The operation of the LHC detectors
Timing

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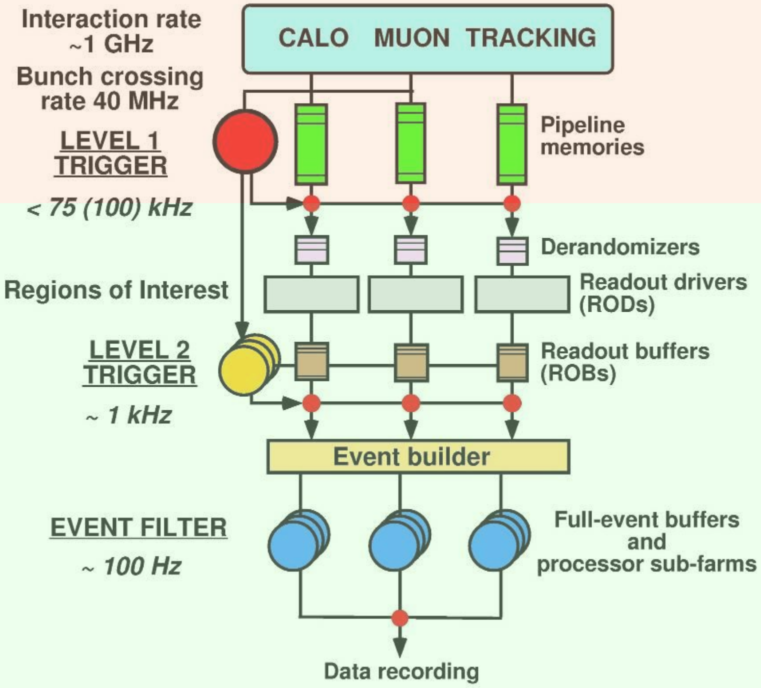
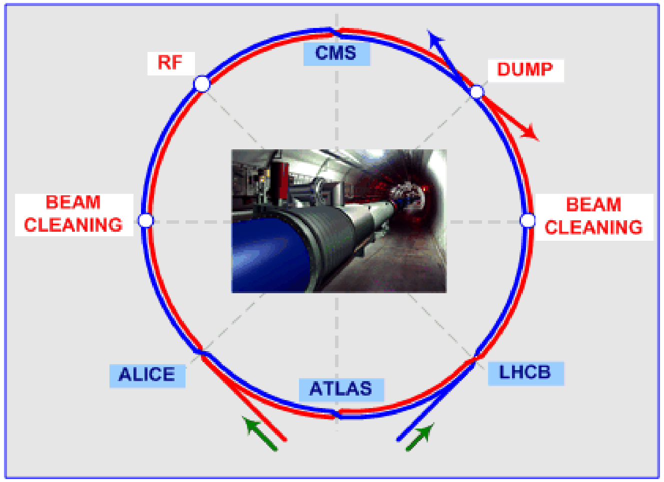
TDAQ: Synchronous and Asynchronous Readout and Trigger Paths



- Synchronous trigger and readout path (at 40 MHz)
  - pipelined trigger processing
  - pipelined readout
  - fixed latency
  - needs to be carefully timed in
- Asynchronous trigger and readout path
  - relies on well timed-in synchronous path
  - depends on the order of events, identifier-based, cross-checks

How to trigger on a media day?

- e.g. 10 Sept 2008, 19 Nov 2009, 30 Mar 2010
- Lots of pressure to trigger and readout the first event
- For some of us, this was the first time we saw beam
- Worries:
  - Which trigger are we going to use?
    - sensitive enough?
    - good timing? not too early, not too late
  - Will the read-out be ok? busy?
  - Will collisions be in the centre of the detector?

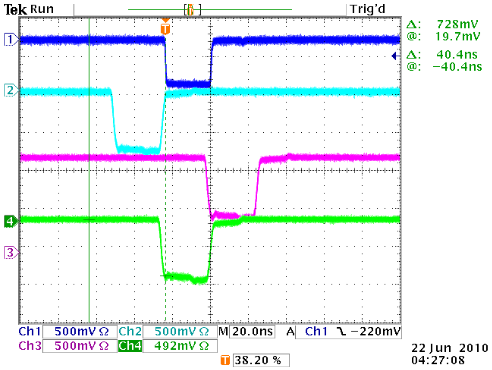


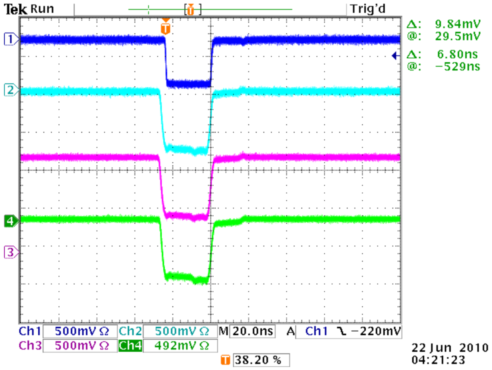
But ...

Timing is trivial!

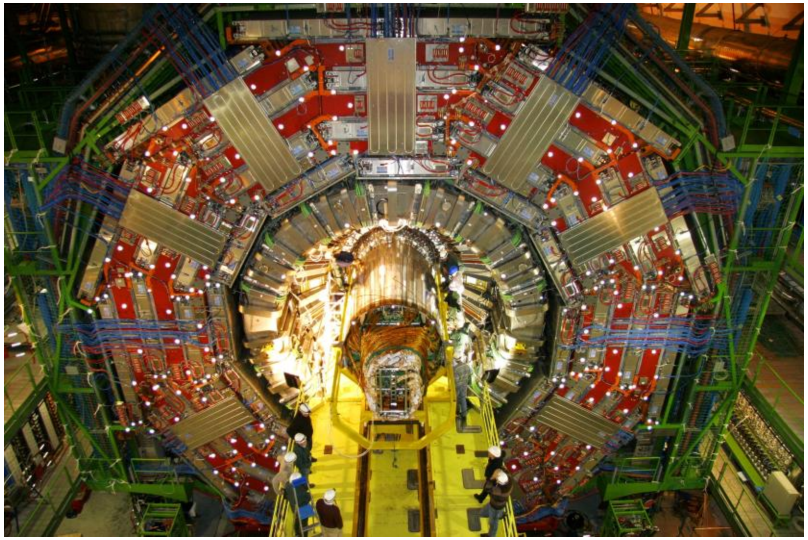
+

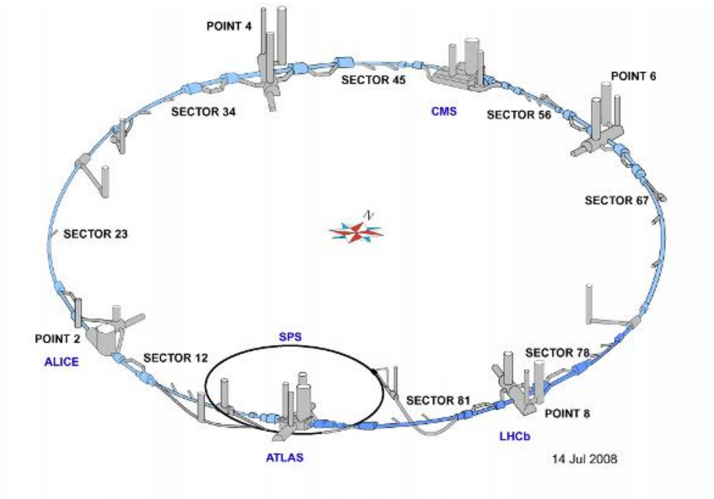
- Need to know all propagation delays and make them the same length
  - precision required: e.g. 1ns = 30cm
- Can use time = distance / velocity to convert a known distance into time
  - vacuum: c_0= 30cm/ns
  - cable/fibre: typically 2/3 c_0 = 20cm/ns
- Measure
  - time of flight with a yard stick
  - electronics delays with oscilloscope
  - cable and fibre lengths with yardstick or with time-domain reflectometry (reflection method)
- Time in: compensate for propagation differences by adjusting delays
  - e.g. extend or shorten existing cables
  - use programmable delay electronics
- Why is timing a challenge?





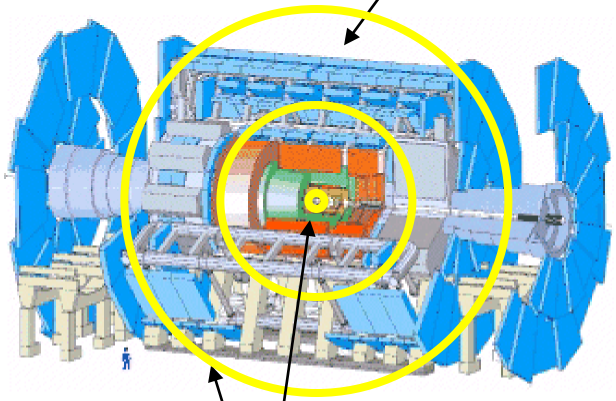
Timing Challenge





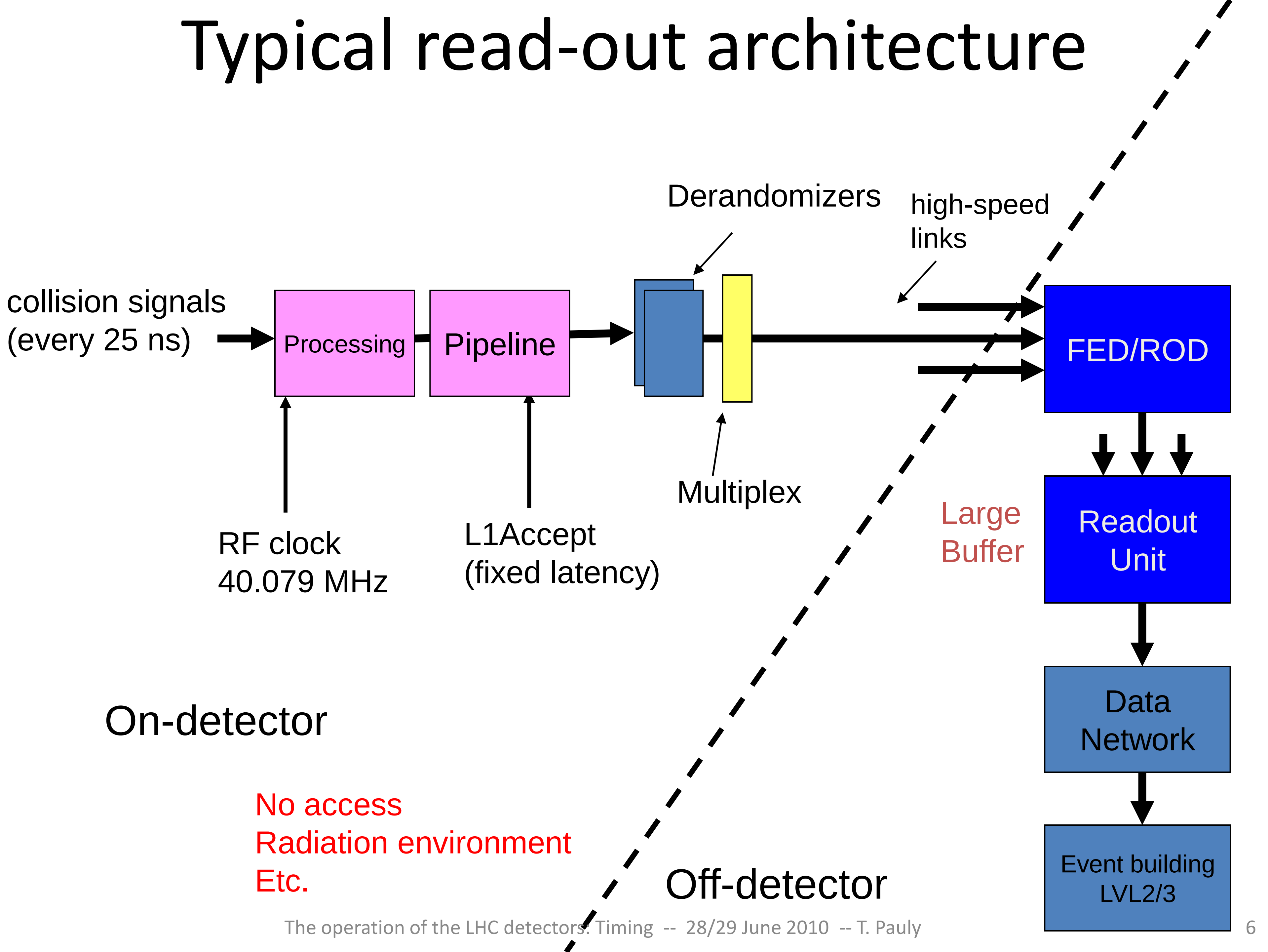
- Huge detector systems and LHC machine, short bunch spacing
  - e.g. ATLAS 25m x 25m x 40 m
  - bunch spacing 25ns (7.5m)
- Large data volumes, many channels (10^8)
- Complex system with many electronics components
- Need procedures to
  - measure the delays before installation
  - time in and check the timing in situ

Trigger finds high-p_T muon here $\Rightarrow$ select event



Need to read out also here

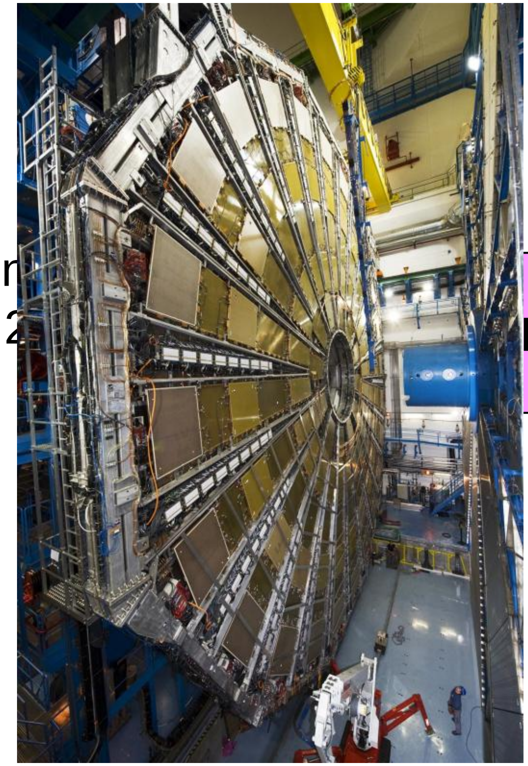
Typical read-out architecture



No access
Radiation environment
Etc.

Typical read-out architecture

collision
(every 2



h-speed
ks

Multiplex

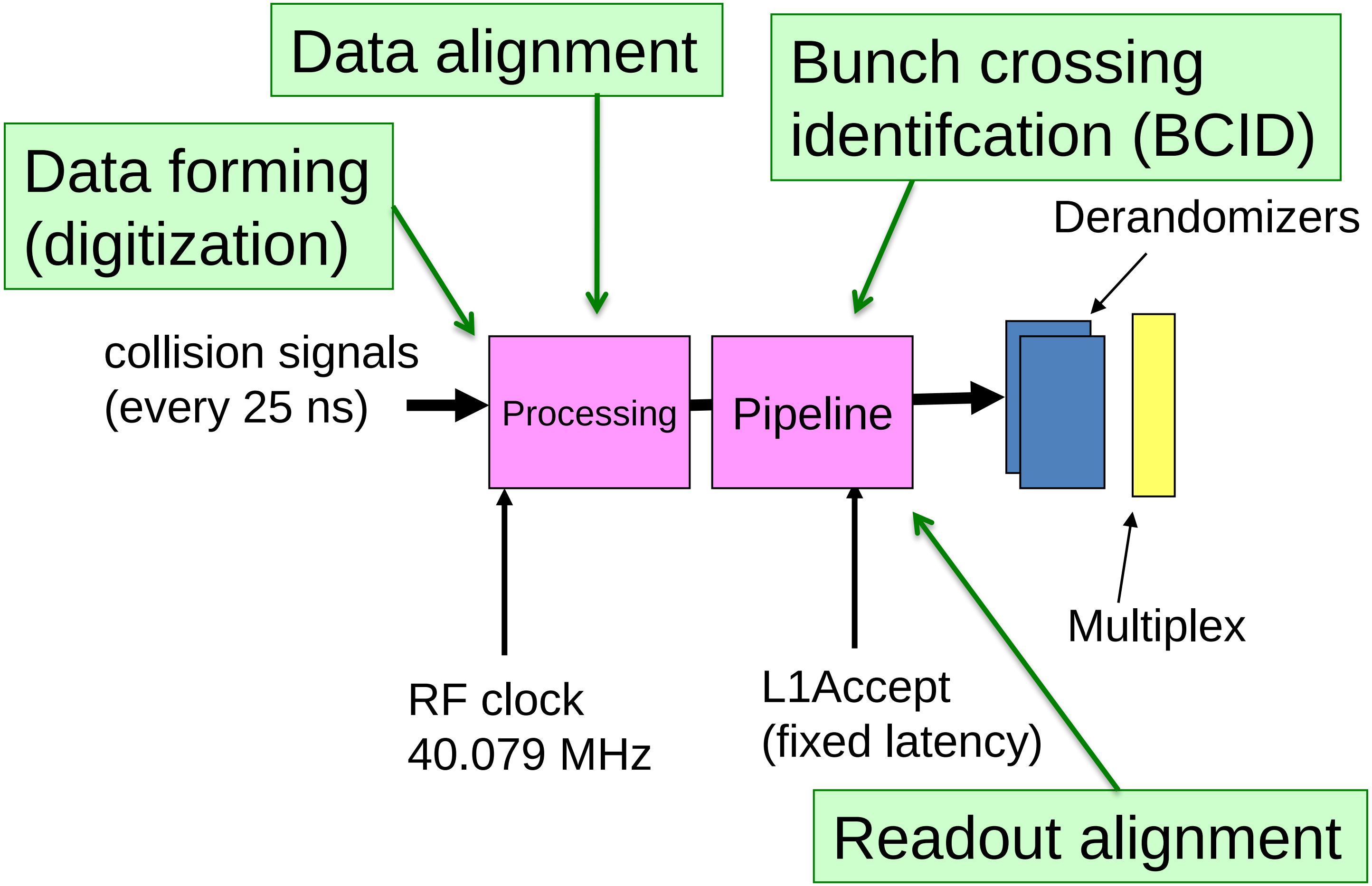
LVL1
(fixed latency)

On-detector

No access
Radiation environment
Etc.

Off-detector

Timing Tasks



Data alignment

Bunch crossing identifcation (BCID)

Data forming (digitization)

Derandomizers

collision signals (every 25 ns)

Processing

Pipeline

Multiplex

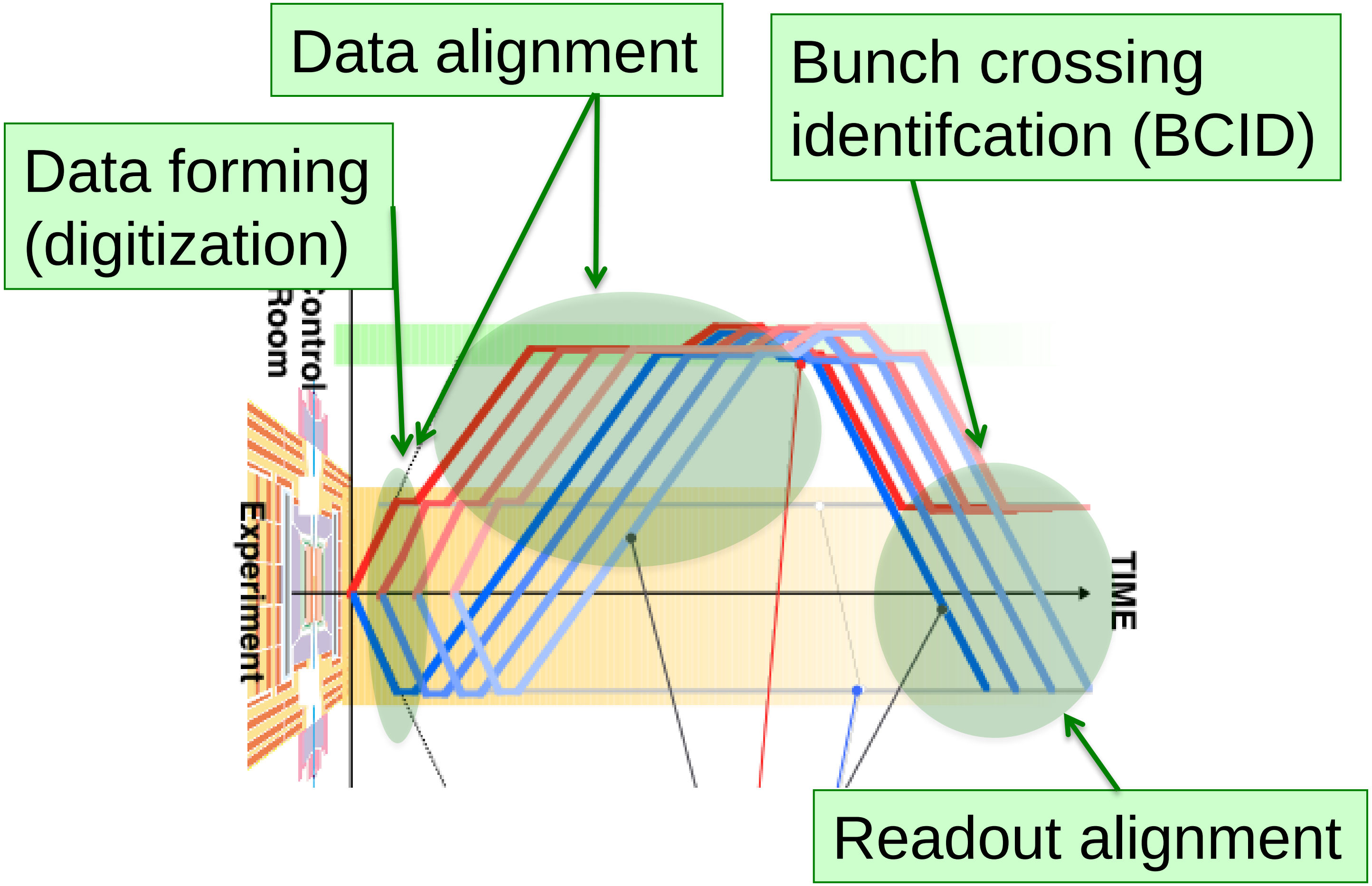
RF clock 40.079 MHz

L1Accept (fixed latency)

Readout alignment

Distinguish between local and global alignment

Timing Tasks


Data alignment

Bunch crossing identifcation (BCID)

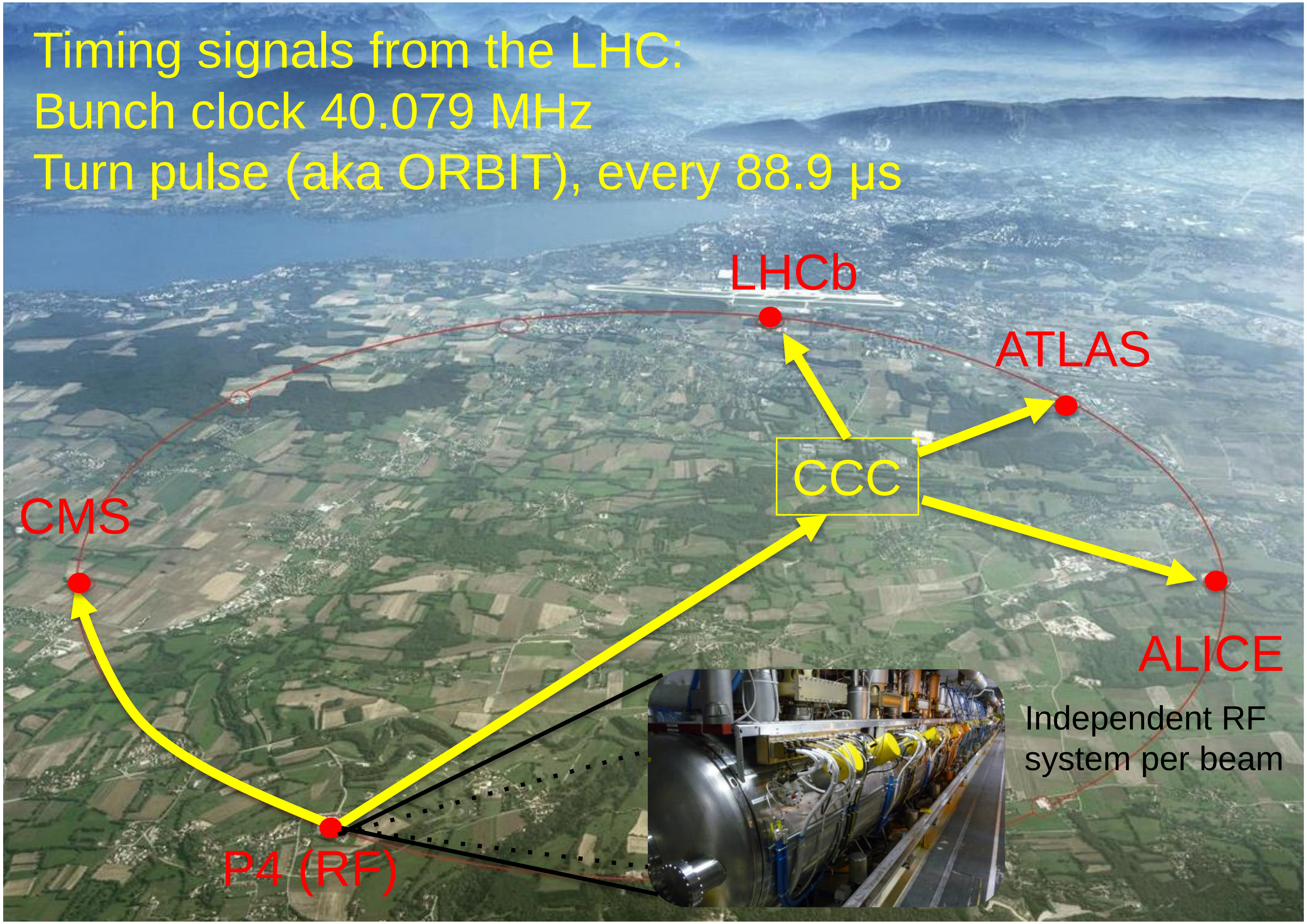
Data forming (digitization)

Readout alignment

Experimental Setups and Tools

- Clock and timing distribution
- Detector standalone:
  - test pulses
  - comics
- Detector with beam:
  - beam timing pick-ups (BPTX)
  - single beams, splashes
  - collisions

LHC Timing Signal Distribution

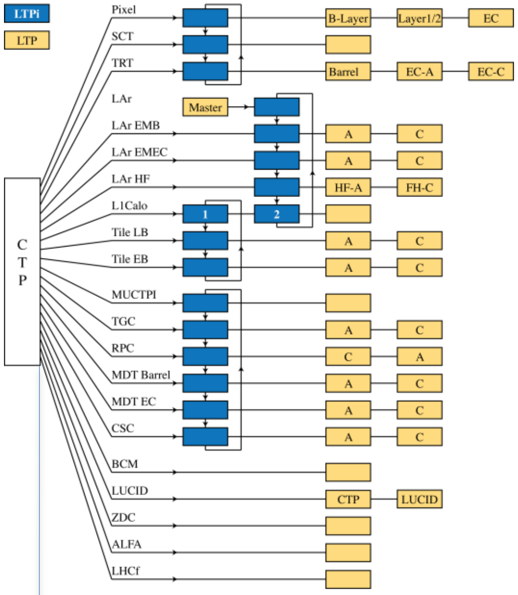


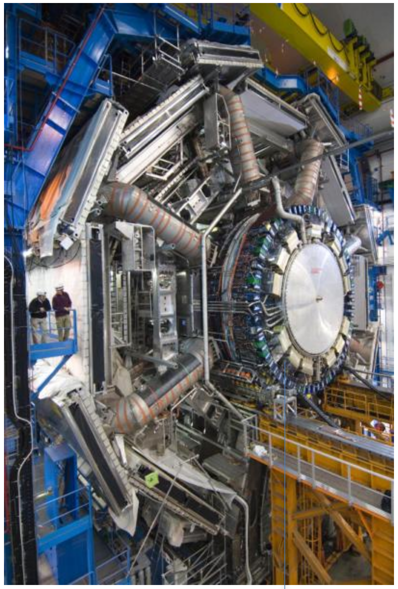
Timing signals from the LHC:
Bunch clock 40.079 MHz
Turn pulse (aka ORBIT), every 88.9 µs

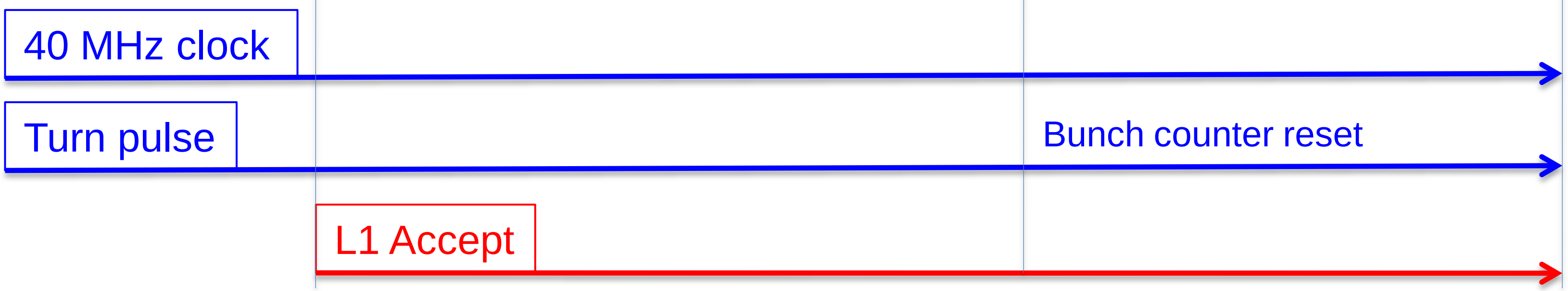
Independent RF system per beam

Timing Distribution within an Experiment

LHC







few km

counting room O(30m)

to cavern O(100m)

40 MHz clock

Turn pulse

Bunch counter reset

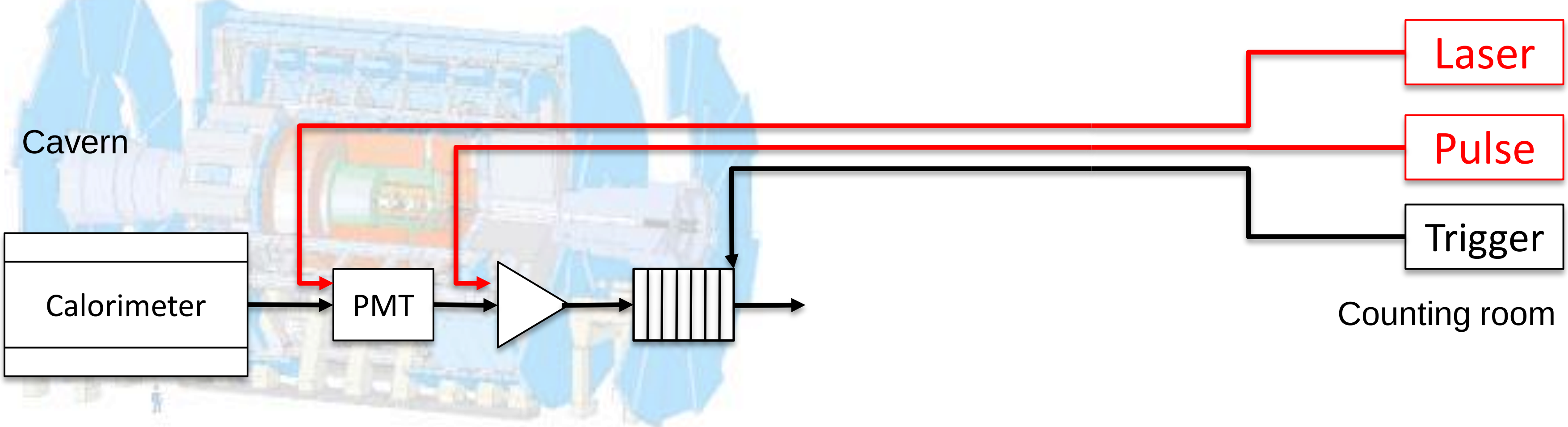
L1 Accept

Many adjustable delays available for timing-in

Global delays → Local delays

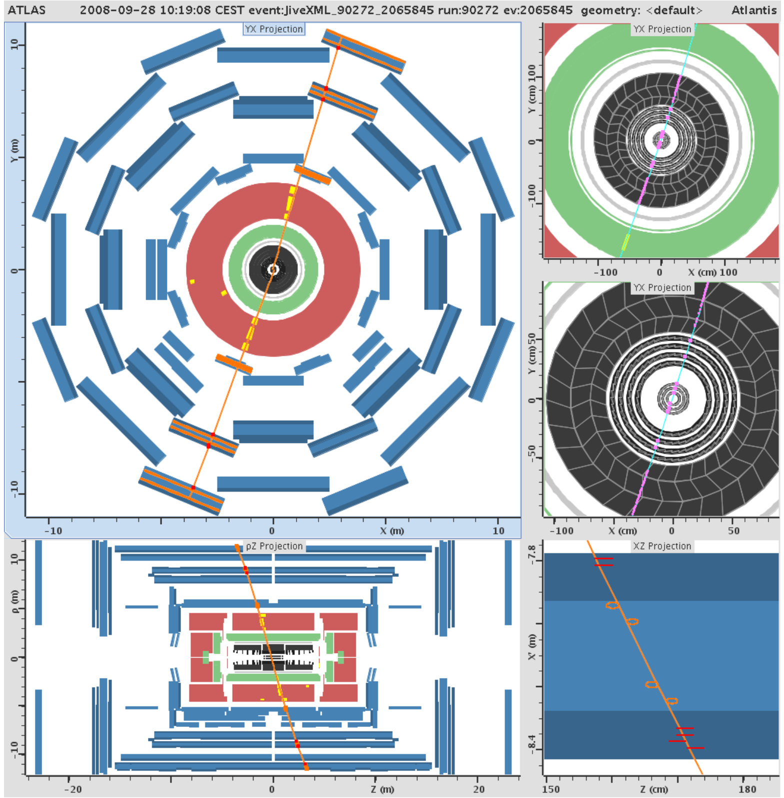
Timing with Test Pulses

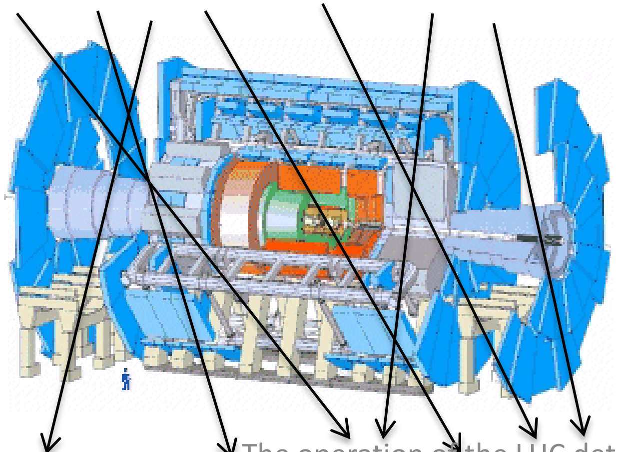
- Sub-detector standalone test setup
- Single pulse generator as common timing reference, for example
  - charge injection into the front-end electronics
  - laser pulse in PMT
- Send L1Accept to capture the generated data
  - possible to measure various relative propagation delays of the sub-detector readout and trigger path

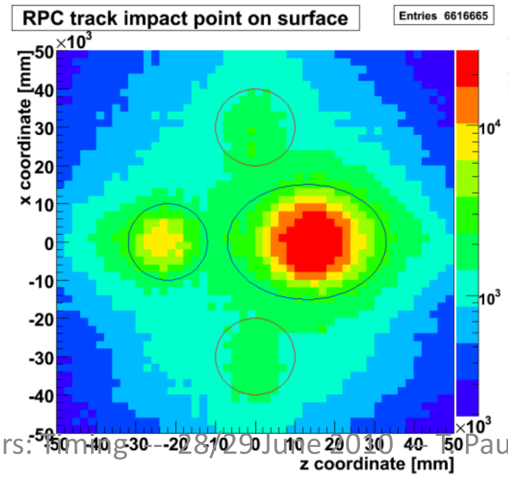


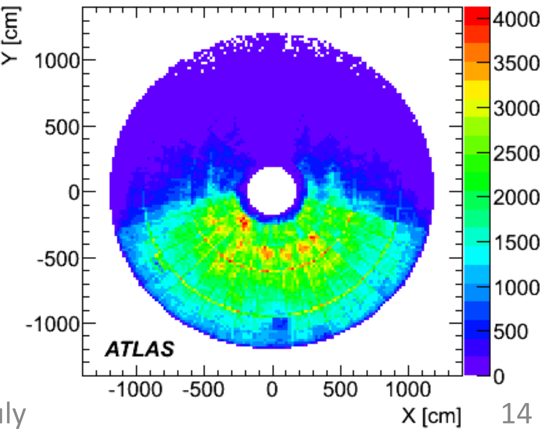
Timing with Cosmics

- Cosmics flux: O(Hz)
  - depending on geometry and momentum cuts
- Cosmics arrive out of phase to the 40 MHz clock
- Geometry not ideal
  - not like collisions
  - opposite timing in upper half, collision timing in the lower
  - time-of-flight corrections needed



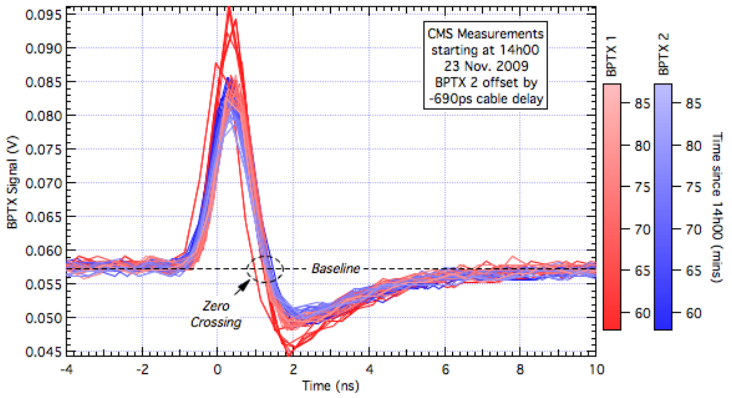


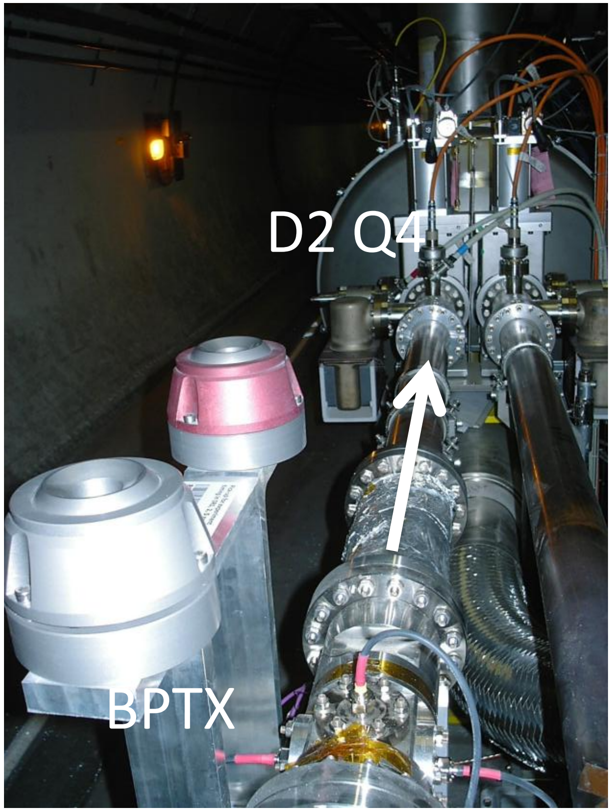


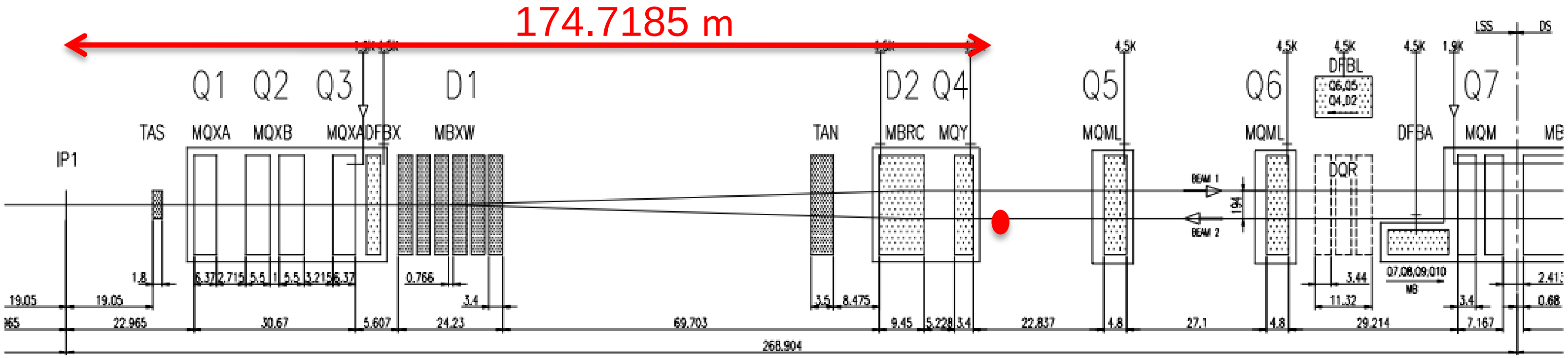


Beam Timing Pick-ups (BPTX)

- Beam pick-ups 175m upstream of each experiment
- Used as accurate (100ps) timing reference of the beams
  - very simple: passive device + 200m cable
- Used for Level-1 trigger

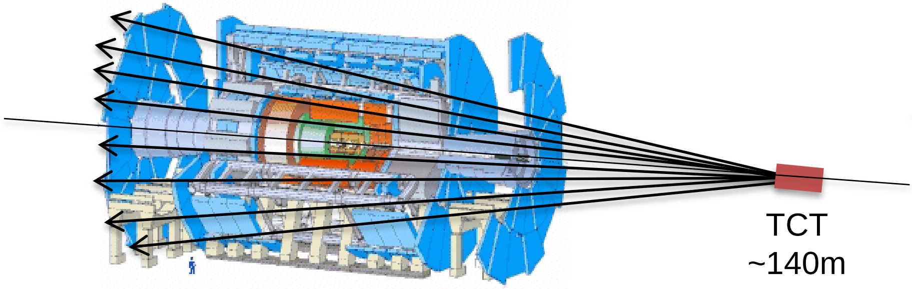


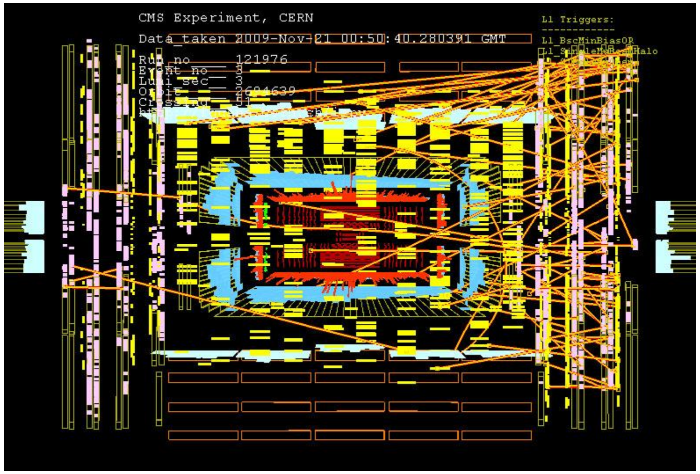




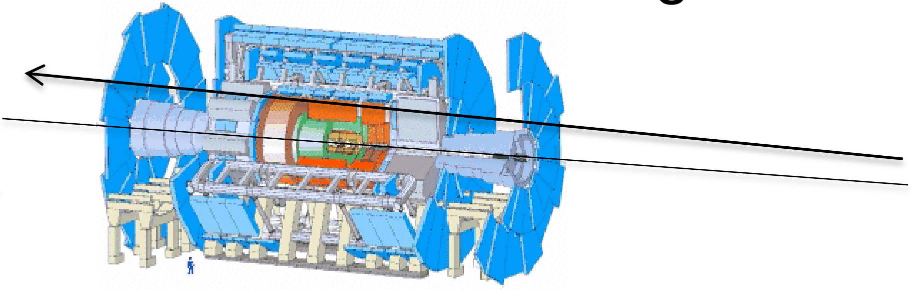
Timing with Single Beams, Splashes

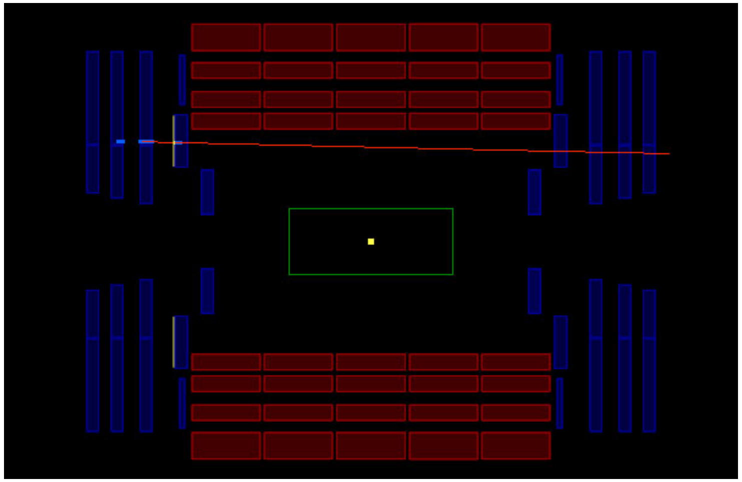
Collimator dumps: splashes





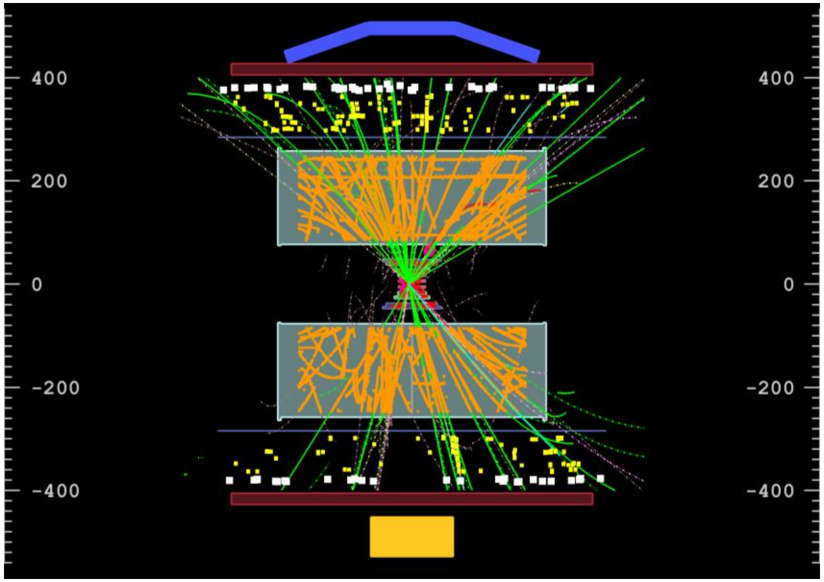
Beam-induced background





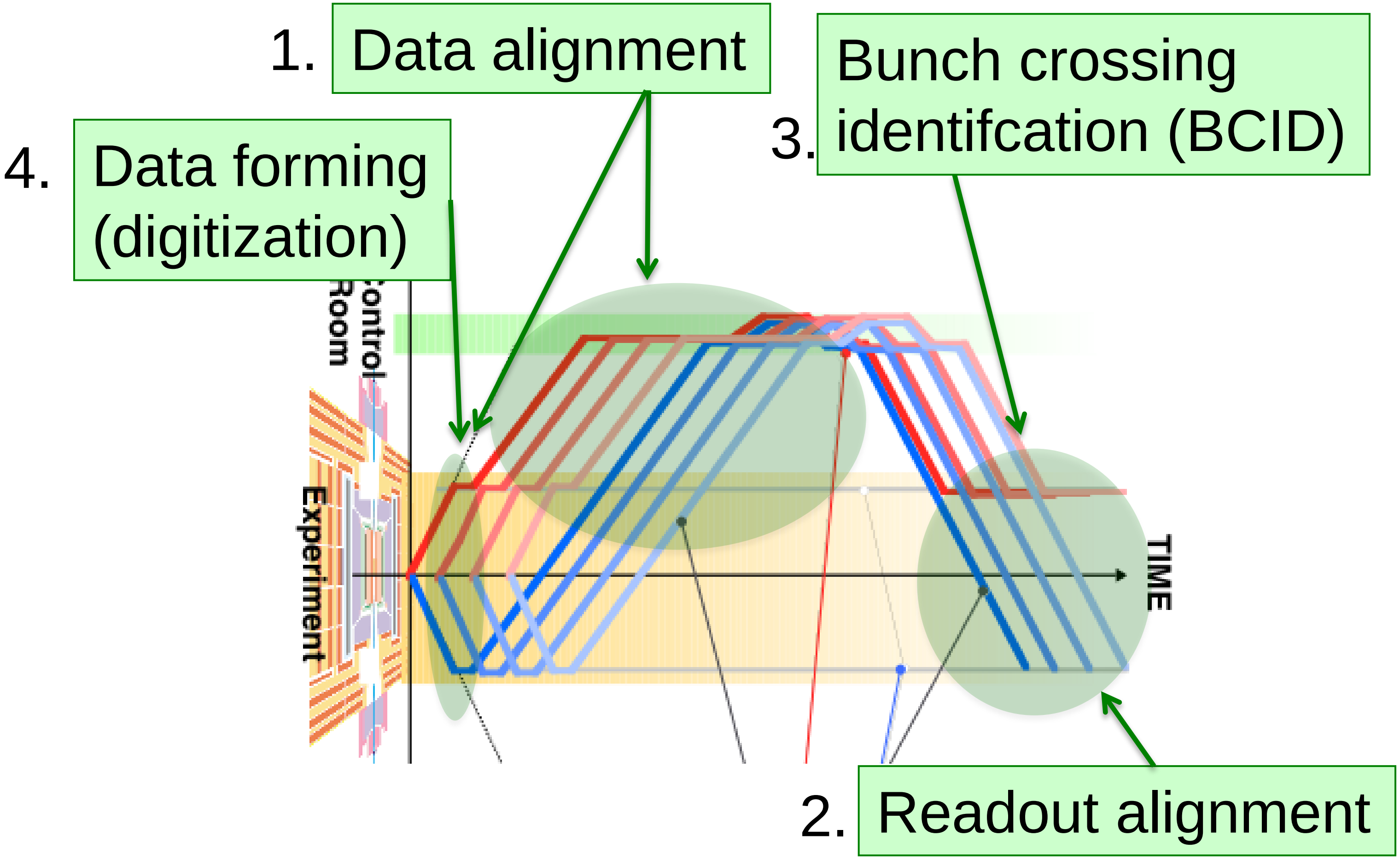
- particles roughly in phase with 40 MHz
- similar as collision timing for downstream forward detectors
- splashes: pulses sometimes saturated

Timing Setup with Collisions



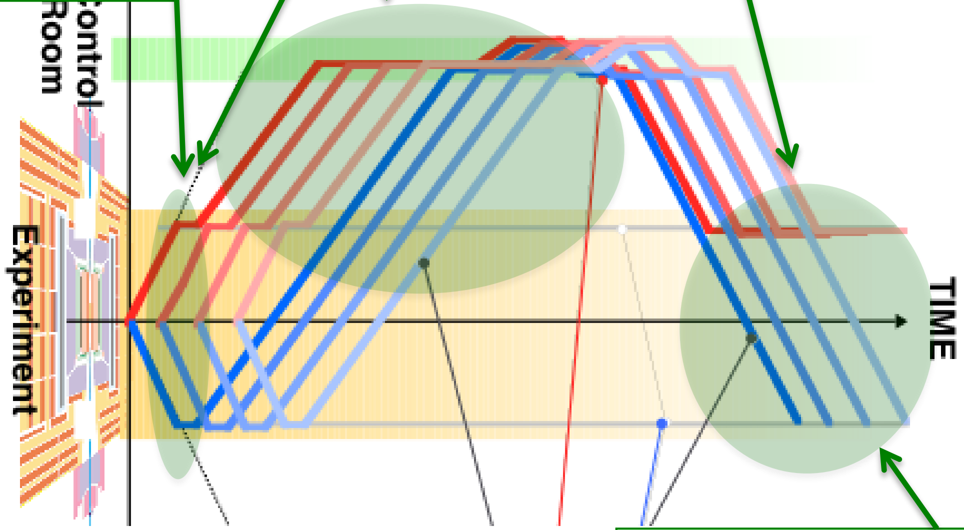
- Ideal geometry:
  - detector optimized for collisions
  - particles in phase with the 40 MHz clock
- Need large bunch spacing
  - much bigger than timing uncertainties (few BC)
- Need enough luminosity for timing in
  - for good data per channel, e.g. muons, or hadrons E_T>5 GeV

Timing Tasks



1. Data alignment
4. Data forming (digitization)
3. Bunch crossing identifcation (BCID)
2. Readout alignment

Timing Tasks



1. Data alignment

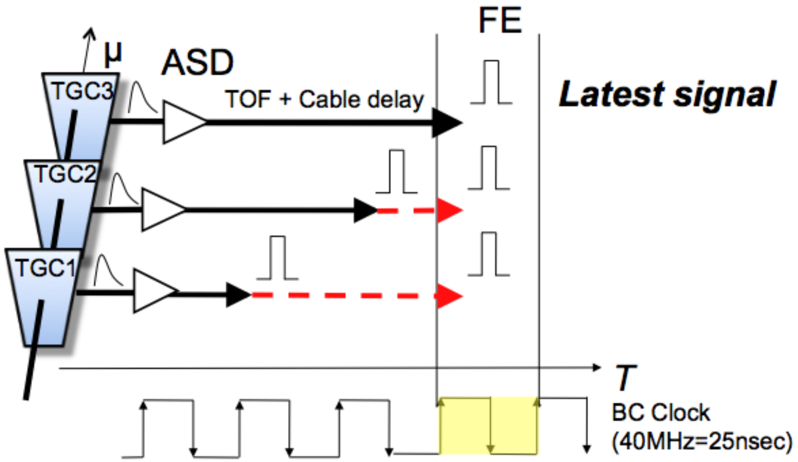
3. Bunch crossing identifcation (BCID)

4. Data forming (digitization)

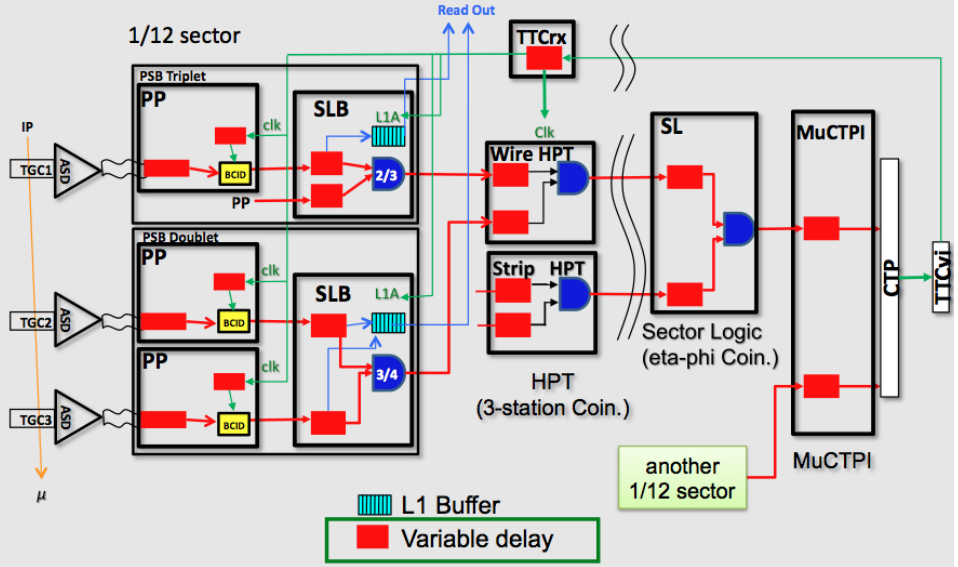
2. Readout alignment

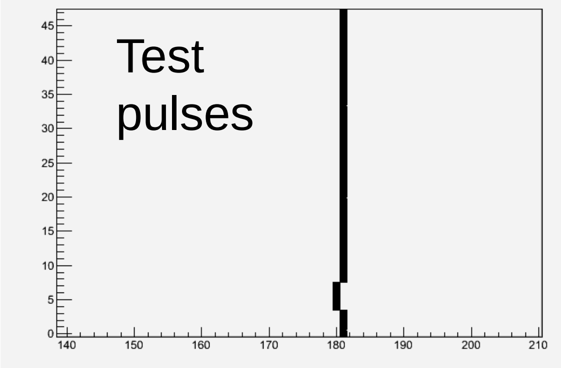
Data Alignment

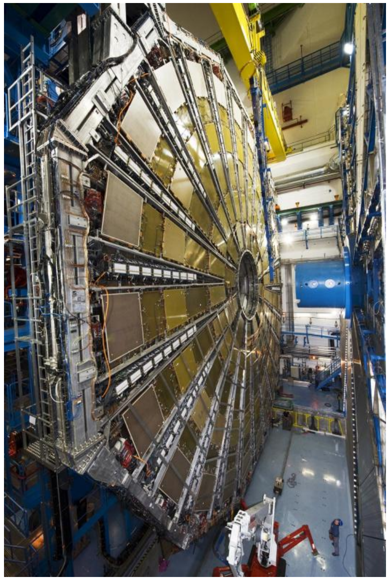
- At every stage of processing, data fragments must be aligned in time
  - fine alignment (<25ns)
  - coarse alignment (steps of 25ns)
- Data alignment typically uses a common reference, often in combination with detector readout
  - single pulse generator
  - cosmic muons
  - beams
- examples:
  - ATLAS Level-1 endcap muon trigger
  - ATLAS Level-1 calorimeter trigger
  - Global alignment of the Level-1 triggers with beam

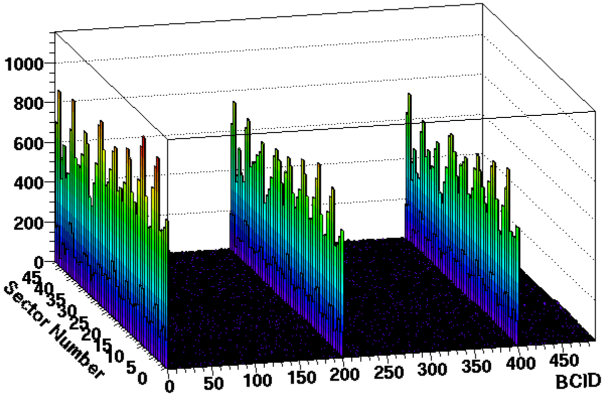


Data Alignment in the ATLAS Forward Muon Trigger (TGC)

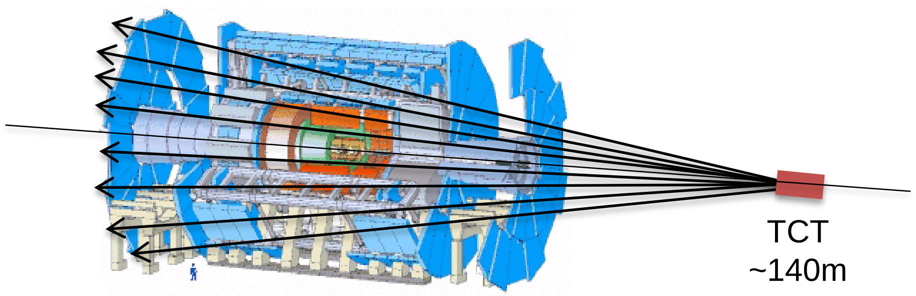


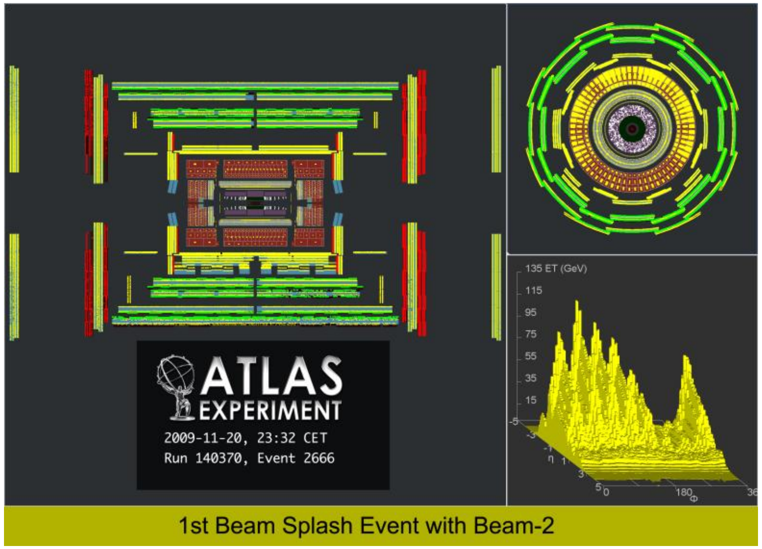




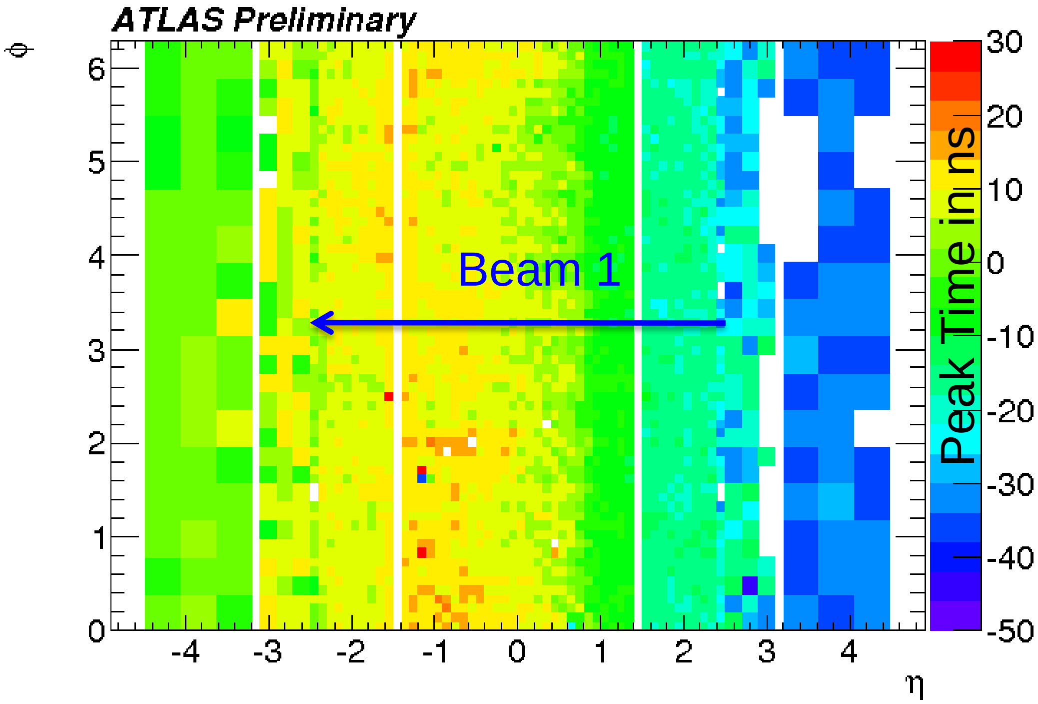


Data Alignment in the Level-1 Calorimeter Trigger





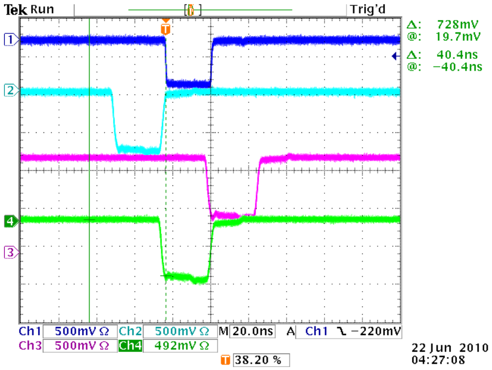
1st Beam Splash Event with Beam-2

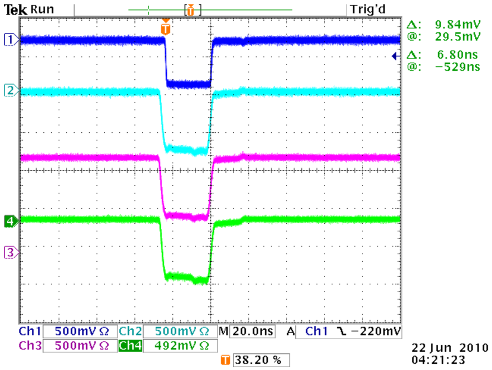


Achieved accuracy:
Cosmics: 25ns
Splashes: <5ns

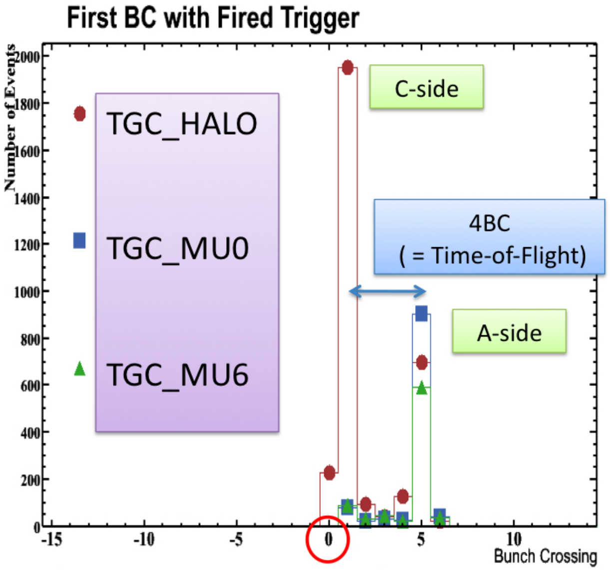
Global Data Alignment of the Level-1 Trigger

In general: timing with oscilloscope





Global timing alignment of ATLAS TGC muon trigger with single beam

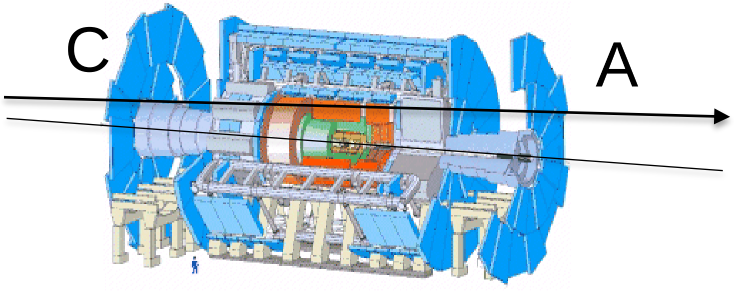


C-side

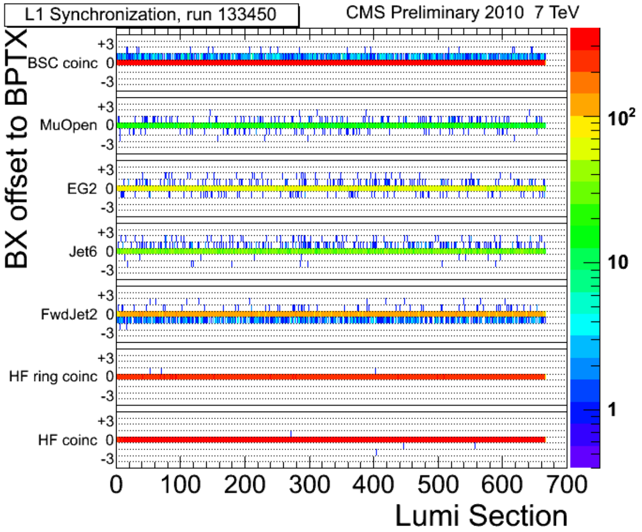
4BC
(= Time-of-Flight)

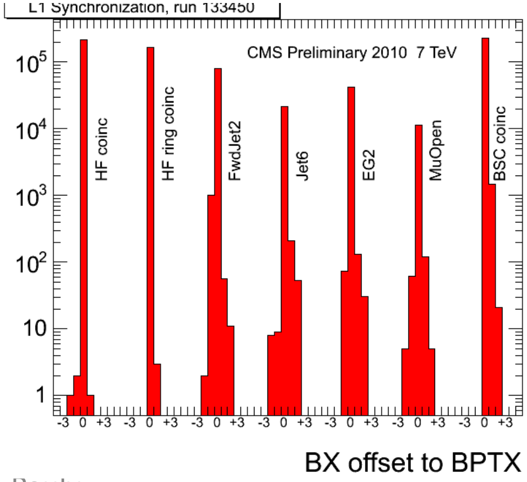
A-side

target timing (= BPTX2)

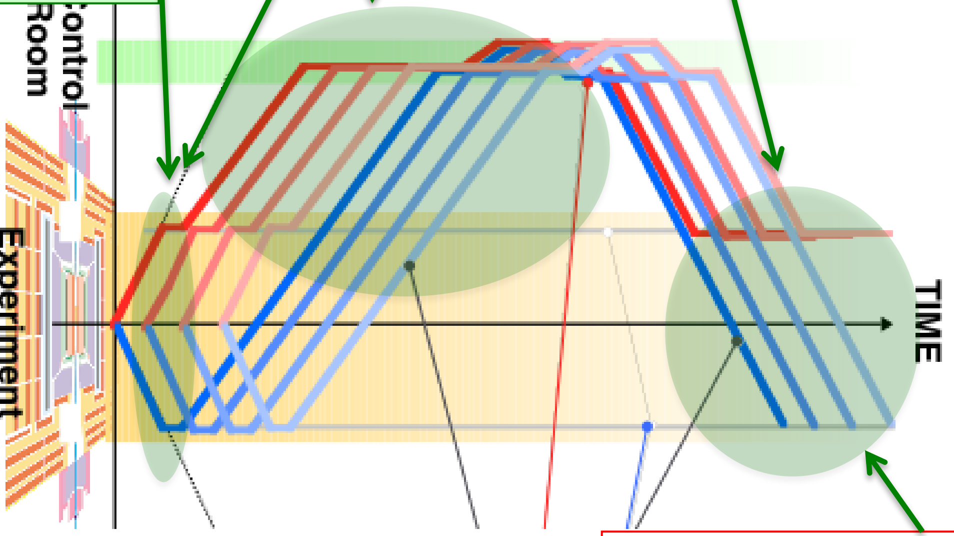


Global timing alignment of CMS Level-1 Trigger





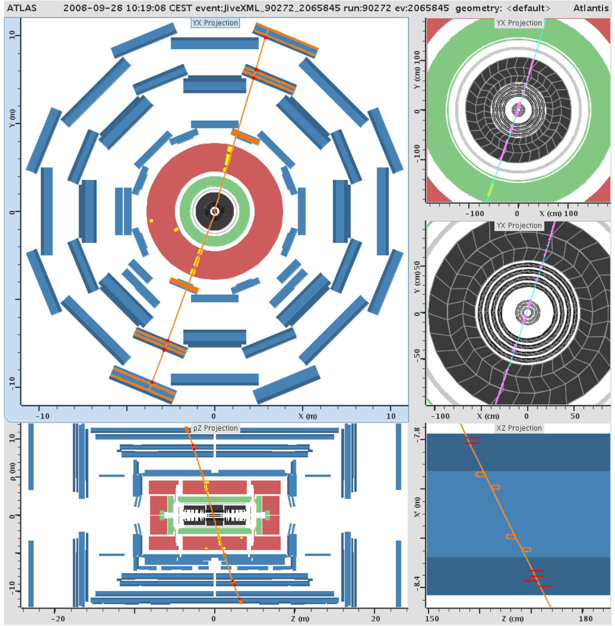
Timing Tasks

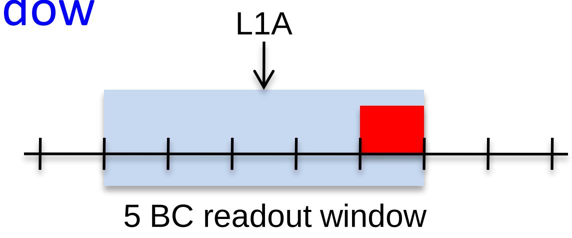


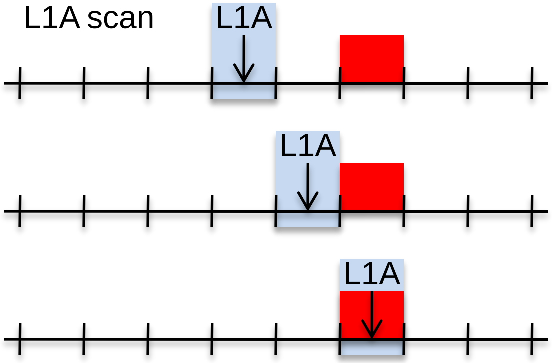
1. Data alignment
2. Readout alignment
3. Bunch crossing identifcation (BCID)
4. Data forming (digitization)

Readout Alignment

- Find the data in the Level-1 buffers
- Need to understand the trigger latency and distribution delays of the trigger decision
- Trigger with well-timed trigger, which provides a common timing reference
- Assumption: large bunch spacing
  - True for cosmics and commissioning beams
- Use enlarged sub-detector readout window

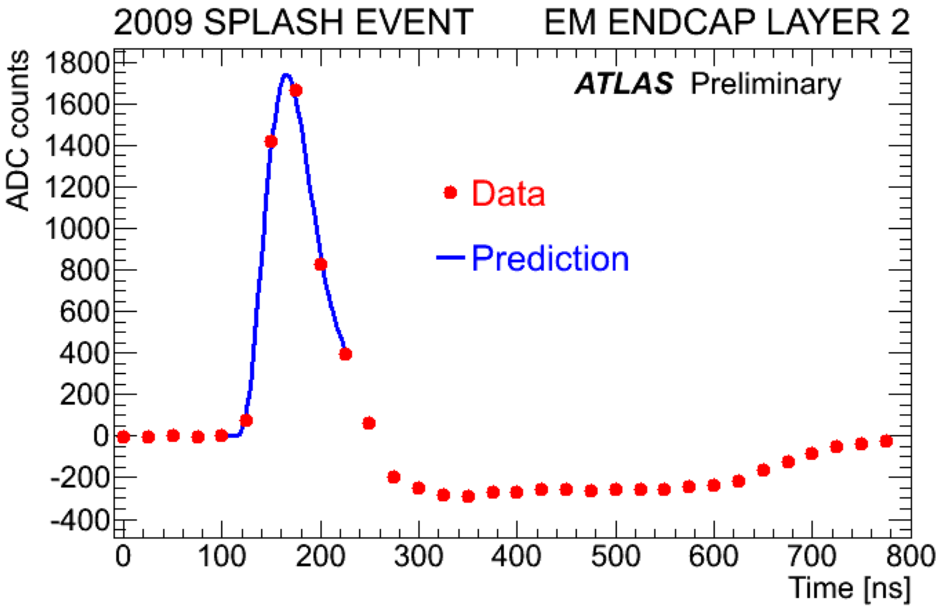


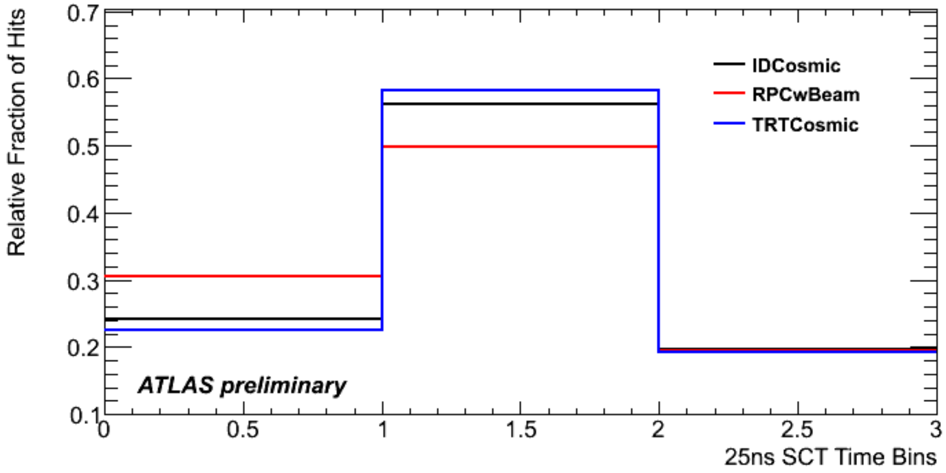


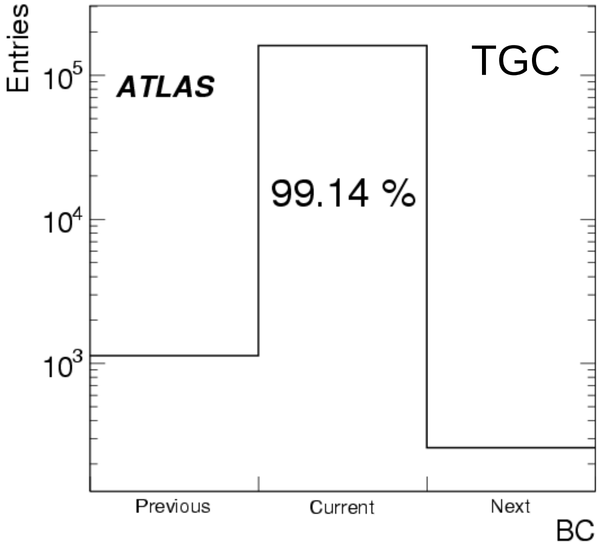


- Possibility of a delay scan for the L1A

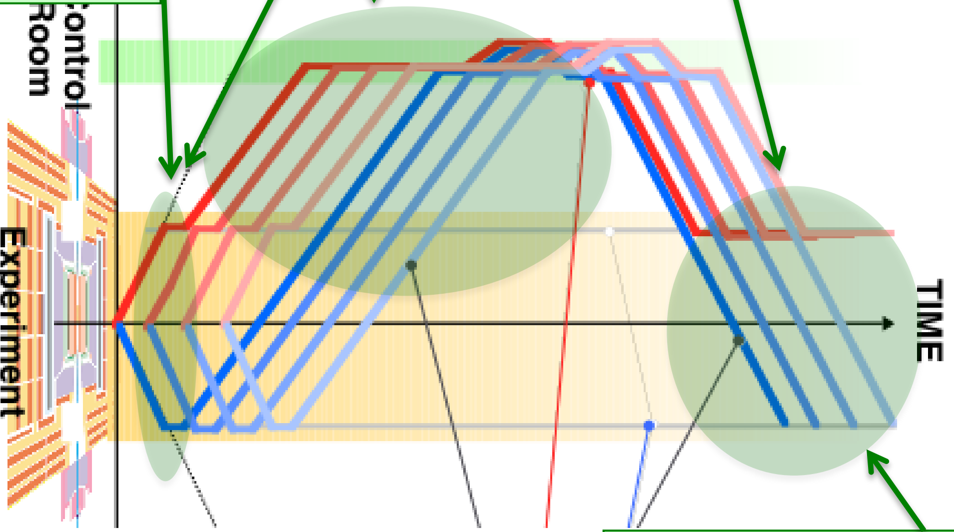
Readout Alignment: Examples







Timing Tasks



1. Data alignment

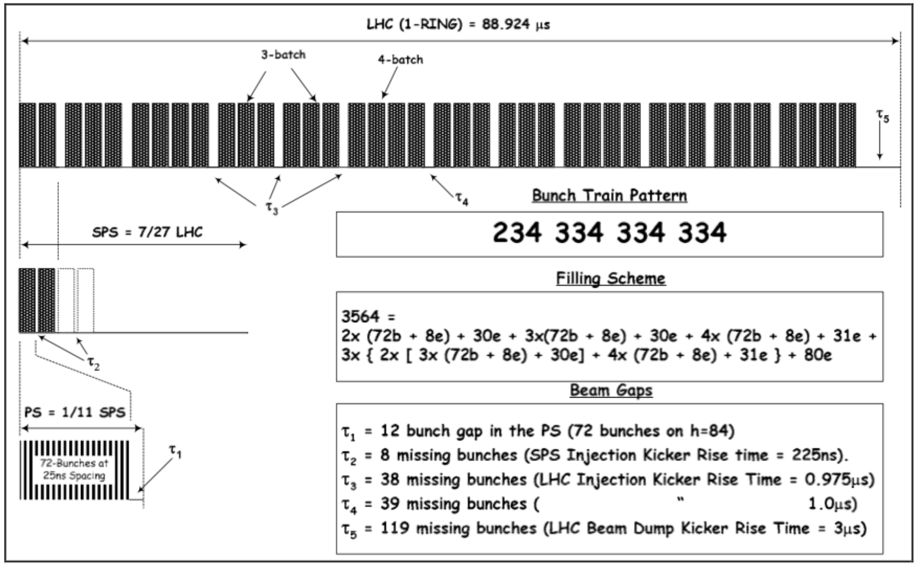
4. Data forming (digitization)

3. Bunch crossing identifcation (BCID)

2. Readout alignment

Bunch Crossing Identification

- Bunch crossing identifier (BCID)
  - a number from 0 to 3563, with 1 being the first bunch in the train (e.g. pilot bunch), just after the abort gap
- Sub-detector data fragments are all labeled with BCID, which is locally applied in the front-end
  - bunch counter increments with 40 MHz
  - reset (synchronized) with delayed LHC turn pulse
- Used as cross-check for readout synchronization in the various event building stages
  - if one sub-detector misses or get spurious L1A signals, it will show up as BCID mismatch
- BCID alignment from bottom to top:
  - first achieve BCID alignment within the sub-detectors (e.g. using cosmics)
  - achieve BCID alignment across sub-detectors within an experiment
  - align BCID with the machine
- Before we align with the machine, we have to BCID align the beams (RF cogging)



Bunch Train Pattern

234 334 334 334

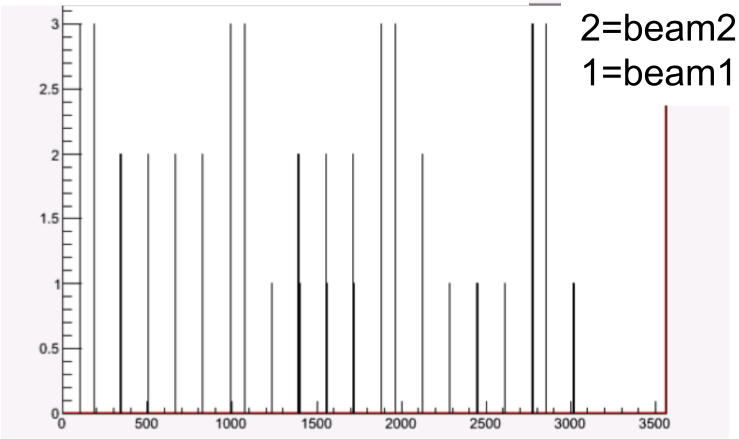
Filling Scheme

3564 =
2x (72b + 8e) + 30e + 3x(72b + 8e) + 30e + 4x (72b + 8e) + 31e +
3x { 2x [3x (72b + 8e) + 30e] + 4x (72b + 8e) + 31e } + 80e

Beam Gaps

τ_1 = 12 bunch gap in the PS (72 bunches on h=84)
τ_2 = 8 missing bunches (SPS Injection Kicker Rise time = 225ns).
τ_3 = 38 missing bunches (LHC Injection Kicker Rise Time = 0.975µs)
τ_4 = 39 missing bunches (" 1.0µs)
τ_5 = 119 missing bunches (LHC Beam Dump Kicker Rise Time = 3µs)

16 x 16 scheme

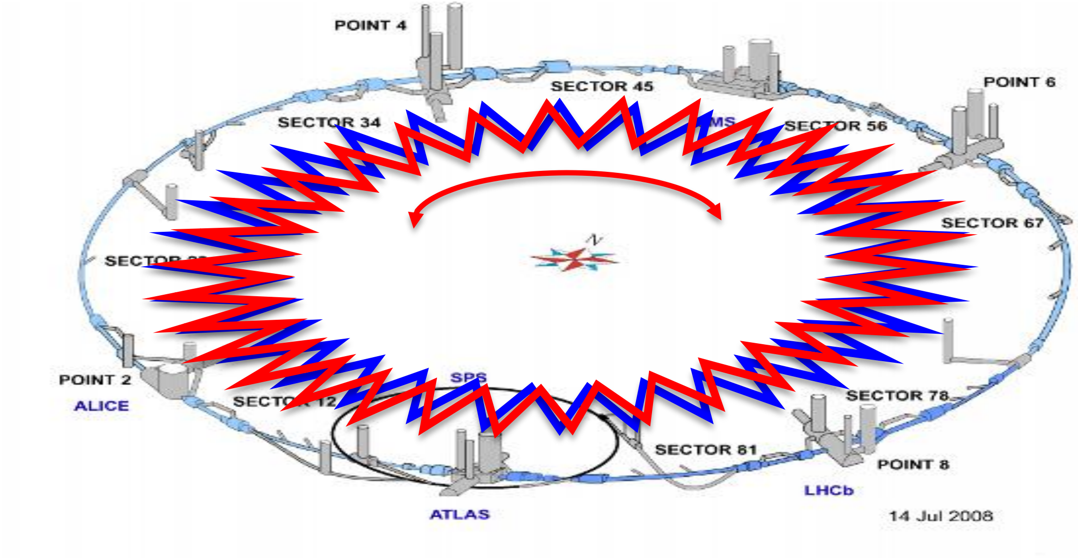


3=beam1+2
2=beam2
1=beam1

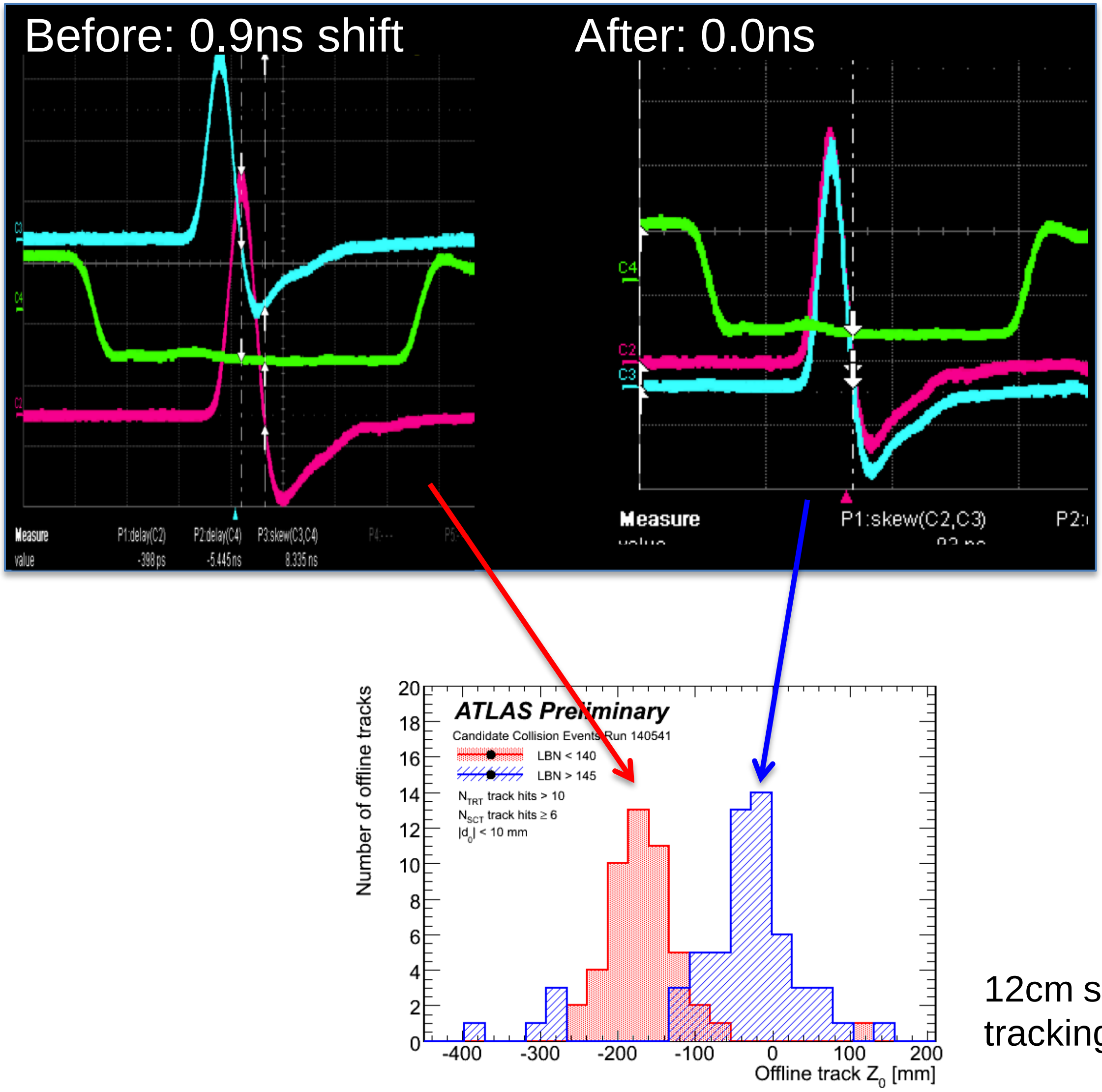
RF Cogging

- Independent RF cavities for each ring
  - Can rotate the beams wrt to each other
- Cogging: rotate one beam with respect to the other in order to get collisions in the experiments' interaction point
- Use experiments' beam timing pick-ups:

  $\Delta T = t_{Beam1} - t_{Beam2}$
- Done for example on 19 Mar 2010: ATLAS and CMS measured -2495ns for the longitudinally displaced beams
  - confirmation: 30 Mar 2010, collisions in the middle of the detector

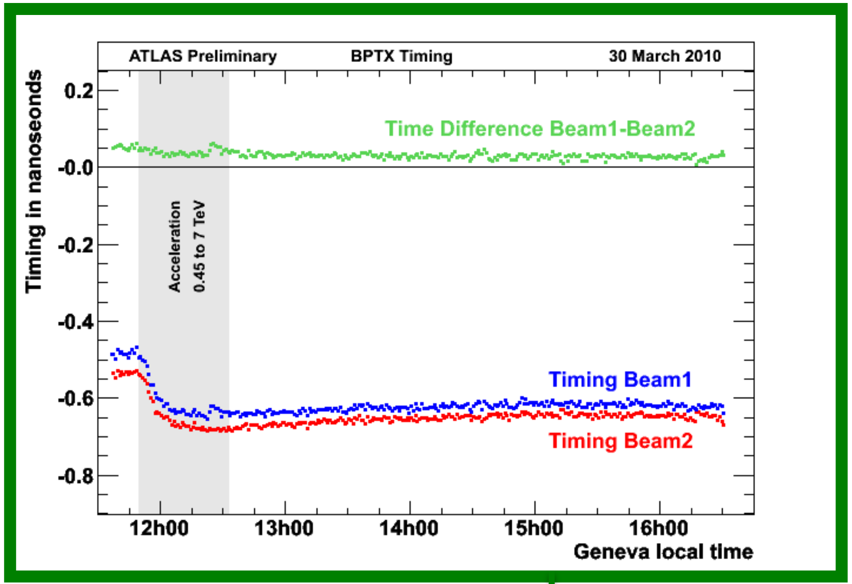


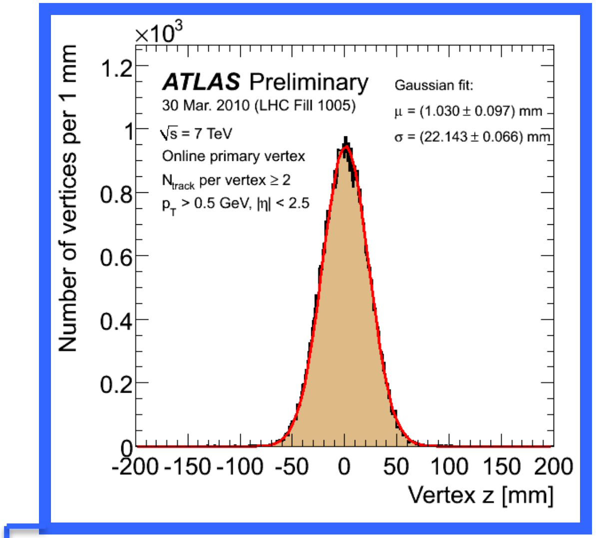
RF Cogging: Fine-tuning

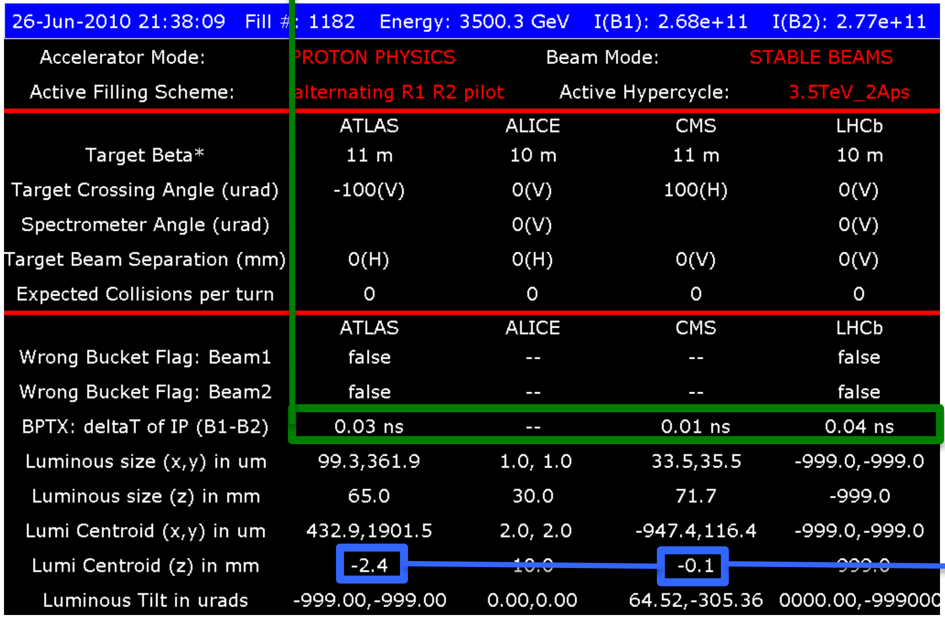


12cm shift observed in tracking

RF Timing and Longitudinal Beamspot





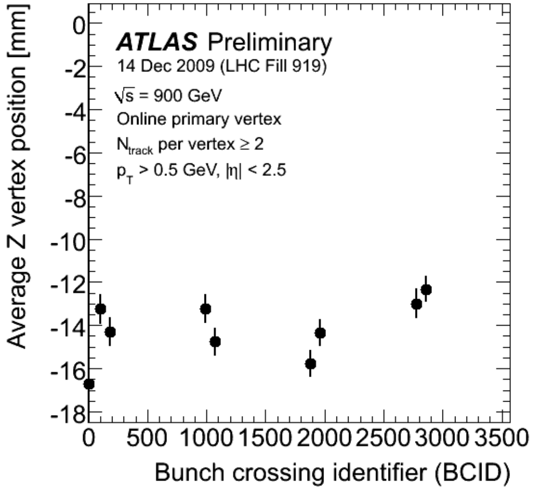


26-Jun-2010 21:38:09 Fill #: 1182 Energy: 3500.3 GeV I(B1): 2.68e+11 I(B2): 2.77e+11

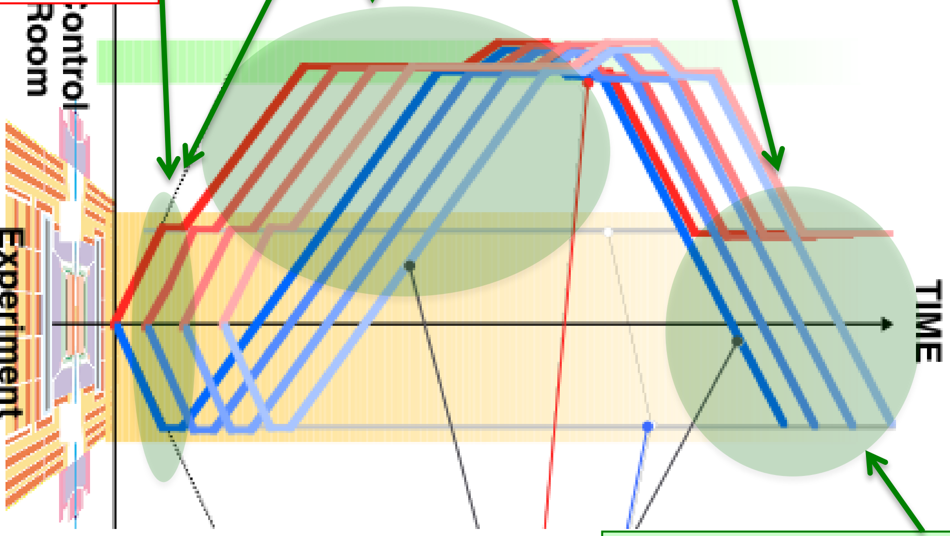
Accelerator Mode:	PROTON PHYSICS	Beam Mode:	STABLE BEAMS
Active Filling Scheme:	alternating R1 R2 pilot	Active Hypercycle:	3.5TeV_2Aps

	ATLAS	ALICE	CMS	LHCb
Target Beta*	11 m	10 m	11 m	10 m
Target Crossing Angle (urad)	-100(V)	0(V)	100(H)	0(V)
Spectrometer Angle (urad)		0(V)		0(V)
Target Beam Separation (mm)	0(H)	0(H)	0(V)	0(V)
Expected Collisions per turn	0	0	0	0

	ATLAS	ALICE	CMS	LHCb
Wrong Bucket Flag: Beam1	false	--	--	false
Wrong Bucket Flag: Beam2	false	--	--	false
BPTX: deltaT of IP (B1-B2)	0.03 ns	--	0.01 ns	0.04 ns
Luminous size (x,y) in um	99.3,361.9	1.0, 1.0	33.5,35.5	-999.0,-999.0
Luminous size (z) in mm	65.0	30.0	71.7	-999.0
Lumi Centroid (x,y) in um	432.9,1901.5	2.0, 2.0	-947.4,116.4	-999.0,-999.0
Lumi Centroid (z) in mm	-2.4	10.0	-0.1	-999.0
Luminous Tilt in urads	-999.00,-999.00	0.00,0.00	64.52,-305.36	0000.00,-99900



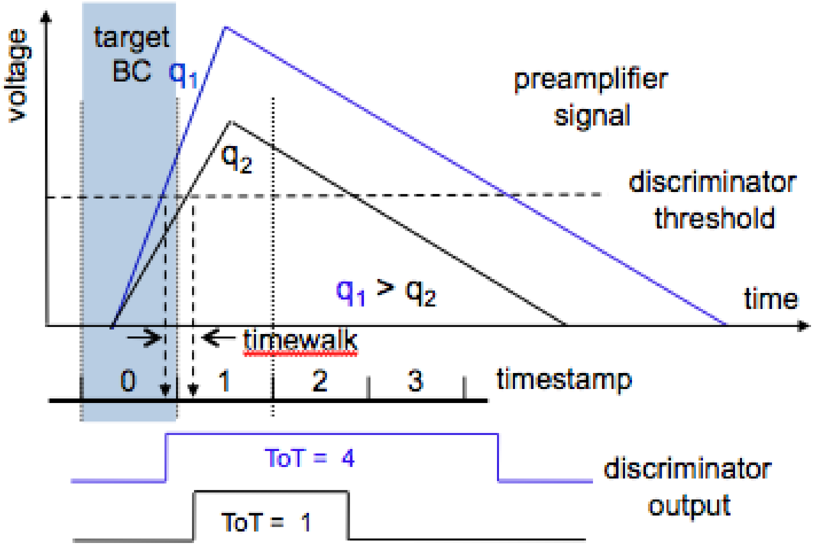
Timing Tasks

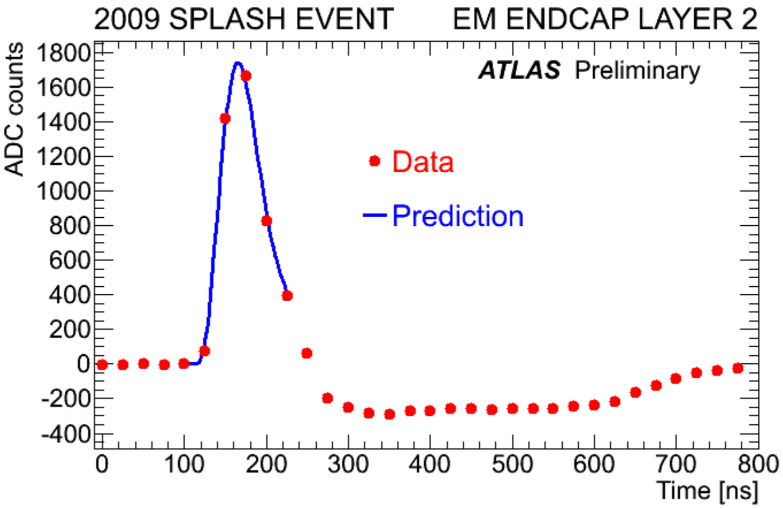


1. Data alignment
2. Readout alignment
3. Bunch crossing identifcation (BCID)
4. Data forming (digitization)

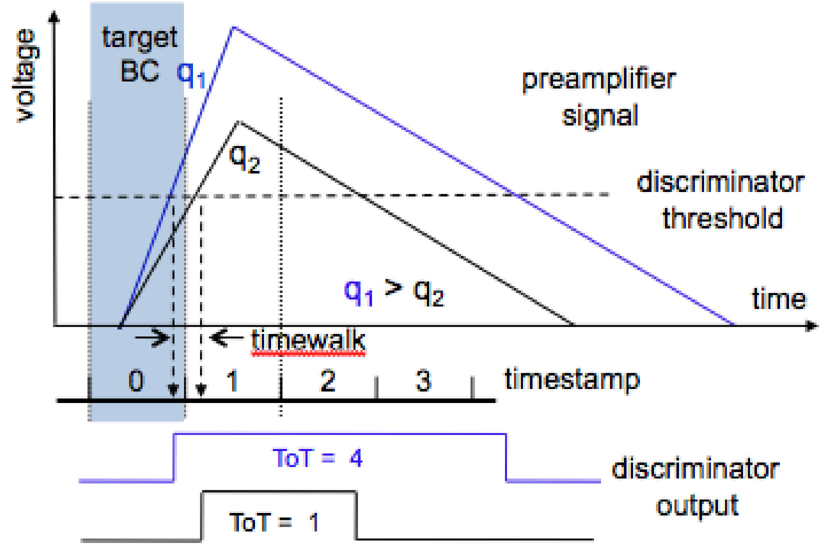
Data Forming

- e.g. digitization or discrimination of the detector signals
- Optimal phase relationship between clock and collisions
  - often tuned with a fine-delay scan (local clock shift in small steps)
    - move clock in small steps and observe break down in efficiency or bunch crossing identification
- Phase of clock with respect to collision/bunch must be stable
  - sometimes to better than 1ns
  - long-term drift (3ns) of LHC clock identified
    - Temperature acting on optical fibres



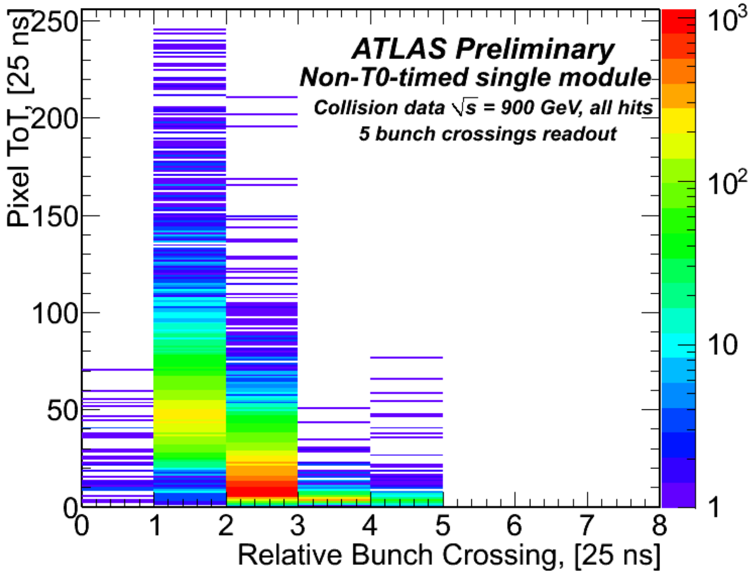


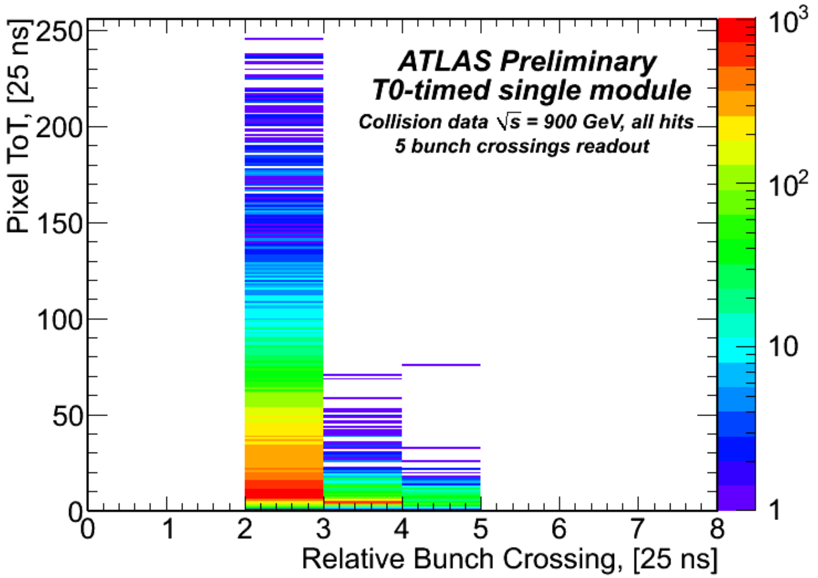
Data Forming for ATLAS Pixel detector



Sampling clock phase relative to collision timing must be optimized for collection of pixel hits in a single bunch crossing

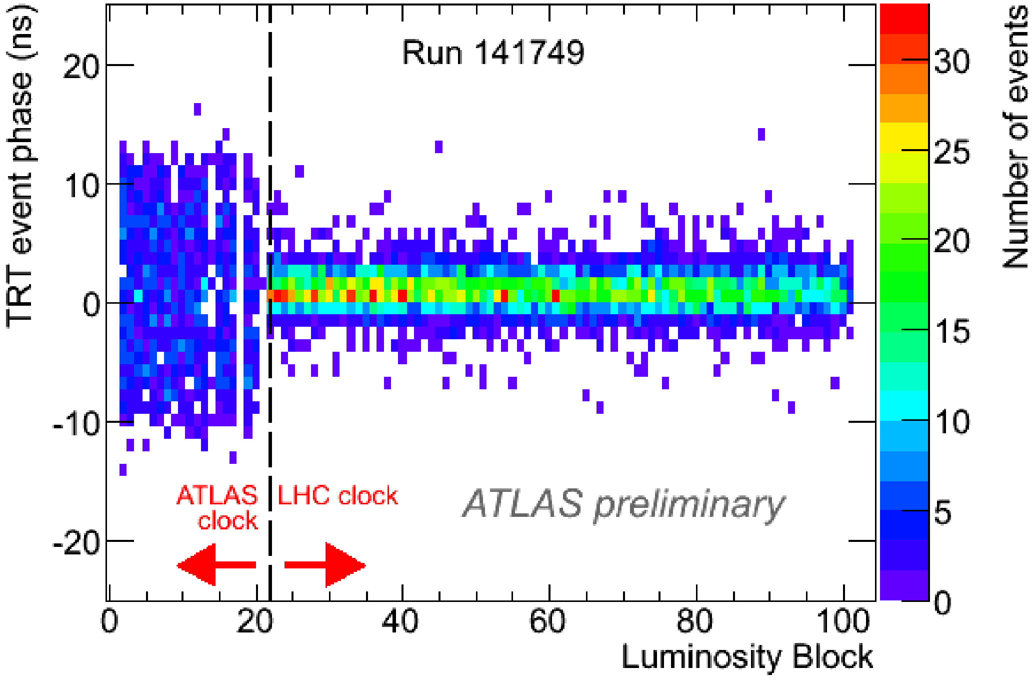
- clock delay scan in steps of 1 ns to find the ideal timing



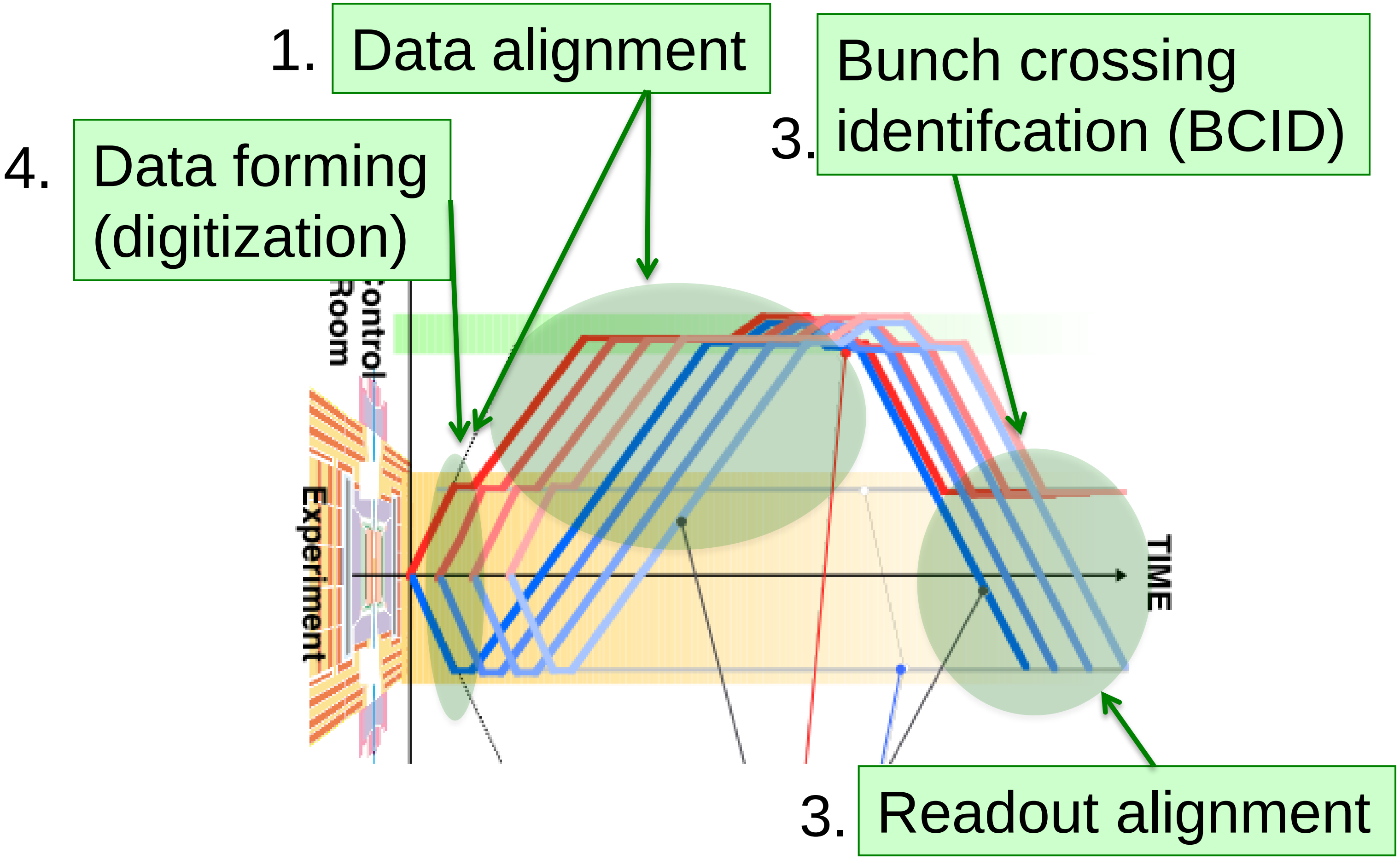


Example: Data Forming

Data forming with internal and external clock



Timing Tasks



1. Data alignment

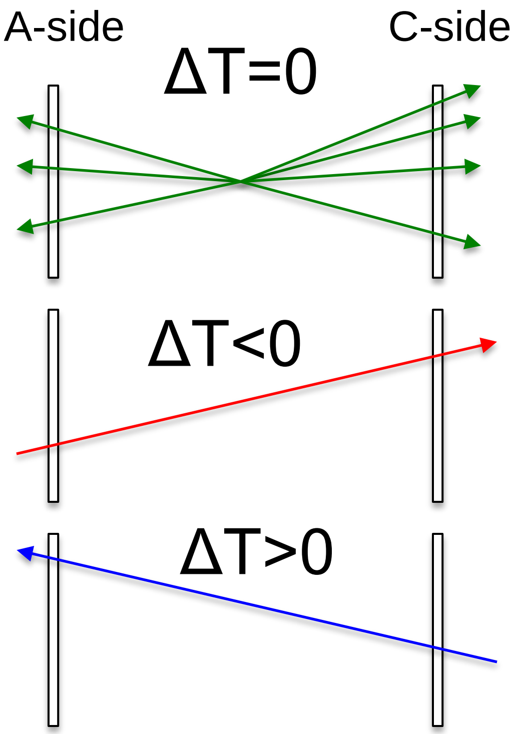
3. Bunch crossing identifcation (BCID)

4. Data forming (digitization)

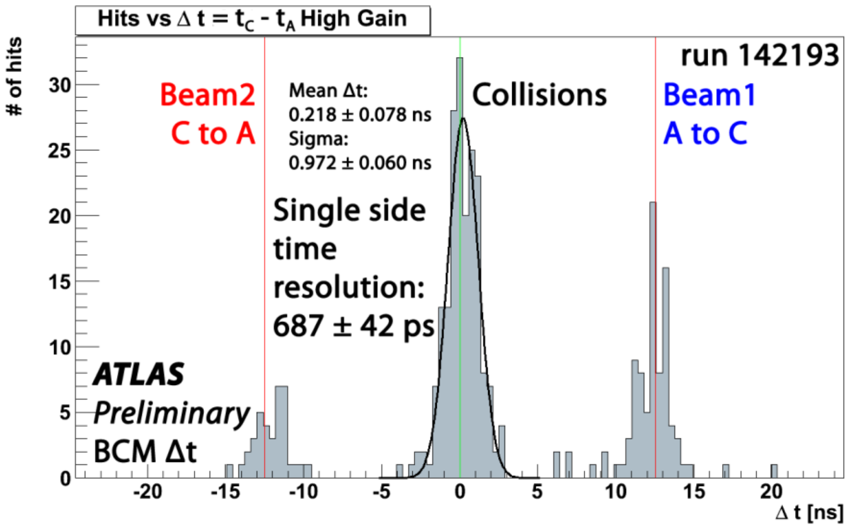
3. Readout alignment

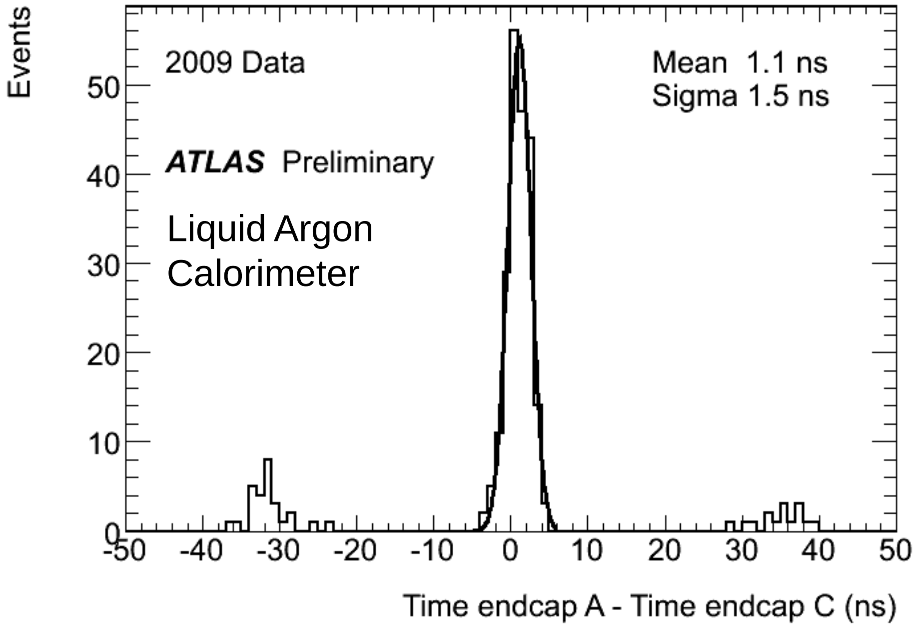
Time the Events

$\Delta T = t_A - t_C$

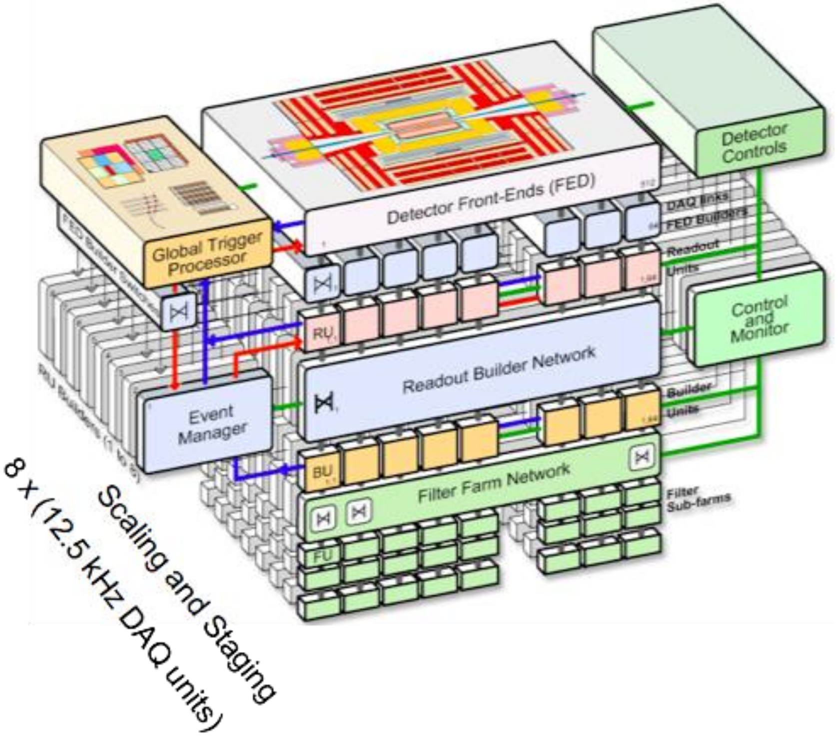


Suppress background with timing





Using Timing in High-Level Trigger and Event Building

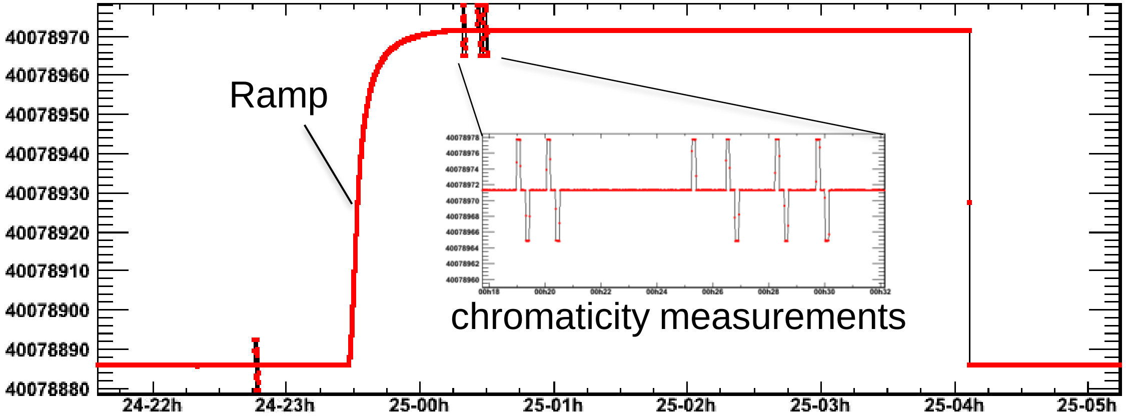


- Asynchronous path, high-level trigger and event building rely on a well timed-in front-end read-out
  - based on order of event fragments (up to FED/ROD)
  - identifier-based afterwards

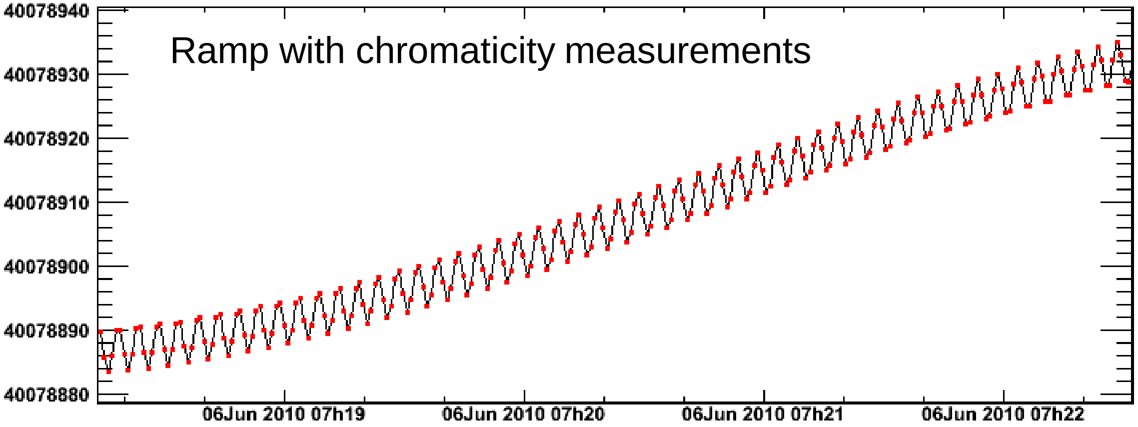
- De-synchronization due to failures, e.g.
  - data jam (large occupancy, trigger bursts)
  - problems in the timing distribution (missing or spurious L1A)
  - 40 MHz clock instabilities
- De-synchronization often results in
  - corrupted event data fragments
  - mixed-up event fragments (BCID provides cross-check)
  - sub-detector busy: no data-taking
- Remedies:
  - (partially) take out sub-detector of the readout (during a run or stop & re-start)
  - reset sub-detector (part) and re-synchronize it with the rest of the experiment

RF clock instabilities

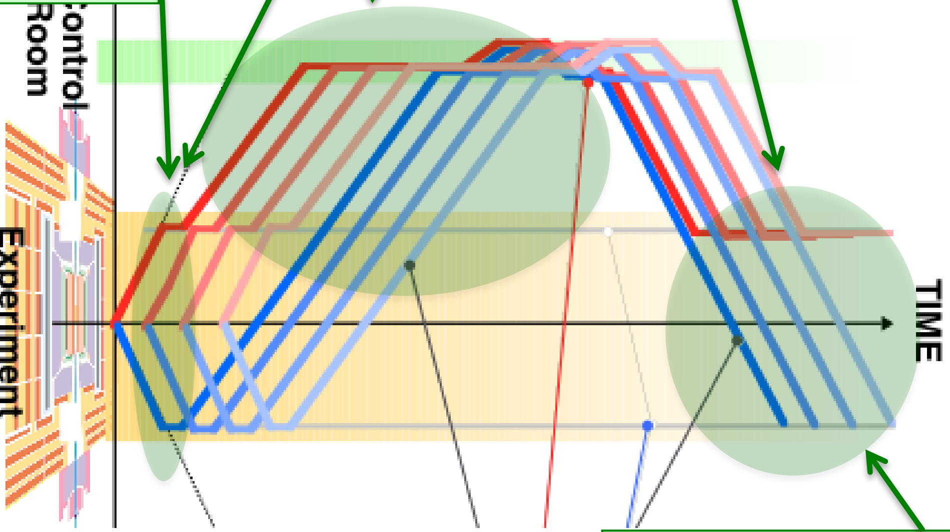
- LHC RF 40 MHz clock is for digitization, but also for high-speed Gigabit readout links
  - stringent requirements on the clock quality (jitter, frequency and phase)



- Clock is not always as stable as we would like it to be:
  - Energy ramp (0.45-3.5 TeV)
  - Jumps (e.g. chromaticity measurements)
  - sometimes leads to de-synchronization of individual sub-detectors or parts of it



Summary



1. Data alignment

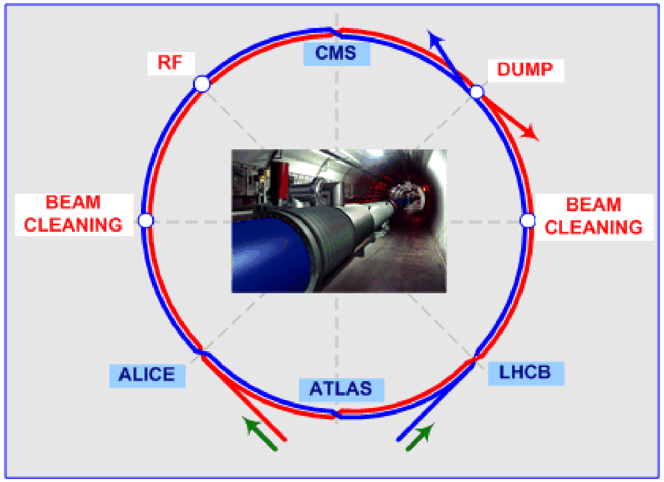
3. Bunch crossing identifcation (BCID)

4. Data forming (digitization)

3. Readout alignment

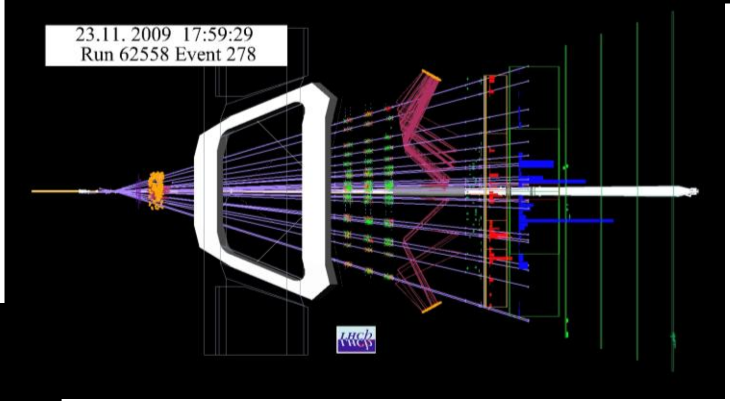
How to trigger on a media day?

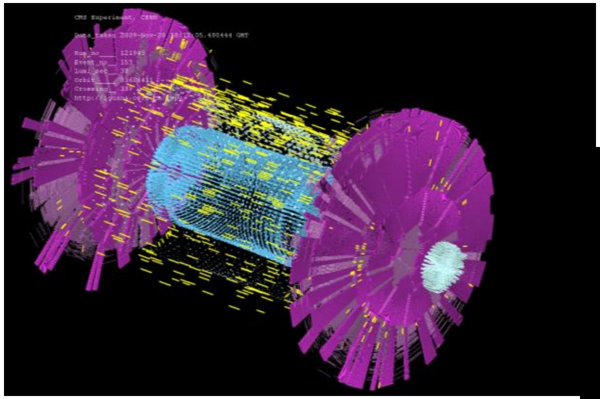
- e.g. 10 Sept 2008, 19 Nov 2009, 30 Mar 2010
- Lots of pressure to trigger and readout the first event
- For some of us, this was the first time we saw beam
- Worries:
  - Which trigger are we going to use?
    - sensitive enough?
    - good timing? not too early, not too late
  - Will the read-out be ok? busy?
  - Will collisions be in the centre of the detector?

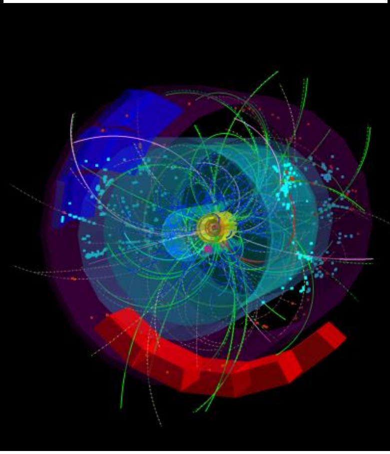


But ...

How to trigger on a media day?







... we all managed. Thanks to the preparatory works of many people over the past years.