

# Trigger and Data Analysis (II)

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# Lecture Themes

- I. Introduction and Challenges
- II. Trigger and Data Acquisition Basics
- III. Trigger Selection at the LHC

*today*

- IV. More in Depth: ATLAS e/ $\gamma$  Trigger
- V. Jet and Muon Triggers
- VI. Trigger/DAQ Commissioning
- VII. Trigger-Aware Data Analysis

*tomorrow*



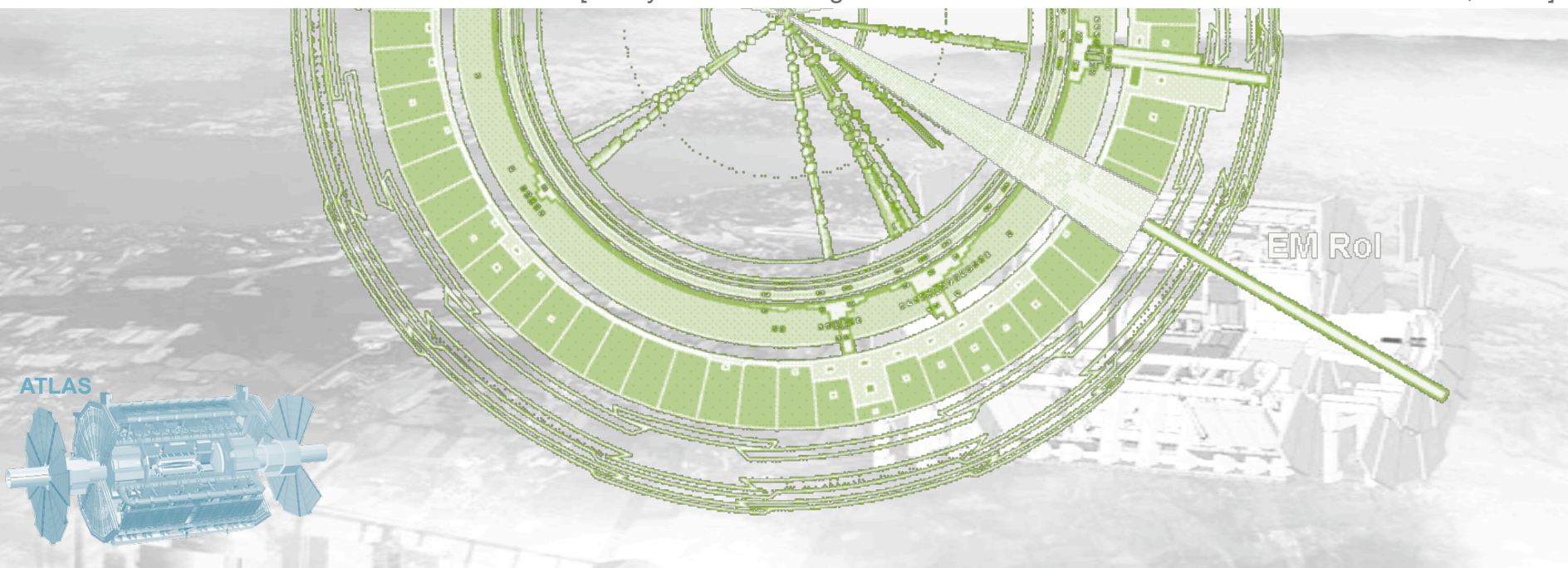
# More in Depth: ATLAS e/ $\gamma$ Trigger

## ATLAS Level-1 Trigger System

L1 e/ $\gamma$  algorithm and implementation — example of pipelined processing

High-level electron trigger — example for sophisticated online selection

[ Many of the following slides taken from N. Ellis' excellent Columbia lecture, 2009 ]



# General Level-1 trigger design goals

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Need large reduction in physics rate already at the first level (otherwise readout system becomes unaffordable)

- From  $O(10^9)$  interaction rate to less than 100 kHz in ATLAS and CMS
- Require complex algorithms to reject background while keeping signal

An important constraint is to achieve a short latency

- Information from all detector channels ( $O(10^8)$  channels!) has to be held in local memory on detector pending the L1 decision
- The pipeline memories are typically implemented in ASICs (Application Specific Integrated Circuits), and memory size contributes to the cost
- Typical L1 latencies are a few  $\mu\text{s}$  (e.g. less than 2.5  $\mu\text{s}$  ATLAS, 3.2  $\mu\text{s}$  CMS)

Require flexibility to react to changing conditions (e.g. wide luminosity range) and — hopefully — new physics

- Algorithms must be programmable (adjustable parameters at least)

# Overview of ATLAS Level-1 Trigger

[ Drawing by Nick Ellis (CERN), 2006 ]

~7200 calorimeter trigger towers

$O(1M)$  RPC/TGC channels

## Calorimeter trigger

Pre-processor  
(analogue  $\sim E_T$ )

Jet / Energy-sum  
Processor

Cluster Processor  
( $e/\gamma, \tau/h$ )

## Muon trigger

Muon Barrel  
Trigger

Muon End-cap  
Trigger

Muon central  
trigger processor

Central Trigger  
Processor (CTP)

Local Trigger  
Processors (LTP)

Timing, Trigger,  
Control (TTC)

Design all digital,  
except input stage of  
calorimeter trigger  
Pre-processor

Latency limit:  $2.5 \mu s$

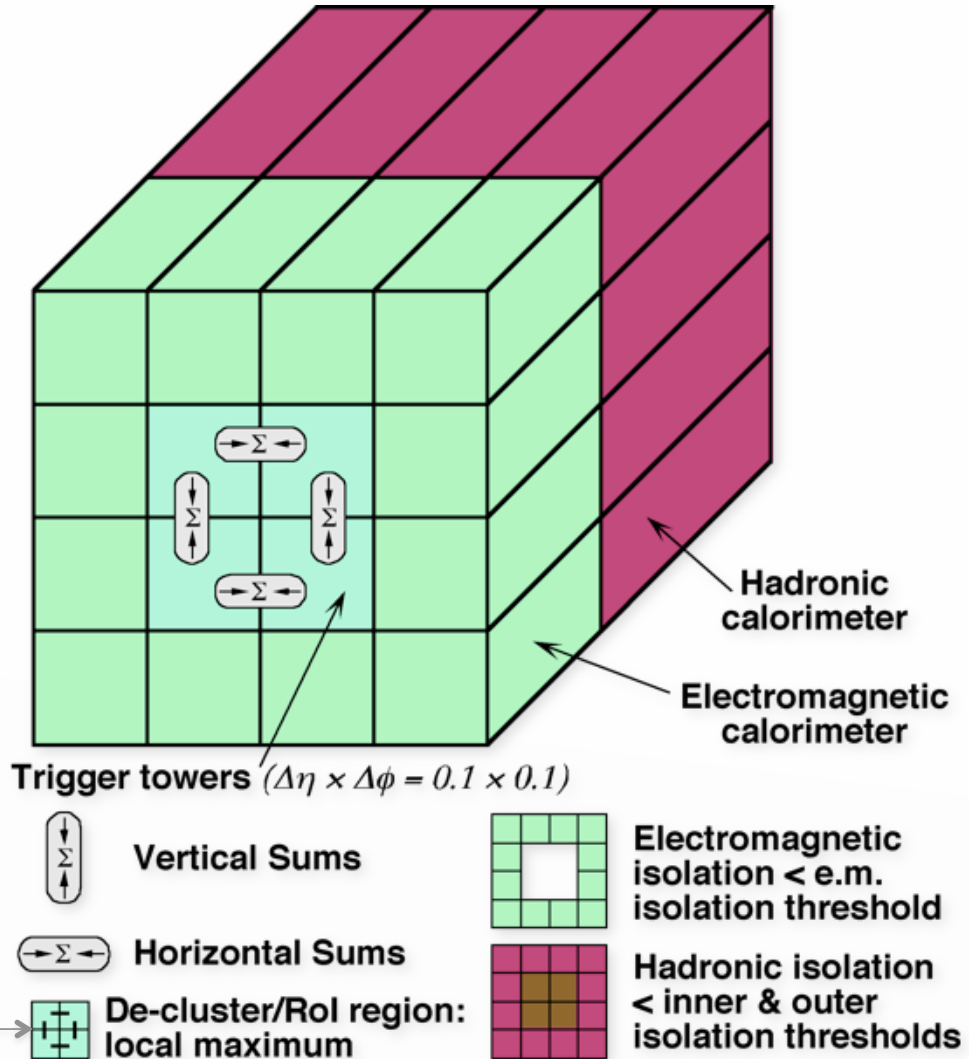
# ATLAS Level-1 $e/\gamma$ Trigger

ATLAS  $e/\gamma$  trigger is based on  $4 \times 4$  *overlapping, sliding windows* of trigger towers

- Each trigger tower  $0.1 \times 0.1$  rad in  $\eta \times \phi$
- $\sim 3500$  such towers in each of the EM and hadronic calorimeters

There are  $\sim 3500$  such windows per system

- Each tower participates in calculations for 16 windows
- This is a driving factor in the trigger design



“De-clustering”: cluster must have more  $E_T$  than 8 surrounding  $2 \times 2$  ones  $\rightarrow$  avoids double counting



# ATLAS Level-1 Calorimeter Trigger

Analogue electronics on detector sums signals to form trigger towers

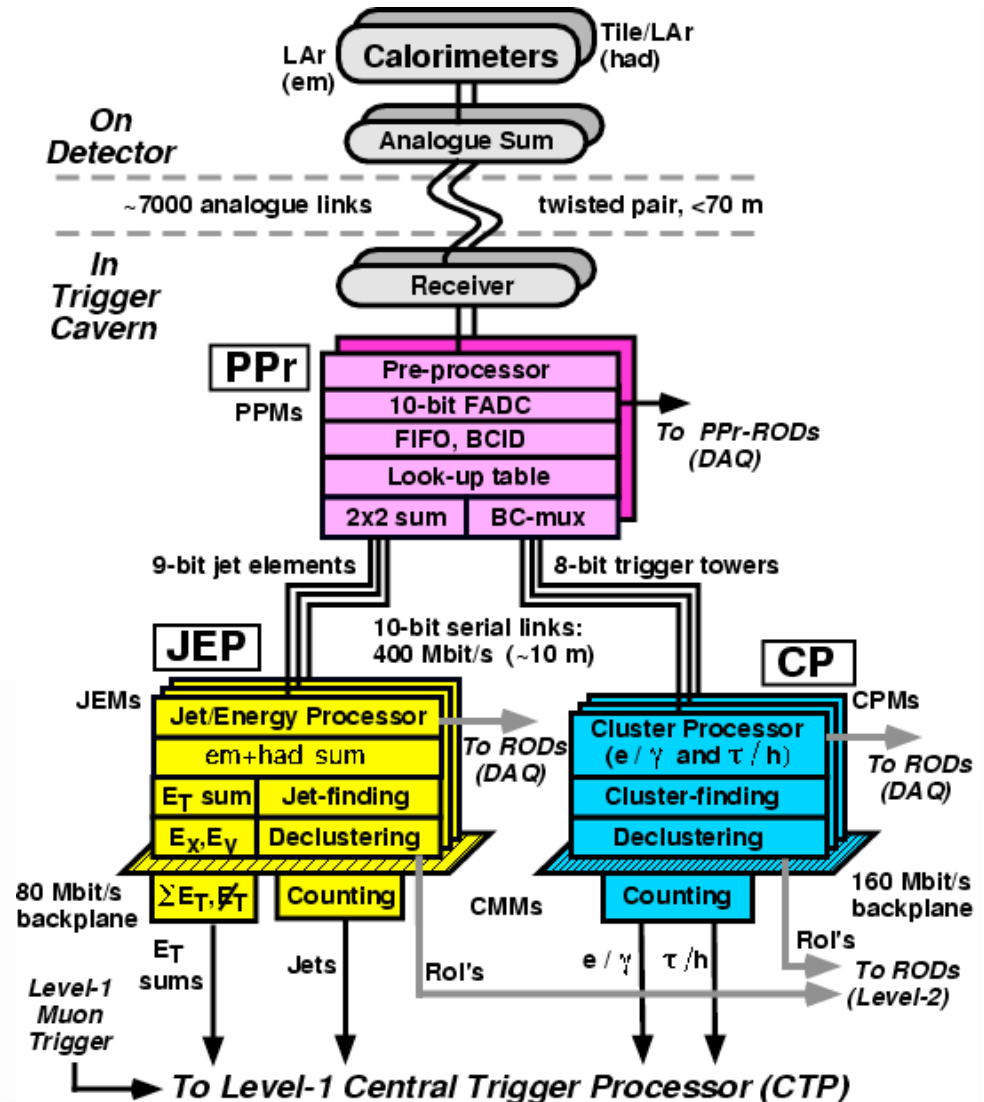
Signals received and digitised

- Digital data processed to determine  $E_T$  per tower for each BC

Tower data transmitted to Cluster Processor performing “object finding”

- Fan out values needed in more than one crate, requiring compact design
- Within CP crate, values need to be fanned out between electronic modules, and between processing elements on the modules

Connectivity and data-movement issues drive the design



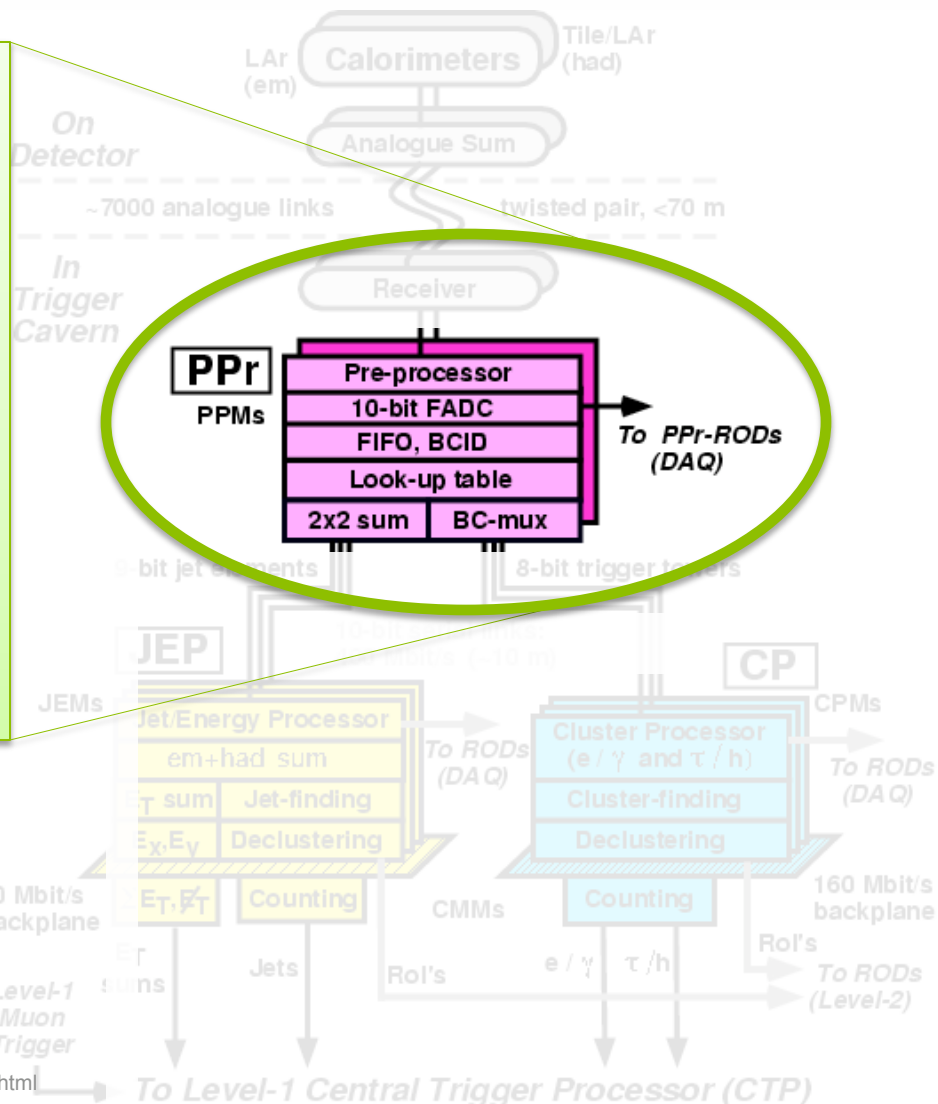
# Digression: Pre-processor

## Pre-processor module (PPr)

Takes signals from the ATLAS calorimeters as shaped analogue pulses

- digitises and synchronises them
- identifies the BCID from which each pulse originated
- performs  $E_T$  calibration
- prepares digital signals for serial transmission

The PPr serves JEP and CP systems



Connectivity and data-movement issues drive the design

More details: <http://www.kip.uni-heidelberg.de/Elektronik/EWweb/PPrSysKomp/PPrSysKomp.html>

# Digression: Jet and Cluster Processors

Analogue electronics on detector  
sums signals to form trigger towers

Signals received and digitised

- Digital data processed to determine  $E_T$  per tower for each BC

Tower data transmitted to Cluster Processor performing “object finding”

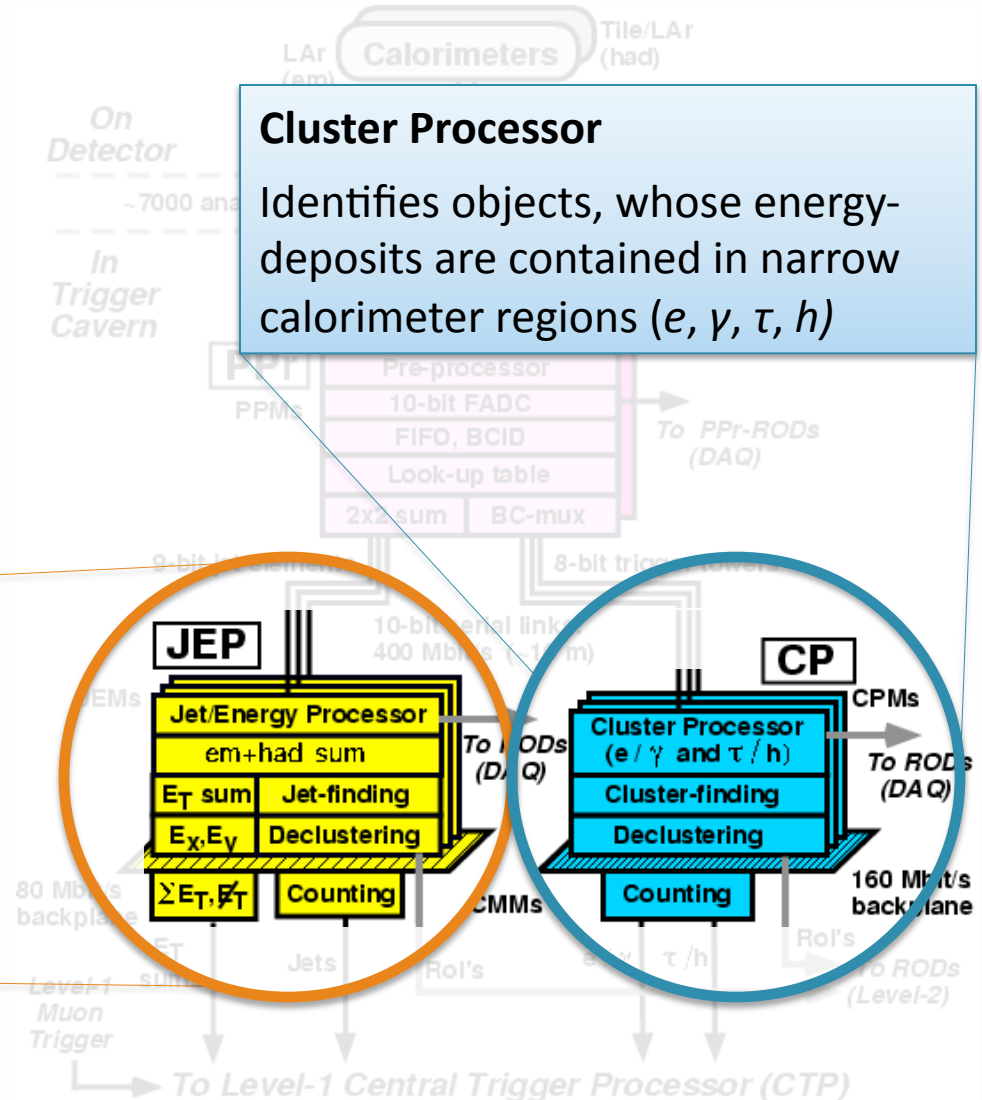
## Jet/Energy Processor

Looks for extended “jet-like” objects in calorimeters and for sum of missing transverse energy

Receives towers with twice coarser granularity from PPr.

## Cluster Processor

Identifies objects, whose energy-deposits are contained in narrow calorimeter regions ( $e, \gamma, \tau, h$ )



# The ATLAS Level-1 Calorimeter Trigger System



Level-1 Calorimeter Pre-processor crate



Analogue trigger cables received in electronics cavern

# Bunch-Crossing Identification

Calorimeter signals extend over many bunch-crossings

- Need to combine information from a sequence of measurements to estimate the energy and identify the bunch-crossing where energy was deposited

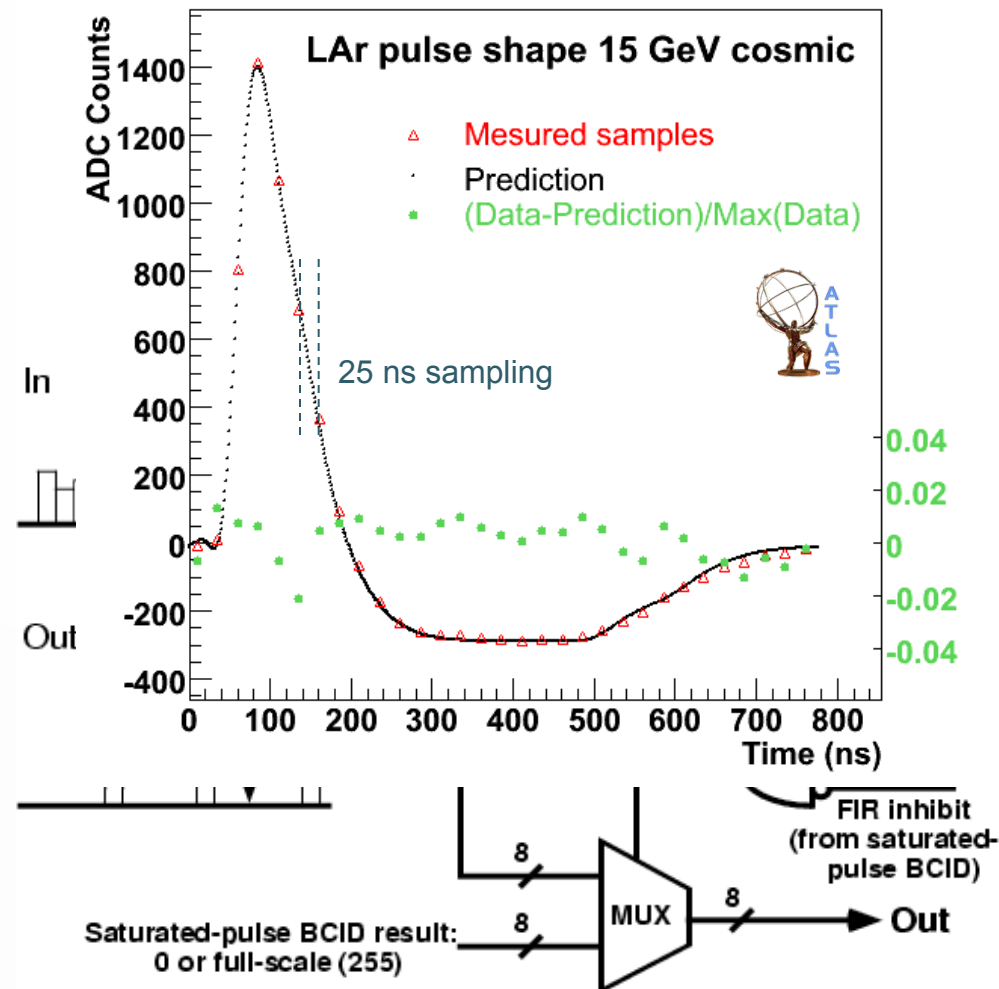
Apply Finite Impulse Response filter

- Result  $\rightarrow$  LUT to convert value to  $E_T$
- Result  $\rightarrow$  peak finder to determine BC where energy was deposited

Need to take care of signal distortion for very large pulses

- Don't lose most interesting physics!

An ASIC\* incorporates the above



\*Application-specific integrated circuit



# Data Transmission and Cluster Processor

The array of  $E_T$  values computed in the previous stage has to be transmitted to the CP

Use digital electrical links to Cluster Processor modules

- ~5000 links at 400 Mbits/s

Fan-out data to neighbouring modules over high-density custom backplane

- ~800 pins per slot in 9U crate
- 160 Mbits/s point-to-point

Fan out data to 8 large FPGAs\* per module

\*FPGA = Field Programmable Gate Array  
i.e. reprogrammable logic

The  $e/\gamma$  (together with the  $\tau/h$ ) algorithm is implemented in FPGAs

This has only become feasible with recent advances in FPGA technology

- Require very large and fast devices

Each FPGA handles  $4 \times 2$  windows

- Needs data from  $7 \times 5 \times 2$  towers ( $\eta \times \phi \times E/H$ )

Algorithm described in programming language that can be converted into FPGA configuration file

- Can adapt algorithms with experience

Parameters can be changed easily

- e.g. cluster- $E_T$  thresholds are held in registers that can be programmed

# HLT Electron Trigger

## L1 $e/\gamma$ trigger already very selective

- Need to use complex algorithms and full-granularity detector data in HLT

## Calorimeter selection

- Sharpen  $E_T$  cut
- Use shower-shape variables to improve jet rejection

## Associate track in inner detector

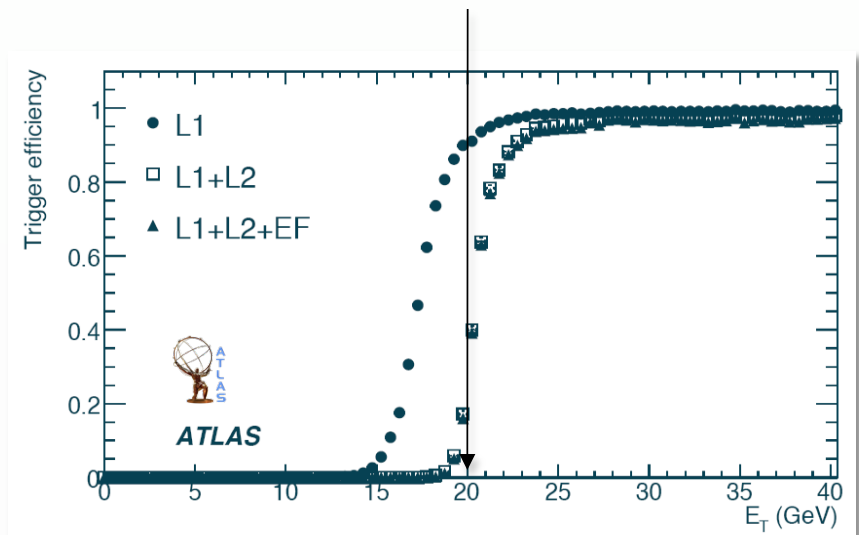
- Matching calorimeter cluster
- Compute  $E/p$

## Optimise signal efficiency and background rejection

- May use multivariate techniques already in trigger !

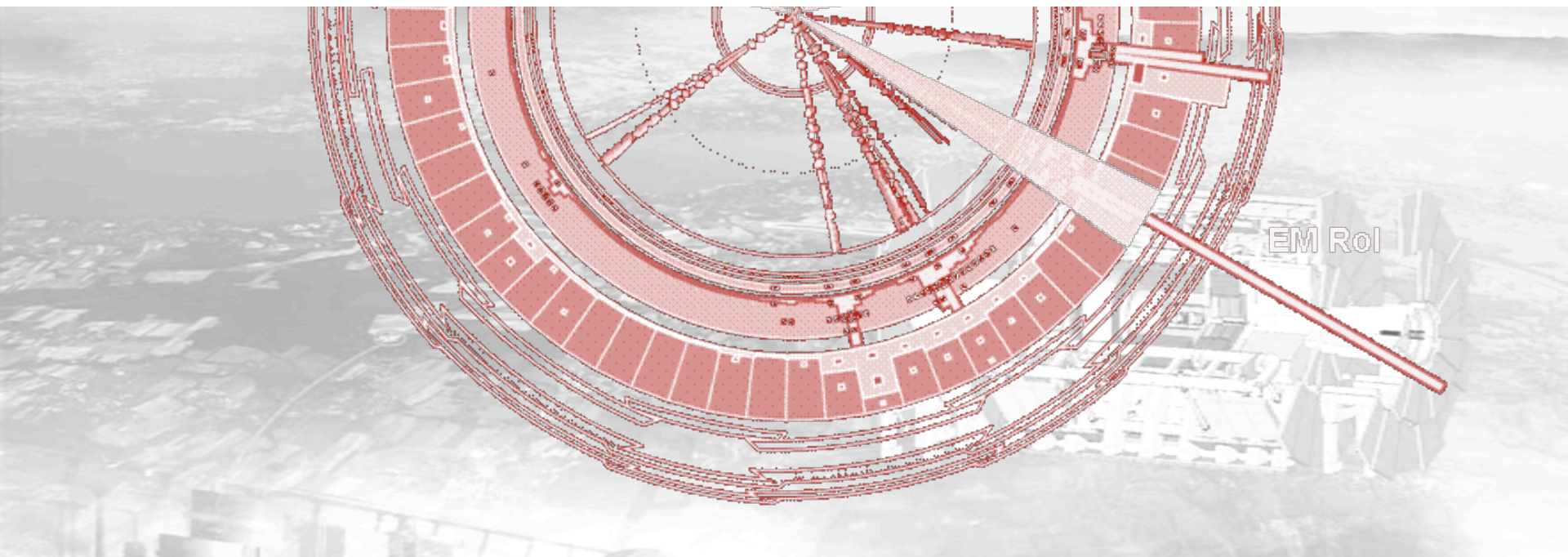
## HLT is implemented in software, running on farms of PCs

- Almost full flexibility within the constraints of the available computing resources
- Available time per event is from tens of ms to a few seconds (second and third trigger levels)



Photon “turn-on” curve for for “ $\gamma 20$ ” trigger

# Triggering on Jets



# Jet Trigger – Principle (ATLAS)

L1 trigger forms “jet elements” made of the sum of  $2 \times 2$  EM and hadronic trigger towers

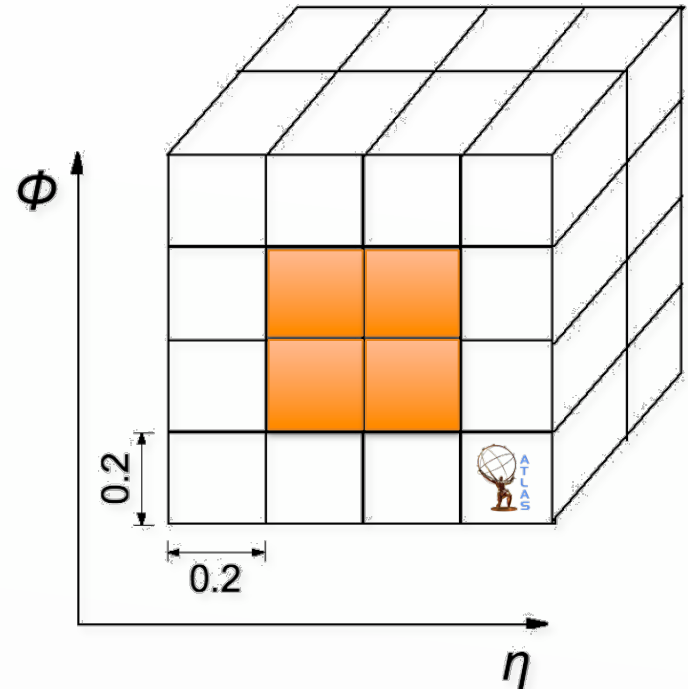
Jet object finding with  $0.8 \times 0.8$  sliding window in  $\eta$ ,  $\phi$  [rad] with 0.2 step size

Jet object is required to have

- Transverse (EM+hadronic) energy within sliding window above given threshold
- Transverse energy in a  $0.4 \times 0.4$  cluster is a local maximum

ATLAS calorimeter is non-compensating: response to EM showers  $\neq$  hadronic showers ( $\rightarrow$  calibration)

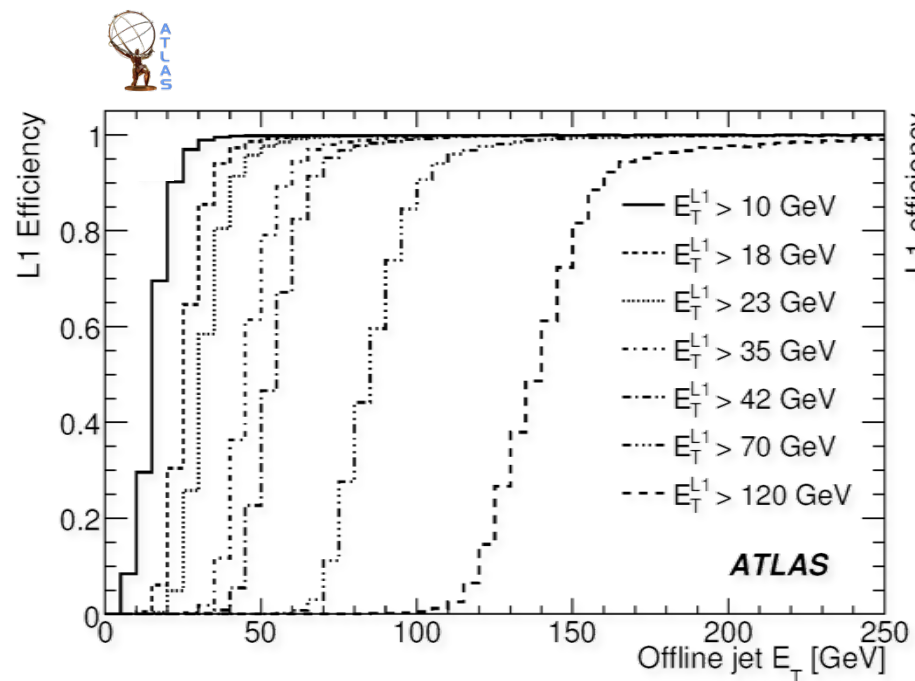
- At L2, clusters in jet at EM energy scale
- Recalibrate to hadronic scale at L2



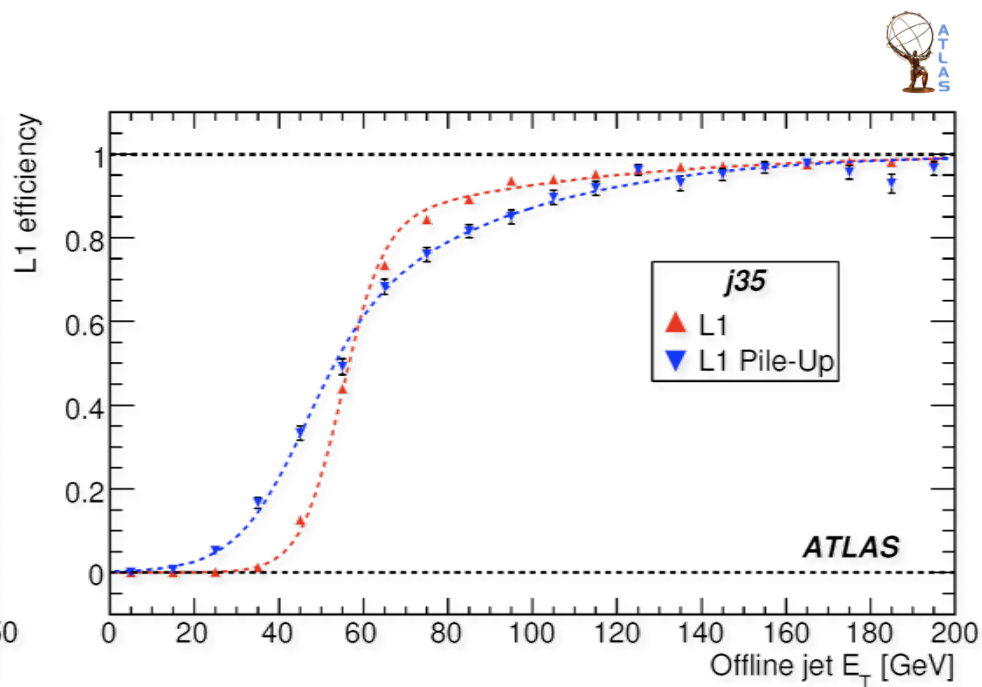
Window of  $4 \times 4$  jet EM+Had elements, and local maximum  $E_T$  cluster of  $2 \times 2$  jet elements.

# L1 jet trigger efficiency curves (ATLAS)

[ CERN-OPEN-2008-020 ]



L1 jet turn-on curves for different  $E_T$  thresholds

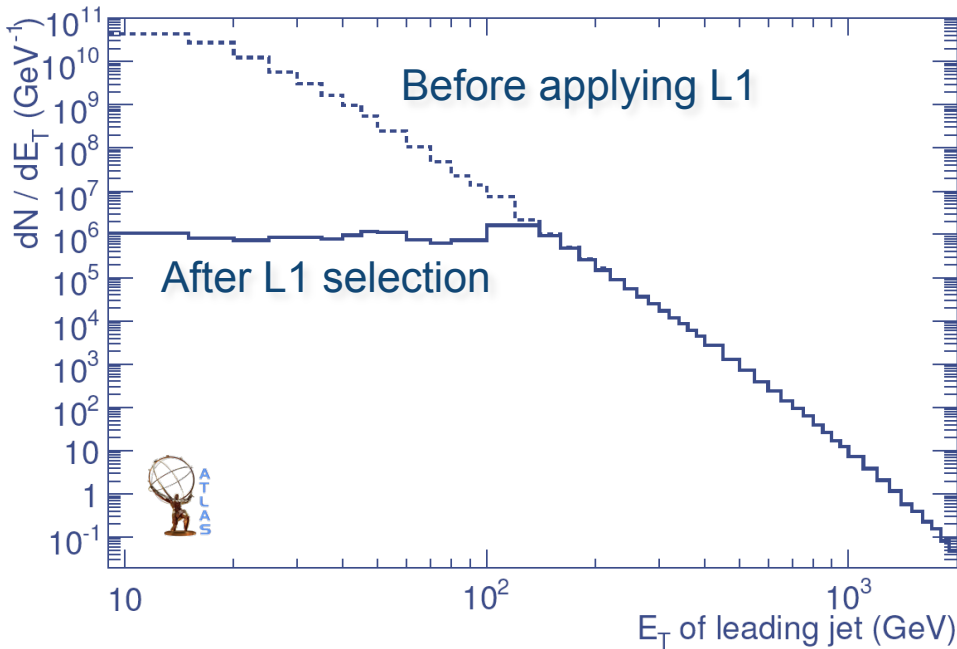


Effect of pile-up (average of 2 interactions per BC)



# Estimated jet trigger rates in ATLAS at $10^{31} \text{ cm}^{-2}\text{s}^{-1}$ peak luminosity

[ CERN-OPEN-2008-020 ]



Differential number of events selected versus the reconstructed transverse energy of the leading jet in the event for  $1 \text{ fb}^{-1}$ .

“**Bootstrapping method**”: use, e.g., j35 trigger to measure j70 efficiency

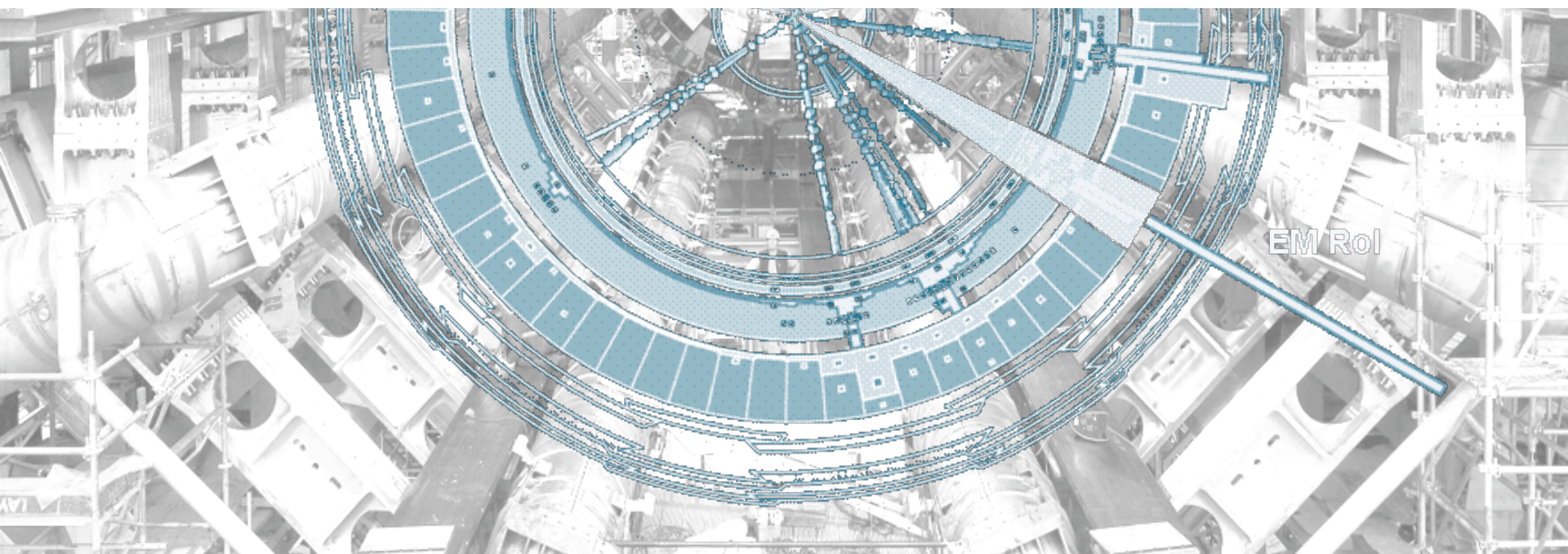
| Trigger           | Overall Prescale | Rate (Hz) |                  |
|-------------------|------------------|-----------|------------------|
| 4j23              | 1                | 6.9       | ( $\pm 0.8$ )    |
| 4j18              | 100              | 0.14      | ( $\pm 0.01$ )   |
| 4j10              | 300              | 0.045     | ( $\pm 0.004$ )  |
| 3j18              | 100              | 0.92      | ( $\pm 0.03$ )   |
| 3j10              | 1500             | 0.061     | ( $\pm 0.002$ )  |
| Total Multi-Jets  |                  | 7.9       | ( $\pm 0.2$ )    |
| j120              | 1                | 8.7       | ( $\pm 0.9$ )    |
| j70               | 15               | 4.2       | ( $\pm 0.2$ )    |
| j42               | 100              | 3.73      | ( $\pm 0.06$ )   |
| j35               | 500              | 1.37      | ( $\pm 0.02$ )   |
| j23               | 2000             | 1.37      | ( $\pm 0.008$ )  |
| j18               | 6000             | 1.02      | ( $\pm 0.004$ )  |
| j10               | 42000            | 3.9       | ( $\pm 0.003$ )  |
| j5                | 300000           | 0.9470    | ( $\pm 0.0004$ ) |
| Total Single-Jets |                  | 24.40     | ( $\pm 0.01$ )   |

Expected rates after HLT at  $10^{31} \text{ cm}^{-2} \text{ s}^{-1}$  peak luminosity

# Triggering on Muons

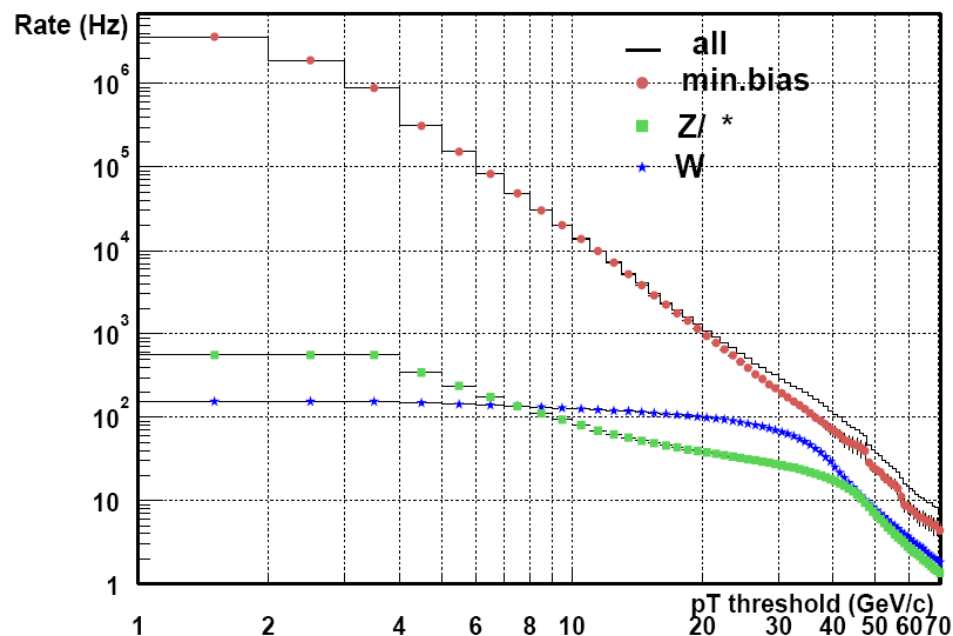
## Requirements (CMS numbers)

- Geometrical coverage for  $|\eta| \leq 2.4$
- Output rate:  $\sim 30$  kHz  $\rightarrow$  reduction factor  $> 100$
- Ghost rate  $< 0.5$  %
- $p_T$  threshold should be set in the range  $\sim 4 - 50$  GeV



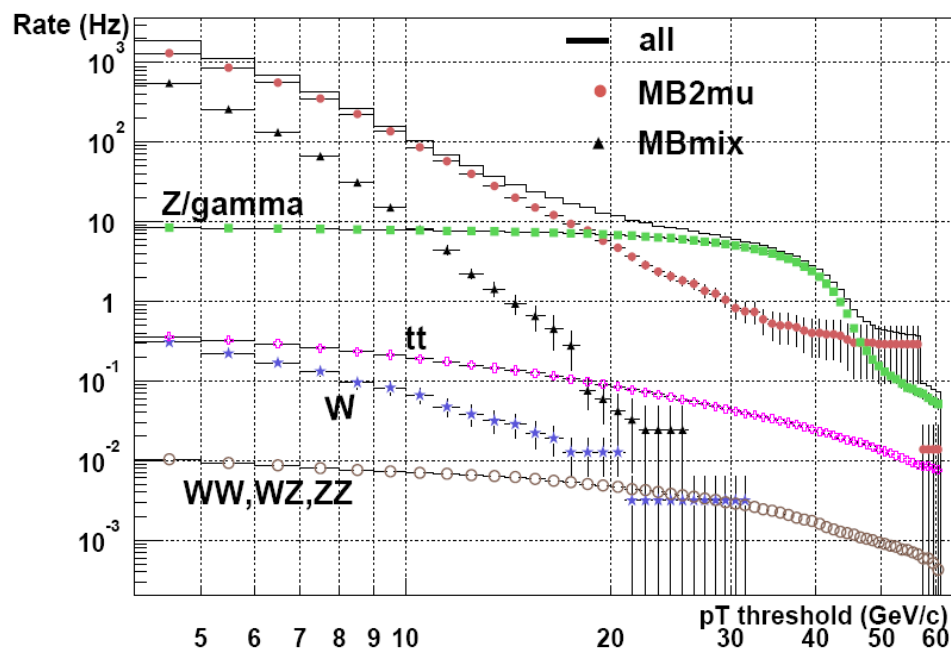
## Single Muon rate at $L = 10^{34} \text{ cm}^{-2}\text{s}^{-1}$ vs. $p_T$ threshold

Good  $p_T$  resolution already  
at trigger level to avoid large  
feed-through from low  $p_T$  muons



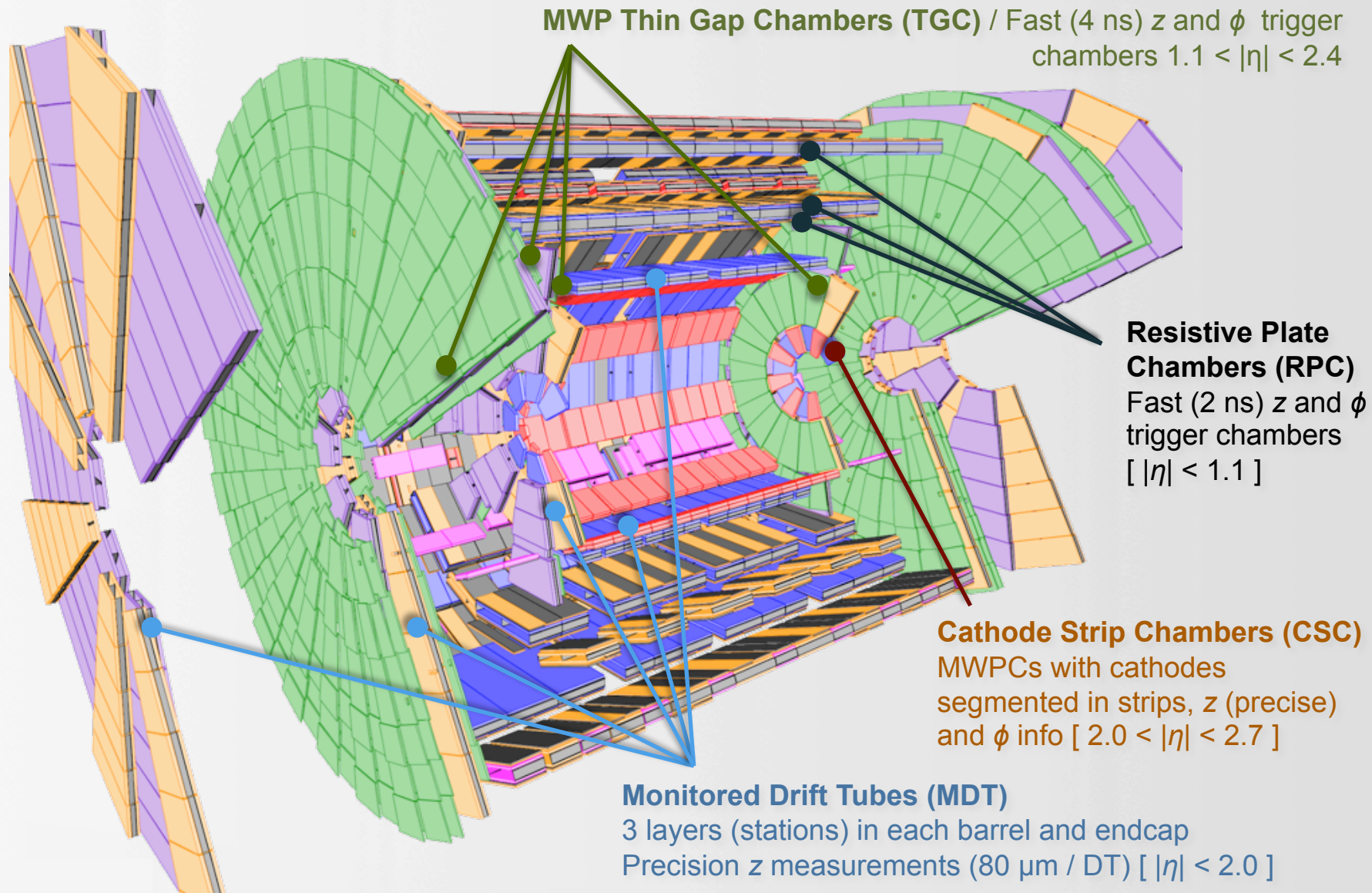
## Di-Muon rate at $L = 10^{34} \text{ cm}^{-2}\text{s}^{-1}$ vs. $p_T$ threshold ( $\sim 1\%$ or less than single muon rate)

Single muon ghost rate below  
0.5 % not to overcome real  
di-muon rate



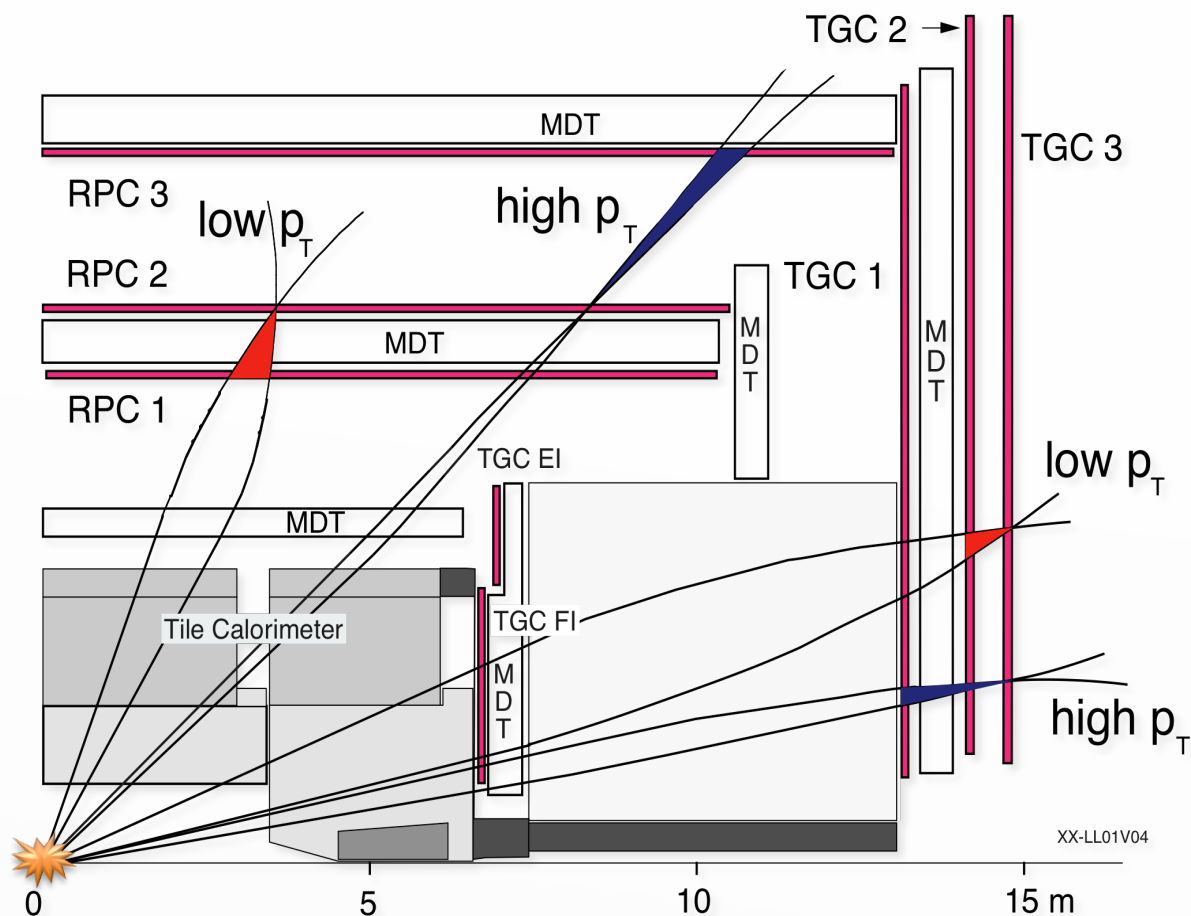


# ATLAS Muon Spectrometer Systems



# Level-1 Muon Trigger (here ATLAS)

Ultra-fast Level-1 trigger requires coincident hits in RPC (barrel) or TGC (endcaps) layers within “roads” corresponding to predefined momenta (thresholds)



Momentum ranges:

“low- $p_T$ ”: 4 – 10 GeV

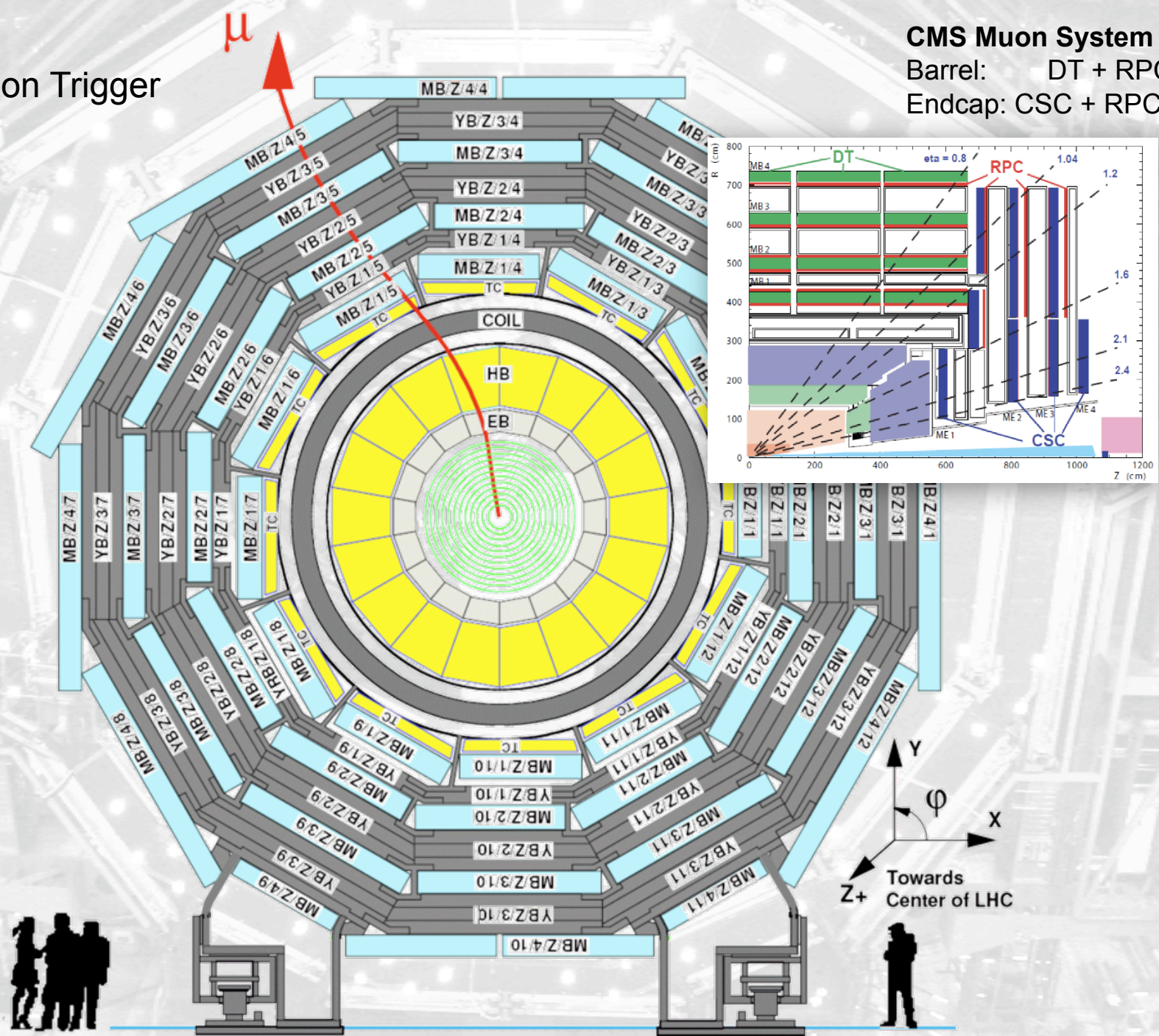
“high- $p_T$ ”: 10 – 40 GeV

Measure muon momentum with very simple tracking in a few planes of trigger chambers



## Level-1 Muon Trigger

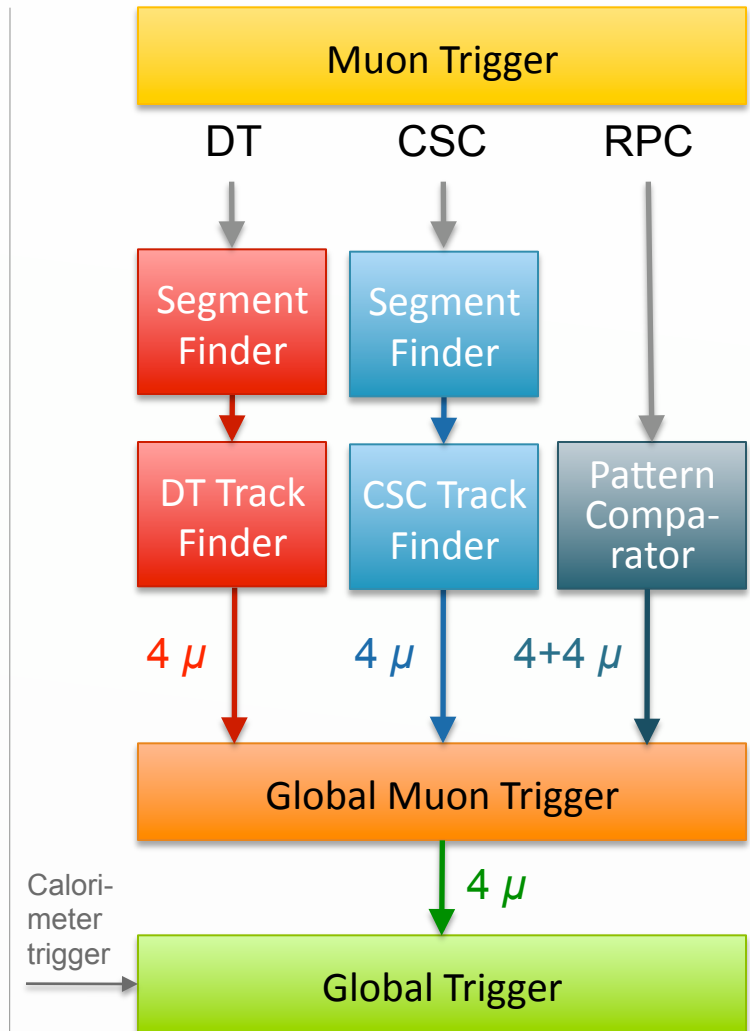
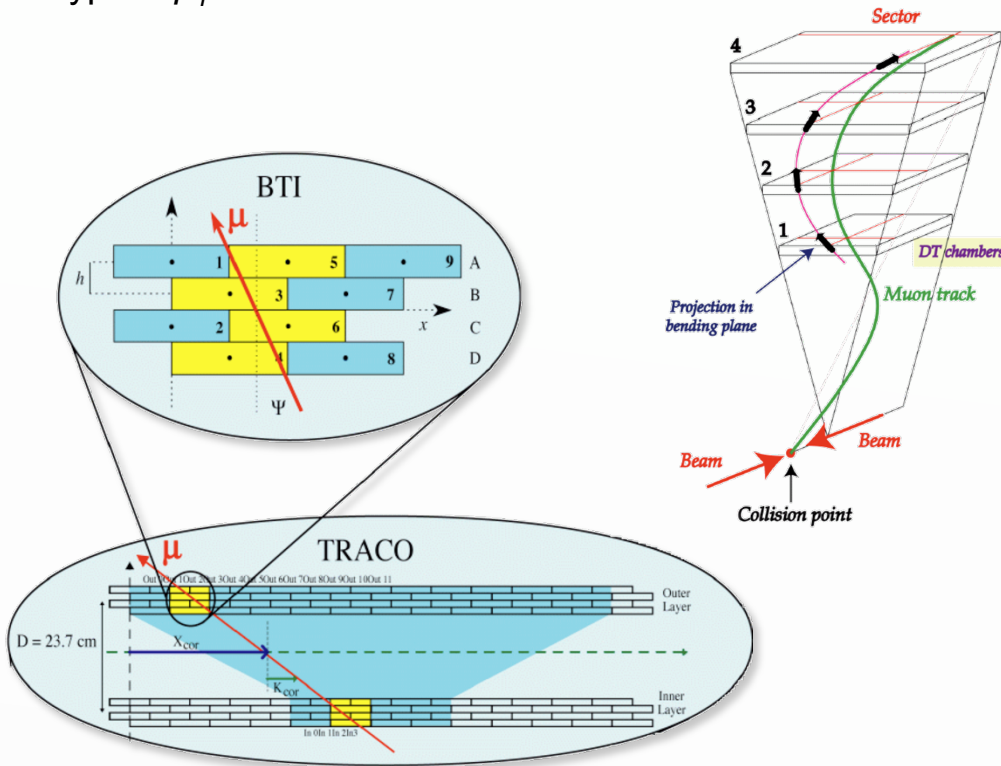
**CMS Muon System**  
Barrel: DT + RPC  
Endcap: CSC + RPC



# Level-1 Muon Trigger (CMS)

Example: trigger with drift tubes in barrel:

- Reconstruct local segments on chambers using ASICs
- Segment position,  $p_T$  and quality sent to Track Finder
- TF combines segments to form  $\mu$  track using FPGAs (LUT)
- Typical  $p_T$  resolution 20%



# Level-1 Muon Trigger (CMS)

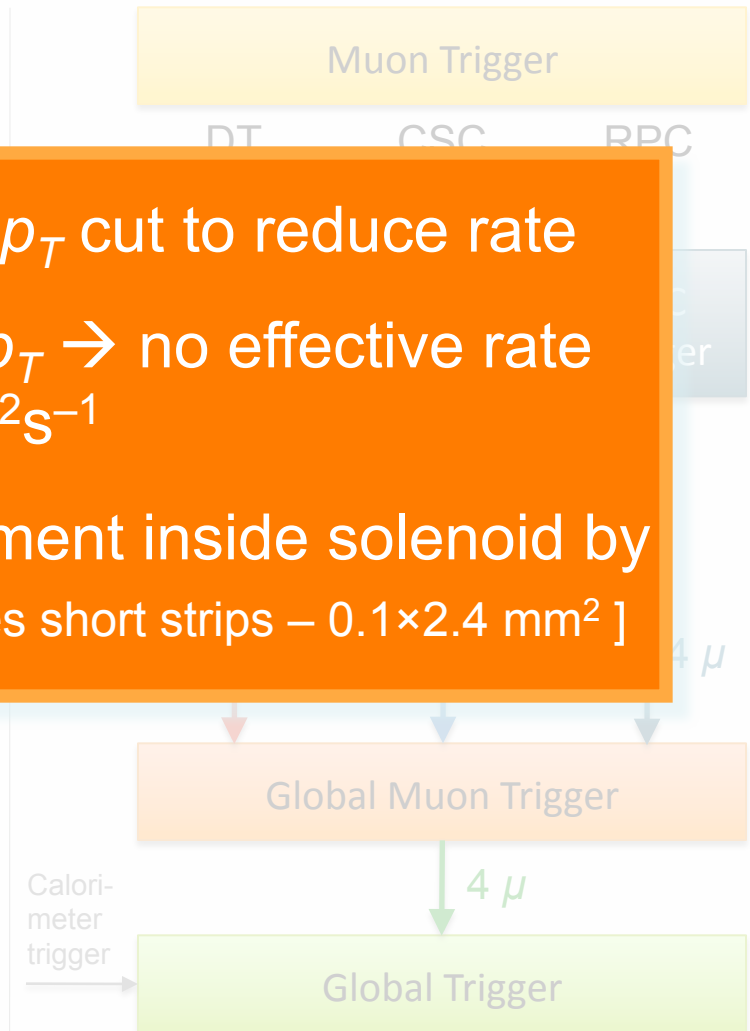
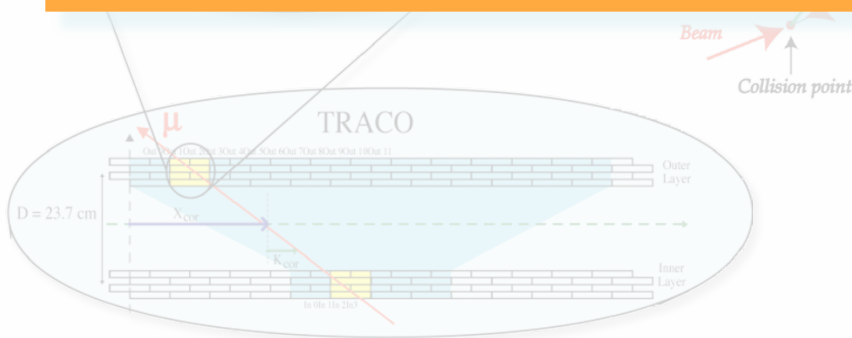
Example: trigger with drift tubes in barrel:

- Reconstruct local segments on chambers using ASICs
- Segment position,  $p_T$  and quality sent to Track Finder
- 
- 

Larger luminosity requires larger  $p_T$  cut to reduce rate

But: resolution deteriorates with  $p_T \rightarrow$  no effective rate reduction already at  $L = 10^{34} \text{ cm}^{-2}\text{s}^{-1}$

A solution: measure another segment inside solenoid by adding CSC layer [ occupancy requires short strips –  $0.1 \times 2.4 \text{ mm}^2$  ]





# LHCb Trigger

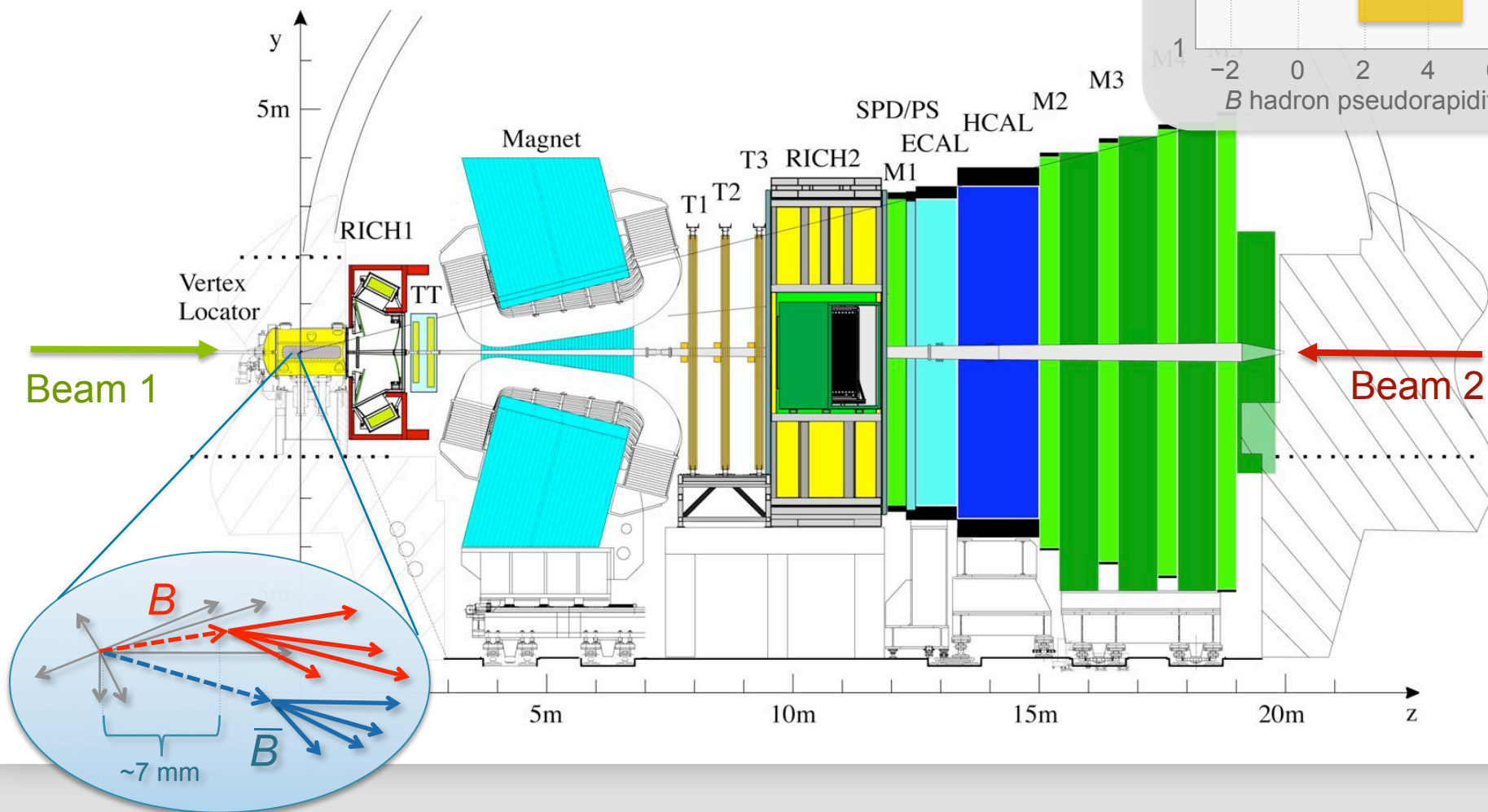
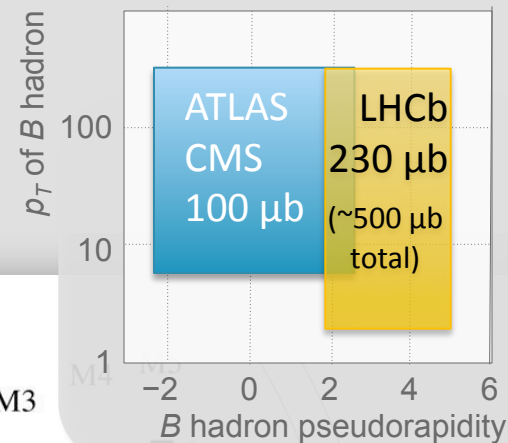


# Triggering at LHCb

Luminosity:  $2 \cdot 10^{32} \text{ cm}^{-2} \text{ s}^{-1}$ , 10 to 50 times lower than ATLAS/CMS, because prefer single  $pp$  collisions to identify  $B$  vertices

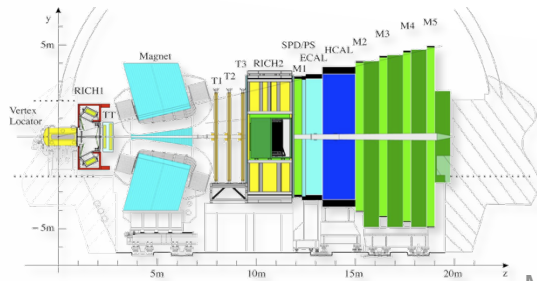
$B\bar{B}$  rate 100 kHz, one  $B$  decay fully in acceptance: 15 kHz

$B$  hadron cross section





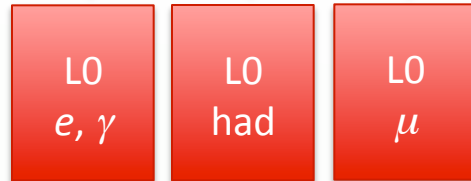
# LHCb Trigger



Minimum  
bias rate:  
10 MHz

40 MHz

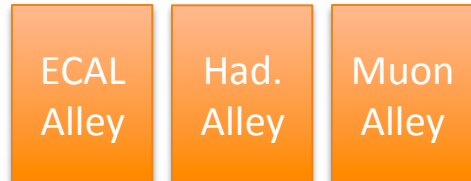
Firmware  
Level-0  
4  $\mu$ s latency)



1 MHz

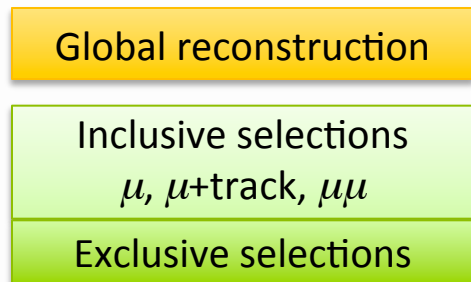
Full  
detector  
readout

HLT-1



30 kHz

HLT-2



2 kHz



Storage: Event size ~35kB

## Level-0 Firmware Trigger

Search for high- $p_T$   $\mu$ ,  $e$ ,  $\gamma$ ,  $h$  candidates, veto pile-up

### Calorimeter Trigger:

- Energy in 2x2 cell clusters
- PID from ECAL / HCAL energy / PS and SPD information

### Muon Trigger:

- Straight line search in M2-M5
- Look for compatible hits in M1 (before calorimeters)
- $p_T$  from a look-up table

## High-Level Trigger

### HLT-1:

- Rols around L0 candidate (*alleys*)
- Confirm L0 candidate on tracker, VELO

### HLT-2:

- Search for all tracks using VELO segments as seeds
- Inclusive selection based on few tracks
- Exclusive selection of ~100 final states

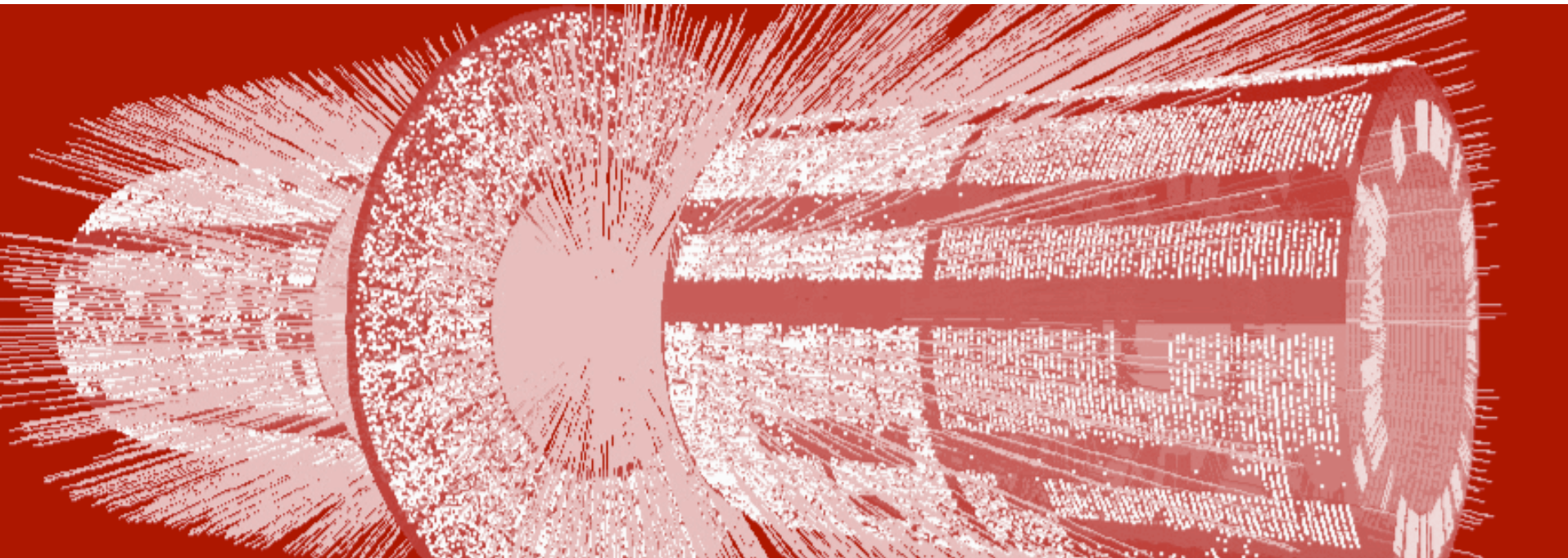
# Trigger Commissioning with Beam

## 10 September 2008, first beam in the LHC

- Both beam directions, 1 bunch at a time, 450 GeV
- Beam on collimators – “beam splash” events
- Beam circulating for a few turns up to tens of minutes
- No collisions (just single beam), no acceleration (injection energy)
- Radio-frequency (RF) capture of bunch

## 19 September 2008, serious incident required shut-down of LHC

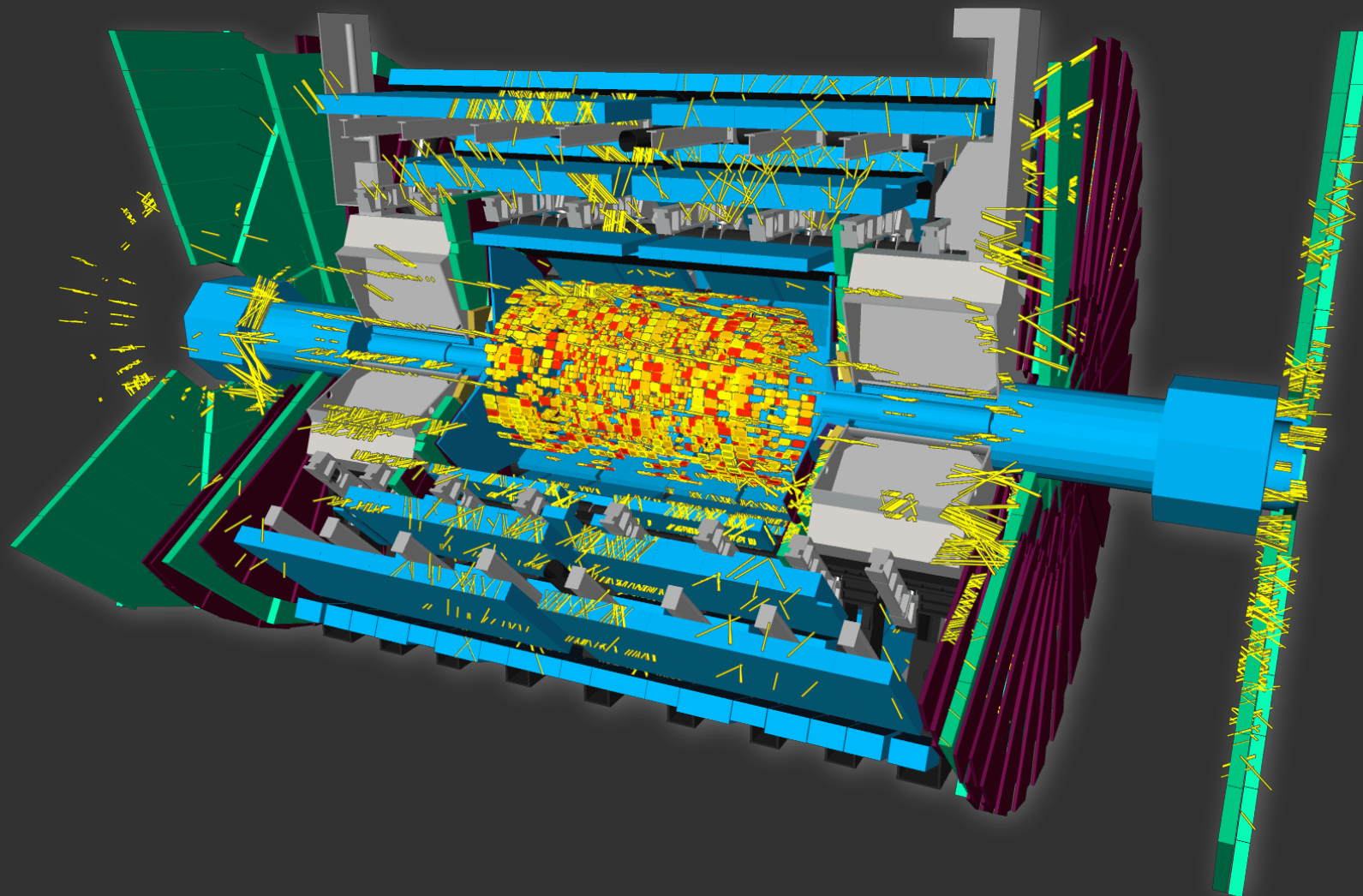
Trigger commissioning restarts with beam this autumn after repairs of the LHC machine



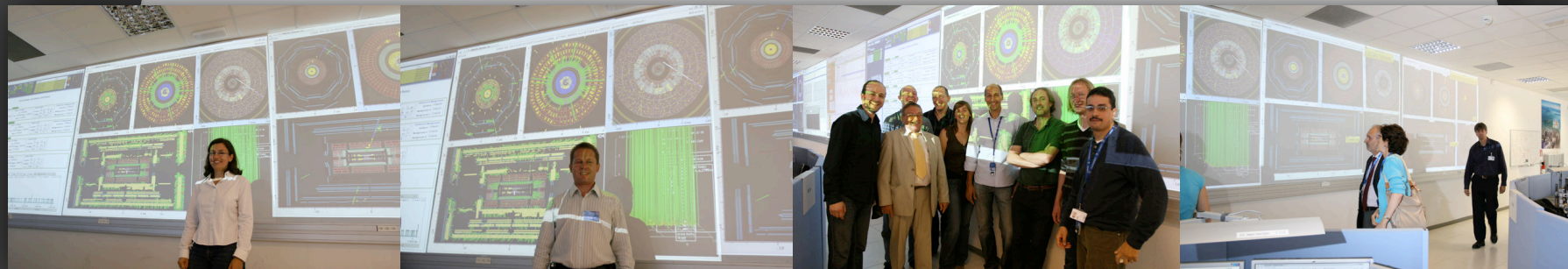
# Most spectacular: collimator “splash” event in **ATLAS**

“Splash” event in ATLAS 3D display

Runs 87764, Event 40050, Sep 10, 2008

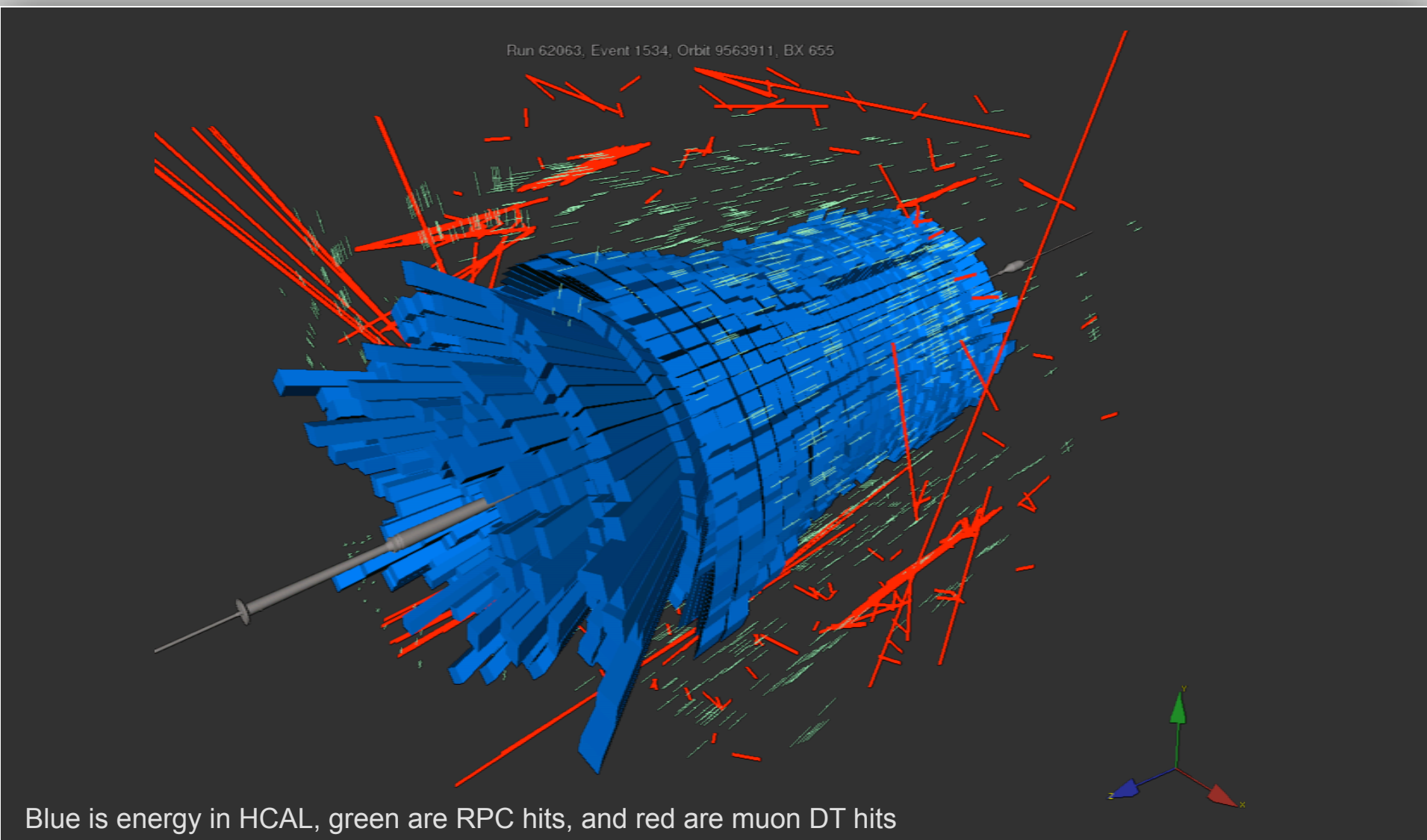






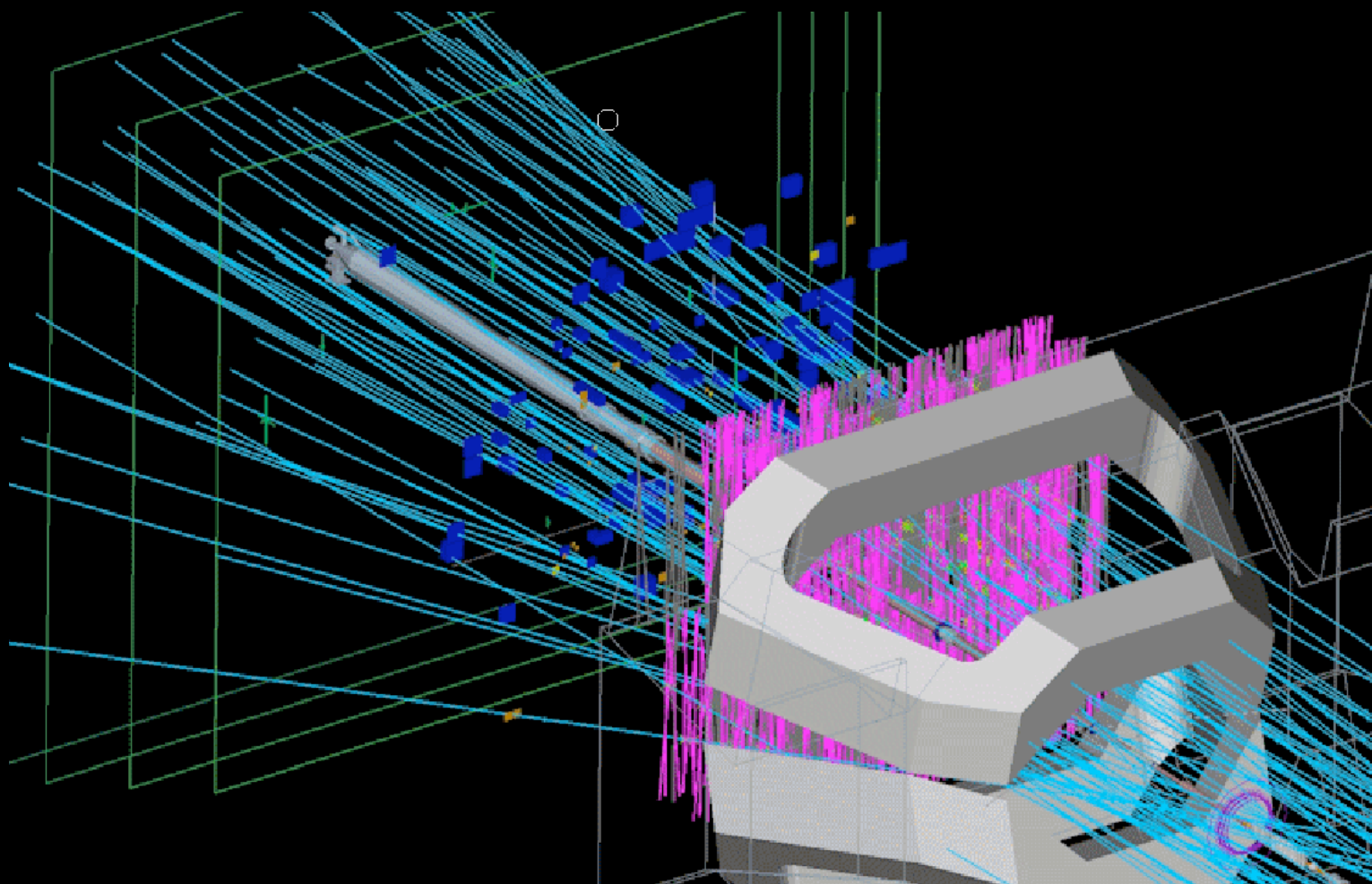
# Beam also stopped in front of, and passed by **CMS** !

“Splash” event taken from: <http://cmsdoc.cern.ch/cms/performance/FirstBeam/cms-e-commentary.htm>

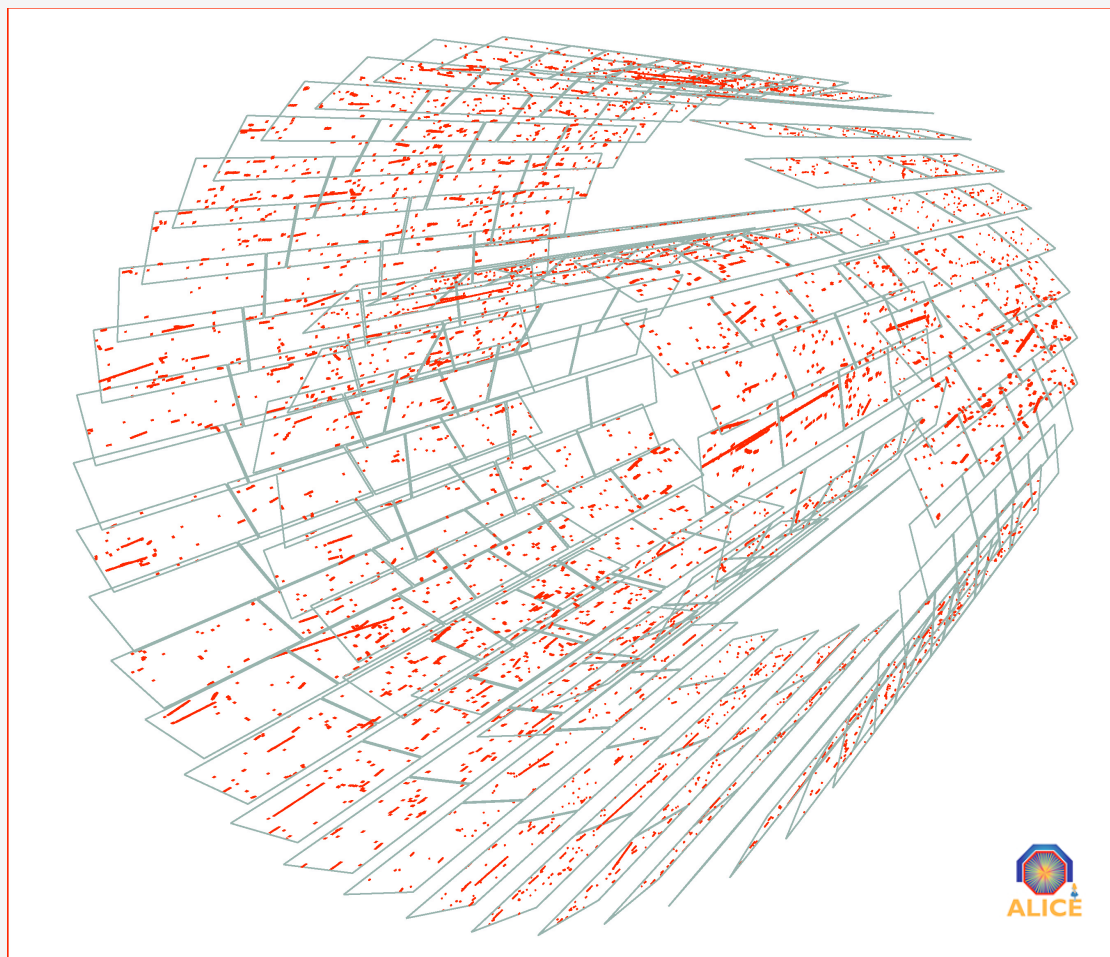




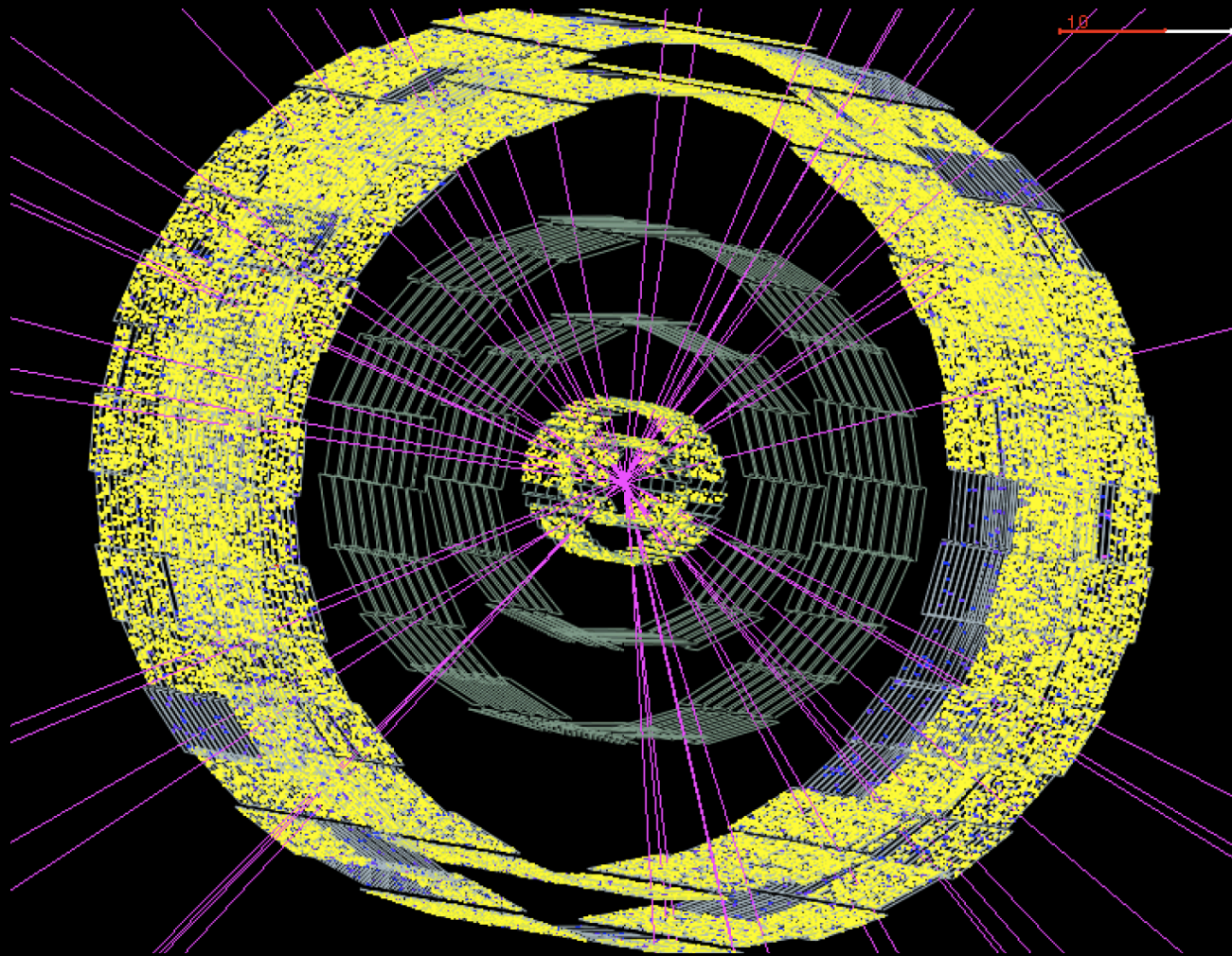
Beam also stopped in front of, and passed by **LHCb** – here, only beam-1 is useful !



Inner tracking devices off, but outer tracker, calorimeters, RICH detectors and muon chambers recording

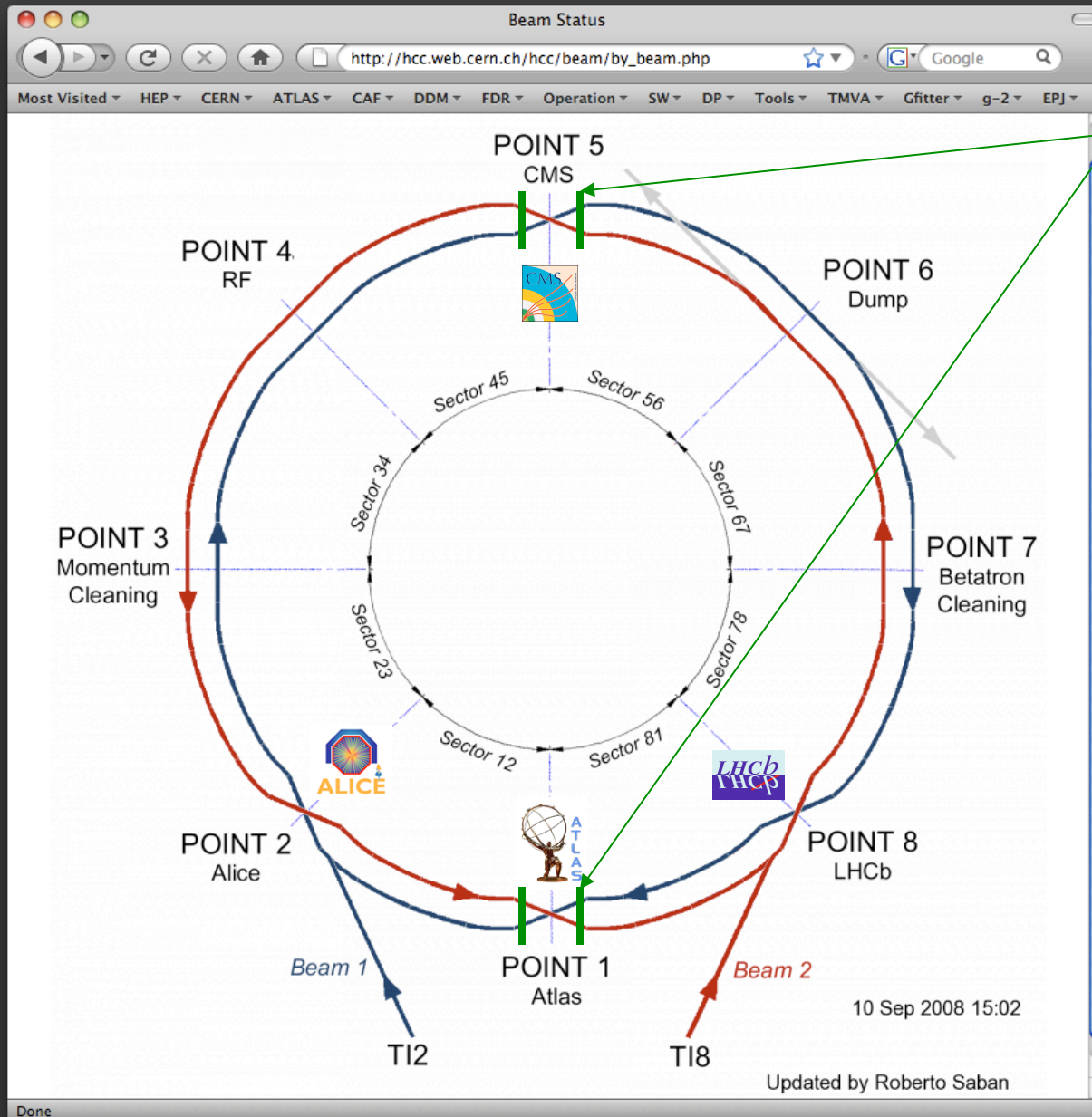


ALICE saw the first tracks at LHC during the first injection test in transfer line TI2.  
The Silicon Pixel detector recorded muon tracks produced in the beam dump near Point 2 of the LHC



Beam dump debris seen in ALICE Inner Tracking System



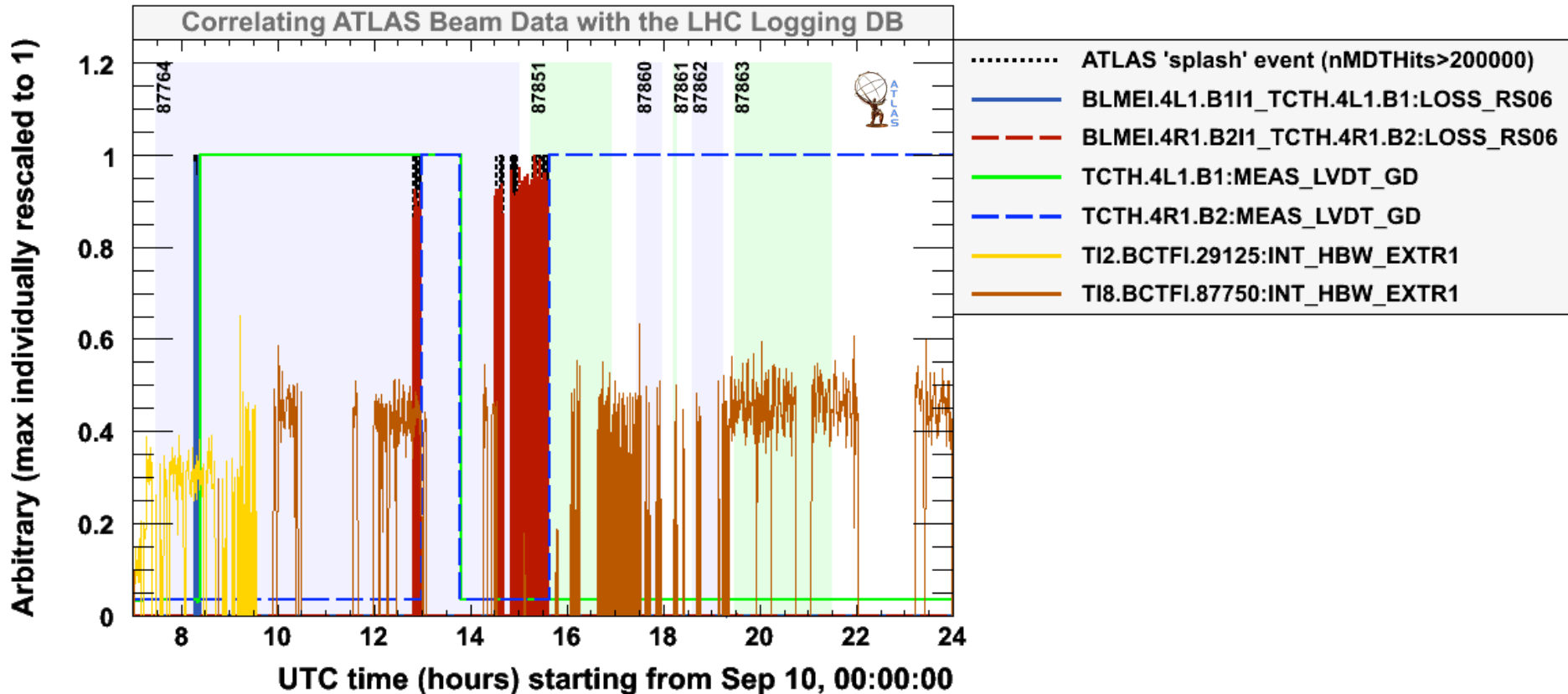


$\pm 140\text{m}$  before  
ATLAS and  
CMS are  
collimators in  
both LHC  
beam lines,  
which – when  
closed – stop  
the beam



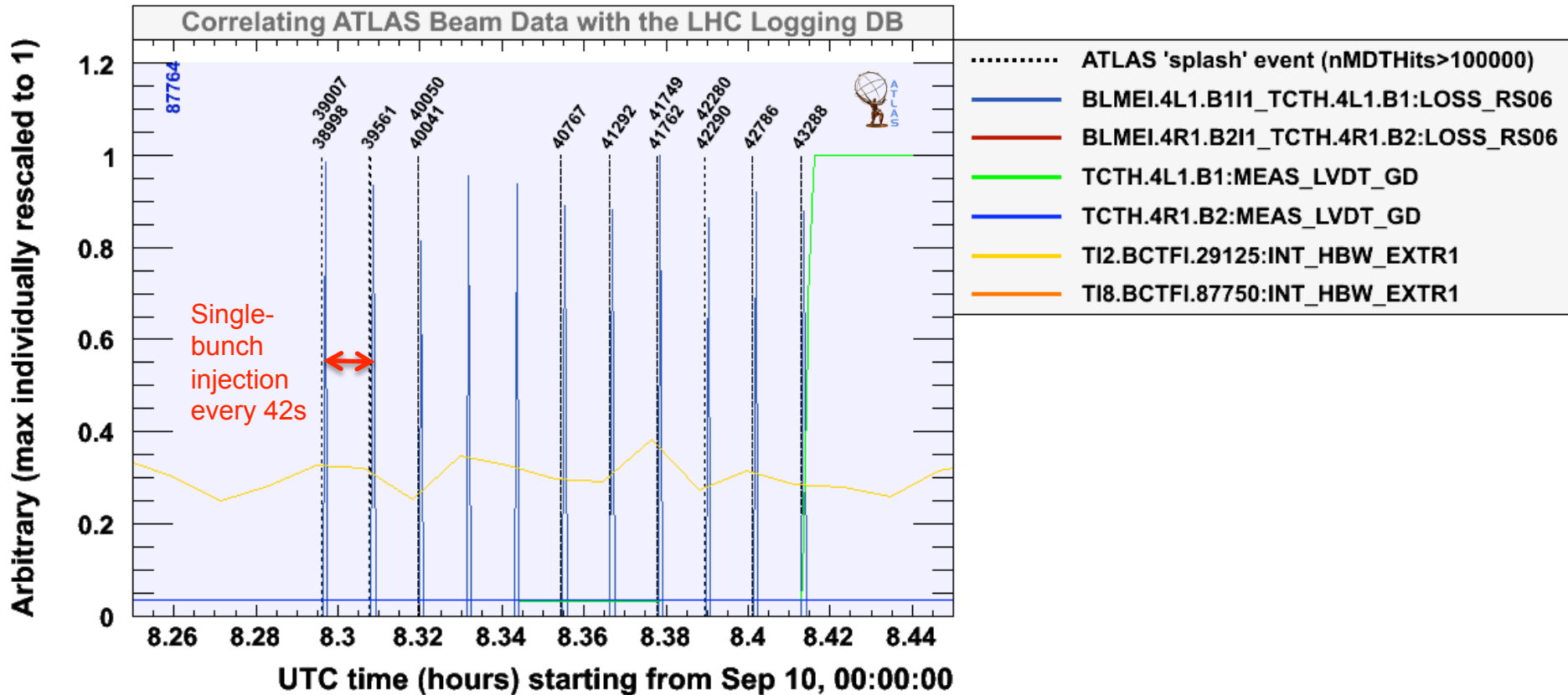
# Sep 10 – 13: Beam History

■ Indeed, for ATLAS there were 3 'splash' phases during Sep 10 → let's zoom...



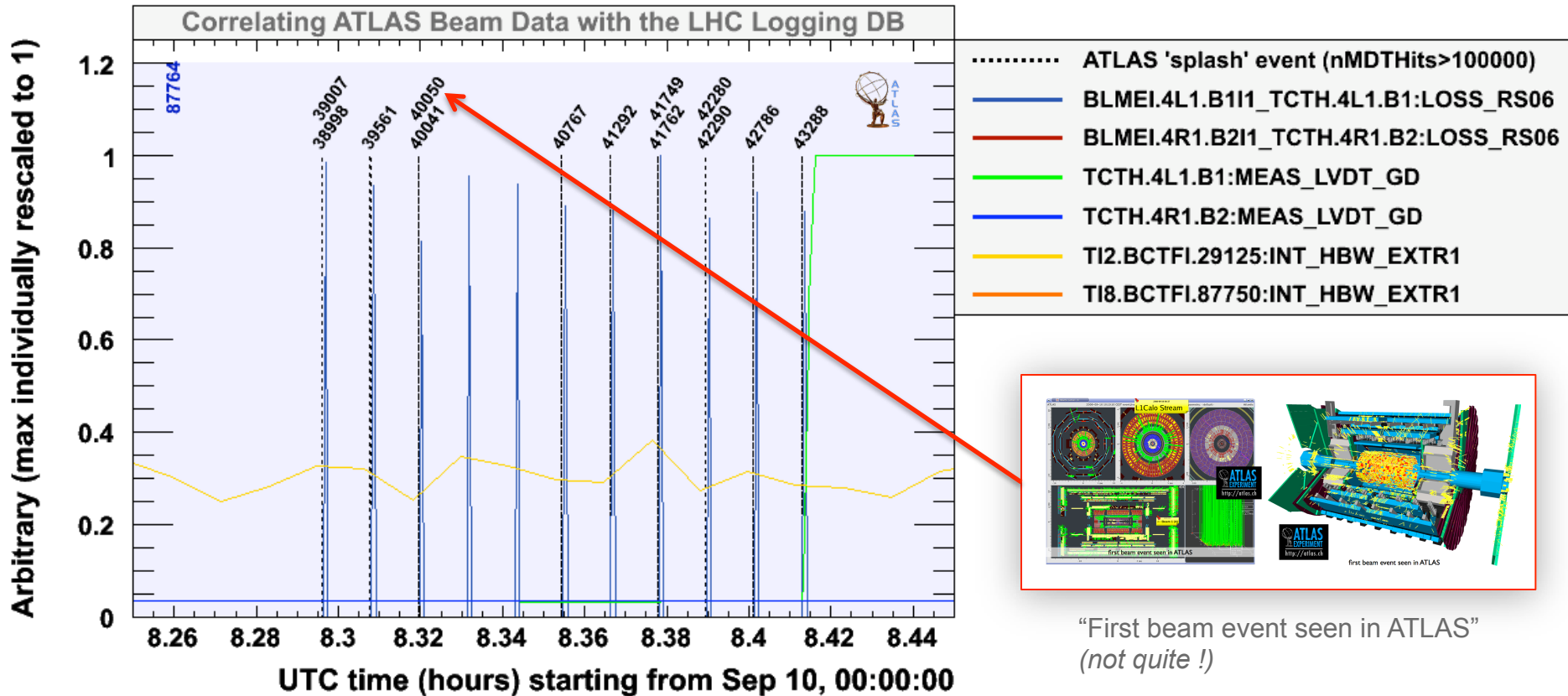
# Sep 10 – 13: Beam History

- And zoom even more, into the 1<sup>st</sup> splash (beam 1) on Sep 10

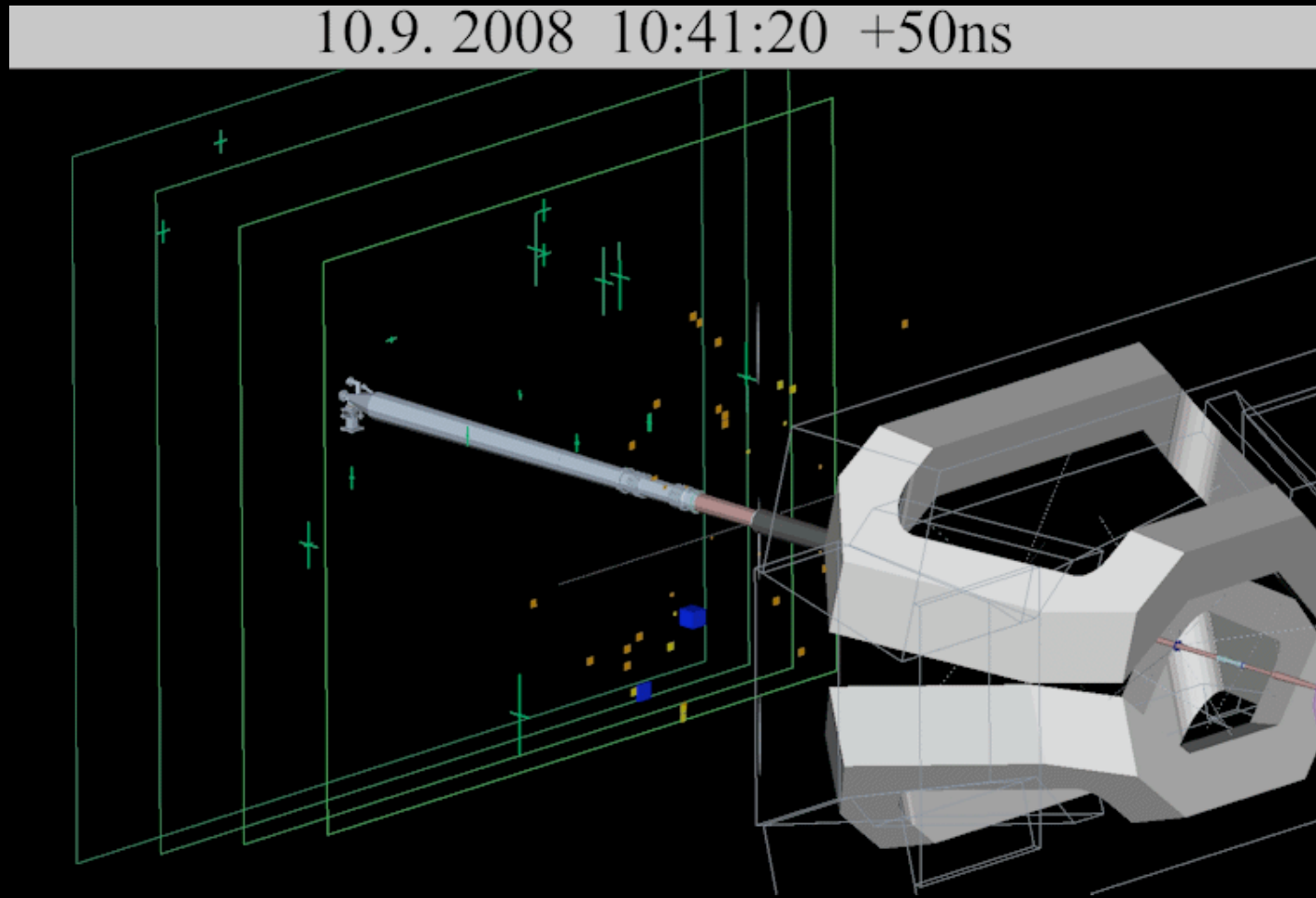


# Sep 10 – 13: Beam History

- We can correlate in time the LHC splashes with ATLAS recorded events !

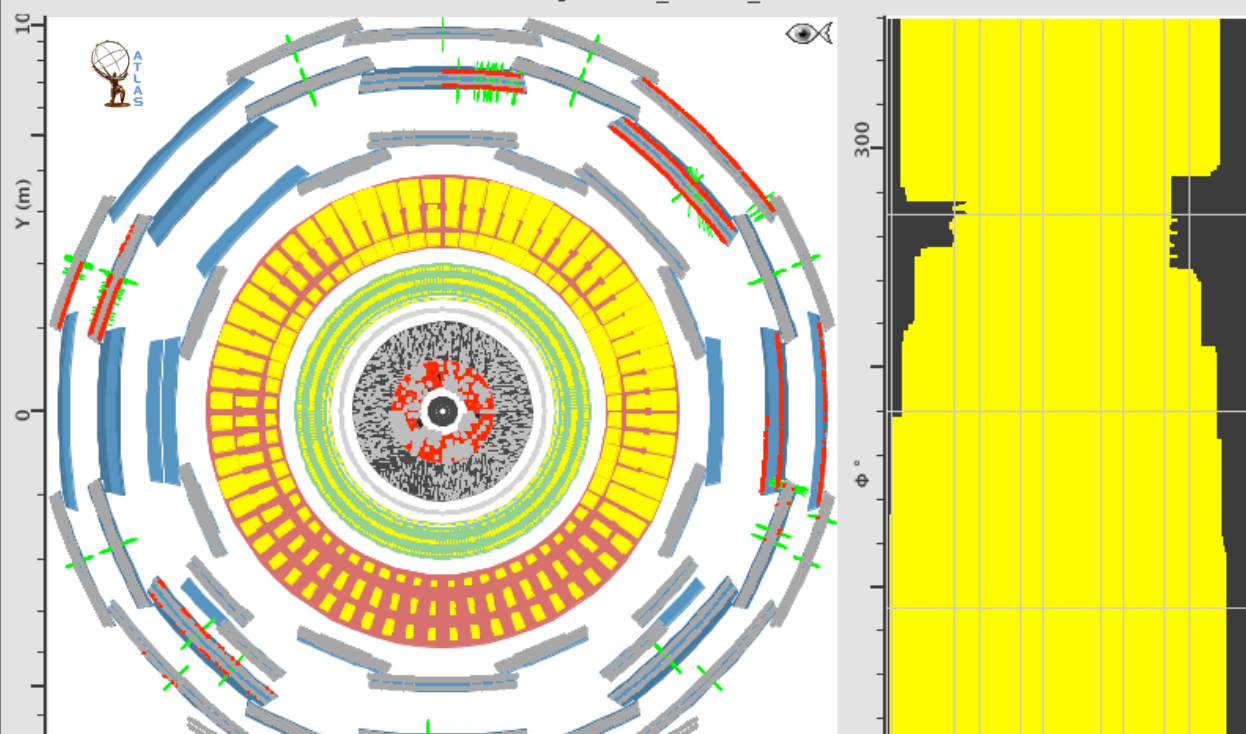


Beam also stopped in front of, and passed by **LHCb** – here, only beam-1 is useful !  
Collimator “splash” event read out with calorimeter and muon chambers



LHCb is capable of triggering and reading out up to 16 consecutive bunch crossings (every 25 ns)



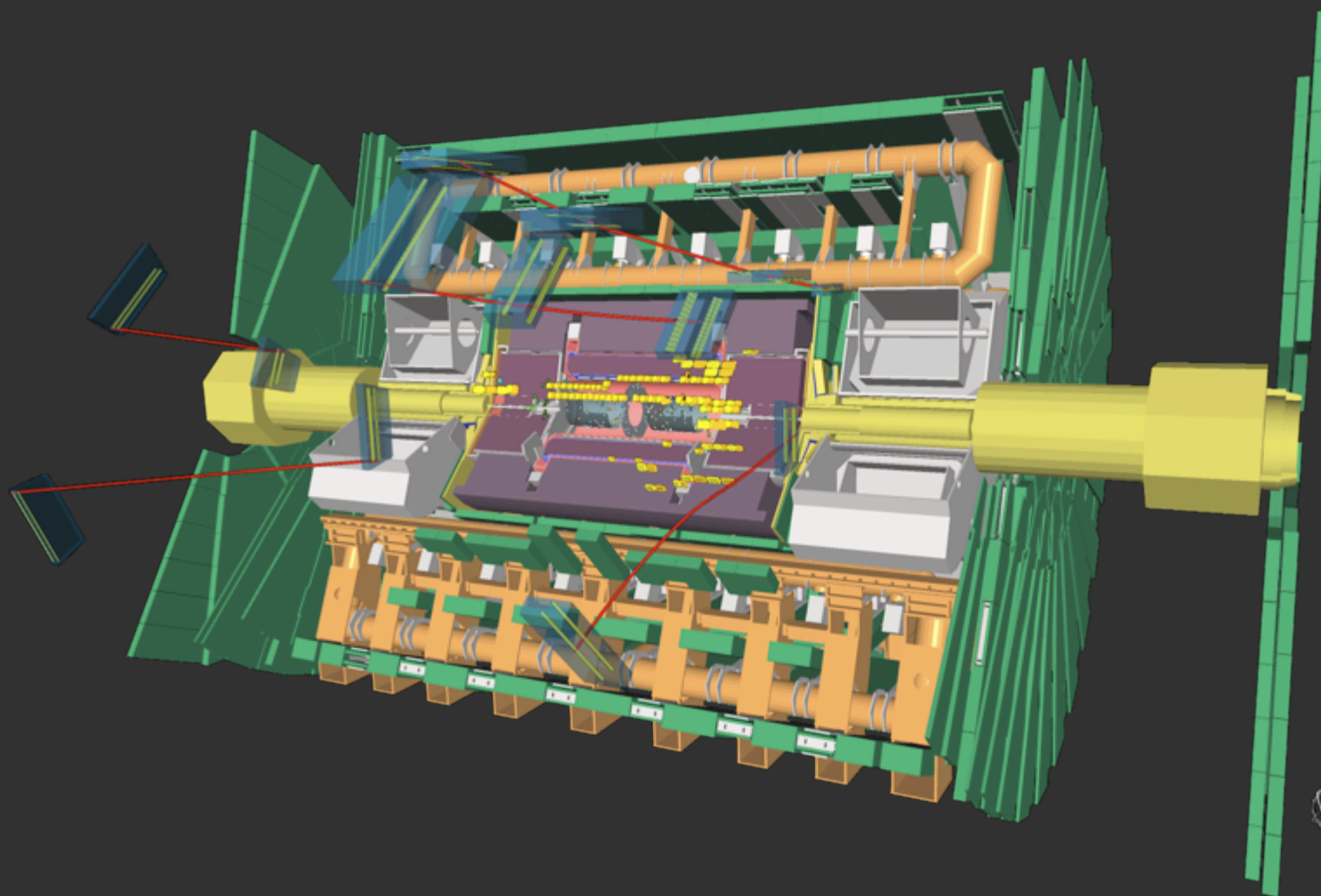


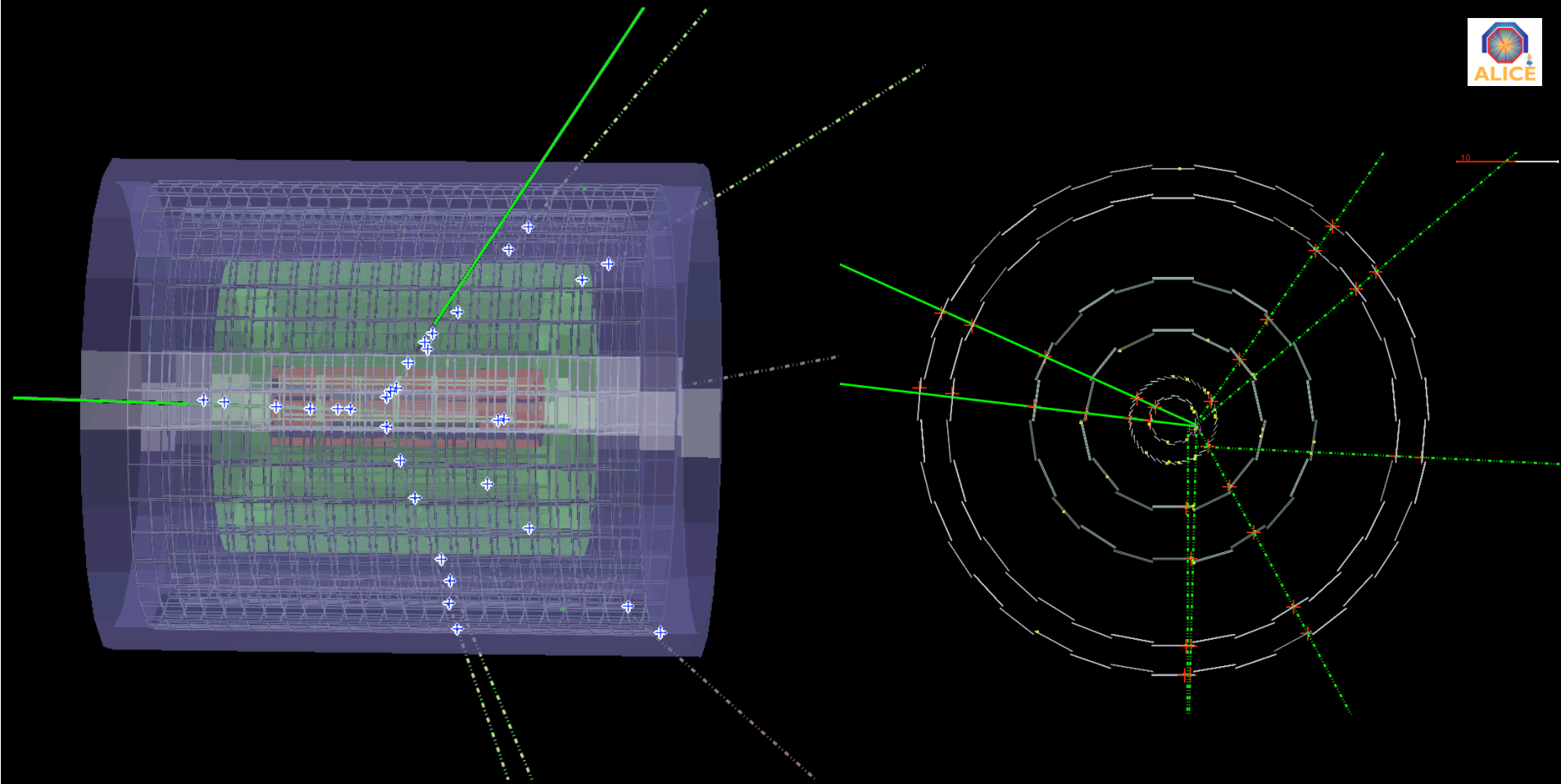
ATLAS has triggered on about 70 splash events from a total of ~100 produced

Apart from being spectacular, they have been used in various ways to:

- Time-in trigger and detector components with the bunch crossing signal
- Correlate position and energy response of various detector systems

The detectors have also recorded “beam-halo” events, originating from single protons leaving the beam pipe and creating secondary muons



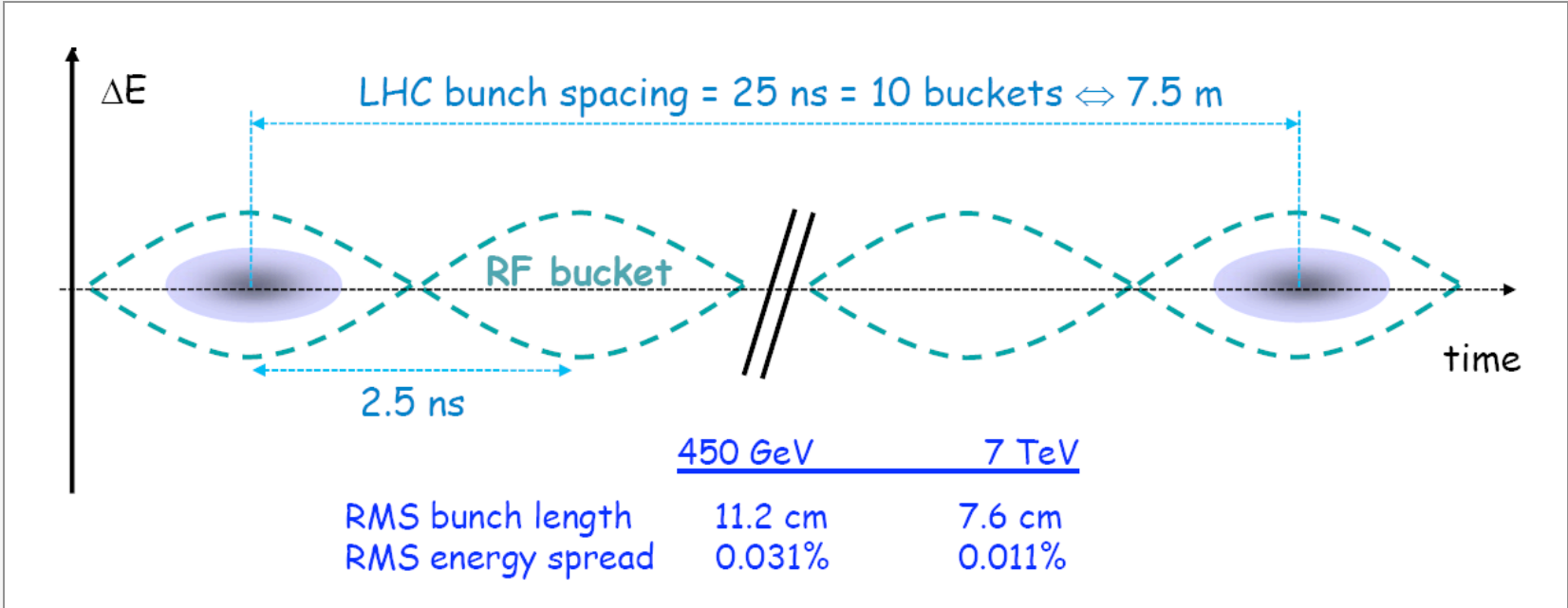


Tracks measured in Inner Tracking System

# Debunching in non-radio-frequency (RF) captured beam in the **LHC**

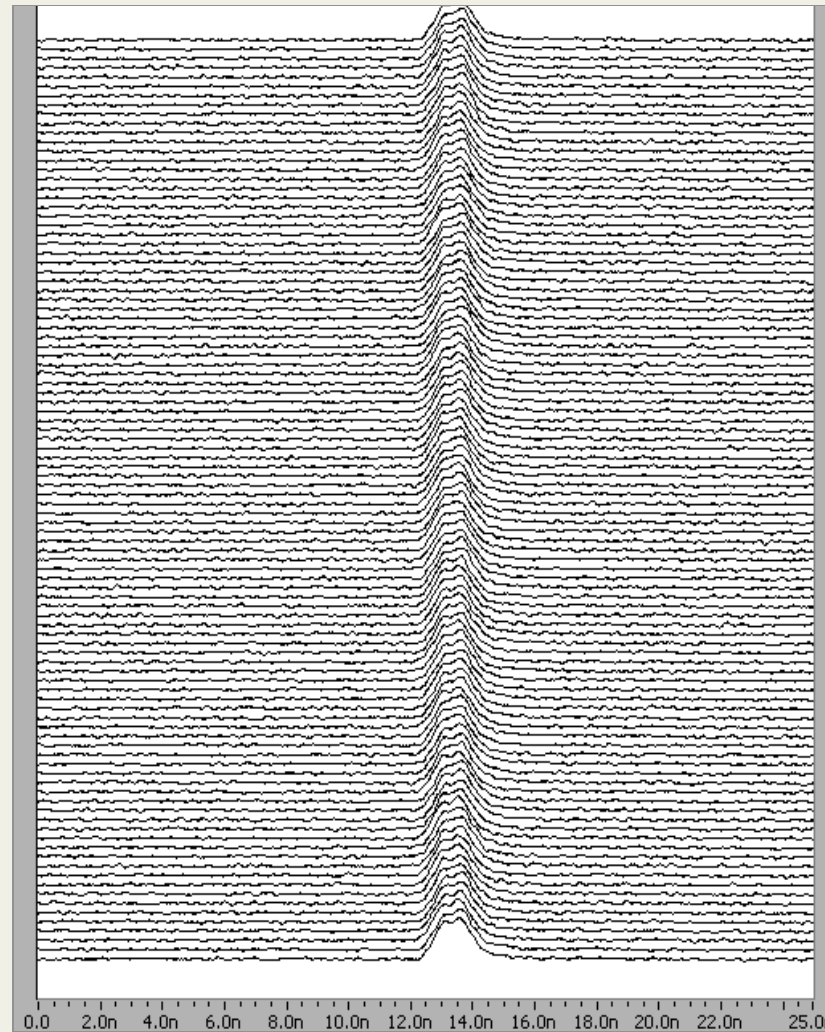
When a bunch (filled proton packet) is injected from the SPS via the transfer lines into the LHC it decays after several turns if it is not trapped inside a radio-frequency voltage defining the bunch structure.

The LHC has a 400 MHz = 2.5 ns bucket structure ...



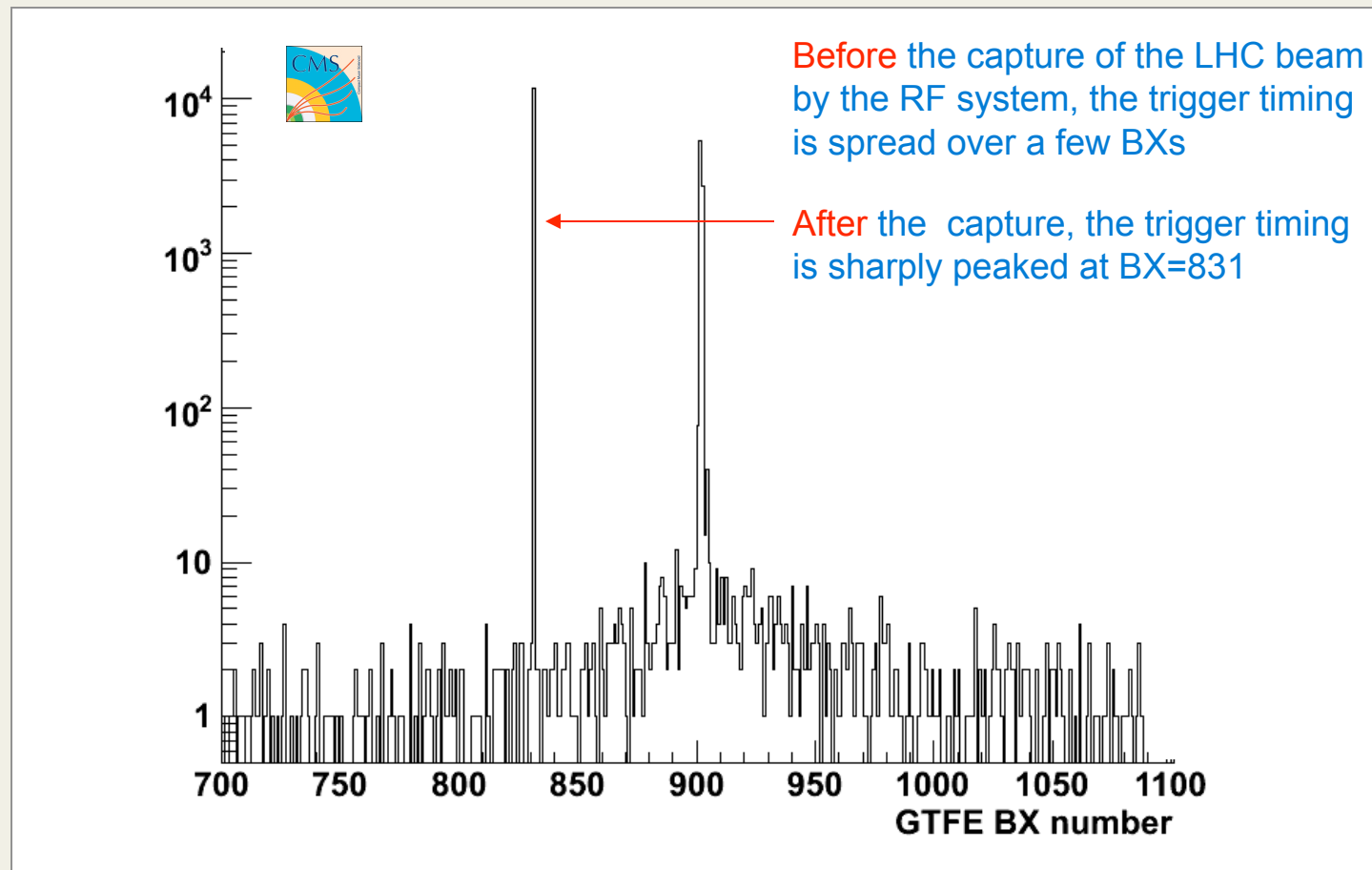


# Radio-frequency capture of bunch in **LHC**

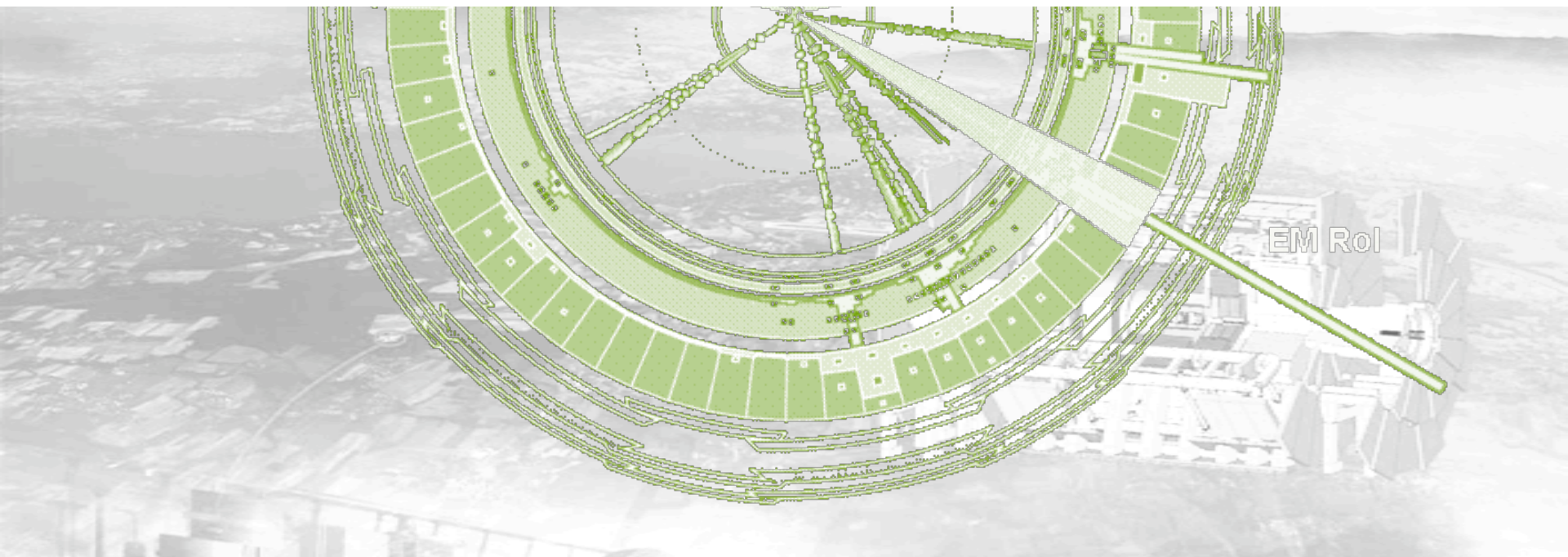


**Capture with optimal  
injection phasing,  
correct reference**

## Triggered events versus bunch crossing (BX) number



# Trigger/DAQ Commissioning



# T/DAQ Commissioning Schedule

---

## Establish a stable time reference

- Trigger on incoming beam (beam pick-ups)

## Time-in the experiment

- Adjust programmable delays to read out the correct BC over the full detector
  - Note that Time-of-Flight corrections are different for outgoing collision products, downward-going cosmic-ray muons, and beam-halo (see later)
- Adjust programmable delays to align all other Level-1 triggers to the reference
  - Minimum-bias trigger
  - Calorimeter triggers
  - Muon triggers

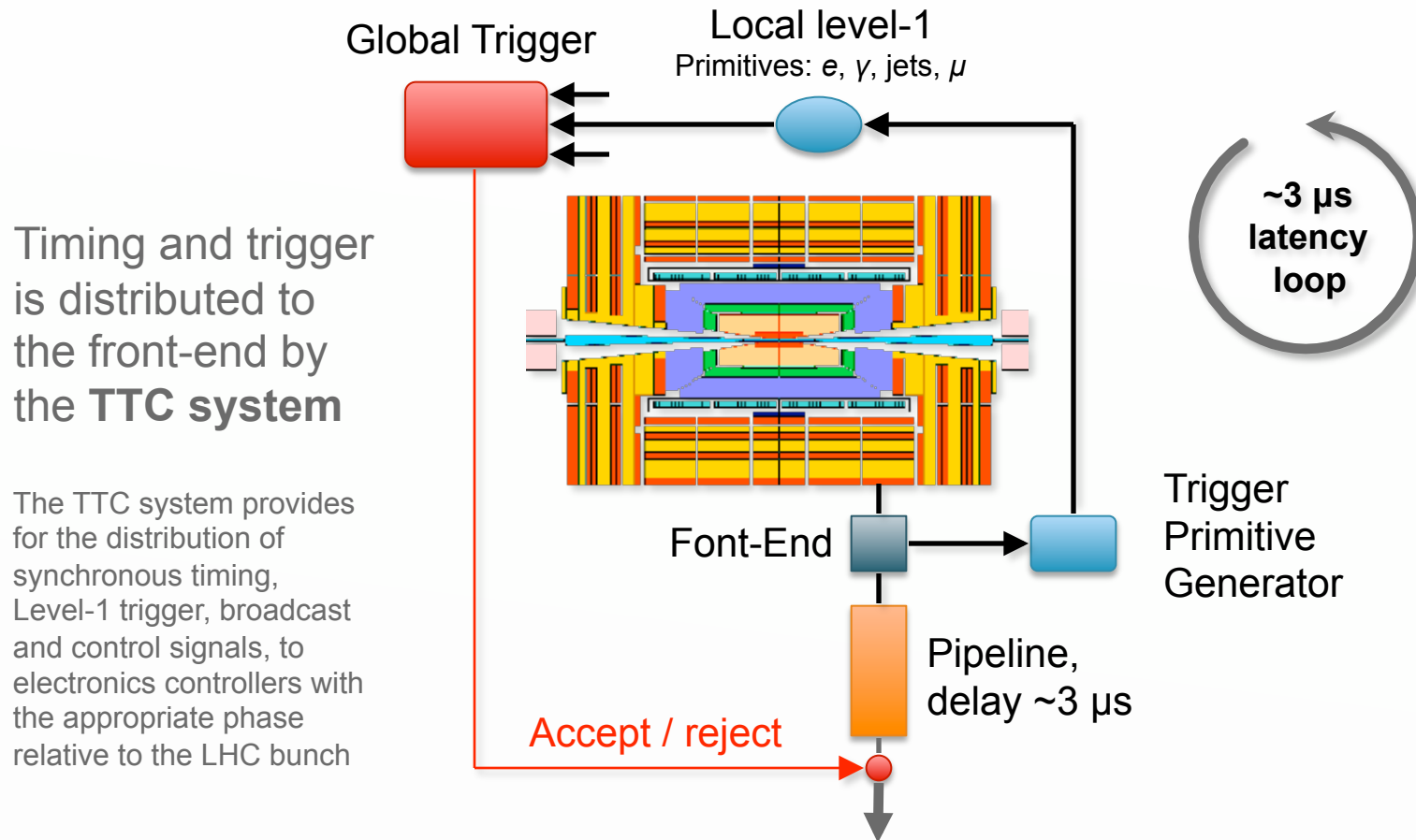
## Provide minimum-bias trigger (for single beam / collisions)

- Trigger on activity in detector as well as (in time coincidence with) beam

## Provide more selective L1 triggers, then progressively add HLT



# Trigger Communication Loop



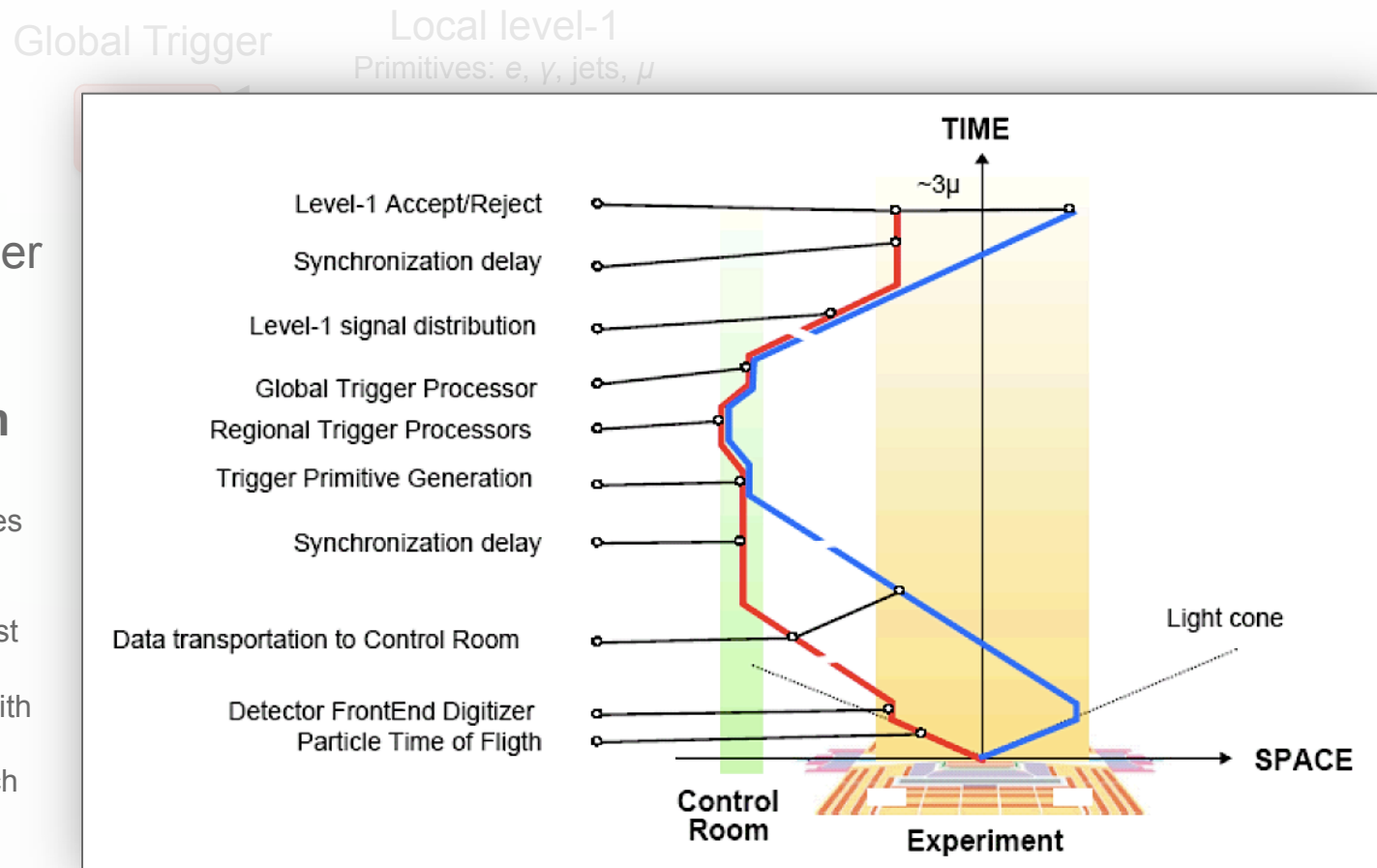
40.08 MHz synchronous digital system

Synchronization at the exit of the pipeline non trivial  $\rightarrow$  Timing calibration

# Trigger Communication Loop

Timing and trigger is distributed to the front-end by the **TTC system**

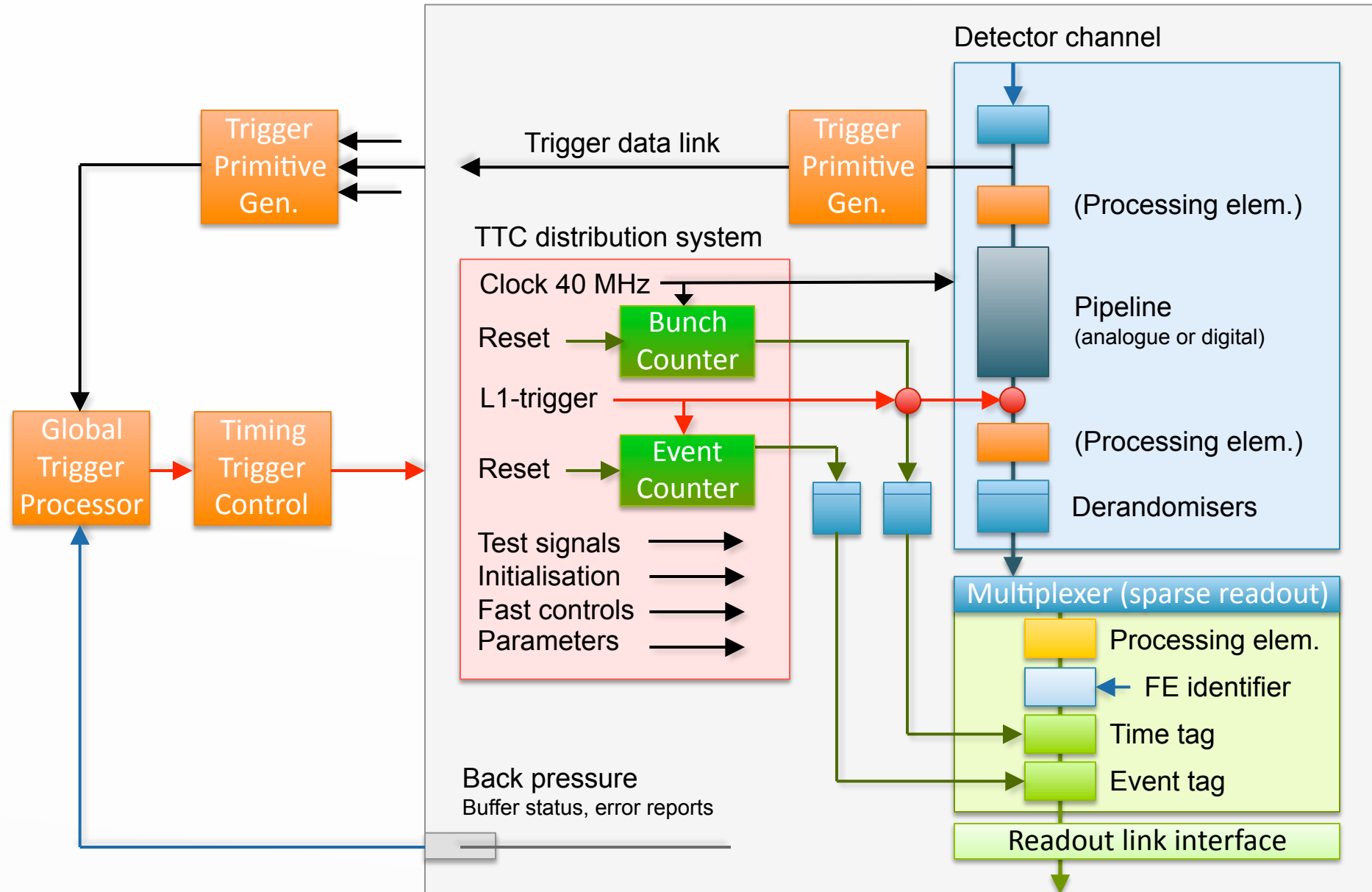
The TTC system provides for the distribution of synchronous timing, Level-1 trigger, broadcast and control signals, to electronics controllers with the appropriate phase relative to the LHC bunch



40.08 MHz synchronous digital system

Synchronization at the exit of the pipeline non trivial → Timing calibration

# Frontend model with Timing, Trigger and Control (CMS)



# Timing-In Trigger and Detector

---

Cannot reconstruct useful data before timing-in of all detector systems

“Timing in” ensures that all data shipped with event belong to same bunch-crossing (BC) ID and L1-accept (L1A) ID

On top of that the detectors need to adjust their own  $t_0$  constants

Timing-in requires 4 adjustments (all systems, incl. L1 trigger → priority!)

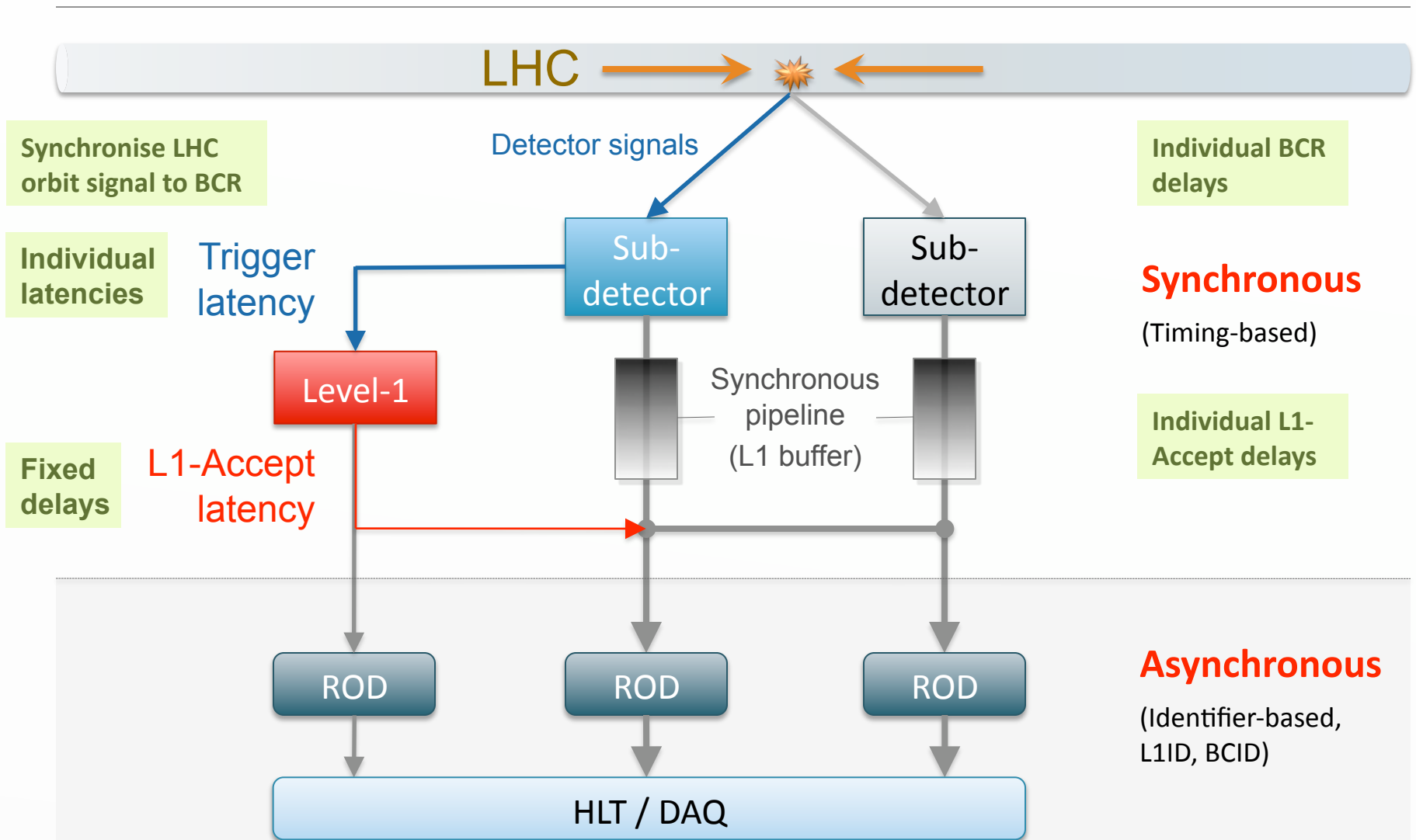
1. Data forming: clock phase between bunch crossing and detector signals
2. Data alignment: in steps of 25 ns
3. BCID identification: individually adjust BC reset delay
4. Readout alignment: individually adjust L1A delay in steps of 25 ns

Steps 2–4 partially known from cosmics commissioning, delay calculations/measurements, test pulses

Timing depends on run configuration (cosmics, single beam, collisions)



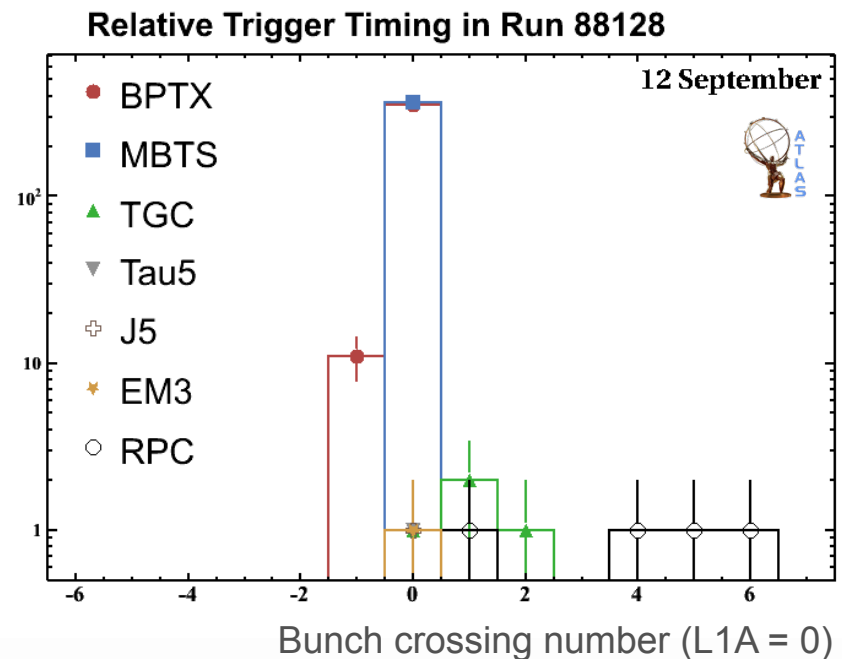
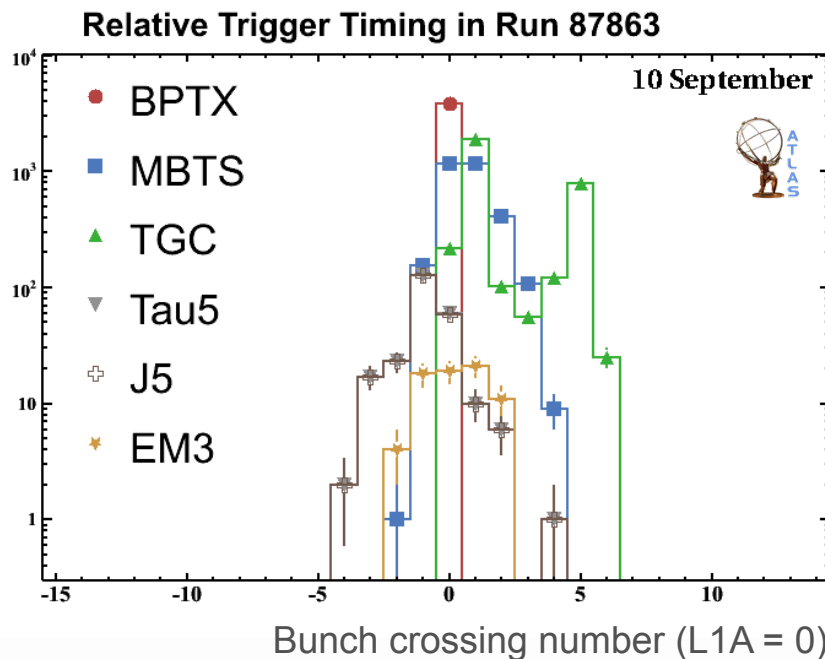
# Timing Schema



# Tuning the Timing of ATLAS trigger

Progress in trigger timing alignment between 10 and 12 Sep 2008

Response of various trigger lines with respect to Level-1 accept signal



# Time-of-Flight of Beam-Halo Muons

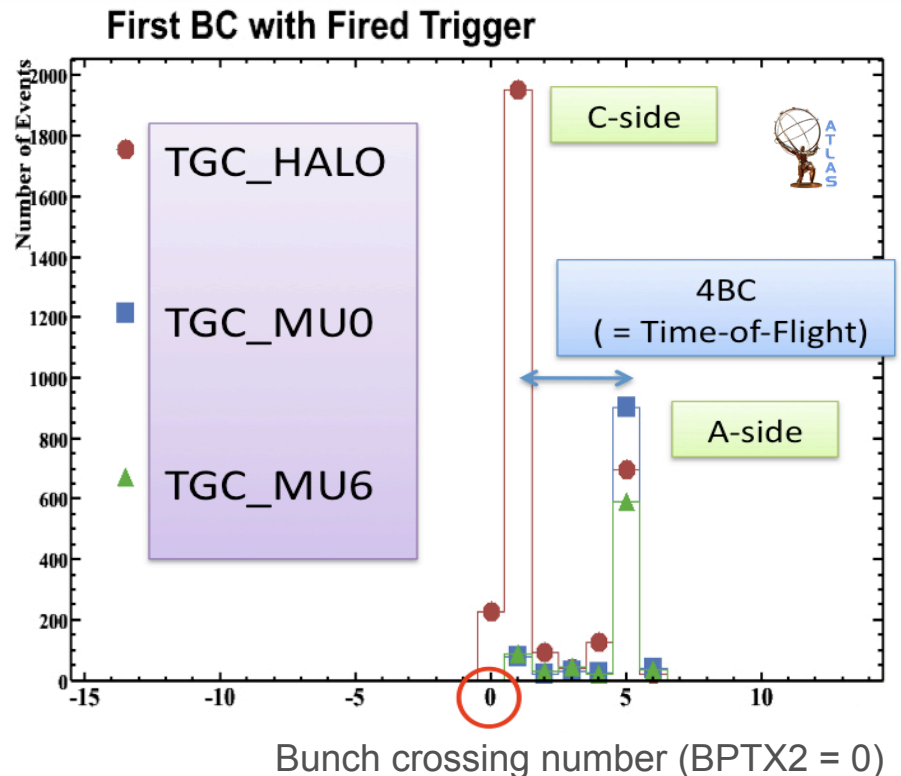
Muons need  $\sim 100$  ns to traverse ATLAS longitudinally

Distance between muon TGC detectors at opposite ends of ATLAS is 28 m (= 92 ns) at speed of light

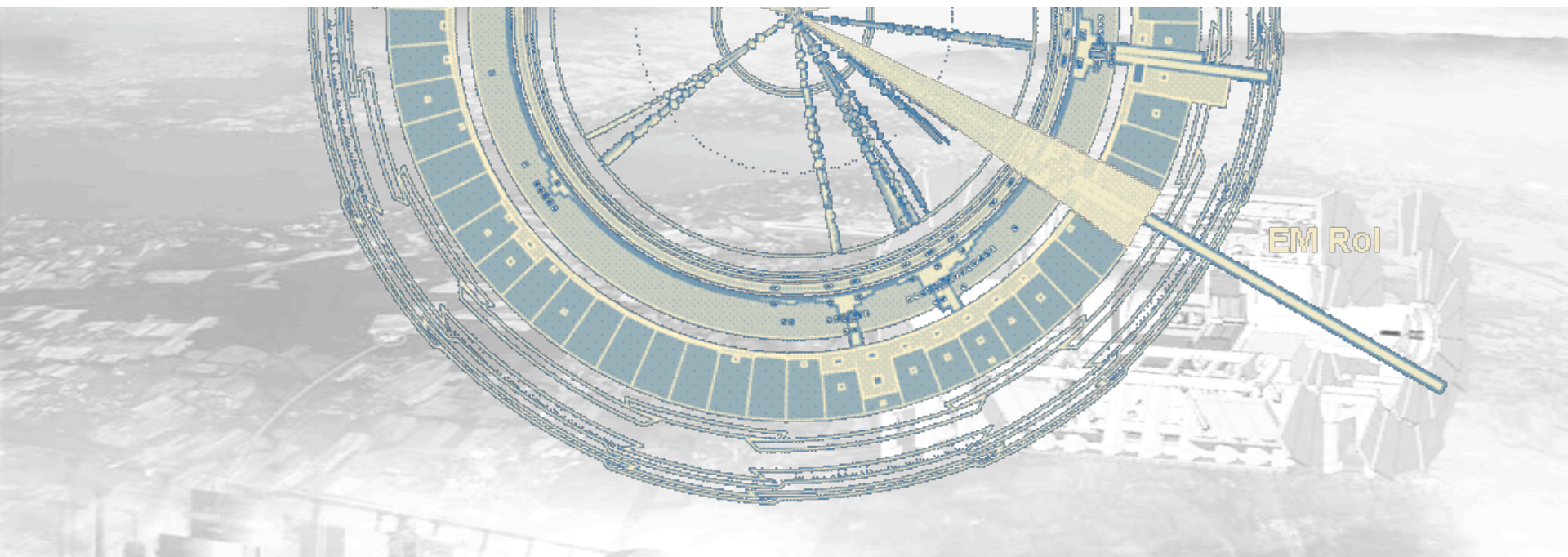
**TGC\_HALO** uses hits from 2 doublet stations. To have acceptance for beam halo which runs in parallel to beam line, two layers on pivot planes in eta direction are used, whereas coincidence of 3 out of 4 layers is applied in phi direction.

**TGC\_MU0**, in addition to TGC\_HALO, required 2 out of 3 coincidence in the 1st triplet station (within full open road).

**TGC\_MU6**, in addition to MU0, requiring the position of 2/3 coincidence be inside the narrower road.



# Trigger Aware Data Analysis



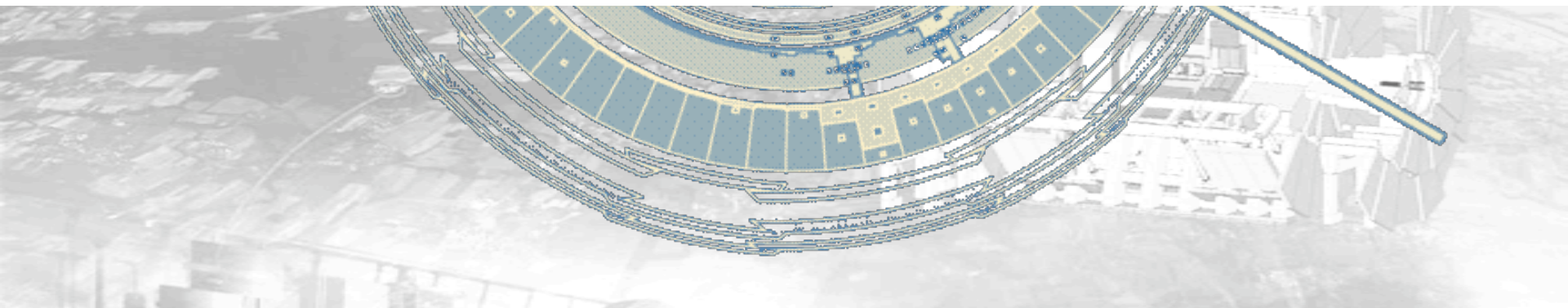
# Trigger Efficiencies (from Data)

The knowledge of the trigger efficiency is required for most LHC analyses

- Corrections to be applied for cross section measurements
- But also kinematic measurements (masses, spin,  $CP$  asymmetries) require the correction of trigger inefficiencies

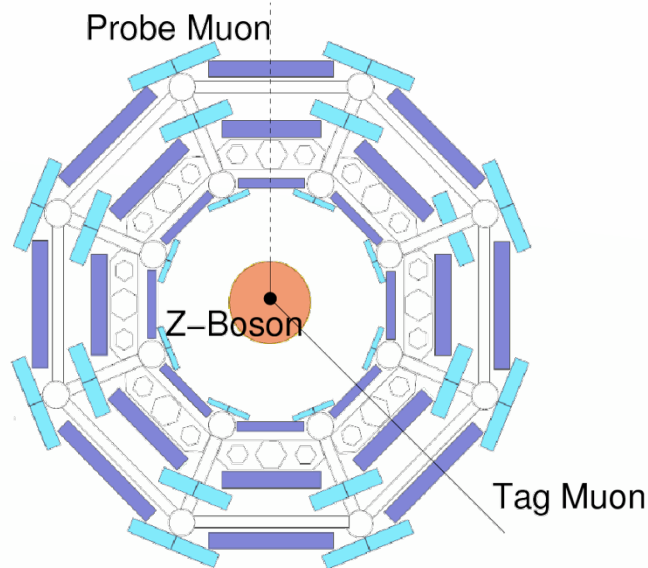
Don't trust Monte Carlo simulation – use data driven methods !

- Tag-and-probe method using known resonances, in particular  $Z \rightarrow e\bar{e}, \mu\bar{\mu}, \tau\bar{\tau}$
- Orthogonal triggers
- Bootstrapping methods
- Reference measurements





# Tag-and-Probe Method



**Example:** muon trigger efficiency with  $Z \rightarrow \mu\mu$

**Tag muon:**

- event triggered by tag muon
- isolated ID-MS muon with  $p_T > 20$  GeV

**Probe muon (unbiased with respect to tag selection):**

- require inner detector track ( $\mu$  candidate)
- $m(\mu\mu) \sim M_Z$  (91 GeV)
- count how often the probe muon has been triggered in the muon system

With sufficient statistics the efficiency can be evaluated in bins of  $p_T, \eta, \phi$

Usually, the result has to be corrected for combinatorial background under the Z peak

The Tag-and-Probe Method is very flexible, many versions of the same idea exist

Simplest case (ignoring backgrounds), just compare rates of  $Z \rightarrow ee$  for two triggers:

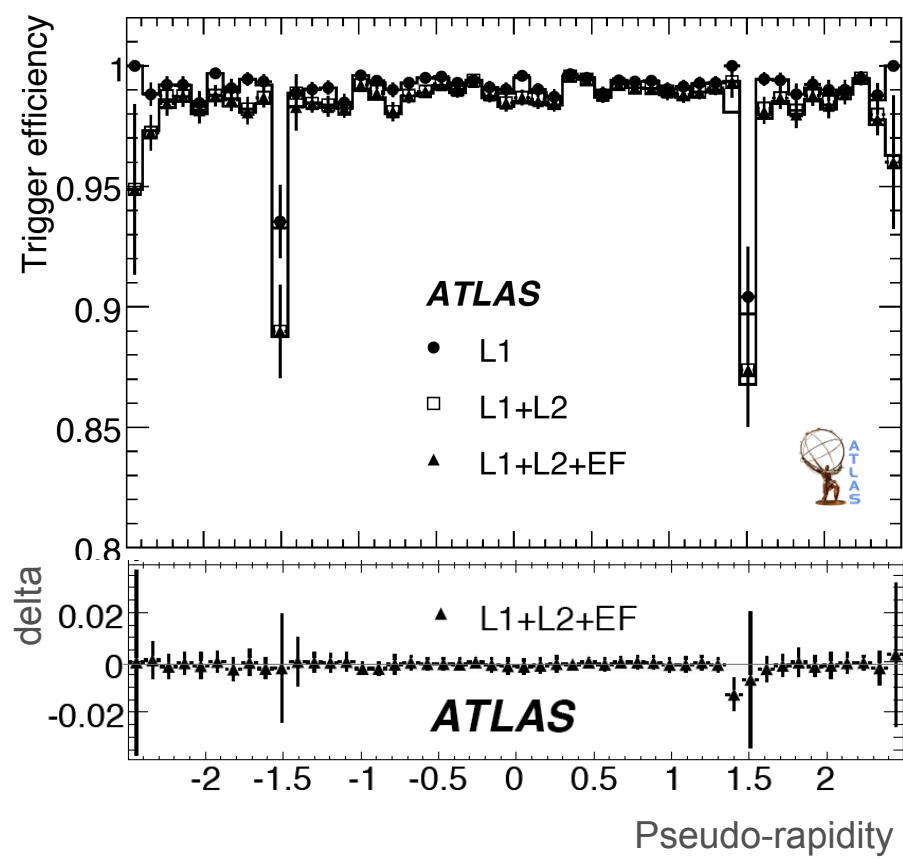
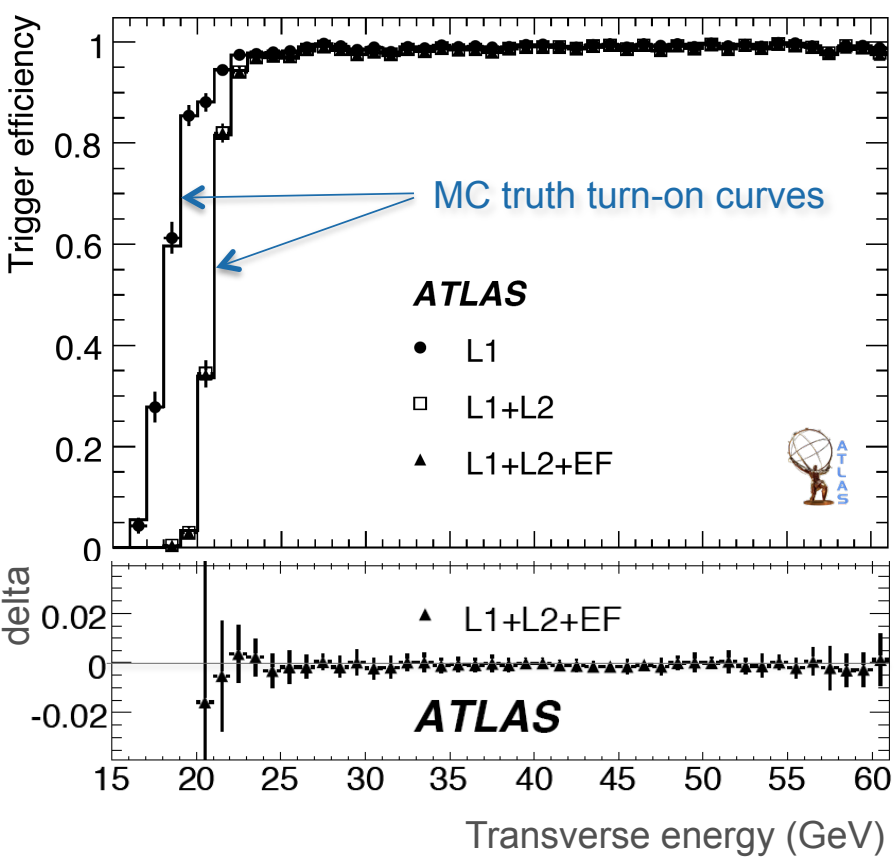
- **e15** ( $N_1$  **observed events**) and **2e15** ( $N_2$ )
- $\epsilon$  = e15 efficiency



$$\left. \begin{aligned} N_2 &= \epsilon^2 \cdot N_{\text{prod}} \\ N_1 &= (2\epsilon - \epsilon^2) \cdot N_{\text{prod}} \end{aligned} \right\} \Rightarrow \epsilon = \frac{2N_2}{N_1 + N_2}$$

# Simulated $Z \rightarrow ee$ tag-and-probe results for the “e20” trigger signature

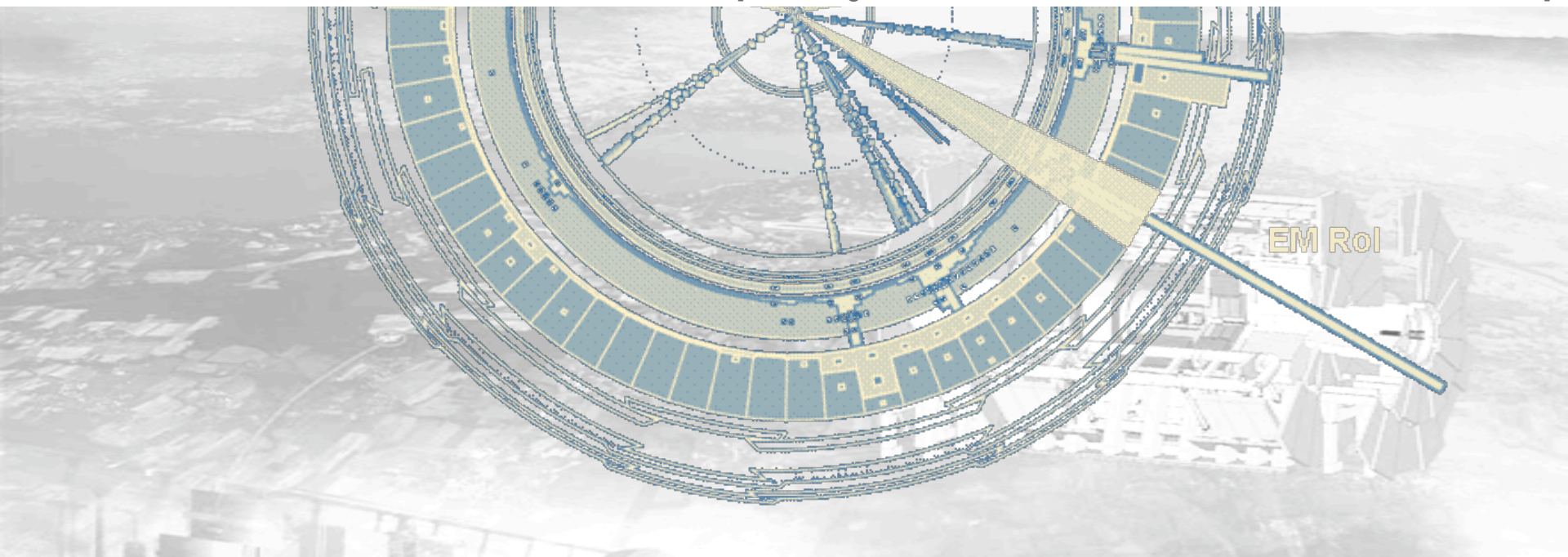
- Trigger efficiencies with respect to tight offline electron selection
- Signal statistics corresponds to  $100 \text{ pb}^{-1}$  (background neglected)



# Combining Triggers in Data Analysis

Show here rather intricate example including the combination of prescaled triggers. Many real use cases will be simpler. However, excellent way to illustrate pitfalls when dealing with trigger inefficiencies (of all kinds) in physics analysis.

[ Following slides follow article: V. Lendermann et al, [arXiv:0901.4118](https://arxiv.org/abs/0901.4118) ]



# Combining Triggers

**Issue:** how to combine data samples collected by several triggers in a physics analysis analysis (e.g., cross section measurement) ?

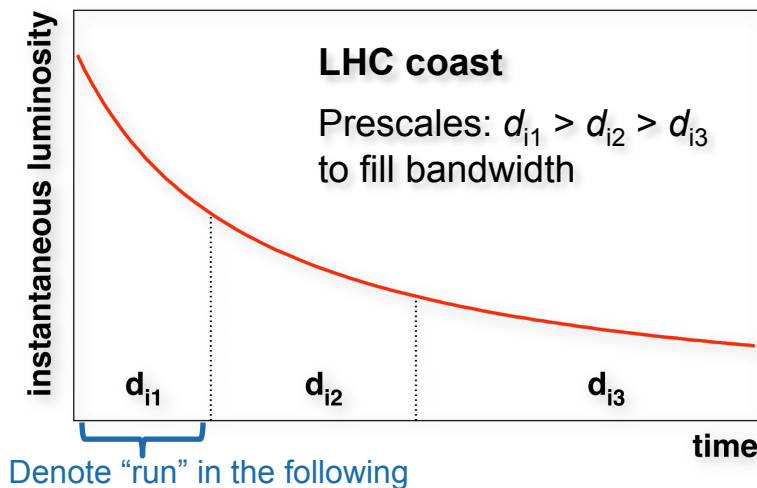
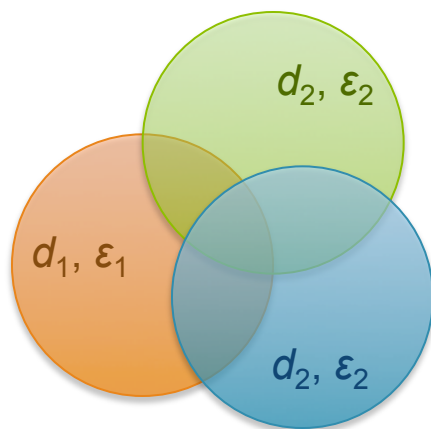
- Limited bandwidth → rate **prescaling** by factor:  $d$
- Limited resources → reduced **efficiency** (with respect to **offline** selection):  $\varepsilon$

Goal: 
$$\sigma = \frac{N_{\text{prod}}}{\mathcal{L}}$$

However, only  $N_{\text{rec}} < N_{\text{prod}}$  events recorded

⇒ Fortunately, knowing  $d$  and  $\varepsilon$ , one finds:  $N_{\text{prod}} = N_{\text{rec}} d / \varepsilon$

**But** – what if several trigger lines overlap, or if  $d_{ik}$  and  $\varepsilon_{ik}$  (for trigger line  $i$  and run  $k$ ) depend on *time* ?

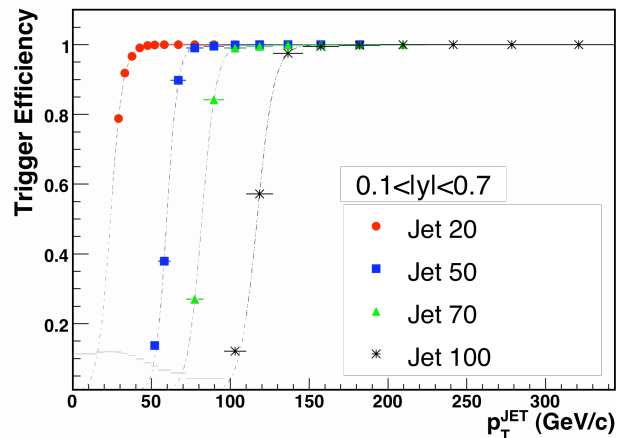


# Why Do We Need to Combine Triggers ?

Cover different phase space regions, detectors with maximum statistics

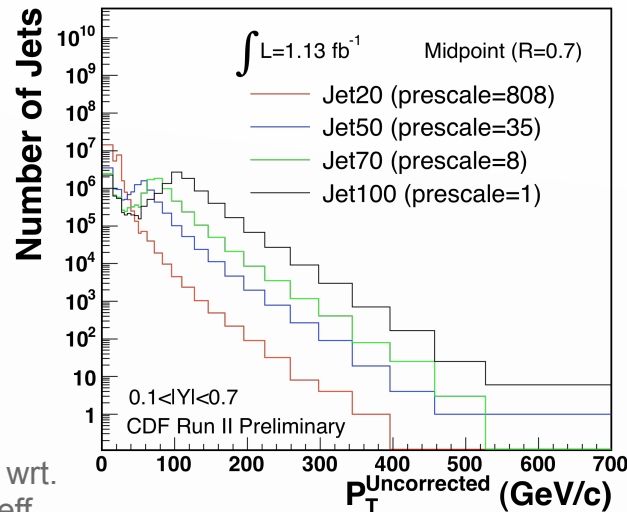
- ➡ **Different sub-detectors** (e.g. di-muon analysis with one  $\mu$  in barrel and one in endcap)
- ➡ **Different signals** (e.g. use jets *or* electron triggers)
- ➡ **Different energies** (e.g. combine trigger lines with different  $p_T$  thresholds)

Turn-on curves for jet triggers

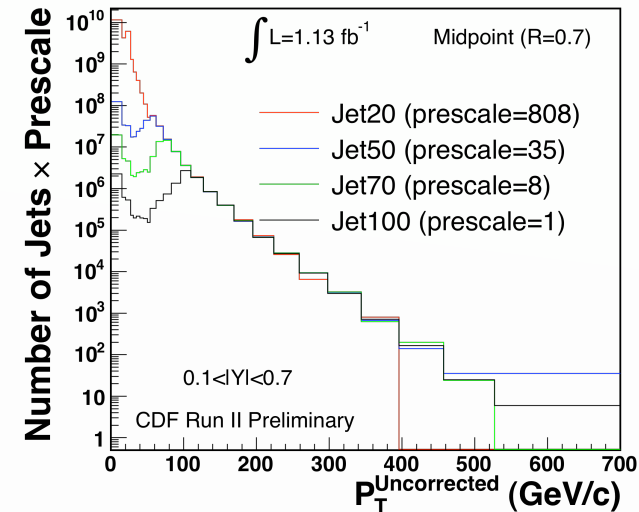


Trigger efficiencies are usually determined wrt. offline selection: important to know trigger eff. to be able to improve in future runs!

Observed numbers of jets



Corrected for prescales





# The Goal is...

...to calculate the weights  $w(j)$  for each event  $j$ , such that:  $N_{\text{prod}} = \sum_{j=1}^{N_{\text{rec}}} w(j)$

Simplest approach for single trigger:  $w_k(j) = d_k / \varepsilon_k$  for (stable- $d$ ) run  $k$

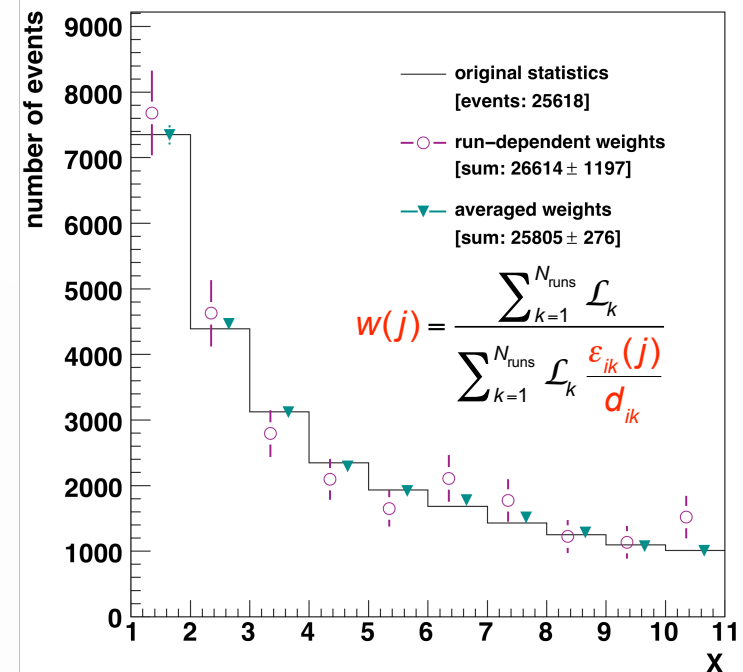
- In case of stable conditions compute **average**  $w(j)$  over **all runs**, instead of individual  $w_k(j)$  per run, even if prescales and efficiencies vary between runs → smaller error !

**Toy example** (single trigger line):

- 10 runs with  $d = 1 \dots 5$  – good LHC conditions
- 10 runs with  $d = 100$  – huge beam backgrounds
- 1000–1500 events per run

**Averaged weights always better than or equal to run-wise weights !**

**Note that averaging requires that the definition of the trigger line did not change between the runs !**



# Combining Triggers

---

Consider combination of triggers for single trigger level

Distinguish three methods, with rising complexity

## 1. *Division method (basic)*

- Divide phase space into distinct regions with only one trigger line per region
- Choose the region providing largest statistics for analysis
- Determine trigger efficiency for this region

## 2. *Exclusion method (better)*

- Divide data sample according to trigger lines and prescale factors

## 3. *Inclusion method (Rolls Royce)*

- A combined weight based on all considered trigger lines is determined for the entire event sample ...

For simple final states, or measurements not limited by statistics, the *Division Method* can be a straightforward choice.

# Exclusion Method (assuming FETC)

Need to first introduce concept of *fully efficient trigger combinations (FETC)*

⇒ “**OR**” of the combination of trigger lines has  $\varepsilon = 1$  with respect to offline selection

- Example:  $s_1 = \{N_{\text{tracks}} > 2\}$ ,  $s_2 = \{N_{\text{tracks}} < 4\} \rightarrow \{s_1 \parallel s_2\}$  is fully efficient

Split data sample according to trigger lines and prescale factors

- Choose the trigger line  $i^*$  with the smallest  $d_{i^*k}$  for which the “raw trigger” passed
- The raw trigger of a line is the trigger response before prescale
- Event weight then given by:  $w_k(j) = d_{i^*k} a_{i^*}(j)$ , where “actual trigger”  $a_{i^*}(j) = 1$  (0) if event passed (did not pass) trigger line  $i^*$  after applying prescale
- Again, instead of computing  $w_k(j)$  per run  $k$ , compute average weight over runs  $w'_{i^*}$ , giving the event weight:  $w(j) = w'_{i^*} a_{i^*}(j)$

$$w'_i = \frac{\sum_{k=1}^{N_{\text{runs}}} \mathcal{L}_k}{\sum_{k=1}^{N_{\text{runs}}} \mathcal{L}_k / d_{ik}}$$

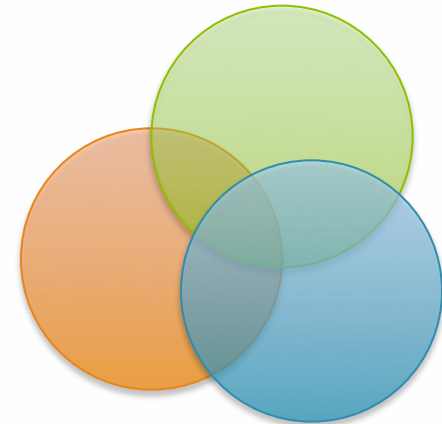
Sufficient for many statistically non-critical analysis

[ e.g. used for inclusive measurements of structure functions at low  $Q^2$  by H1 ]

# Inclusion Method

Determine combined weight based on all considered trigger lines

Use *all events* passing *at least one* trigger



- Probability to trigger event:

$$P_k(j) = 1 - \prod_{i=1}^{N_{\text{lines}}} \left( 1 - \frac{r_i(j)}{d_{ik}} \right)$$

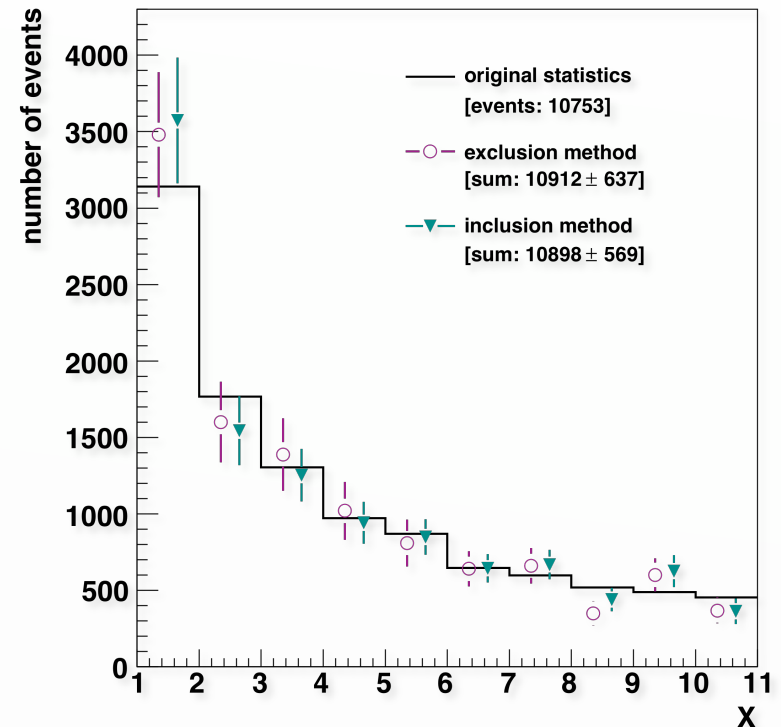
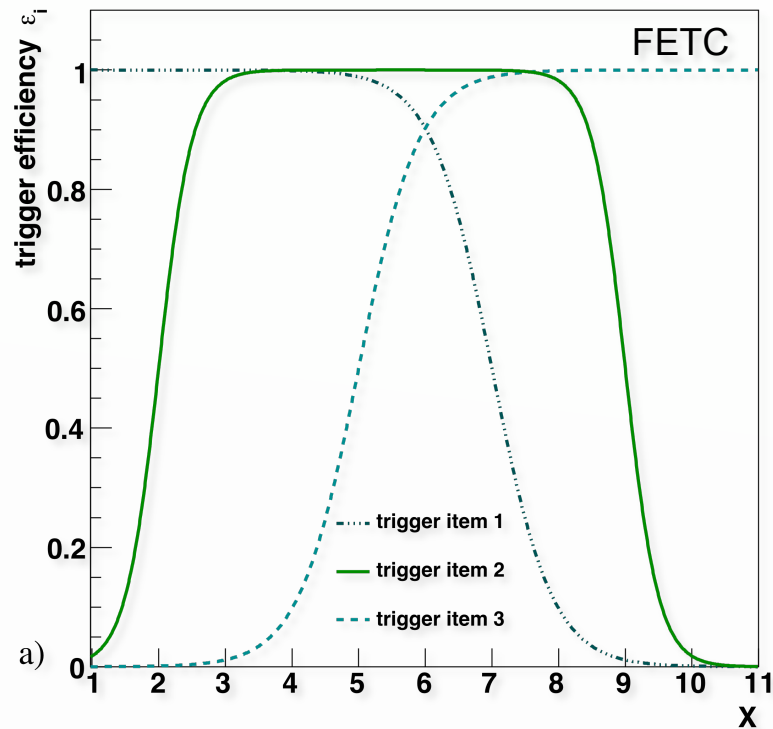
- Run-wise weight:  $w_k(j) = 1 / P_k(j)$ , or better run-averaged:  $w(j) = \frac{\sum_{k=1}^{N_{\text{runs}}} \mathcal{L}_k}{\sum_{k=1}^{N_{\text{runs}}} \mathcal{L}_k P_k(j)}$
- Note: assumes independent application of prescales !

Optimum correction in presence of prescaled triggers that significantly overlap (unless equivalent to exclusion method)

# Comparison between Methods

## Toy Monte Carlo example:

- 20 runs with varying luminosity, 500–600 events per run



Similar performance for many practical cases ...



# Trigger (In)efficiency Corrections

Departing from FETC requires to modify expressions. Simplest solution, just applying a single global efficiency correction has drawbacks

- Global efficiency depends on particular analysis requirements
- Efficiency correction applied on top of prescaled triggers and must thus be determined from data for the combination of not prescaled trigger items
- Determination of correction from data may be impossible if no triggers orthogonal to the used trigger combination exist, requiring MC simulation to obtain global efficiency

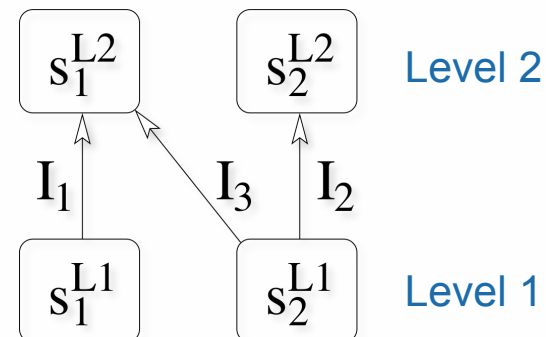
Alternatively, determine efficiency corrections  $\epsilon_{ik}(j)$  separately for each trigger line (potentially **run** and **event** dependent)

- Requires modification of weight calculations by replacing  $d_{ik} \rightarrow d_{ik} / \epsilon_{ik}(j)$  everywhere
  - That's not all: since the  $\epsilon_{ik}(j)$  are determined wrt. offline analysis, one needs to replace the raw/actual trigger bits by the “expected” ones in offline
- ⇒ If an event has a raw hit ( $r_i(j) = 1$ ), but would not be selected by offline,  $r_i(j)$  is set to 0
- ⇒ Moreover, efficiency correlation between trigger lines need to be taken into account

# Multiple Trigger Layers

## Extension to multi-layer triggers

- Straightforward extension, but complicated if trigger lines ( $I_i$ ) overlap **[avoid !]**
- See [arXiv:0901.4118](https://arxiv.org/abs/0901.4118) for details. Basic conclusion: inclusion method becomes really, really complicated...



As before **need to know raw and actual trigger response for all lines**

- Recall: **early accept mechanism** (e.g. H1 in early HERA).
  - Once decision to keep the event is made, the remaining code is not executed
  - HLT items must be recalculated offline – with the same calibration, alignment etc.
- Recall: **early reject mechanism** (e.g. ATLAS, CMS).
  - If  $a_i(j) = 0$  for all  $i$ , the corresponding algorithms at higher levels are not executed
  - Lines must be finished in HLT, if the event is accepted

# Recommendations for Trigger Operation

[ From: [arXiv:0901.4118](https://arxiv.org/abs/0901.4118) ]

Include all trigger bits in event record. *Raw bits must not be omitted*

- For efficiency determination
- For FETC methods

Provide *all bits* from *all levels*

- Compute all HLT trigger bits when event has been accepted

Do not use the actual decision at lower levels as input to higher levels

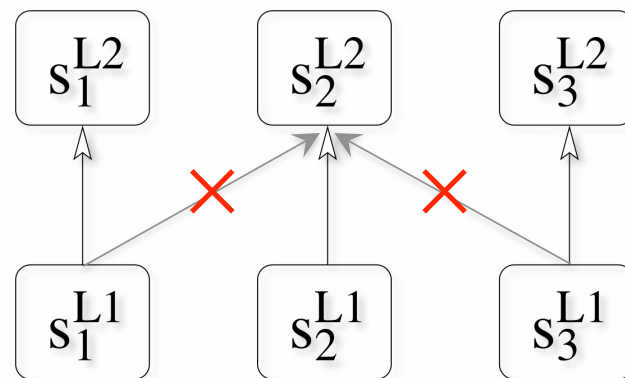
- Correlates triggers and invalidates FETC

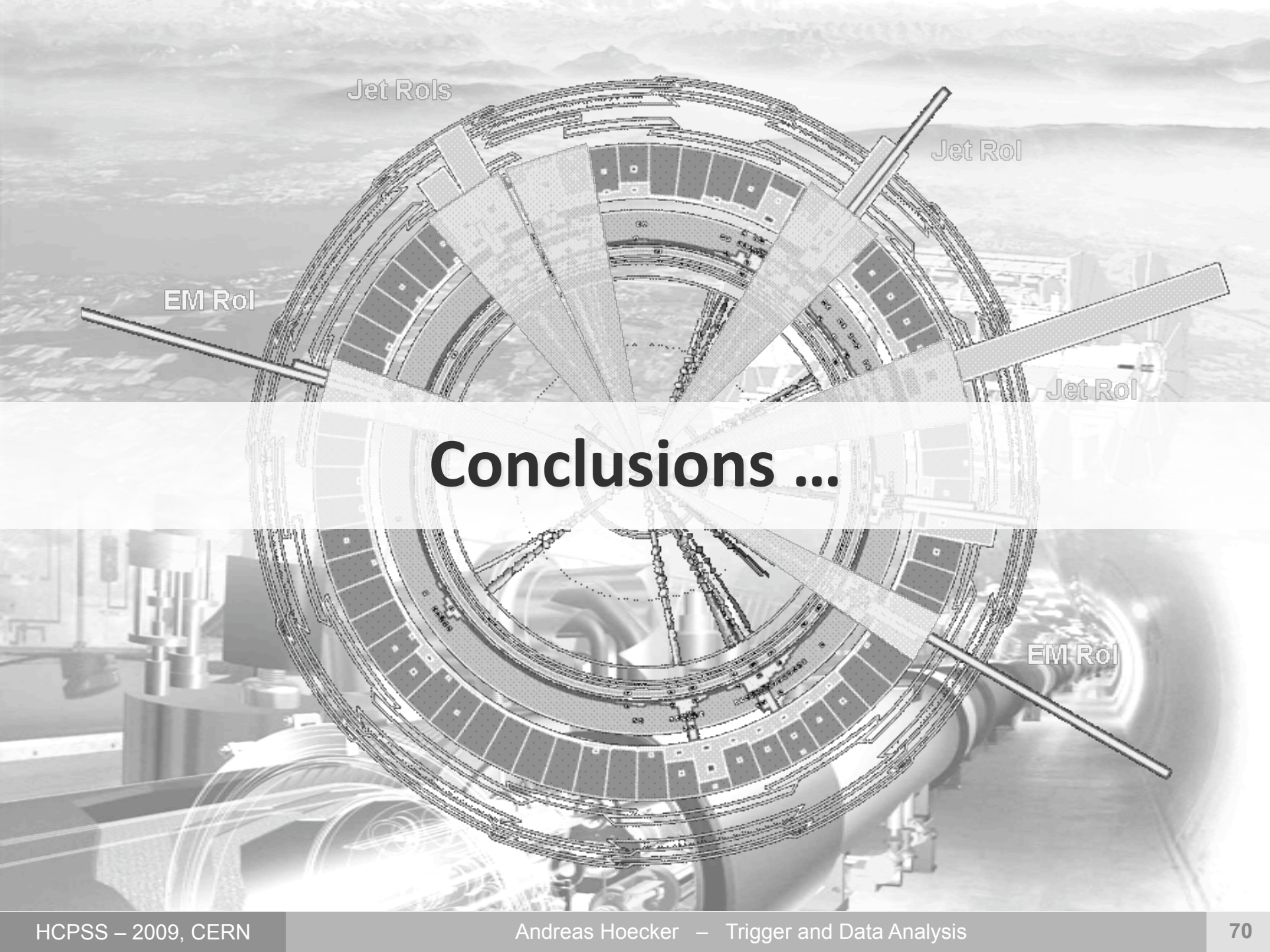
Avoid overlaps between trigger lines

- Correlates trigger lines

Keep trigger definitions simple and stable !

- Simplifies efficiency calculations
- allows to average over runs !





Jet Rols

Jet Rol

EM Rol

Jet Rol

# Conclusions ...

EM Rol

We've seen that Trigger analysis can become quite complicated...



We've seen that Trigger analysis can become quite complicated... We've also seen that triggering is a huge challenge at the LHC.

We've seen that Trigger analysis can become quite complicated... We've also seen that triggering is a huge challenge at the LHC. Moreover, the trigger shoulders large responsibility for the entire experiment.

We've seen that Trigger analysis can become quite complicated... We've also seen that triggering is a huge challenge at the LHC. Moreover, the trigger shoulders large responsibility for the entire experiment. A useful recommendation to experiments could thus be...

Be kind to your trigger expert, and  
make sure he or she gets **enough  
sleep** ! (...when data rolls into the pipelines)