^5$	12
TGC	$4.4*10^5$	6
LVL1		28

Atlas event size: 1.5 MB (140 million channels)

→ at 40 MHz: 1 PB/sec

affordable mass storage: 450 MB/sec

→ storage rate: ~ 300 Hz

→ ~ 4 PB/year for offline analysis

Data Acquisition Restrictions

adequate precision need **small granularity detectors**: **many readout-channels**

A) totally 140 million channels → **event size ~ 1.5 MB**

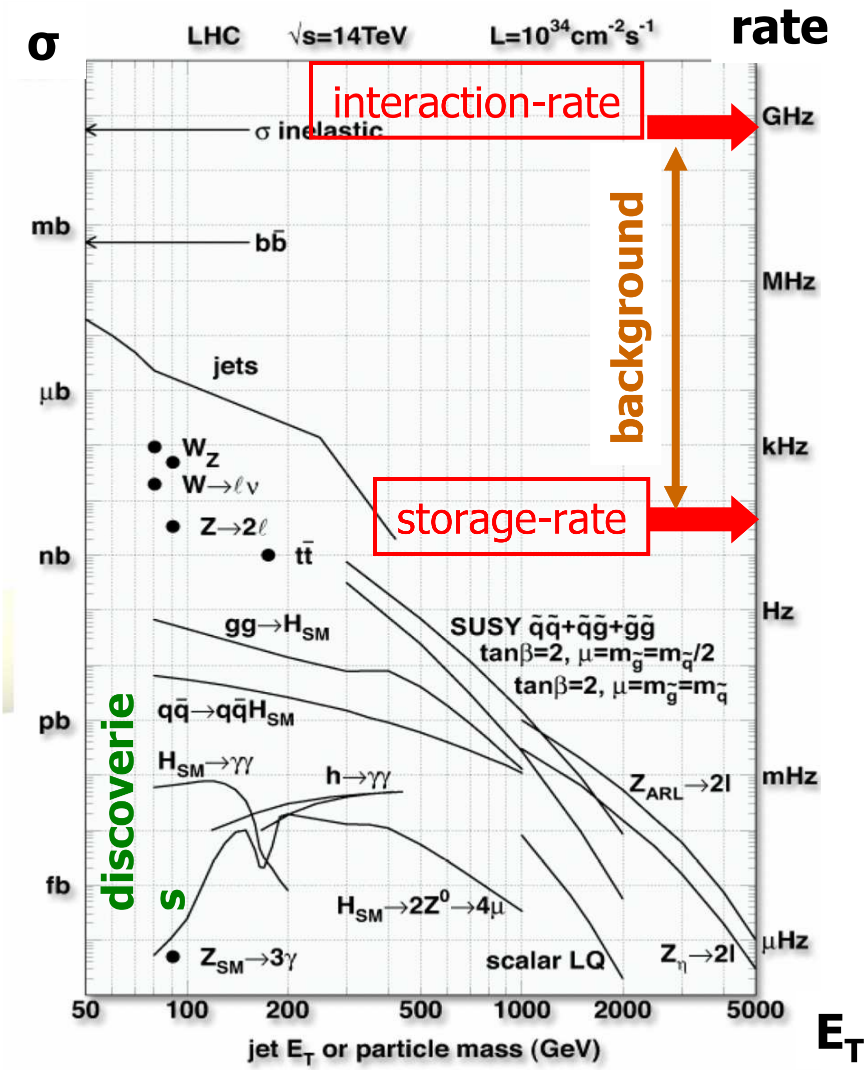
at 40 MHz: **1 PB/sec**
available bandwidth: **450 MB/sec**
→ **storage rate:** **~ 300 Hz**: **4 PB/year** for offline analysis

B) read-out takes time → **dead time of about 10 ms**

if read-out would be triggered just by randomly available events,

probability to get events with rates of 10^{-5} Hz would be 0!

Requirements for the Trigger System



interaction-rate: ~ 1 GHz

bunch crossing-rate: 40 MHz

storage-rate: ~ 300 Hz

→ "online"-reduction: **99.9995%**

powerful and reliable trigger inevitable:

selection of **rare events** out of the extremely **high background** LHC environment:

physics trigger:

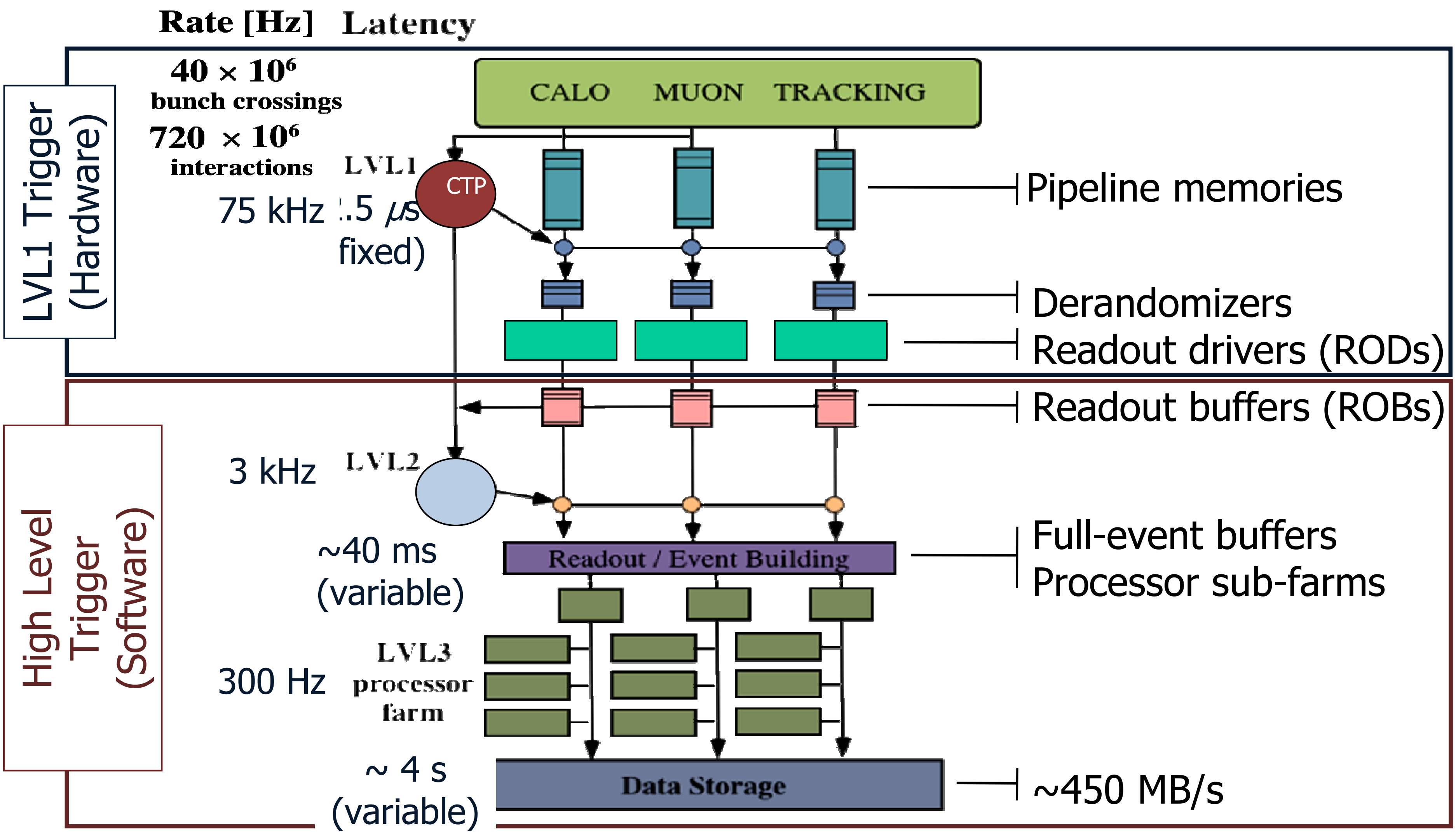
high p_T / E_T / MET (**physics objects**)

low p_T / MinBias ("prescaled", excl.)

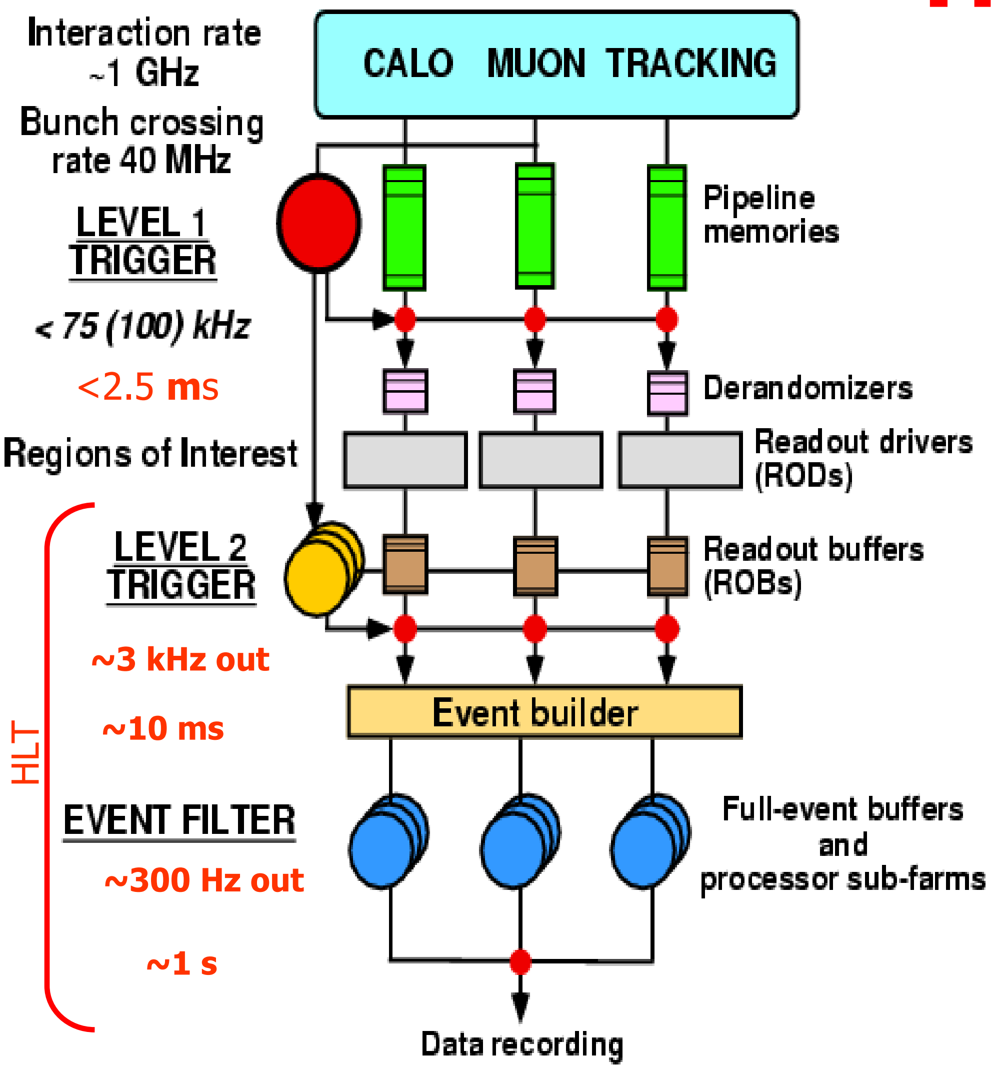
technical trigger:

monitoring and calibration trigger

The Atlas Trigger Concept



ATLAS Multi-Level-Trigger



LVL1: hardware

LEVEL 1

- hard ware based: FPGAs, ASICs
- uses larger granularity of the calorimeter and muon information
- identify **R**egions **o**f **I**nterest for further processing
- reduction from 1 GHz to 75 kHz
- **latency of 2.2 μs**

HLT (LVL2 + EF): software

LEVEL 2

- full granularity within the **RoI**
- seeded by LVL1-trigger
- fast reconstruction
- only data within **RoI processed**
- combination of detectors within **RoI**
- reduction from 75 kHz to 1 kHz
- **execution time of ~ 40 ms**

EVENT FILTER

- seeded by level 2
- full event information available
- full granularity of detectors
- "offline like" algorithms
- reduction from 1kHz to 200 Hz
- **averaged execution time of 4 s**

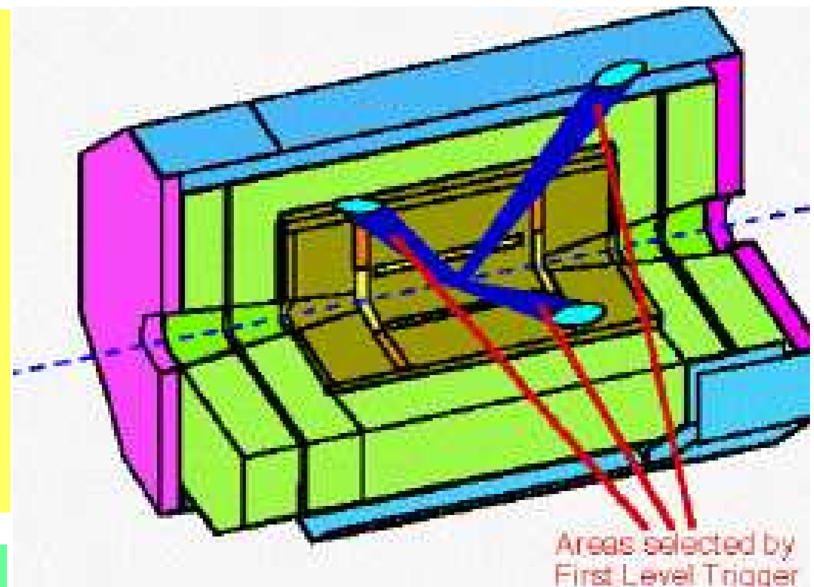
RoI Trigger Concept

Level 1: reduction from 1GHz to 75 kHz (2.5 ms)

- **triggering on** (high) p_T-objects
- L1-Calo **and** L1-Muon **sends** Regions of Interest (RoI) **to** LVL2 **for** e/g/τ/μ/jet candidates **for a** certain energy threshold
- **pure** hardware-trigger**, larger granularity,** synchronuos **to LHC bunch structure**

Level 2: from 75 kHz to 3kHz (10 ms)

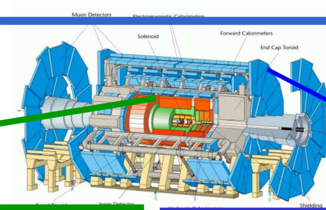
- uses **L1-Regions of Interest** as **"seed"** of the reconstruction (full granularity)
- only **data within the RoI** are used:
  small data transfer:
  - only **~2% of total event data**
  - combination of different detector-information within the RoIs.
- **software-trigger**, **readout** after L2-aceptance



Event-Filter: from 3kHz to 300 Hz (1s)

- **full event information**, quasi-"offline"-algorithms
- pure **software-trigger** (high felexibility)

LVL1 Trigger Overview



calorimeter trigger

Pre-Processor (analogue $\rightarrow E_T$)

Jet / Energy-sum Processor

Cluster Processor (e/g, t/h)

muon trigger

Muon Barrel Trigger (RPC)

Muon End-cap Trigger (TGC)

Muon-CTP Interface (MuCTPI)

multiplicities of e/g, t/h, jet for 8 p_T thresholds each; flags for ΣE_T, $\Sigma E_T^{\ j}$, E_T^{miss} over thresholds

Central Trigger Processor (CTP)

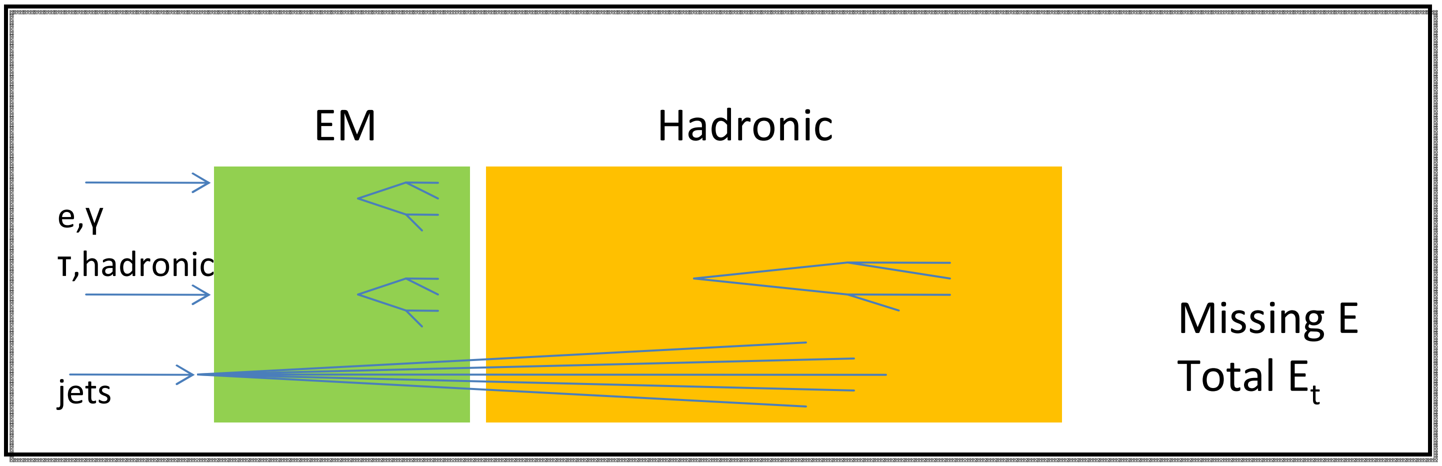
multiplicities of m for 6 p_T thresholds

L1A signal

LVL1 Trigger-items: calo-clusters or muon-candidates

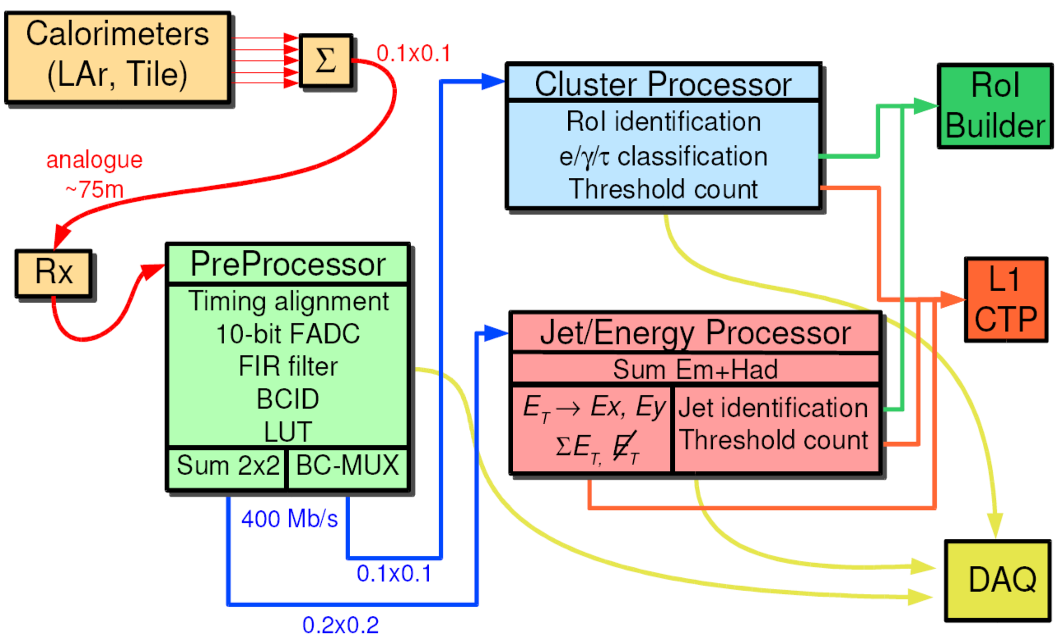
Calorimeter Trigger (L1 Calo)

- Provides e, γ (L1_EM) counting for various energy thresholds,
- τ(L1_TAU) counting,
- jet counting(L1_J/FJ),
- total transverse (L1_TE/JE) and missing (L1_XE) energy,
- and RoIs to LVL2



LVL1 Calorimeter Trigger

electronic components (installed in counting room outside the cavern; heavily FPGA based):

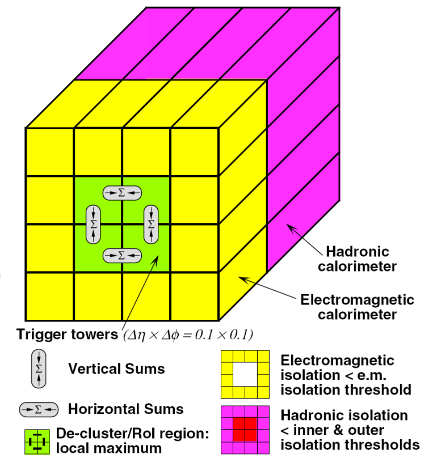


output:

- at 40 MHz: multiplicities for e/γ, jets, τ/had and flags for energy sums to Central Trigger (CTP)
- accepted events: position of objects (RoIs) to LVL2 and additional information to DAQ

available thresholds:

- EM (e/gamma): 8 - 16
- Tau/ hadron: 0 - 8
- Jets: 8
- fwd. Jets: 8
- E_T^{sum},
- E_T^{sum}(jets),
- E_T^{miss} : 4 (each)

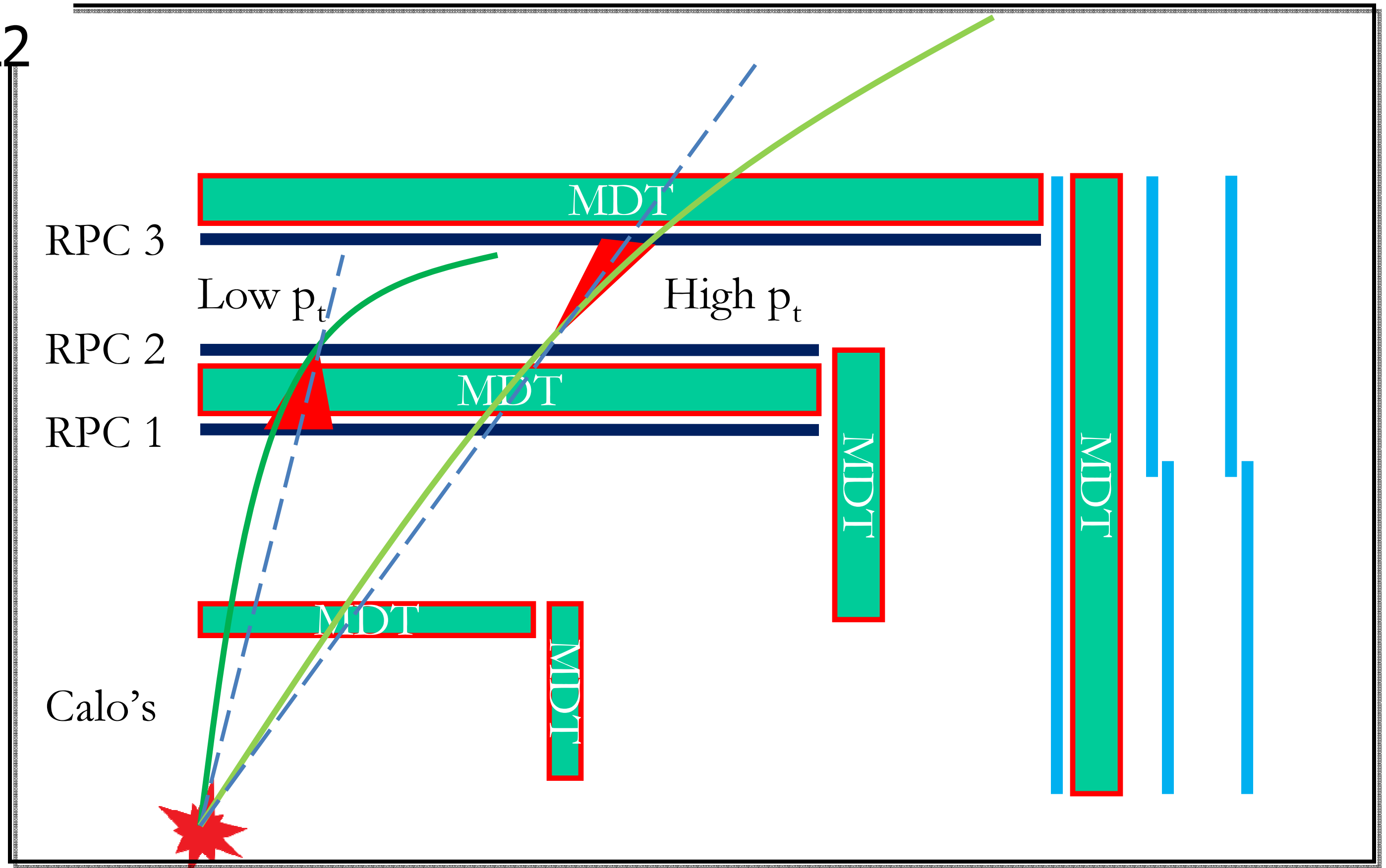


example: e/g algorithm:

- goal: good discrimination e/g ↔ jets
- identify 2x2 RoI with local E_T maximum
- cluster/ isolation cuts on various E_T sums

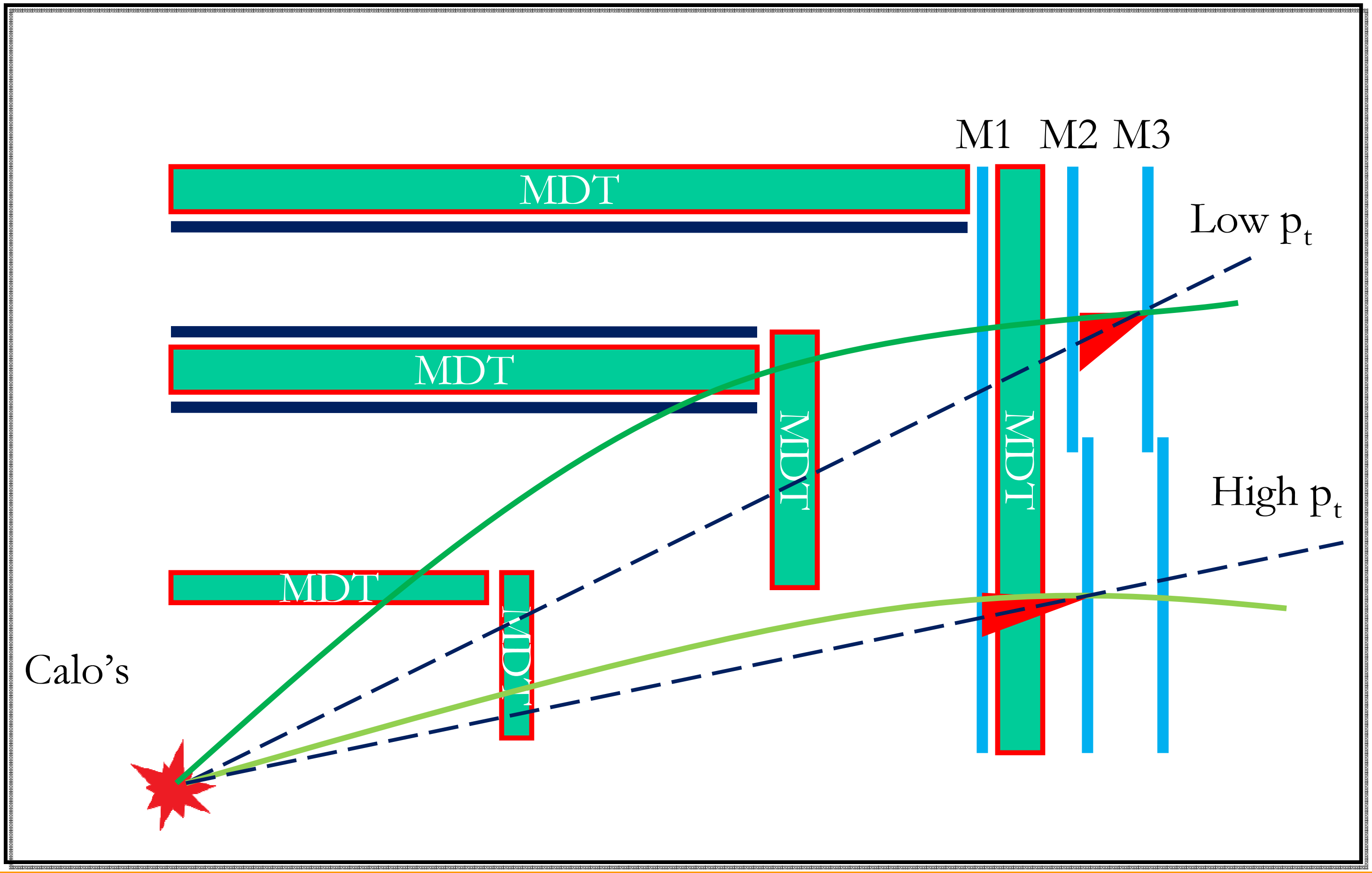
Muon Trigger (Central)

- Muon Barrel Resistive Plate Chamber (RPC)
- counts low-p_t and high-p_t muons (L1_MU)
- RoIs to LVL2

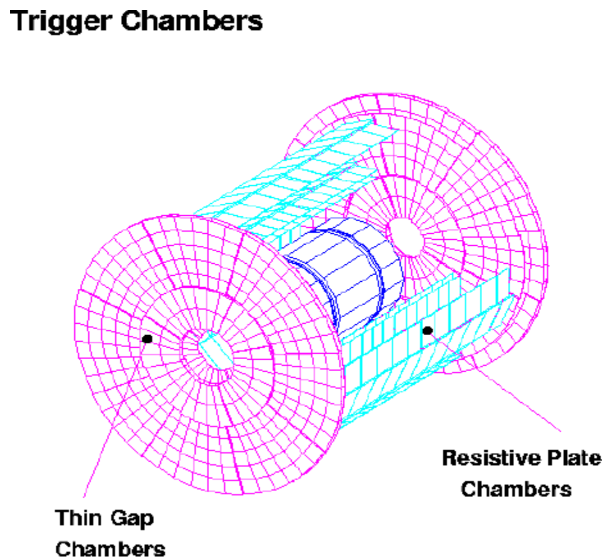


Muon Trigger (Fwd)

- Muon End Cap Thin Gap Chamber (TGC)



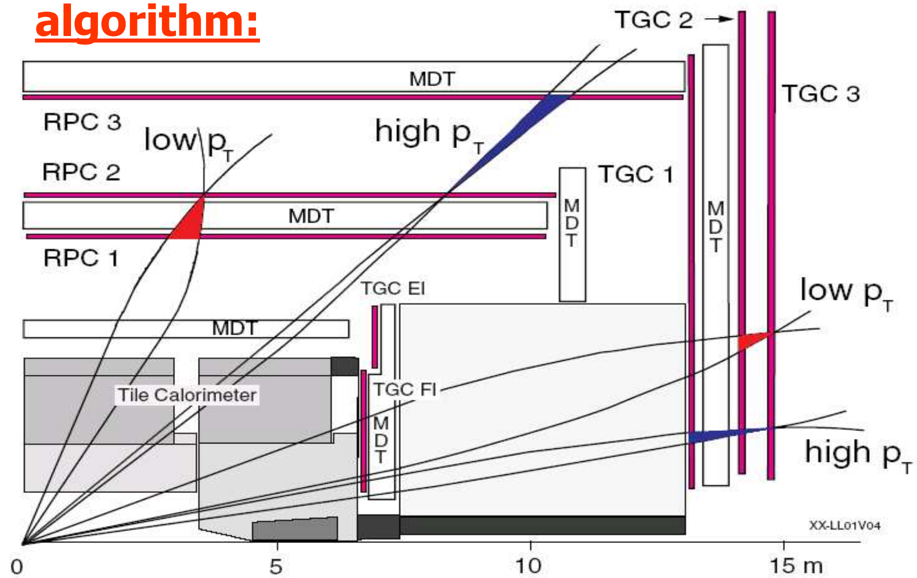
LVL1 Muon Trigger



dedicated muon chambers with good timing resolution for trigger:

- Barrel |η|<1.0 :
  Resistive Plate Chambers (**RPCs**)
- End-caps 1.0<|η|<2.4 :
  Thin Gap Chambers (**TGCs**)
- local track finding for LVL1 done on-detector (ASICs)

algorithm:

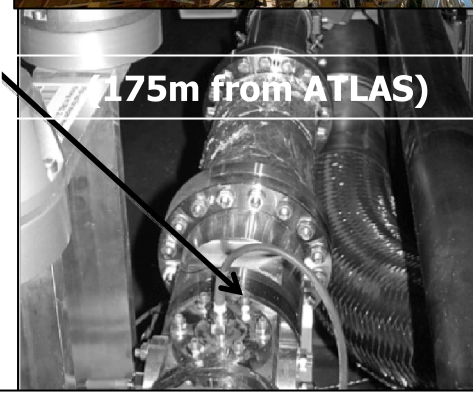


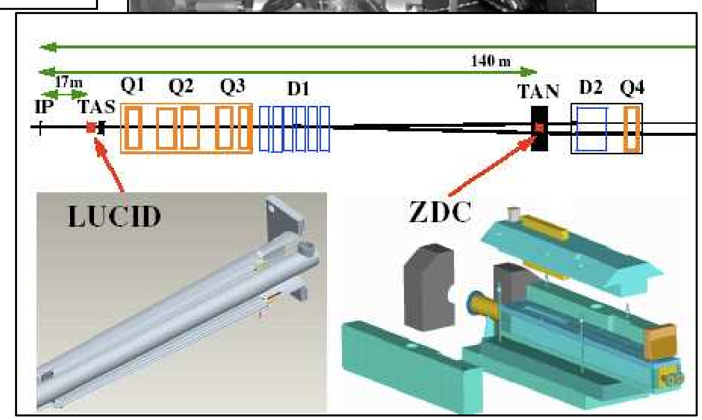
- looking for **coincidences** in chamber layers
- programmable widths of 6 coincidence windows determines p_T threshold
- available thresholds: muon 6

Other Lvl1 Trigger Items

other L1 trigger systems:

- L1_MBTS: → Minimum Bias Trigger Scintillators
- L1_BPTX: → Beam Pickup Timing Experiment
- L1_BCM: → Beam Condition Monitors
- L1_LUCID: → Luminosity Measurement with Cherenkov Integrated Detector
- L1_ZDC: → Zero Degree Calorimeter
- L1_TRT:
  Cosmic Track Trigger
- L1_CALREQ:
  Calo Calibration Triggers
- L1_RD0/L1_RD1 (random)





LVL1 Trigger Decision in CTP

<u>CTP</u>: (one 9U VME64x crate, FPGA based)
central part of LVL1 trigger system

<u>signals from LVL1 systems:</u>
8-16 EM, 0-8 TAU
8 JET, 8 FWDJET
4 XE, 4 JE, 4 TE, 6 Muon

<u>other external signals</u> e.g. MB scintillator, …

<u>calculation of trigger decision</u> for up to 256 trigger items:
e.g. "XE70+JET70"
→ raw trigger bits

<u>internal signals:</u>
2 random rates
2 pre-scaled clocks
8 bunch groups

<u>application of pre-scale factors</u>
→ actual trigger bits

<u>application of veto/ dead time</u>

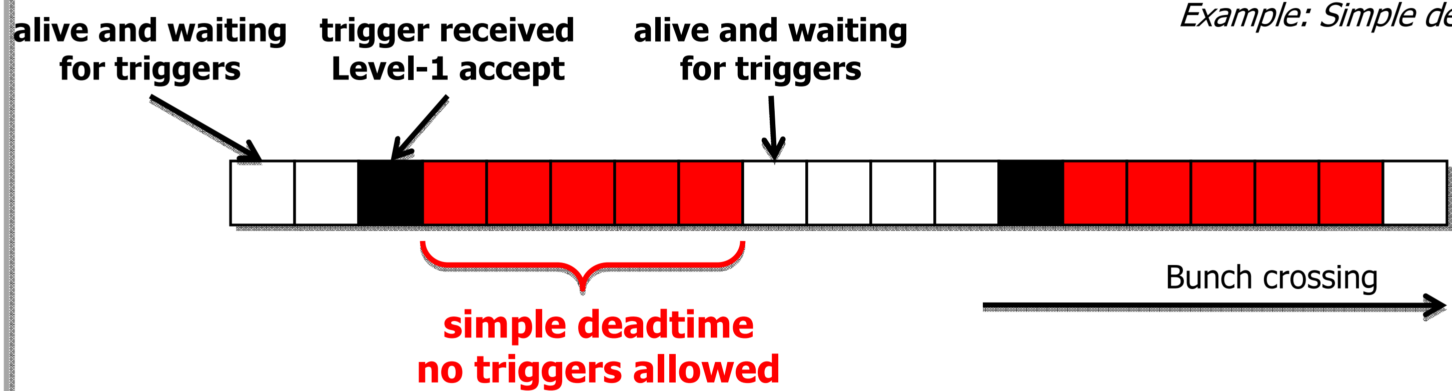
L1A

CTP

CTP: Simple and Complex Dead-time

Simple Deadtime | Prevent overlapping samples in detector front-ends

Example: Simple dead-time = 5 (BC)



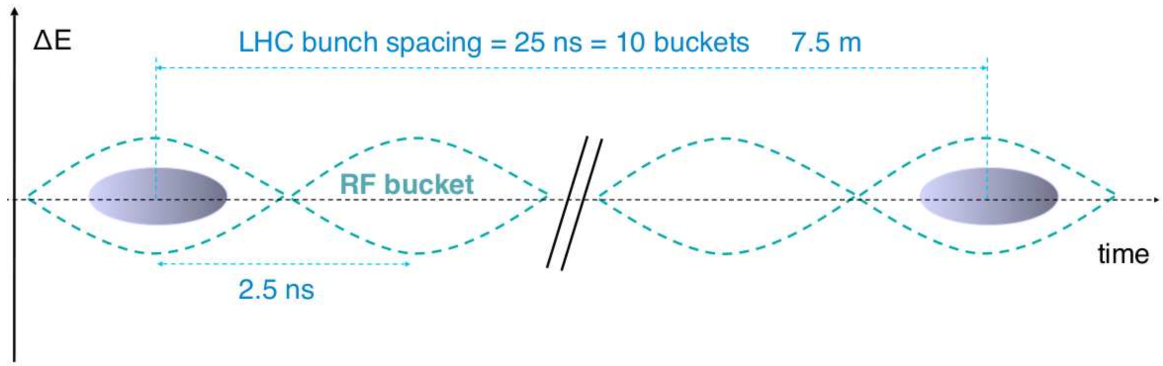
Complex Deadtime | Protect readout buffers from trigger bursts

Example: Complex dead-time = 4/570

leaky bucket algorithm:

- bucket is filled with L1A tokens at constant rate up to bucket size
  (e.g. 1 token every 570 BC until 4 tokens in bucket)
- every L1A takes one token out of the bucket
- if bucket is empty (no L1A tokens left), deadtime is applied

CTP: Bunch Groups



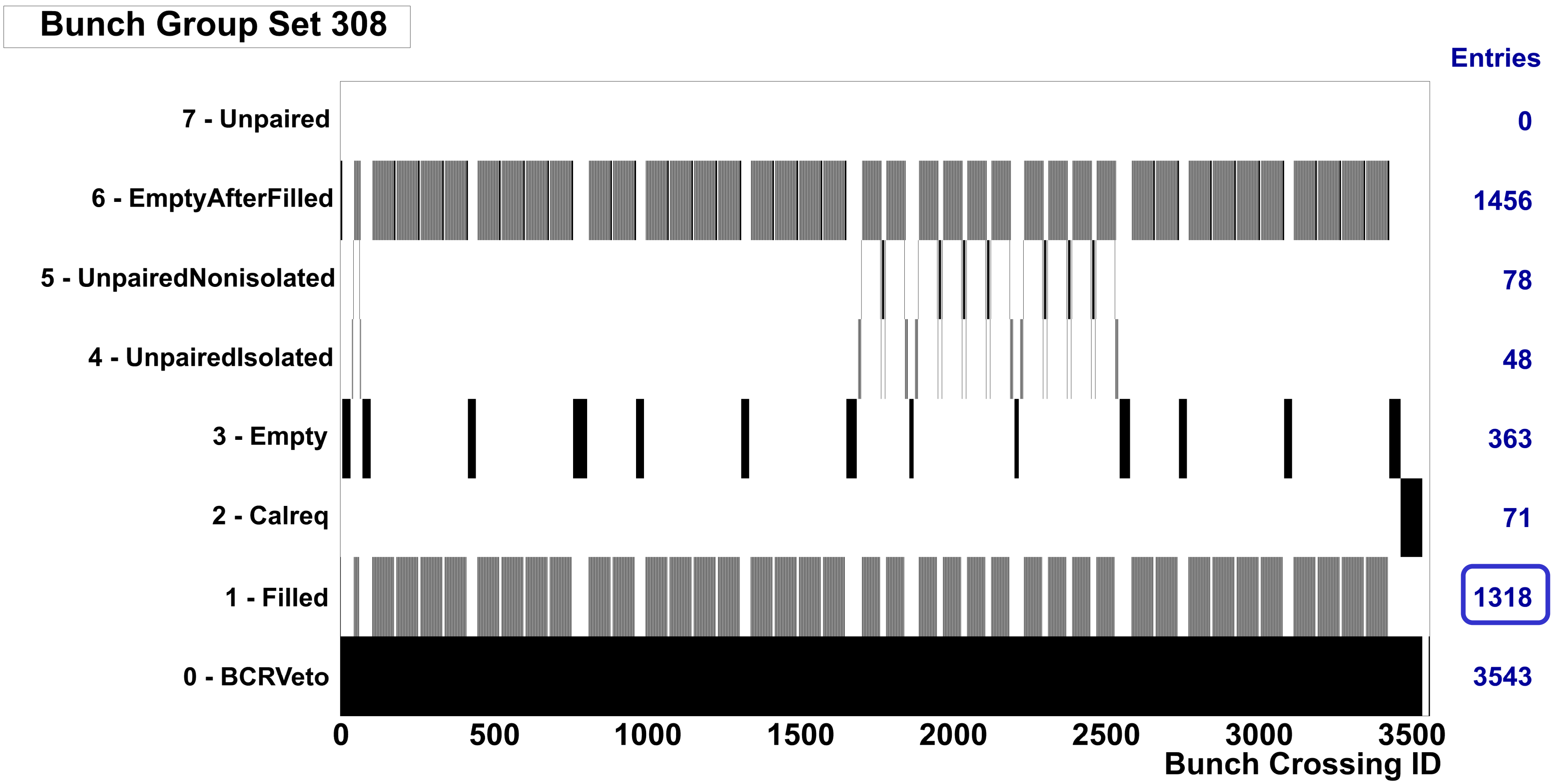
- each LHC bunch has 2.5 ns RF buckets
- 3564 possible bunches in LHC identified by Bunch Crossing Identifier (BCID = 0,...,3563)
- the crossing bunches can be
  - "paired" = both beams with protons
  - "unpaired" = only one beam with protons
  - "empty" neither beam with protons
- ATLAS defines additional crossings for special purposes

Bunch Groups

- a Bunch Group is a list of BCIDs:
  1. BCRVeto: allows triggers everywhere but in a small region 3540-3560 when the bunch counter reset is sent
  2. Paired: Colliding bunches in ATLAS
  3. CalRec: calibration requests for Tilecal (laser/charge injection) in the abort gap
  4. Empty: empty BC without any beam activity 5 BC before and 5 BC after (for cosmics, noise)
  5. IsolatedUnpaired: unpaired bunches with no beam activity (in the other beam) in ± 3 BC (for background monitoring, excluding leakage tails from the other beam)
  6. NonIsolatedUnpaired: unpaired bunches not covered by 4)
  7. EmptyAfterPaired: empty 5 BC following a paired BC (for long-lived particle searches)
  8. Currently Unused
- all 8 bunch groups form a Bunch Group Set

Bunch Group Example

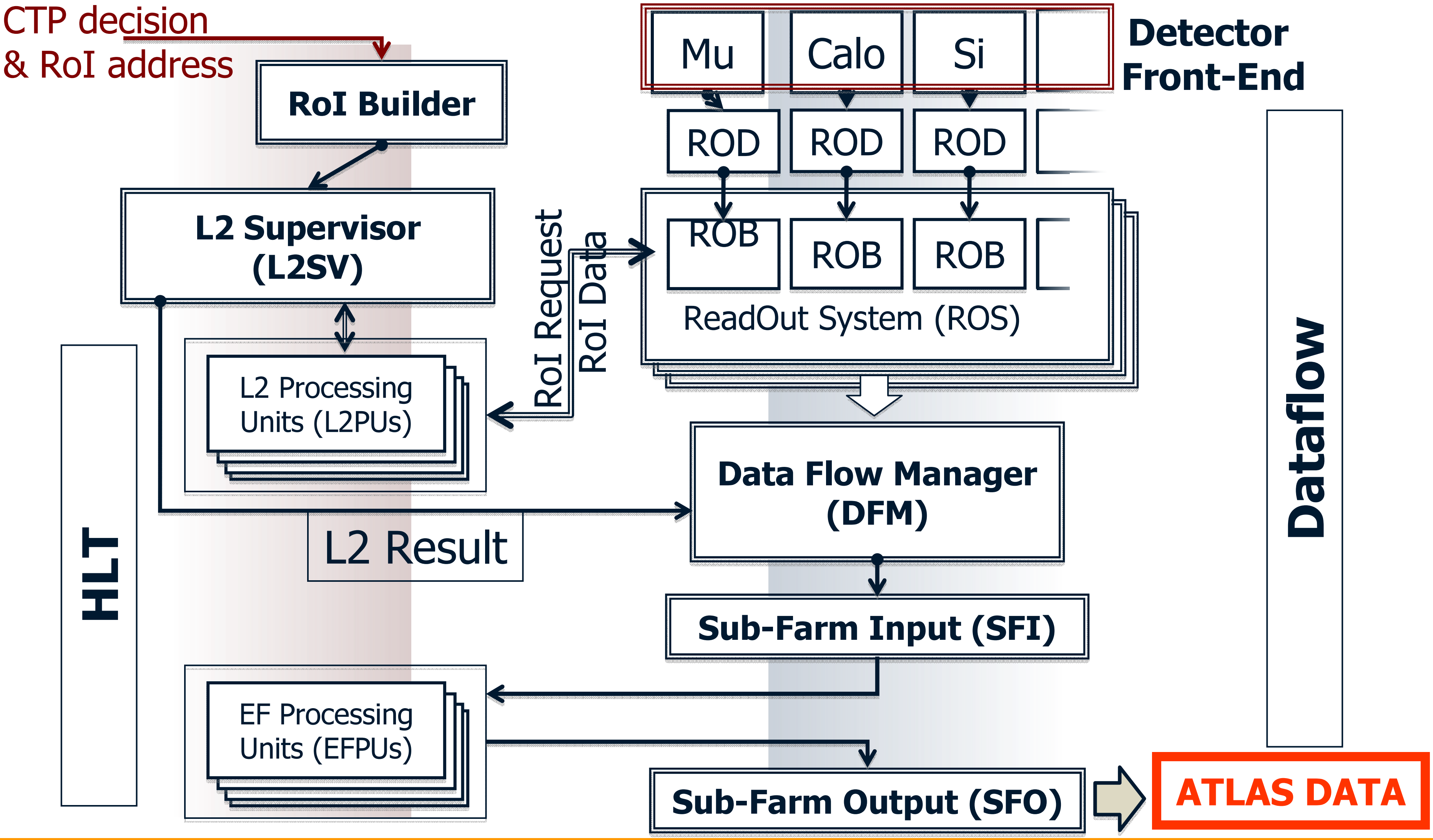
- **used bunch group:** (50ns_1380b+1small_1318_39_1296_144bpi)



L1 Triggers and the Bunch Group

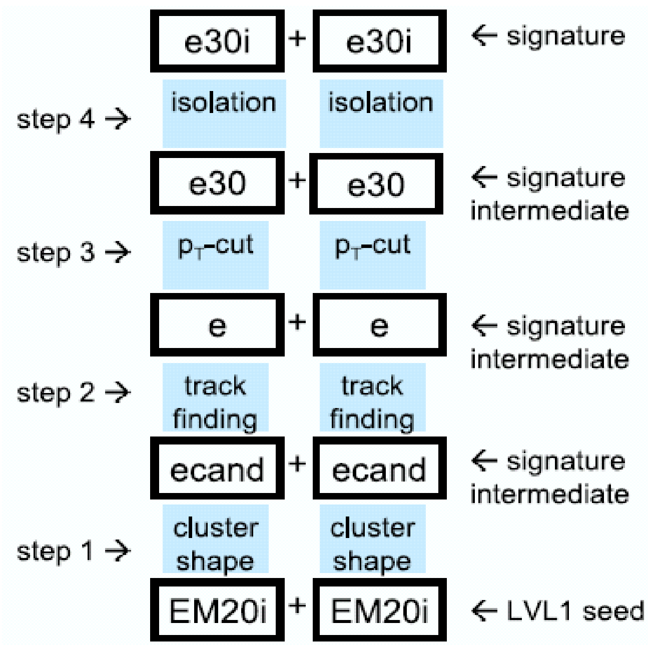
- All L1 trigger items have one or more explicit or implicit bunch group requirements
  - All triggers are ANDed with BCRVeto
  - Physics triggers (L1_EM5): PAIRED is implicit
- Other triggers carry the bunch group in their name:
  - L1_EM3_EMPTY
  - L1_TAU5_UNPAIRED
- **Random triggers**
  - L1_RD0_EMPTY, L1_RD0_FILLED, …
  - L1_RD1_FILLED, …

High Level Trigger & Dataflow



HLT Selection Strategy

LVL1-items are the start for HLT activity:



example: di-electron trigger

ATLAS trigger terminology:
- **Trigger chain**: whole decision sequence
- **Trigger signature**: intermediate result
- **Trigger element**: trigger object

step-wise processing and decision
fast algorithms first
increasing complexity of algorithms

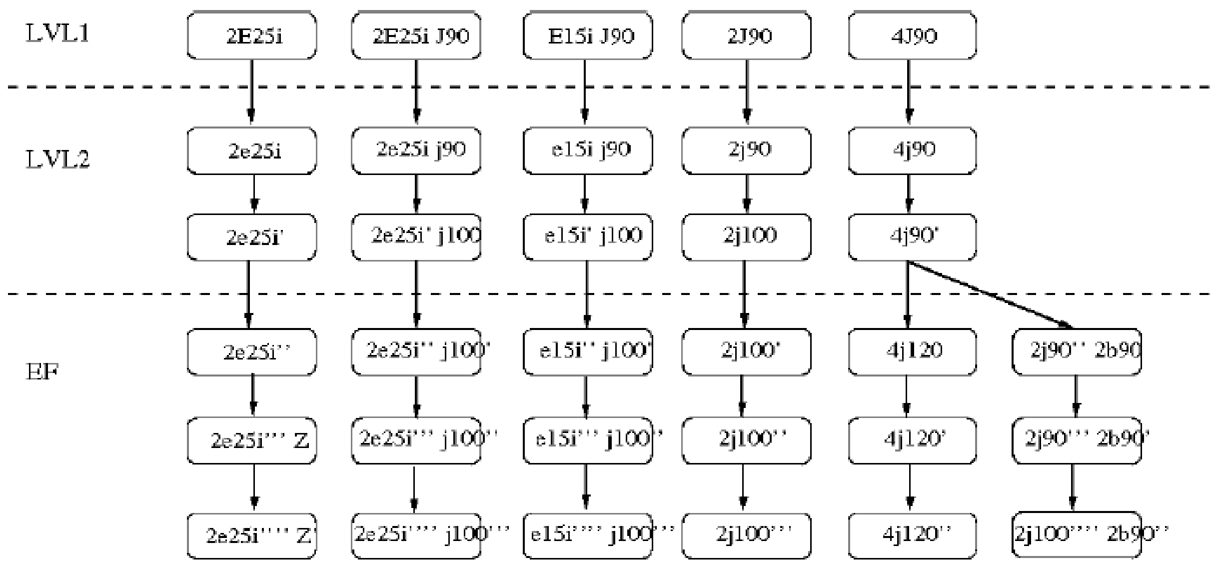
seeded reconstruction
algorithms use results from previous steps
initial seeds for LVL2 are LVL1 RoIs Chains
can be split at beginning of new level

LVL2 confirms & refines LVL1
EF confirms & refines LVL2
Event read-out and building after LVL2
EF accept events according to physics selection

early reject
as soon a signature fails, all following
connected chains at all levels are switched off

Trigger Chains: paralell processing

HLT steering enables running of trigger chains in parallel w/o interference



trigger chains are independent:

→ "easy" to calculate trigger efficiencies

→ "easy" to operate the trigger (finding problems, pre-dictable behavior)

→ scalable system

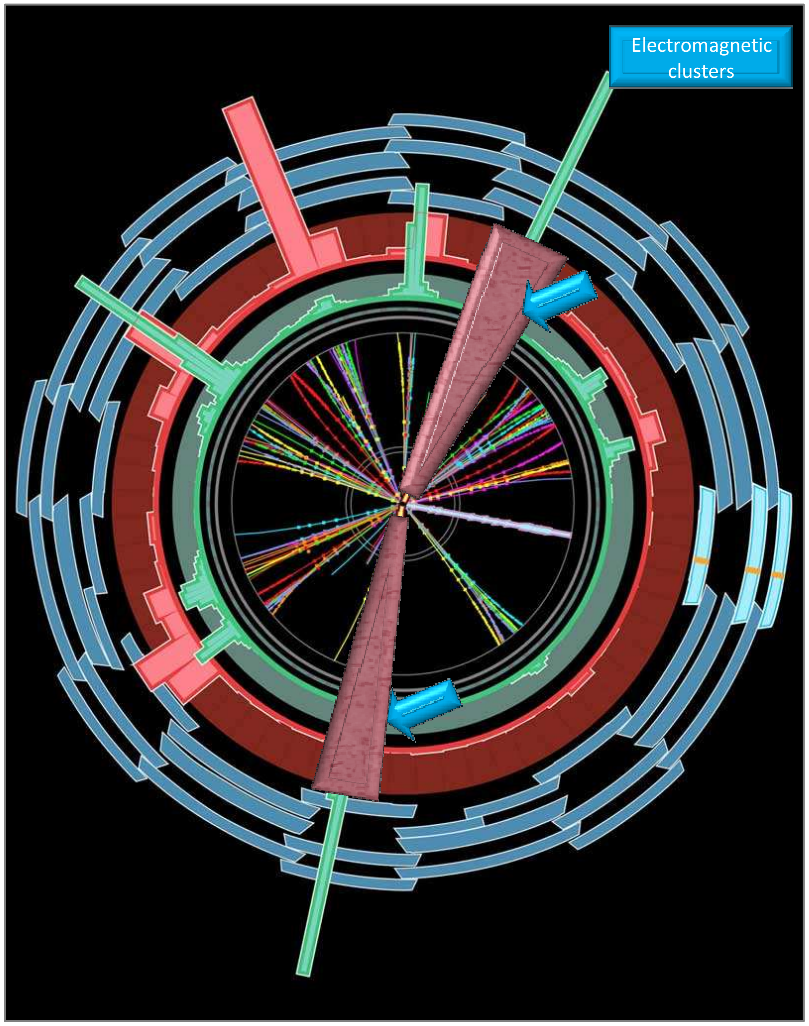
ATLAS follows "early reject" principle:

- look at signatures one by one
  - i.e. do not try to reconstruct full event upfront
  - if no signatures left, reject event
- Save resources
  - minimize data transfer and required CPU power

in principle: N-Level trigger system

but: Only one pre-scale per chain per level.
(to be discussed if used in HLT)

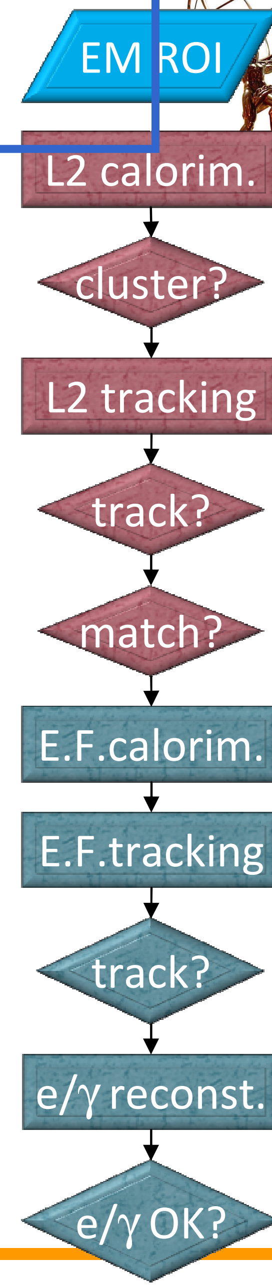
Trigger exectution (L2_electron)



Level1:
Region of Interest is found and position in EM calorimeter is passed to Level 2

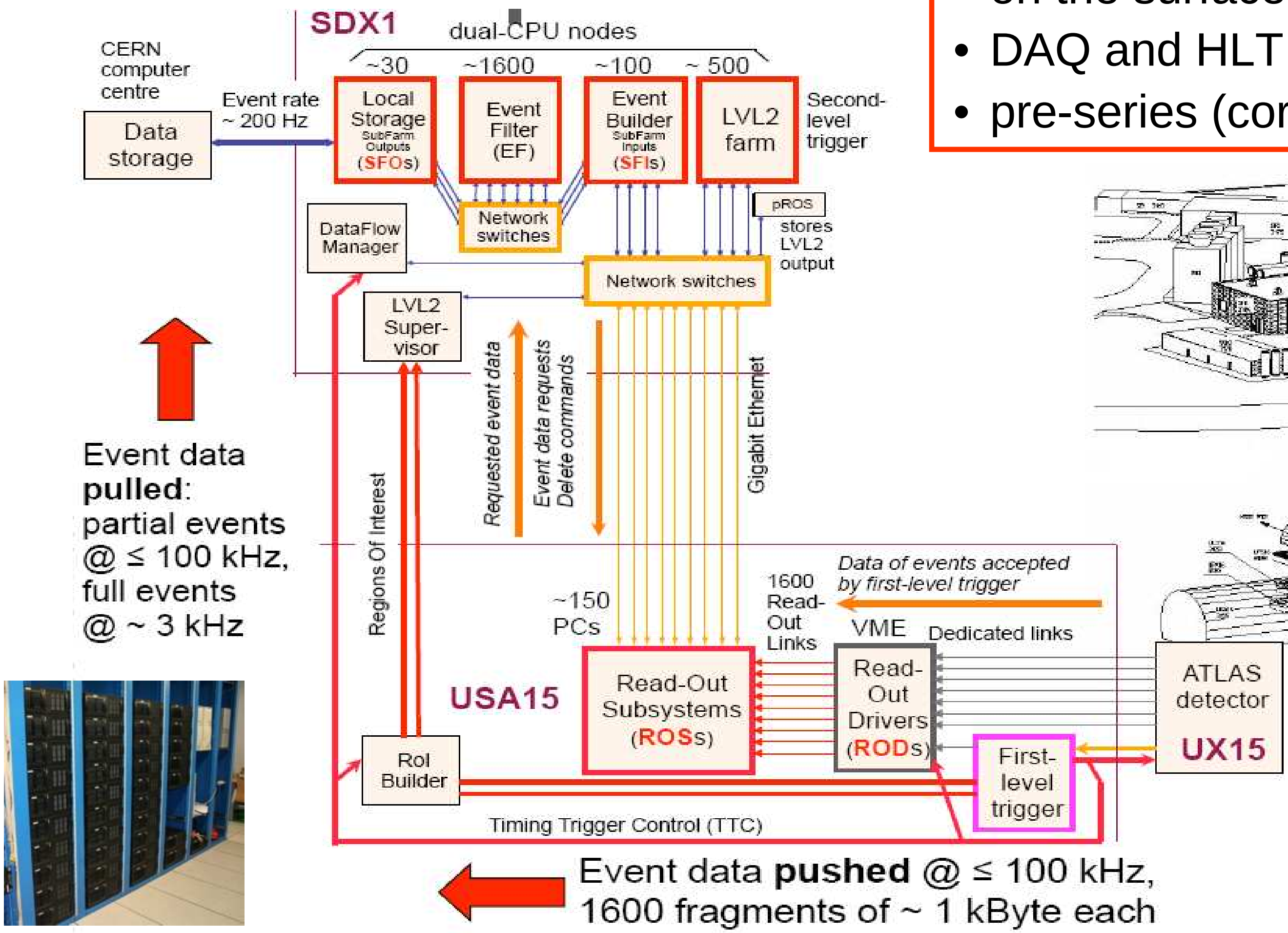
Level 2 seeded by Level 1
- Fast reconstruction algorithms
- Reconstruction within RoI

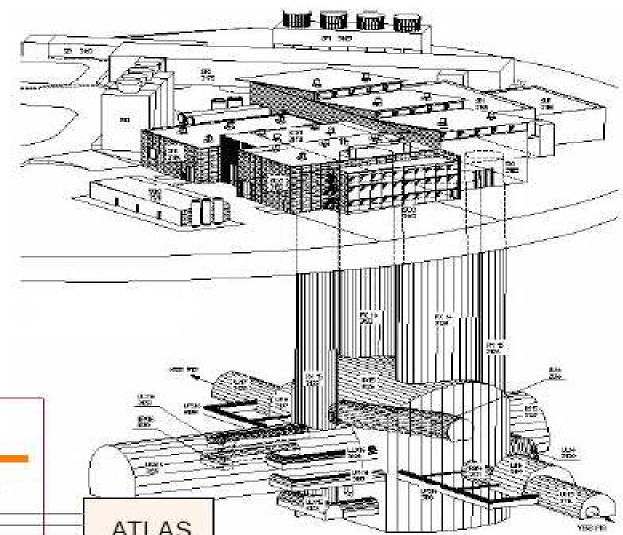
Ev.Filter seeded by Level 2
- Offline reconstruction algorithms
- Refined alignment and calibration



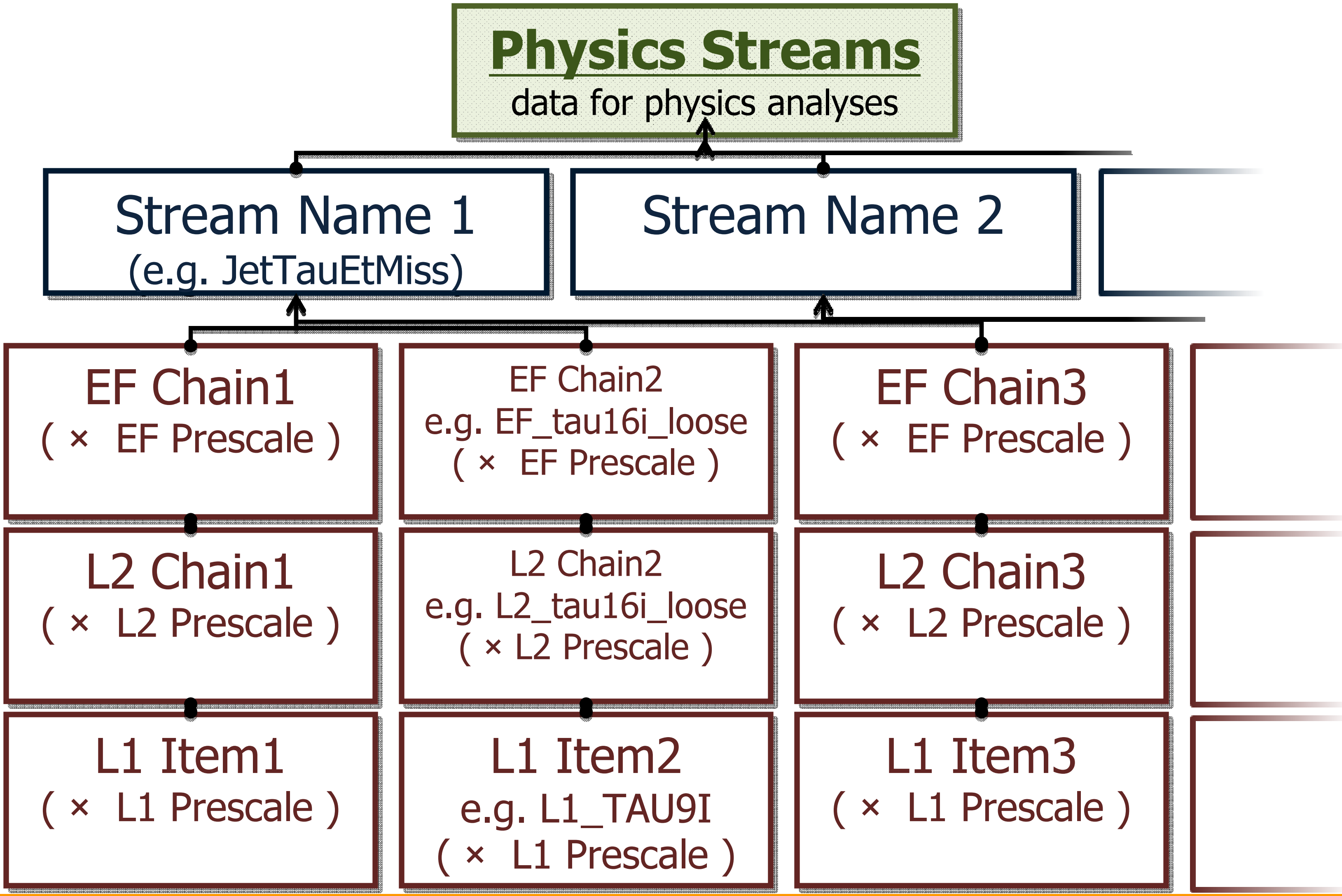
ATLAS Trigger / DAQ Architecture

- LVL2 and EF run in large PC farms on the surface
- DAQ and HLT closely coupled
- pre-series (corr. ~10% of HLT)





The Physics Streams



Data Streaming

- streaming is based on trigger decisions at the HLT
- the Raw Data physics streams are generated at the SFO
- all streams are inclusive, except the debug stream

Debug Streams
events without full trigger decision, due to failures in parts of the online system

Physics Streams
data for physics analyses

Egamma
Muons
JetTauEtMiss
MinBias
...

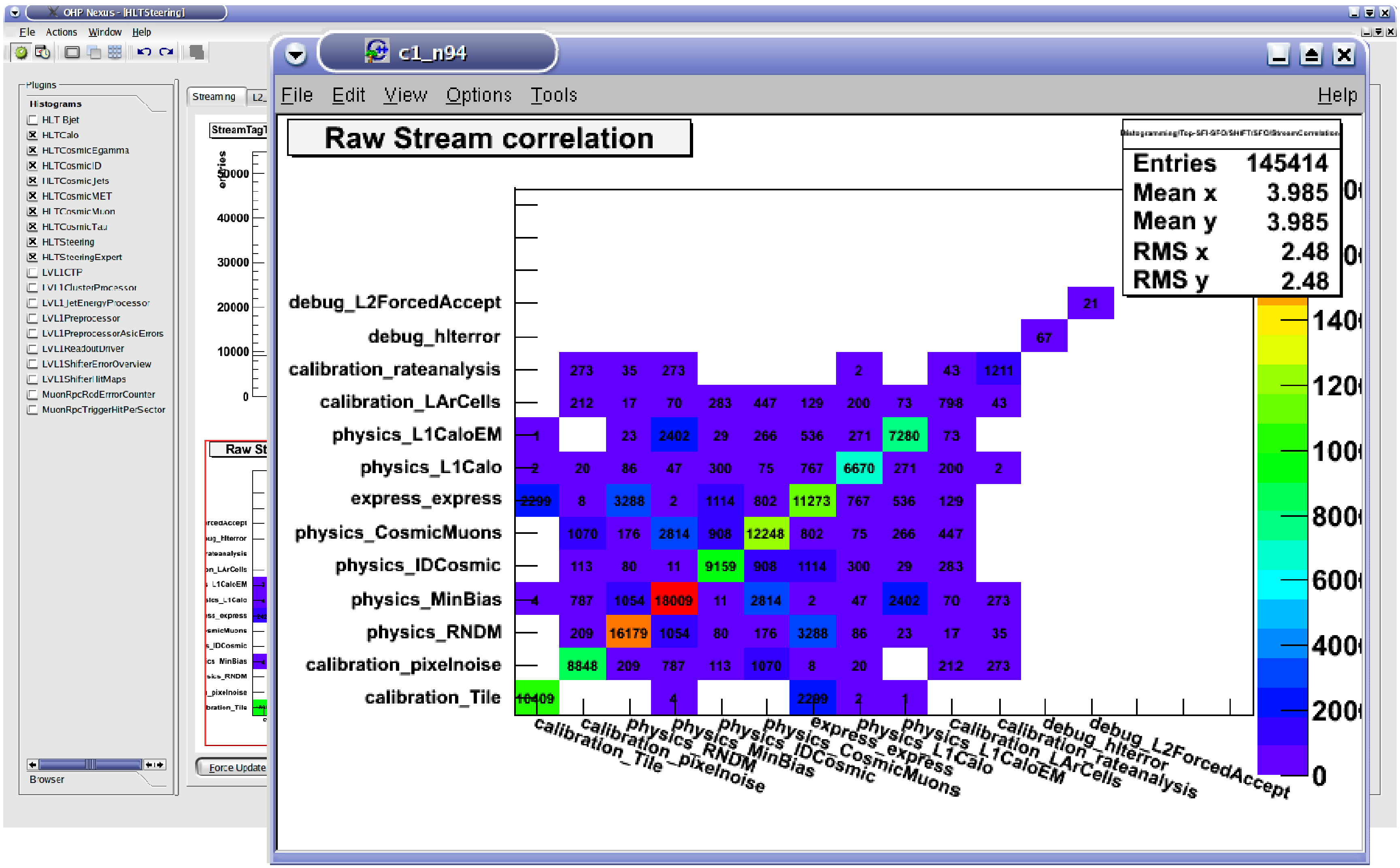
Express Stream
Events for prompt reconstruction (calibration loop)

Calibration Streams
events delivering the minimum amount of information for detector calibrations at high rate

partial events

ATLAS DATA

Stream Correlations



Physics Analysis: the Trigger Part

analysis preparation:

- setup/ optimize a trigger for your physics signal
  - define a trigger strategy (based on the available resources)
  - convert to trigger chain (already existing?)
  - determine rates and efficiencies from MC
- define a monitoring strategy
  - define trigger chain to be used for monitoring of your physics trigger (efficiency from data)
  - rates of the monitoring trigger (pre-scales?)
- integrate this in the overall trigger menu (done by Trigger Menu Coordination for online running)

threshold?
more exclusive?
pre-scaling?
more conditions?

not OK

OK

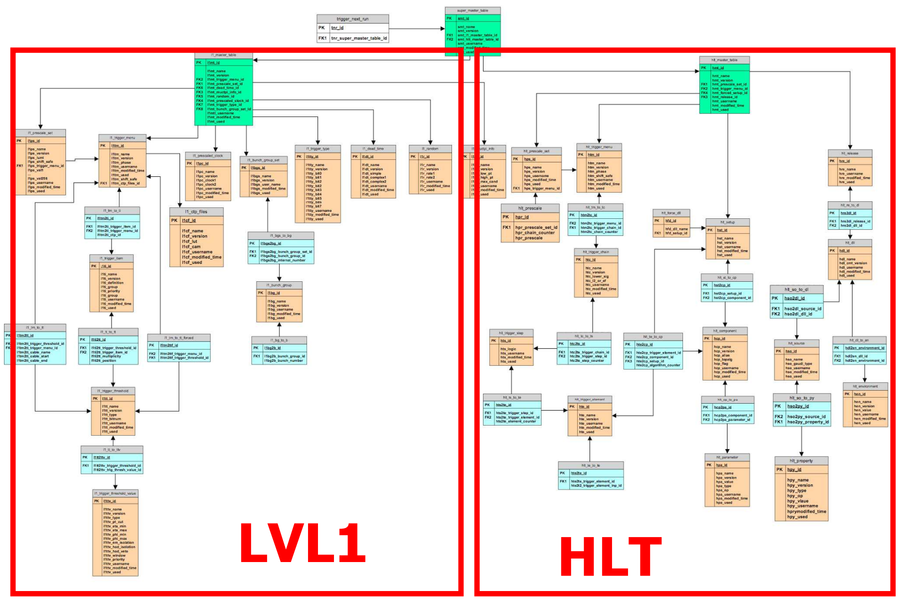
- use the trigger online (take data)
- monitor trigger quality
- determine trigger eff. (from data)
- correct your measurement

The Trigger Configuration

unique menu key: **SMK**

TrigConf system

- trigger menu can only be changed between runs
- pre scale keys can be chaged “on the fly” between lumi blocks
- book-keeping of all settings essential



TriggerDB:

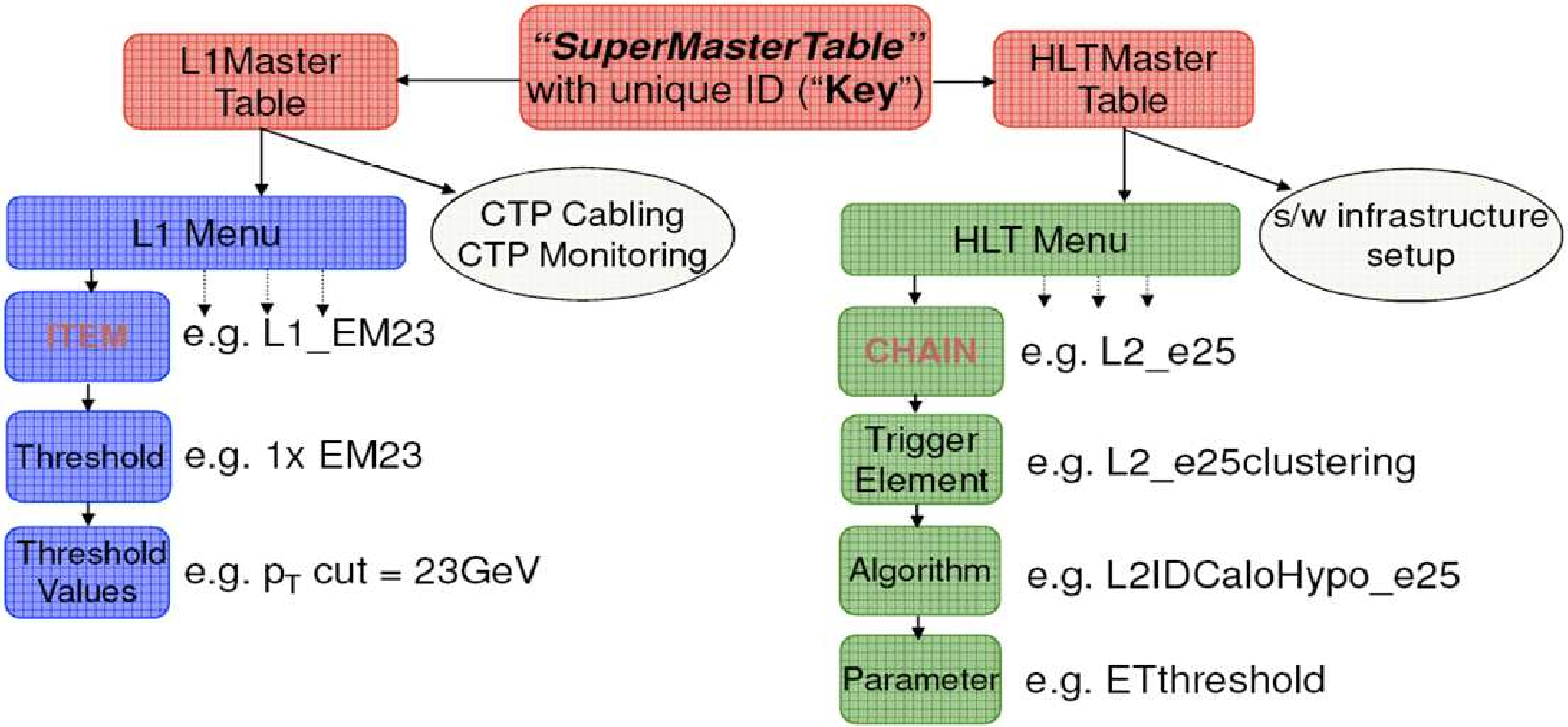
- stores all information for the online selection
- stores all versions of trigger settings.
- identified with a unique key to be stored in CondDB for menu and pre scales.

unique prescale keys: **L1PSK / HLTPSK**

Offline data analyzer users will have to look up the TriggerDB to interpret the trigger result in the events, e.g. to find the settings for their triggers and the corresponding run ranges.

Trigger Configuration

The **TriggerDB** stores the L1 and HLT Menus and the setups (= configurations of L1 hardware and HLT software) to realise these: **Configuration = Menu + setup**



The TriggerTool is the user interface to the TriggerDB

The Trigger Configuration Keys

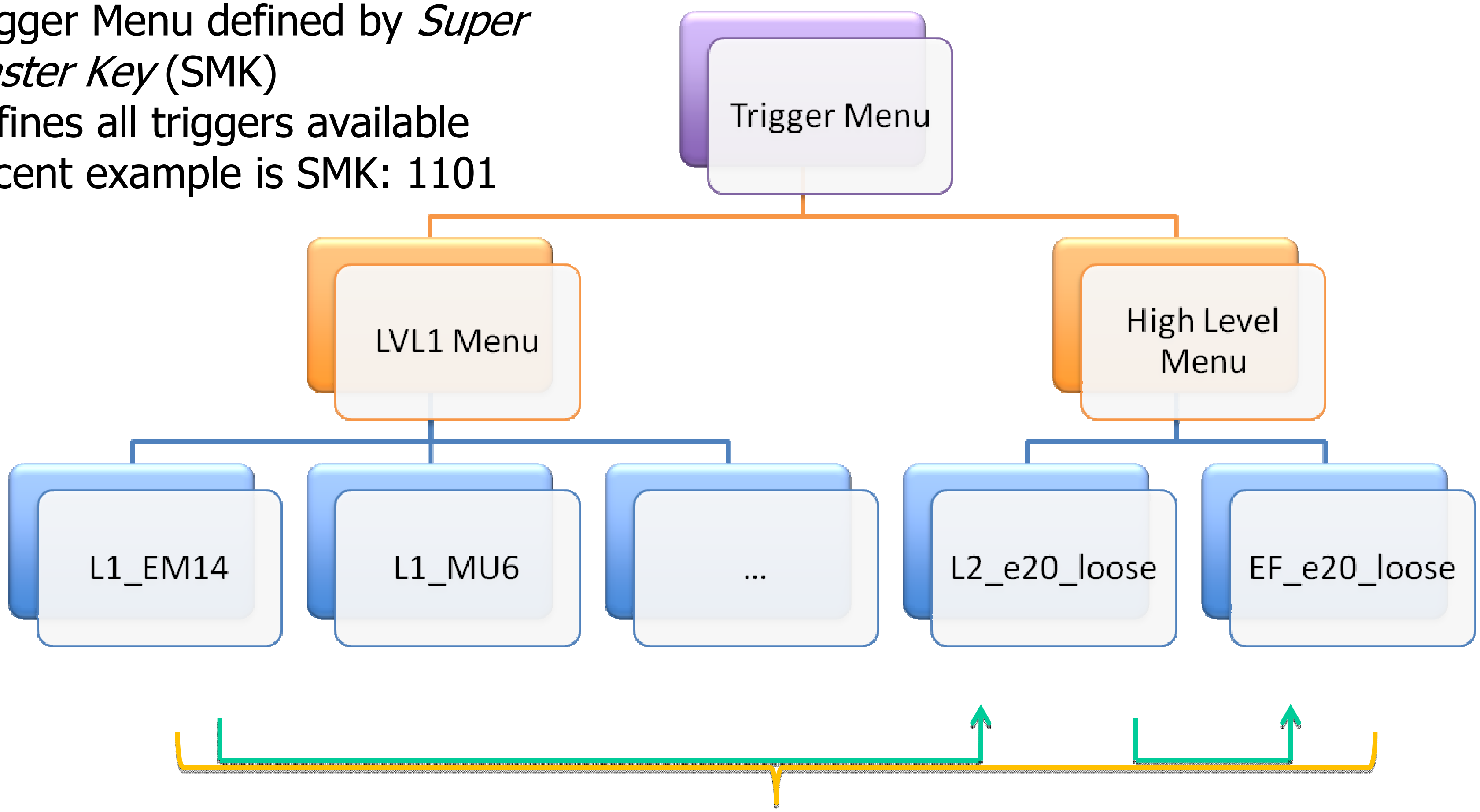
- ***Supermaster key (SMK)*** chooses one unique configuration (Menu, configuration, deadtime settings, etc.)
- every menu has a selection of compatible L1 and HLT ***Prescale Sets*** that can be applied
- three "keys" are therefore required to completely specify the configuration:
  - *Supermaster key (L1 + HLT Menus)*
  - *L1 Prescale Set key*
  - *HLT Prescale Set key*

  } Can be changed (also enabling and disabling triggers) during the run, at the luminosity block boundaries

- in addition there is a *L1 Bunch Group Set* key, which defines the LHC fill pattern for the CTP

Trigger Configuration

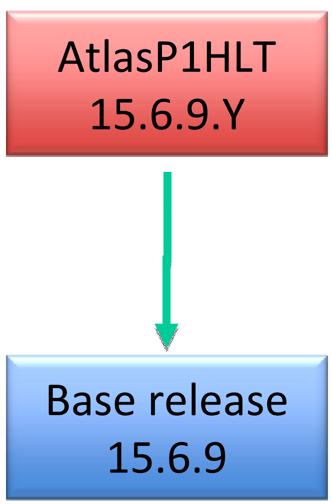
- Trigger Menu defined by *Super Master Key* (SMK)
- Defines all triggers available
- Recent example is SMK: 1101



- SMK also defines trigger chains of L1/L2/EF items, i.e. "e20_loose" composed of L1_EM14, L2_e20_loose, and EF_e20_loose.

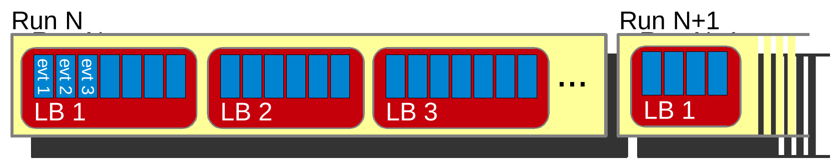
HLT Software and Patches

- HLT uses a separate branch of offline release
  - Move to new base release about twice per year
  - AtlasP1HLT *cache* used to patch base release
  - Patches installed roughly every 1-2 weeks (or as needed)
  - Additional procedure for emergency patches in place
  - In all cases large scale validation before deployment

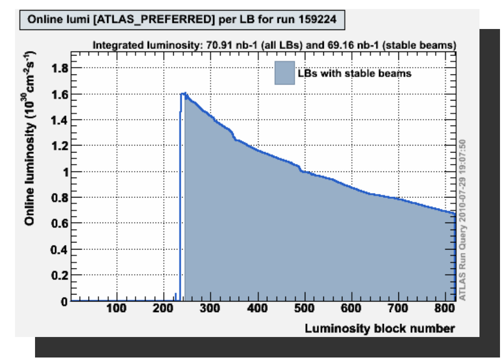


Installation of new AtlasP1HLT release done by Trigger Online Expert between LHC fills after discussion in morning run meeting.

ATLAS Data Taking Strategy



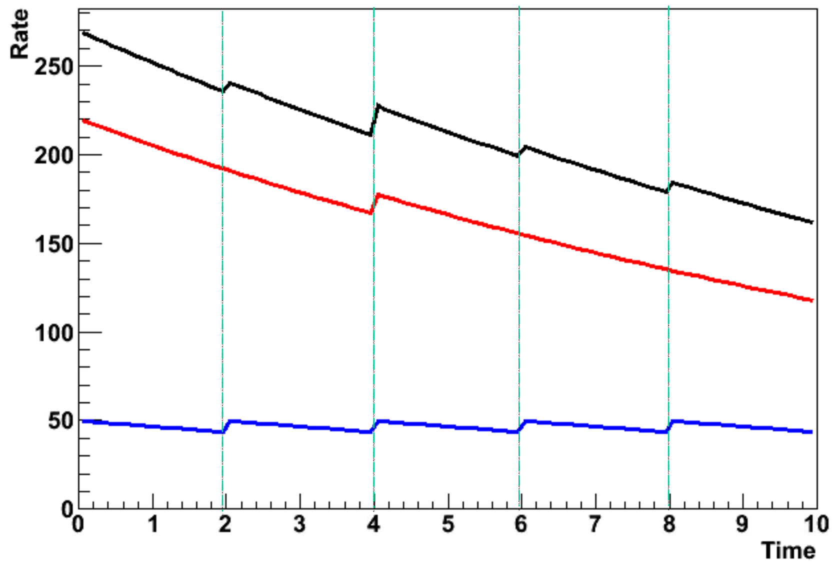
- Run
  - Continuous period of data taking
  - Usually corresponds to LHC fill (many hours)
- Luminosity Block (LB)
  - Luminosity, conditions, and data quality are considered to be approximately constant
  - Time interval (=60 sec) within a run



- Luminosity drops exponentially during fill
  - Record as much physics data as possible
  - Limitations imposed by detector and DAQ system (processing speed, buffer sizes, internal bandwidths), Tier0, and long-term storage capacities.

Trigger Prescale Strategy

- **Total Output Rate** begins with large to-disk rate (~400Hz) which falls throughout the fill, where average over the fill should be ~200Hz.
- **Primary Triggers** run without prescale and therefore have a falling rate throughout the fill. Additional triggers are added after the luminosity drops below a defined luminosity which cannot be run at higher lumi due to pileup.



- **Supporting Triggers** have changing prescales in order to keep their rate constant.
- Trigger menu experts prepare the prescale sets for the different luminosities ahead of time. You always find them on the **TriggerWhiteboard** at Point1.
- Note: prescale changes need not occur at 2 hour intervals as shown in the illustration, but is instead driven by the luminosity.

Standby and Physics Prescales

- **Standby**
  - No beam or un-stable beams (before warm start)
  - Detectors in SAFE mode, high voltage off (low) for inner detector and muon systems
  - Only a few L1 triggers needed for detectors to measure background levels (especially before switching on voltage)
- **Physics (ATLAS ready)**
  - Stable beams, all detectors in physics mode
  - Data for physics analysis, all triggers in, HLT rejection
  - Prescale sets prepared for different luminosities
- **Switch between Standby/Physics by Run Control**
  - Done automatically during "Warm start/stop"
  - Trigger shifter verifies that the correct keys are used

Noisy EMPTY triggers

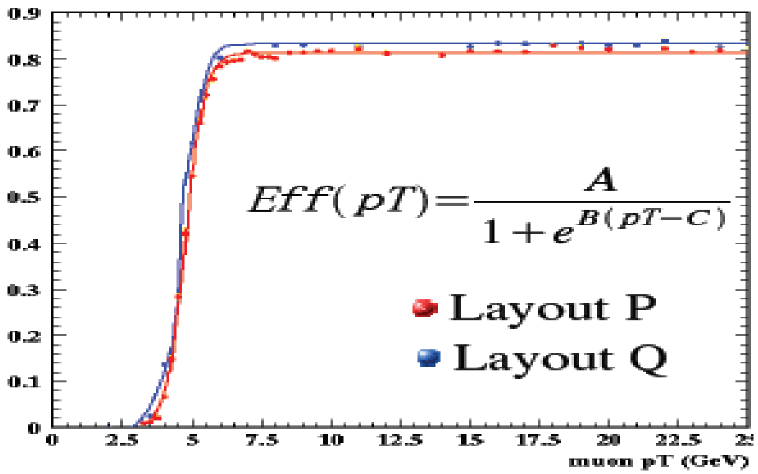
- Low threshold EMPTY triggers (EM3, TAU5, J5)
  - Used for background monitoring, no HLT rejection applied
  - Ideally should be unprescaled
  - If well behaved, rate < 5 Hz
- Noisy cells in LAr can cause
  - Short noise spikes of O(kHz) – usually not a problem
  - Constant noise can increase rate to >100 Hz – need to react by prescaling trigger
- This is done automatically by the AutoPrescale Tool

Physics Analysis: the Trigger Part

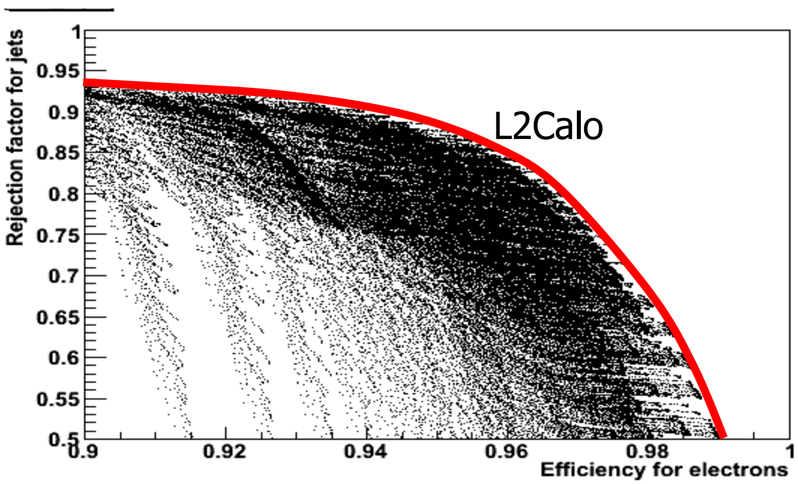
every physics analysis needs dedicated thoughts about the trigger:

- trigger rejects 0.999995 → more or less hard cuts (in the signal region)
- (each) trigger has an inefficiency that needs to be corrected (turn-on curve)
  - similar to offline reconstruction efficiency, but important difference: no retrospective optimization: "The events are lost forever."
- trigger optimization (as early as possible)
- trigger data quality during data-taking is crucial

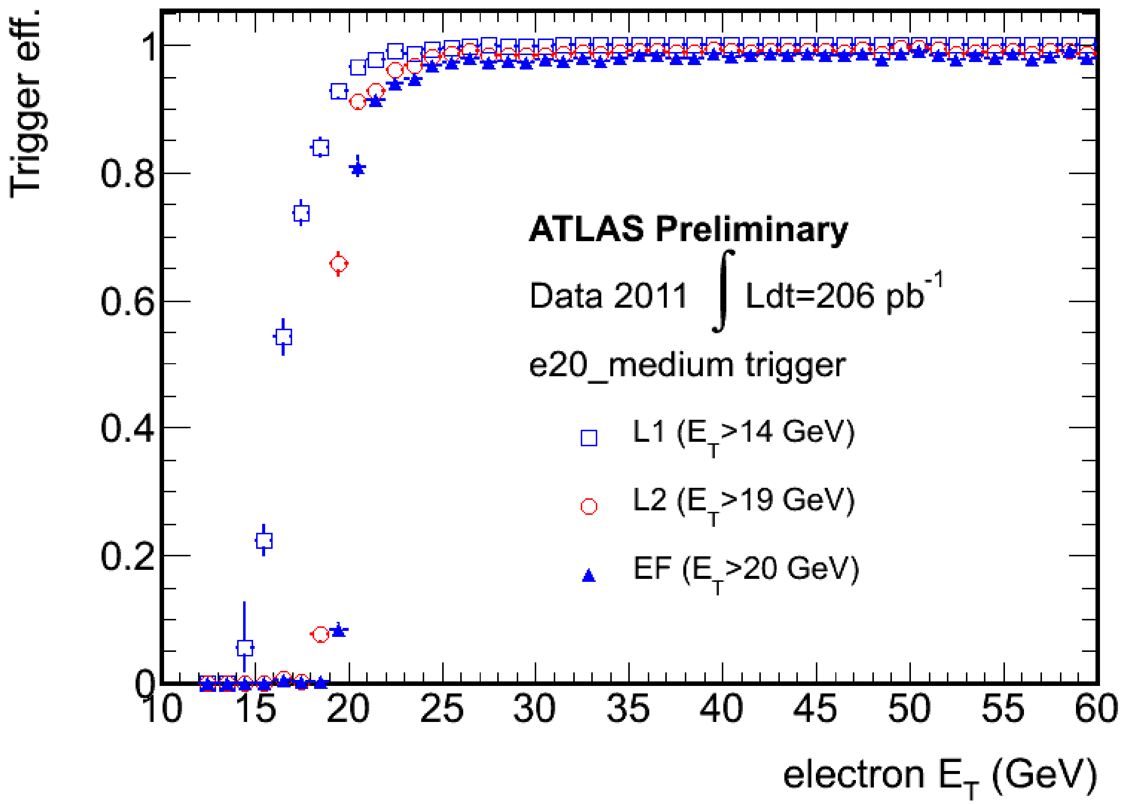
turn-on curve:



trigger optimisation:

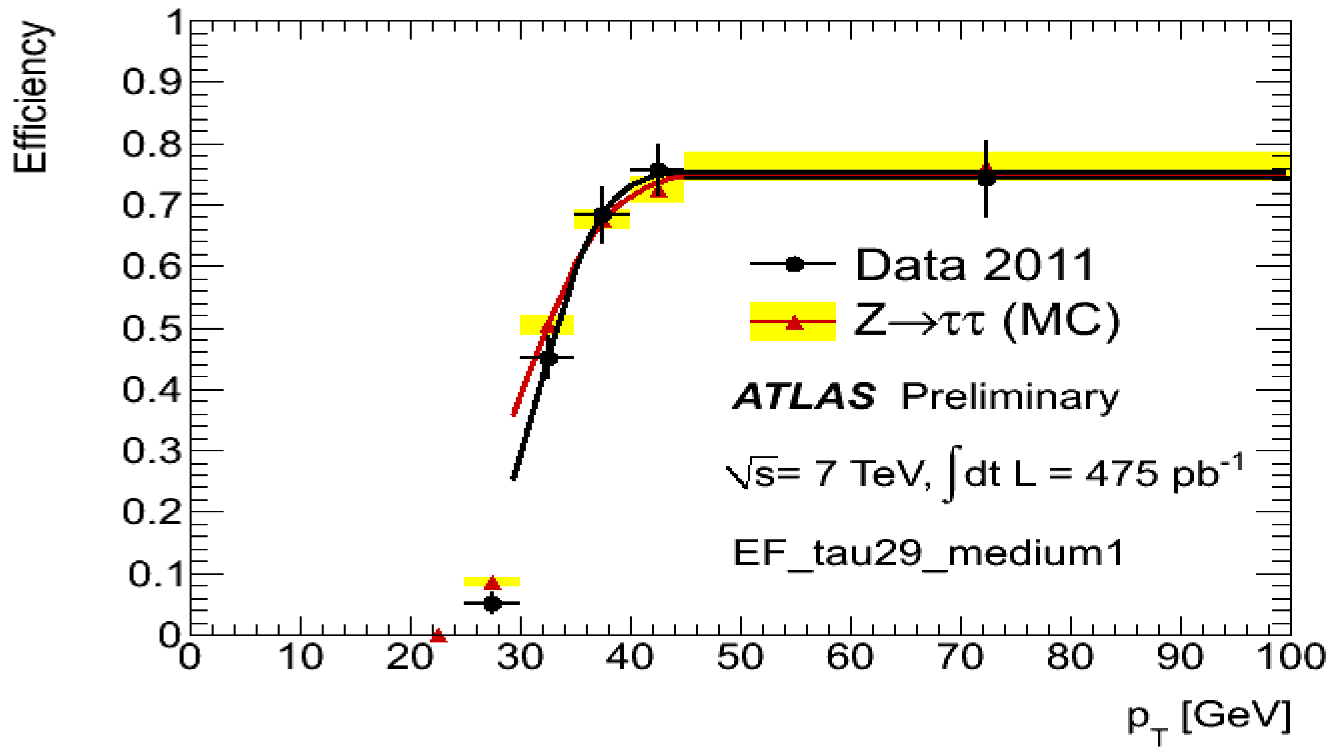


E-gamma Trigger Slice: Efficiency



Efficiencies for e20_medium at each trigger level (L1, L2 and EF) measured with Z->ee events using the tag-and-probe method

Tau Slice: Turn-On Curve

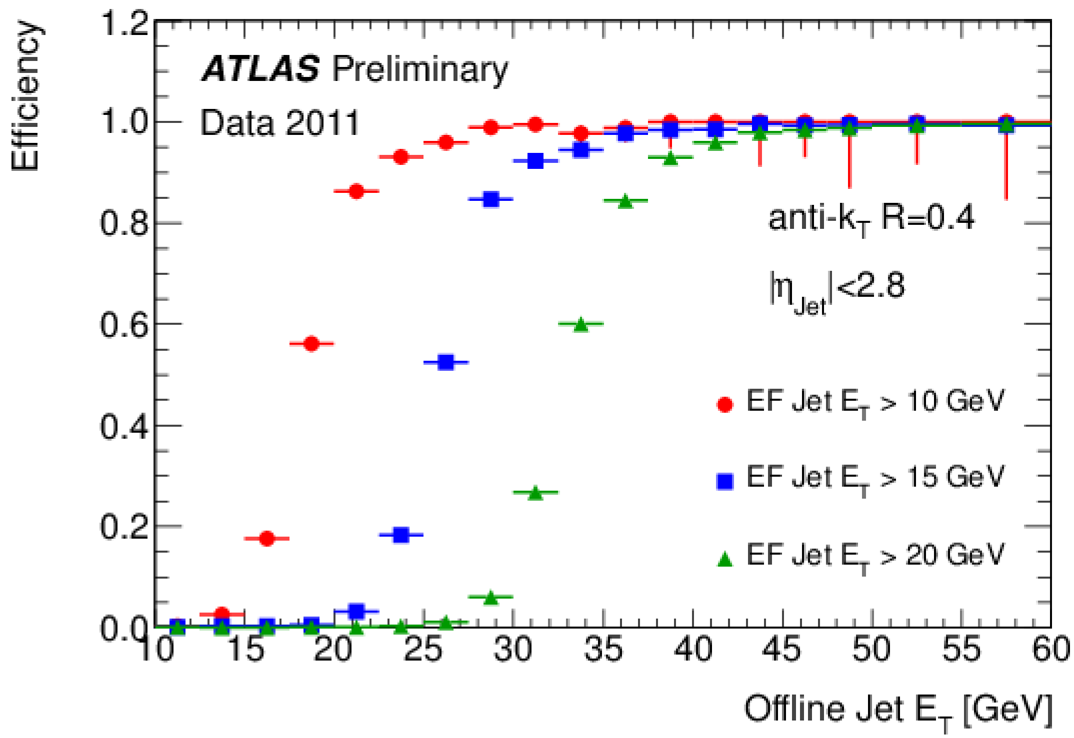


Efficiency of the EF_tau29_medium1 trigger chain with respect to offline reconstructed tau candidates, as a function of the offline pT

The measurement was made using a tag and probe analysis with

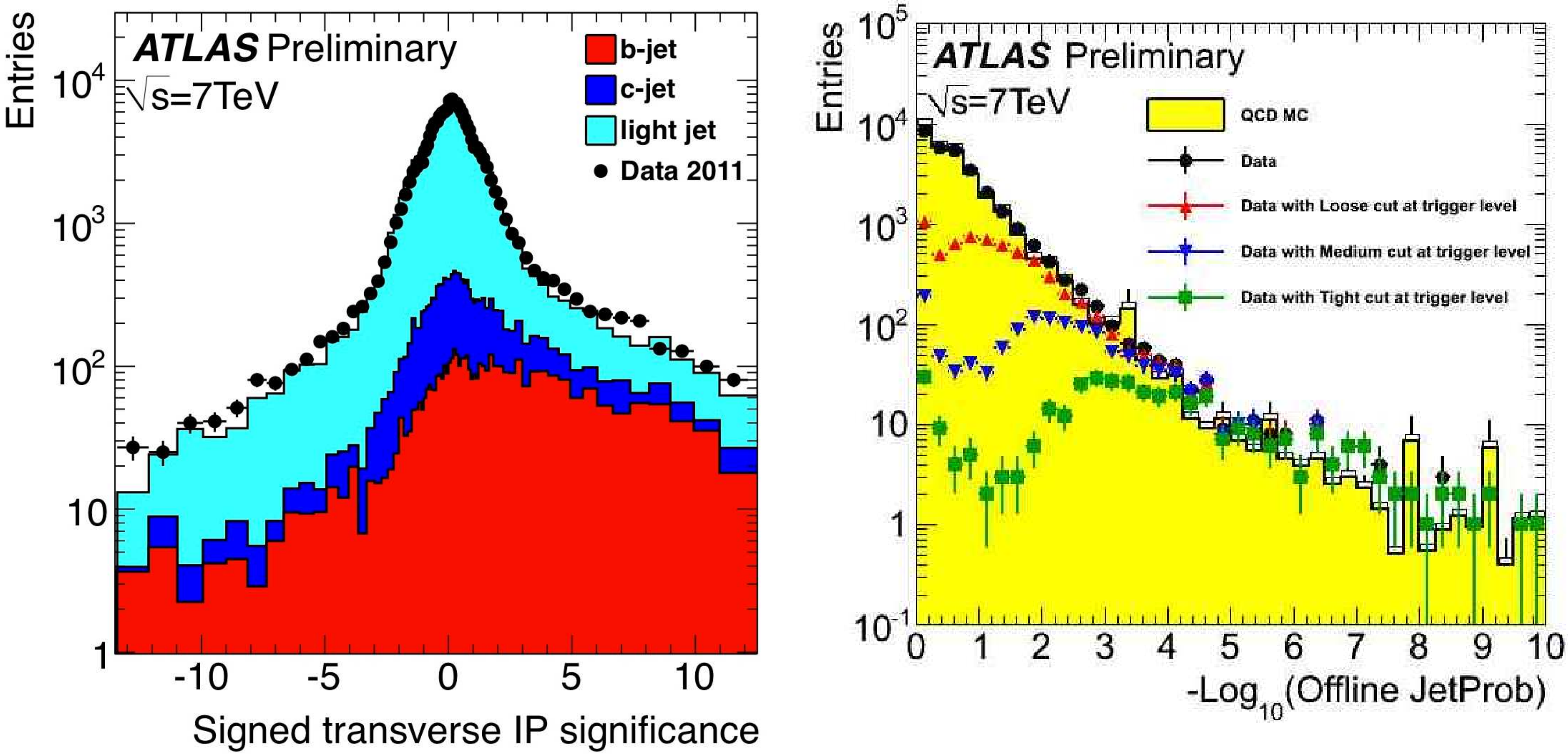
Z → tau tau → mu had events in 2011 data

Jet Trigger



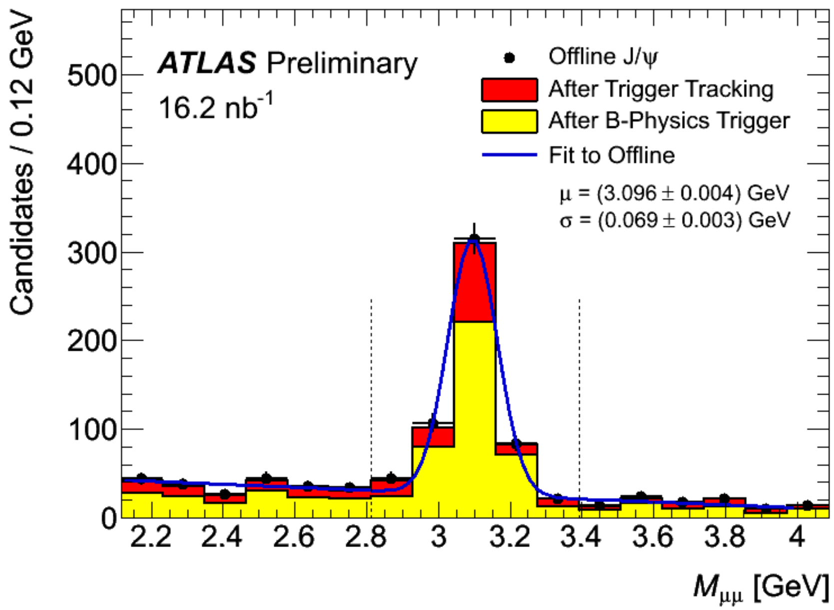
efficiency for anti-kt jets with R=0.4 to satisfy the Event Filter (EF) inclusive jet trigger
EF-jet conditions were applied to random-triggered events.
efficiency is plotted as a function of the offline calibrated jet ET

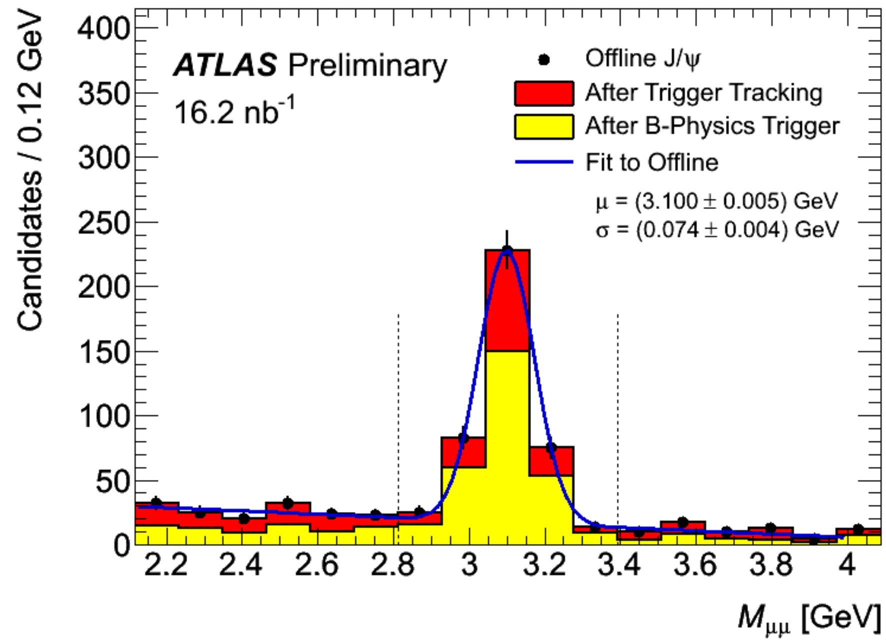
B-jet Trigger: EF-Level



online b-tagging requirements fulfilled

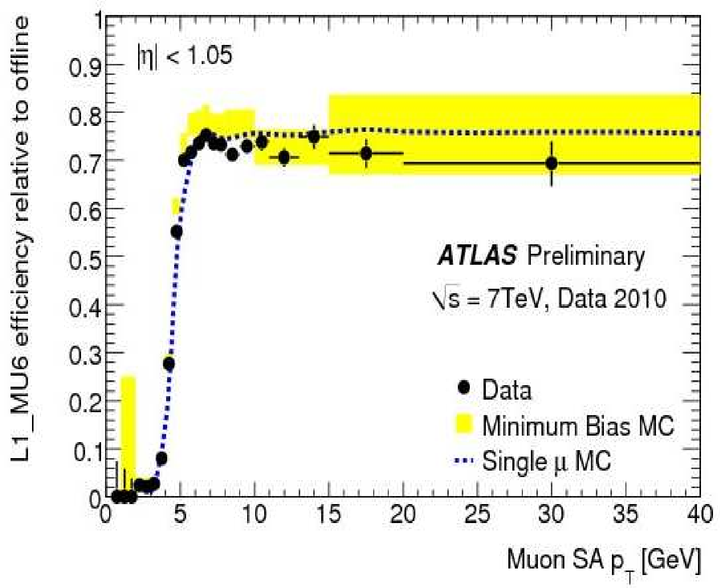
B-Physics Trigger



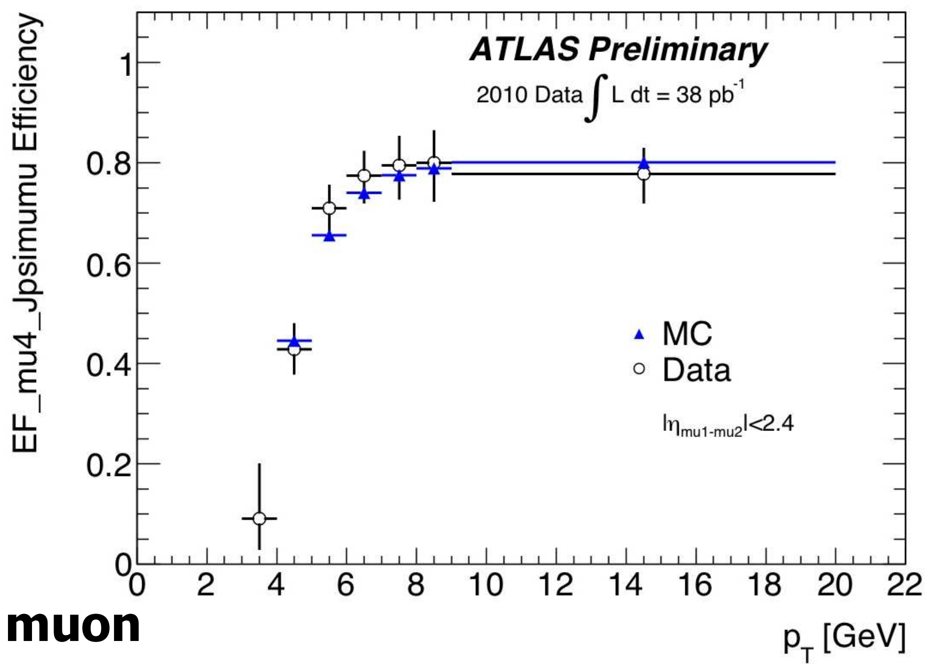


J/Ψ candidates in the di-muon channel for L2 / EF

Muon Trigger slice

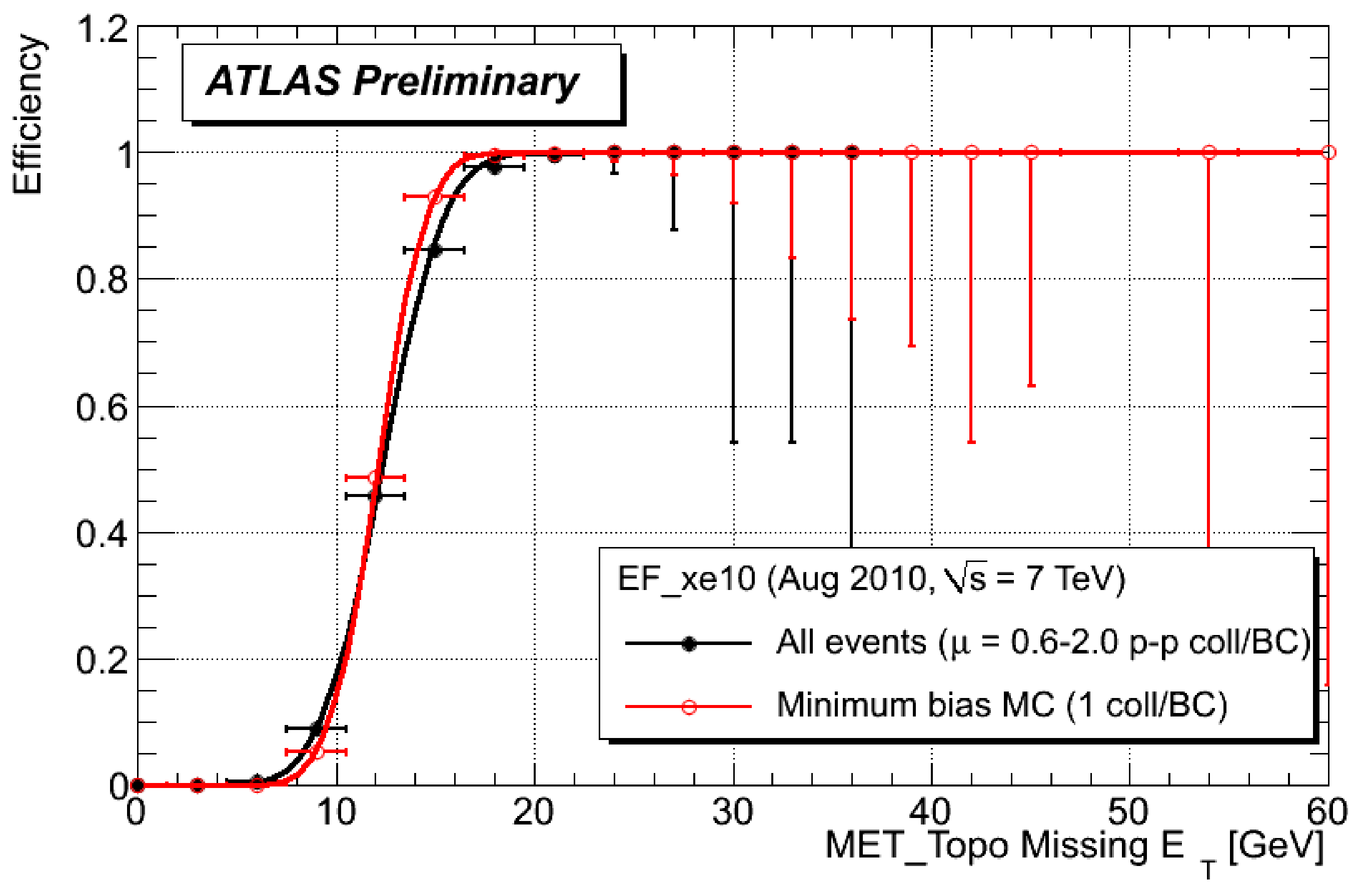


L1 Muon Barrel Trigger (6GeV) Efficiency wrt to offline

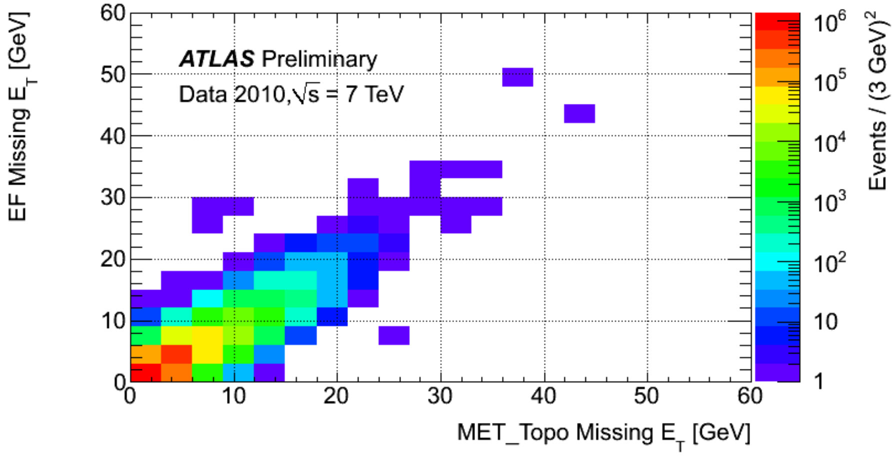


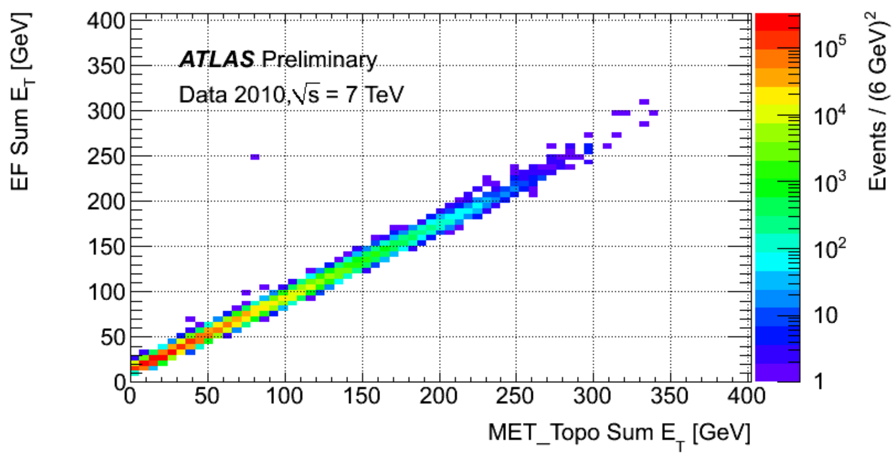
EF di-muon trigger turn on curve:
EF_mu4_jpsimumu efficiency respect to the higher pT combined muon

Missing transverse energy



Energy correlation of MET Trigger





Correlation between the Missing ET (top) and Sum ET (bottom) measured by the Event Filter (EF) trigger algorithm and by the offline algorithm using all calorimeter cells after noise suppression