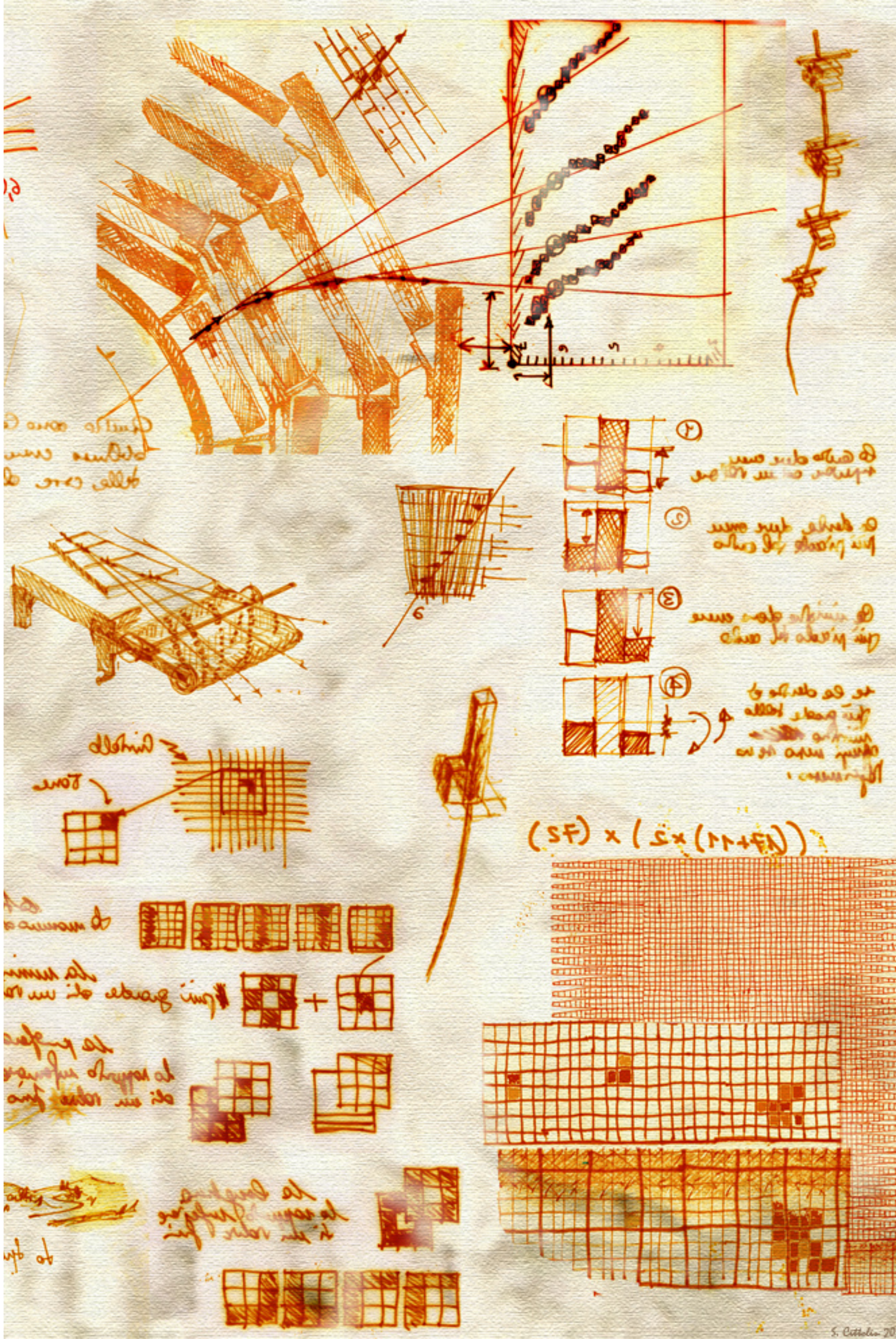
A brief lecture on

DAQ & Trigger

HighRR lecture week

School Horneck, February 2022

Rainer Stamen, Hans-Christian Schultz-Coulon
Kirchhoff-Institut für Physik
Heidelberg University



Content

- Prologue: “Introducing the subject”
- Part 1: “The TDAQ Challenges of today"
- Part 2: “Concepts, dead Time and Buffering”
- Part 3: “Realising trigger Systems”
- Epilogue: “Synchronisation Challenge by Example”

Disclaimer

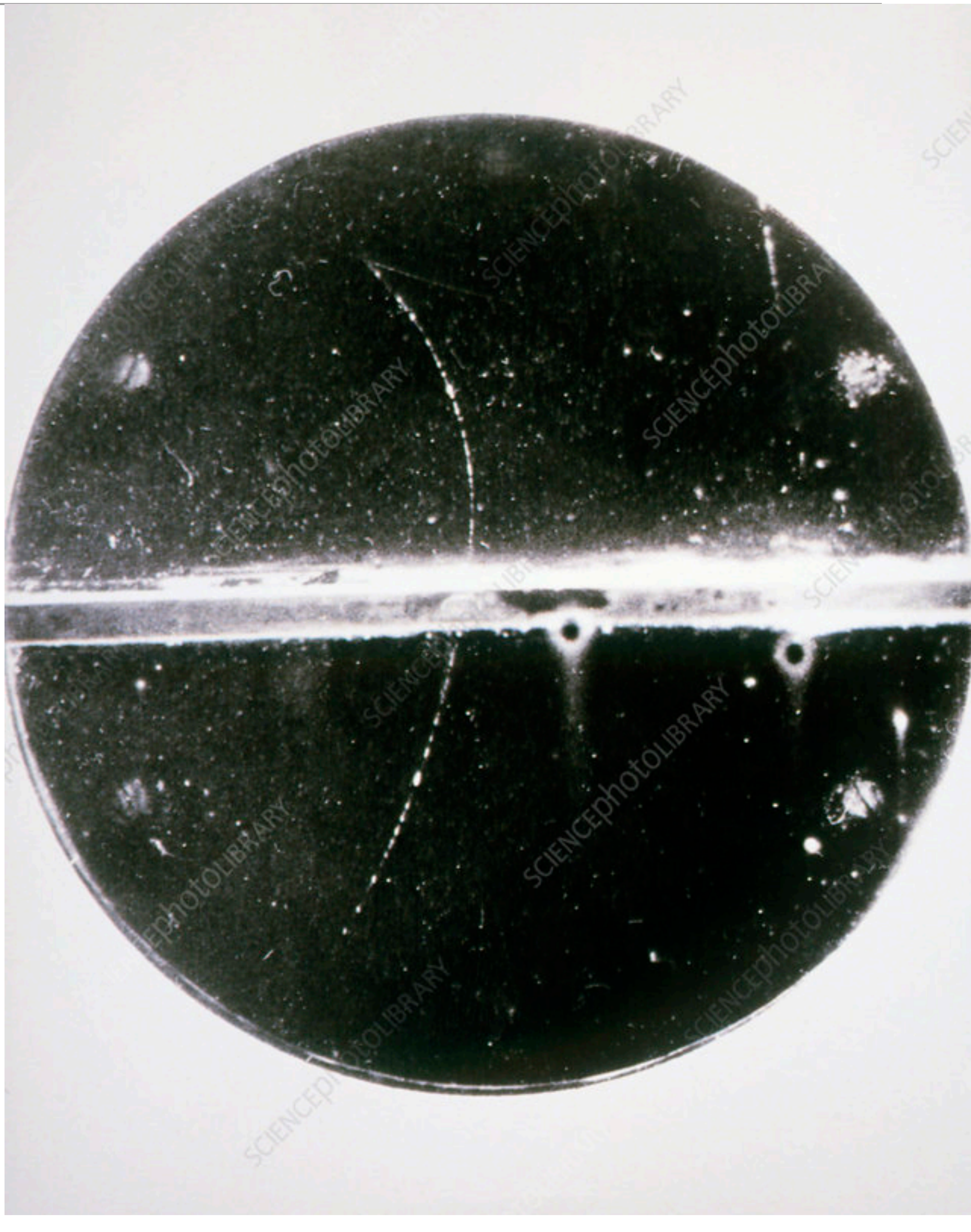
- TDAQ: Very wide field
  - Trigger: L1, HLT
  - DAQ: Data Flow, Data Model, Storage, Data Bases
  - Hardware, Firmware, Software
  - Trigger Menu, Run Strategy, Operation, Monitoring
  - pp, ep, ee, mu3e, …
- Will cover here:
  - Mainly L1 Hardware Triggers at the LHC
  - (Some) Concepts, Examples

Prologue

"Introducing the Subject"

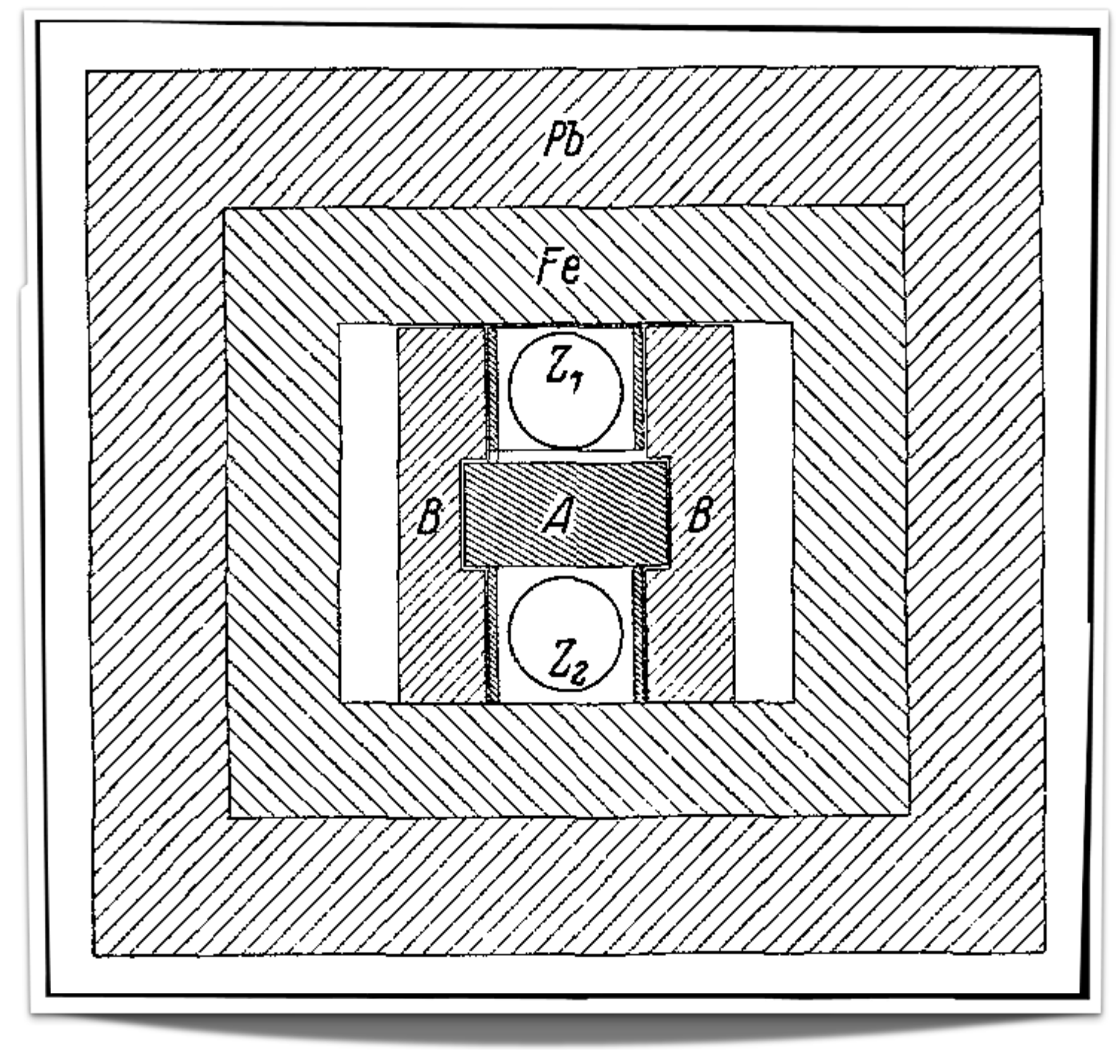
How did it start?

- Discovery of the positron by Anderson, 1932
  - random cloud chamber pictures
  - positively charged, $q < 2|e^-|$
  - mass $< 20\, m_e$
- Nobel Prize 1936
- Limitations:
  - low efficiency (10/1300)
  - no way to easily improve precision
  - no information about production mechanism
- Technological progress needed



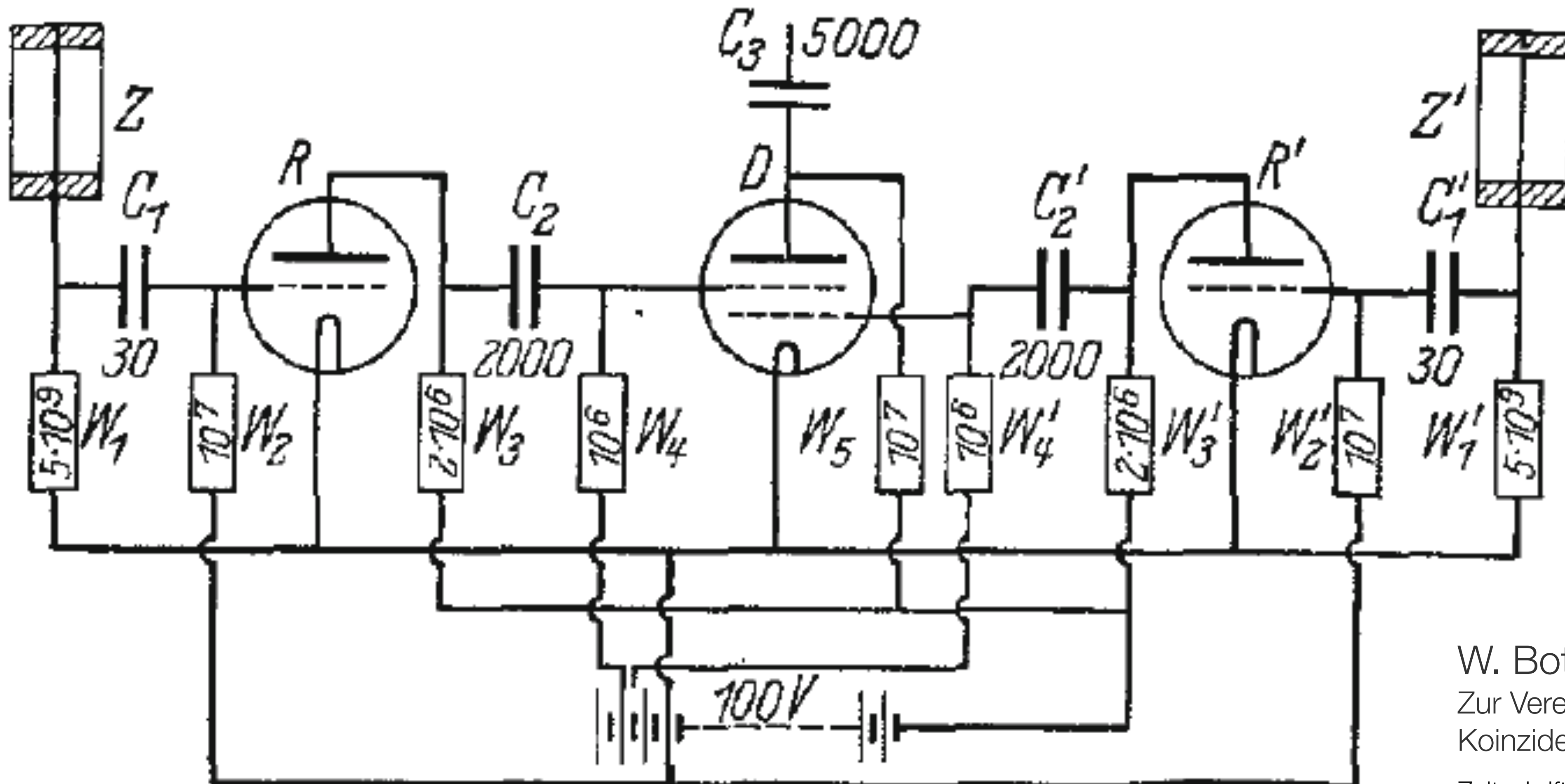
How did it start?

- 1924: Bothe: “Coincidence Method” (electromechanical device)
  - Nobel Prize 1953 (Bothe)
- 1929: Bothe: pure (complex) electrical circuit
- 1930: Rossi came up with a significantly improved circuit
- 1931: Occhialini (Rossis 1st. PhD student) becomes Postdoc with Blackett
- 1932: Design of first triggered cloud chamber
  - Nobel Prize 1948 (Blackett)



Bothe, Kohlhörster
Zeitschrift für Physik 56 (1929)

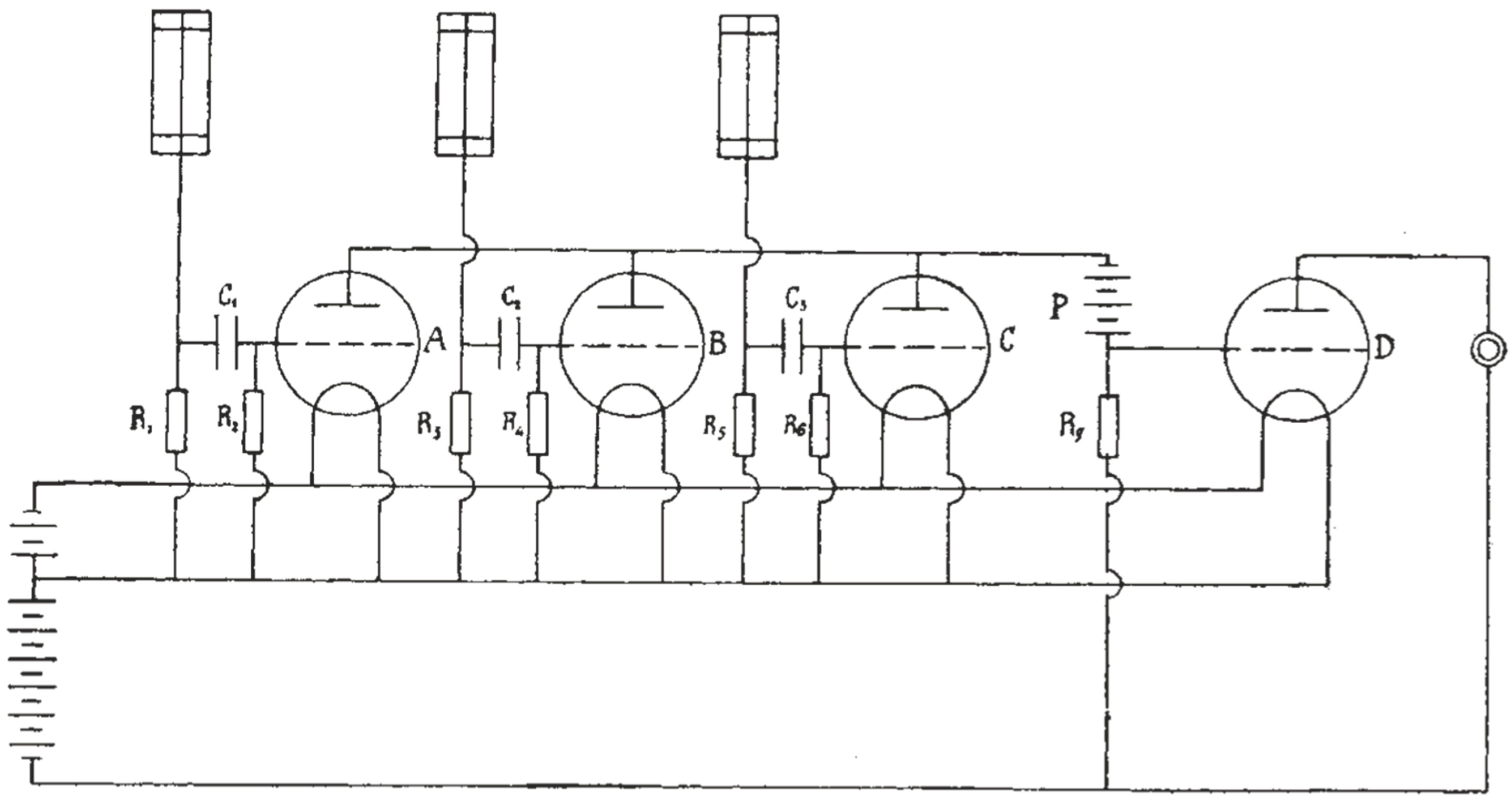
Bothes coincidence circuit (1929)



W. Bothe
Zur Vereinfachung von Koinzidenzzählungen
Zeitschrift für Physik 59 (1930)

- First fully electrical coincidence circuit
    - needs tetrodes (complex components), fine tuning of the voltages needed
    - limited to 2-coincidences

Rossis coincidence circuit (1930)

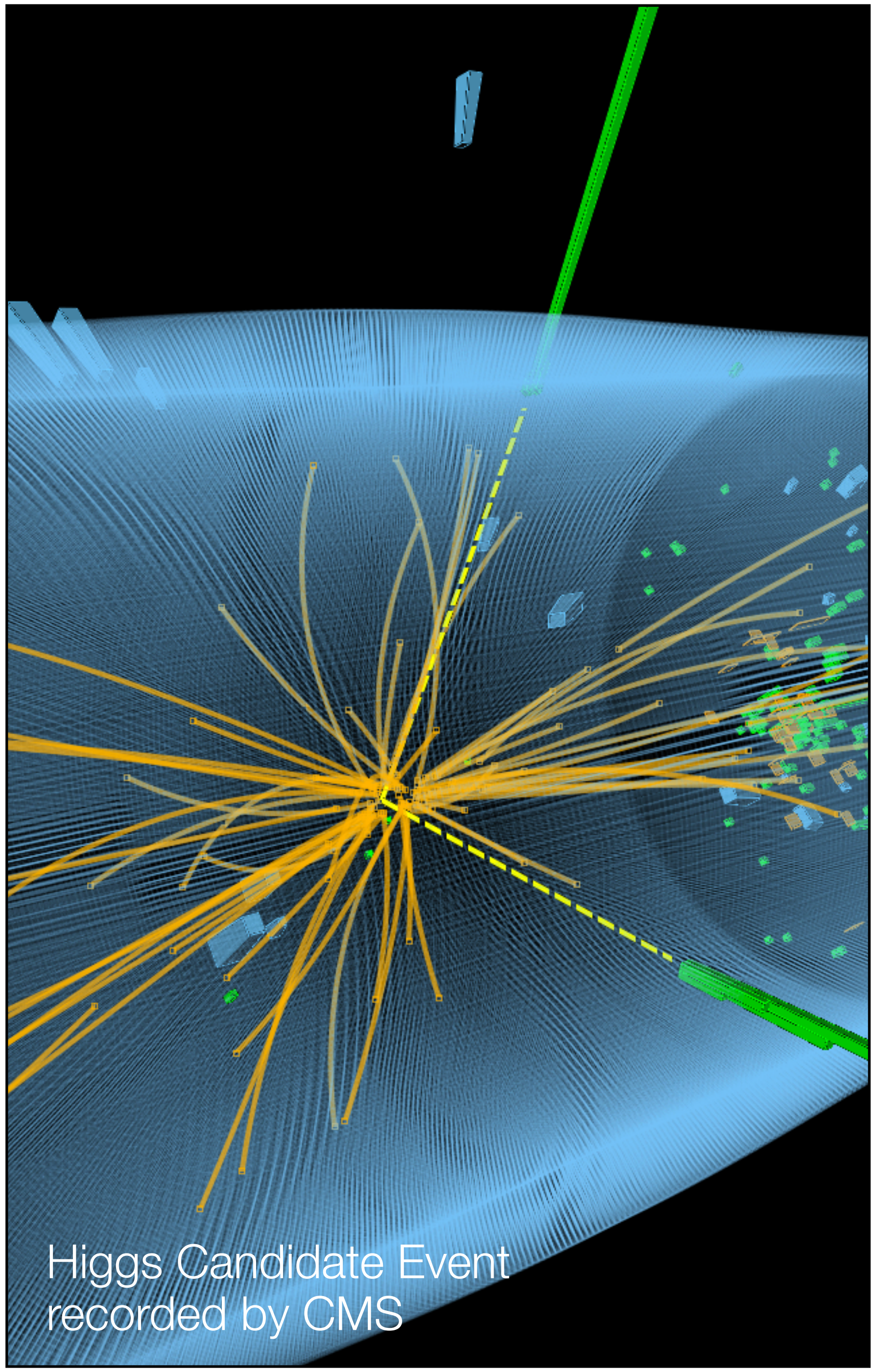


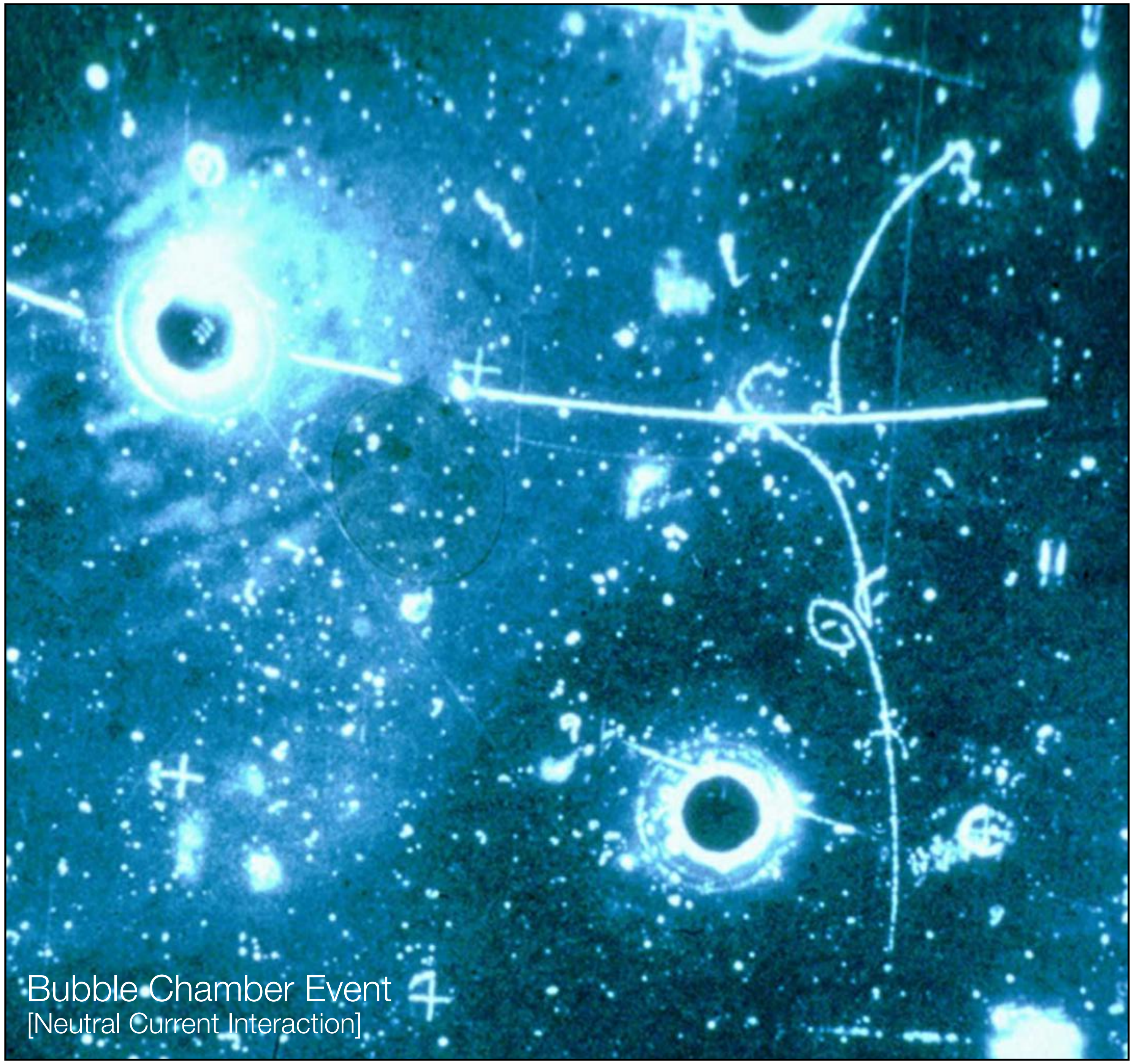
- needs only triodes, robust circuit
- can add a large number of input signals
- “The Rossi coincidence circuit was the first effective electronic device of particle physics” George W. Clark

How did it start?

- Blackett and Occhialini:
- cloud chamber sandwiched between Geiger counters in coincidence
- Data taking efficiency 2-5% -> 80%
- Biased to large multiplicities
- Observation of “Particle showers” (half positive, half negative)
- Understanding of positron production mechanism

Detecting & Recording Particle Reactions





What is the Problem?

Cannot (and do not want to) register all events

"Known physics" occurs more often than new physics

New physics buried under tons of known stuff

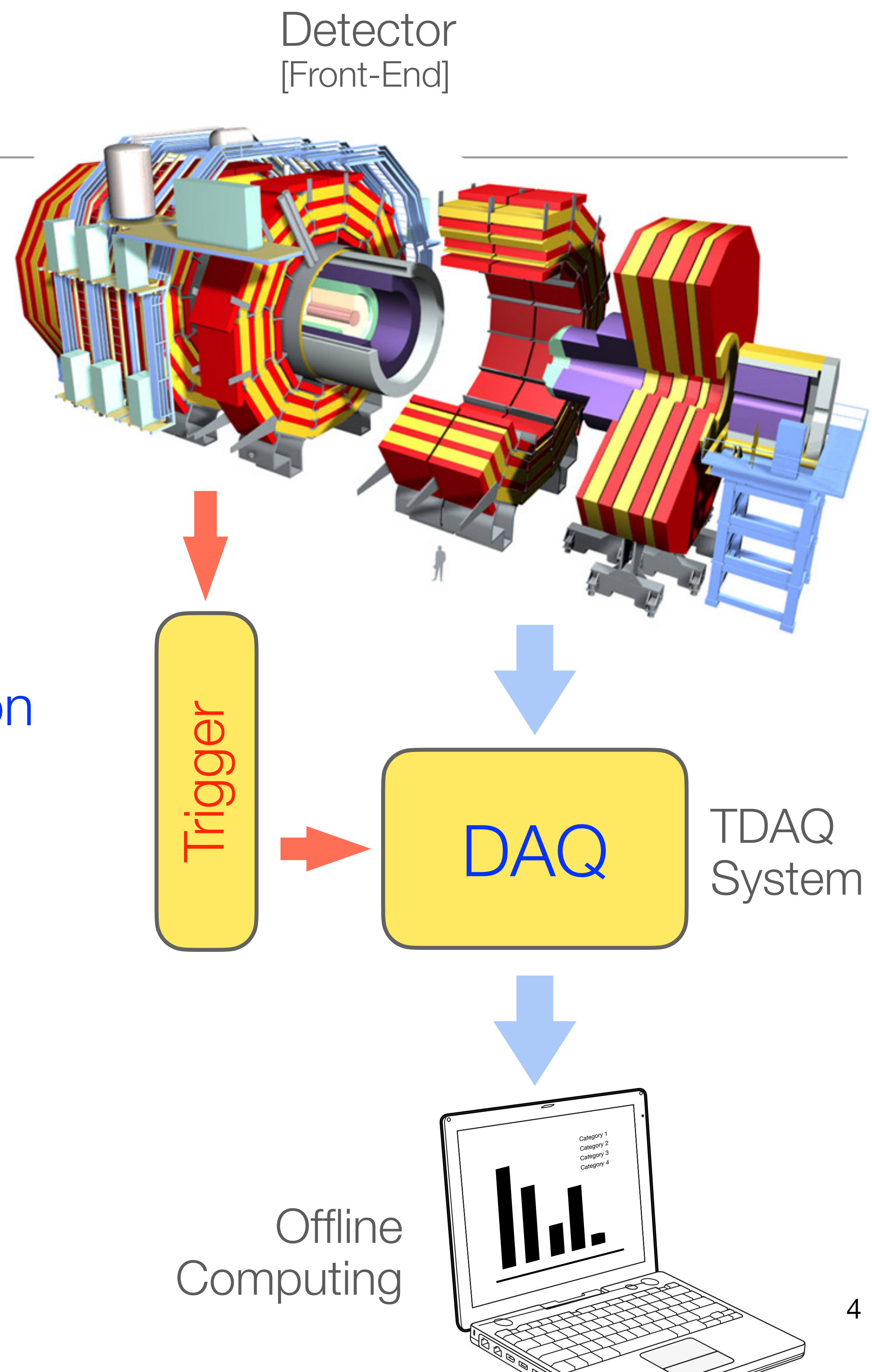
Trigger & DAQ in a Nutshell

DAQ responsible for collecting data from detector systems, digital conversion and recording to mass storage.

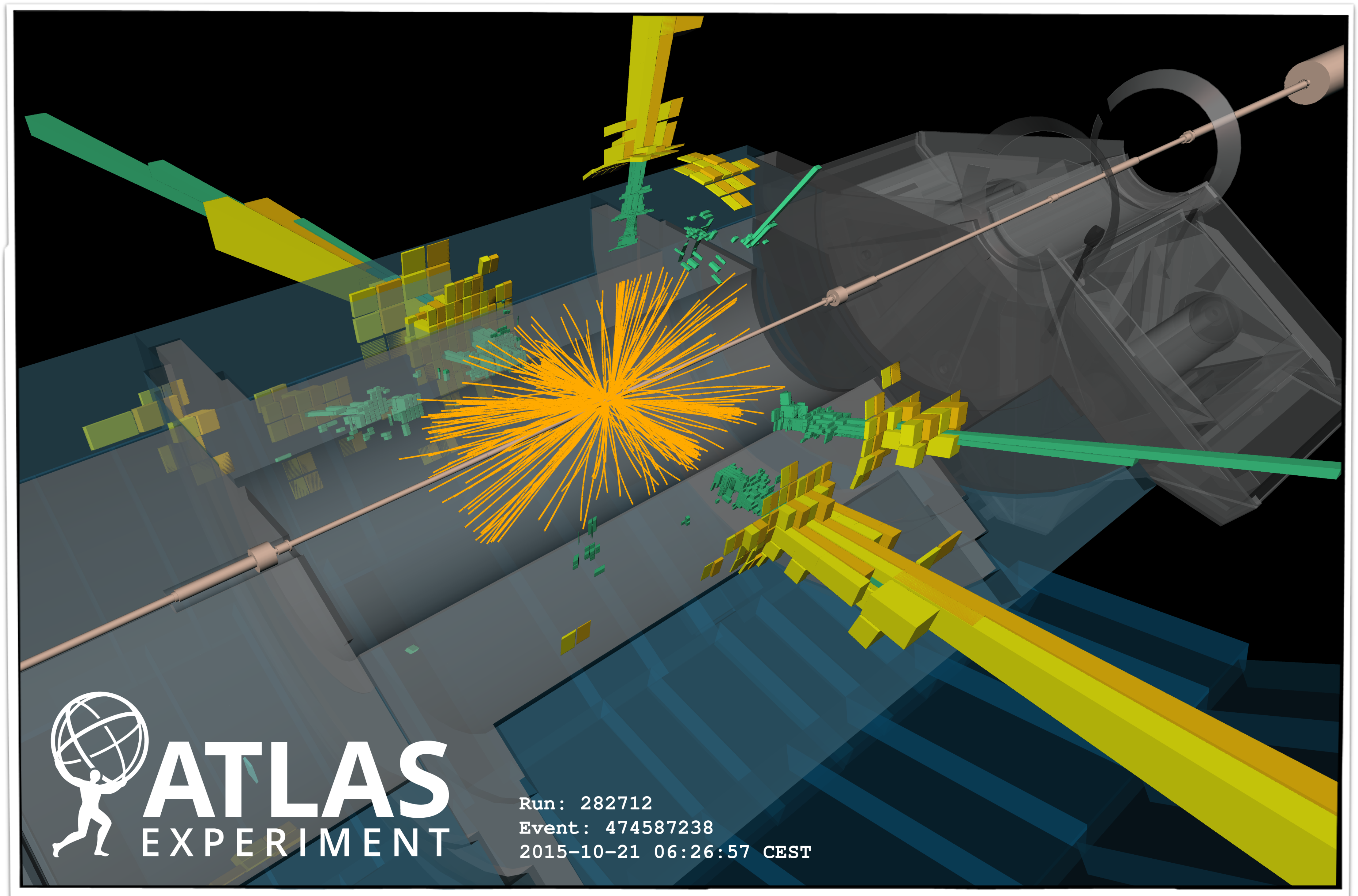
Trigger responsible for real-time selection of the subset of data to be recorded.

The combined system of Trigger/DAQ is often referred to as TDAQ.

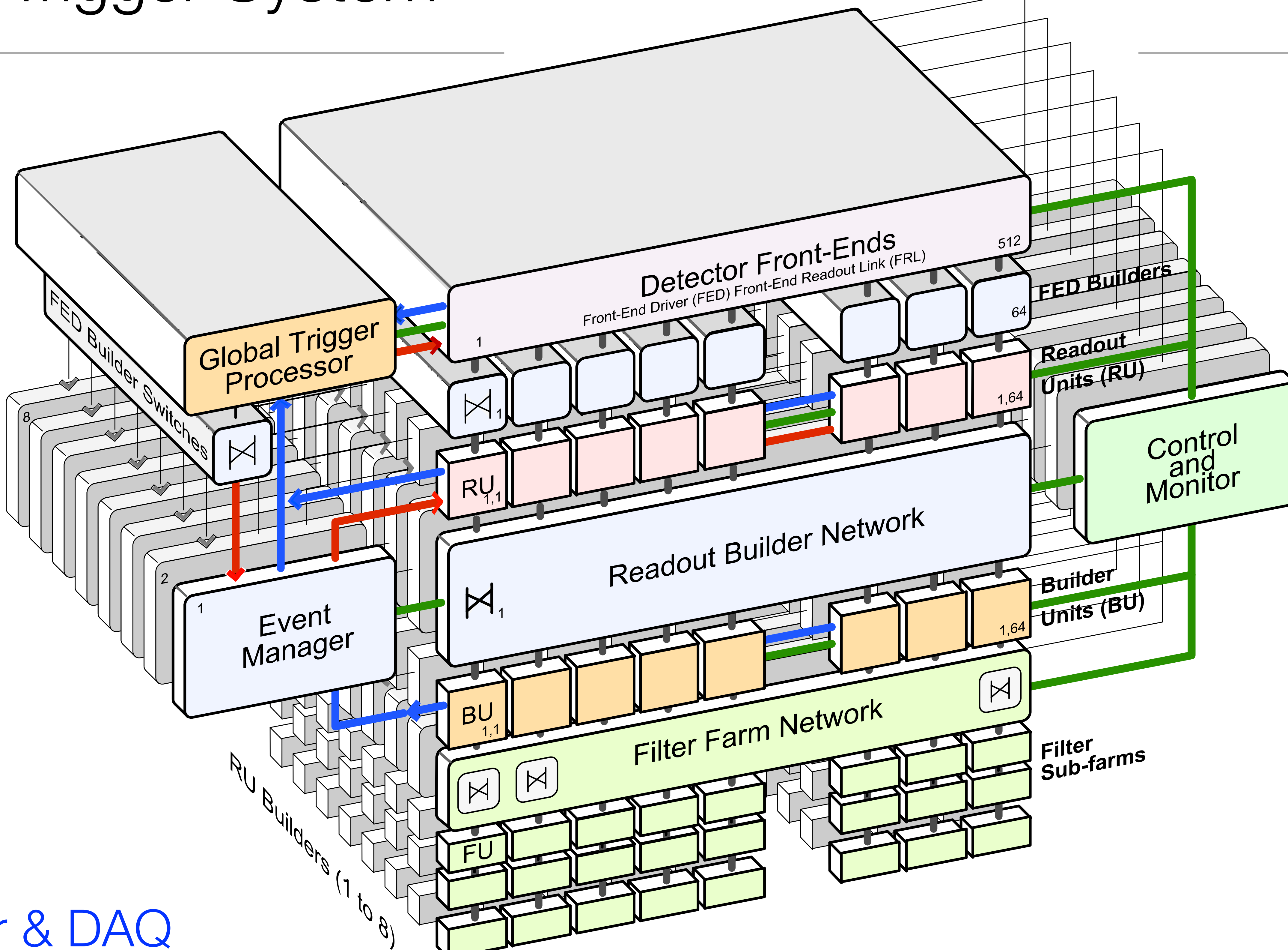
Often interwoven …



ATLAS Multijet Signature



LHC Trigger System

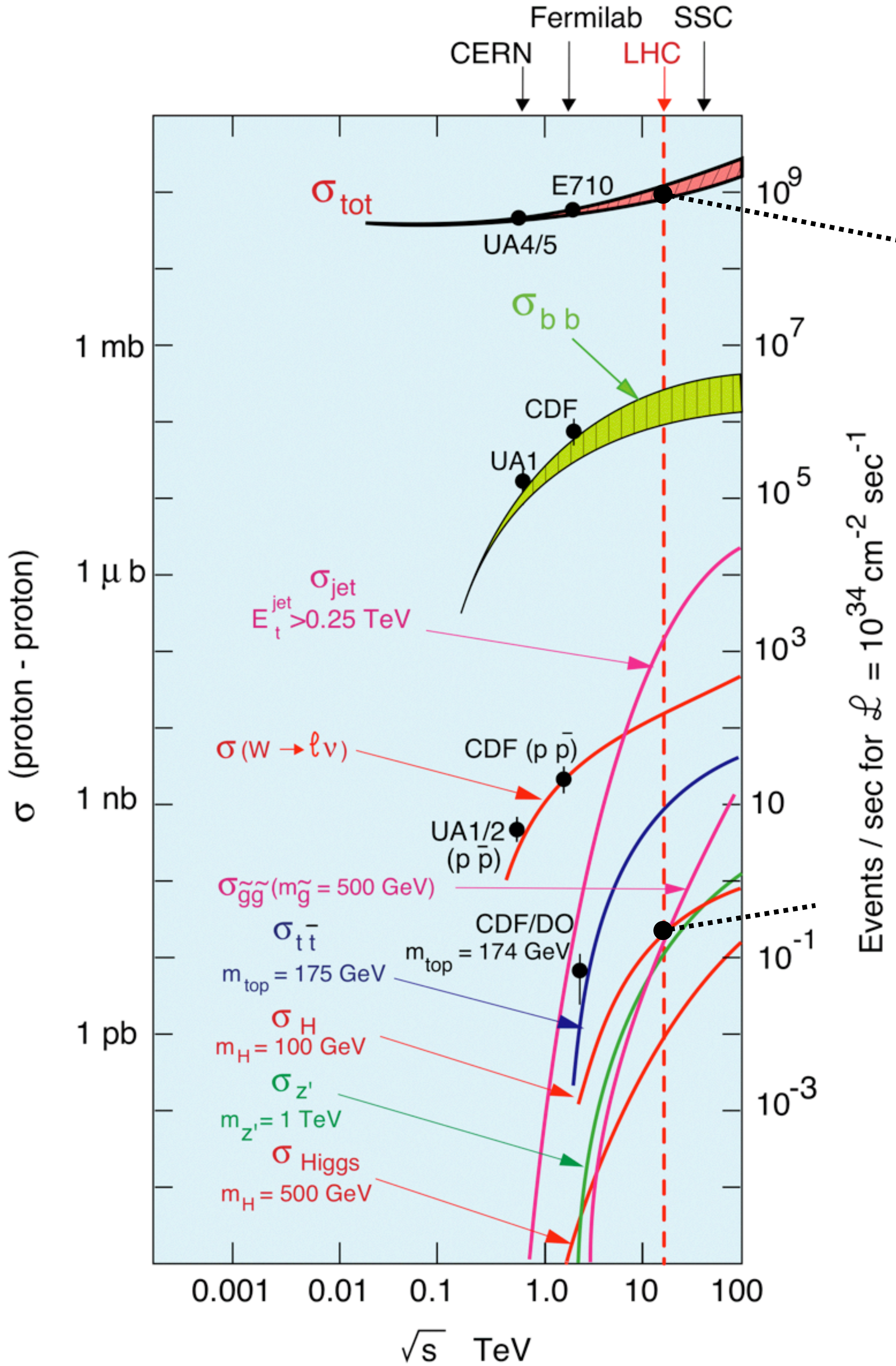


CMS
Trigger & DAQ

Part 1

“The TDAQ Challenges of Today”

LHC Cross Sections and Event Rates



10^9 Events/sec
[1 Mbyte/Event]

$\sim 10^{10}$

Efficient
rate reduction needed

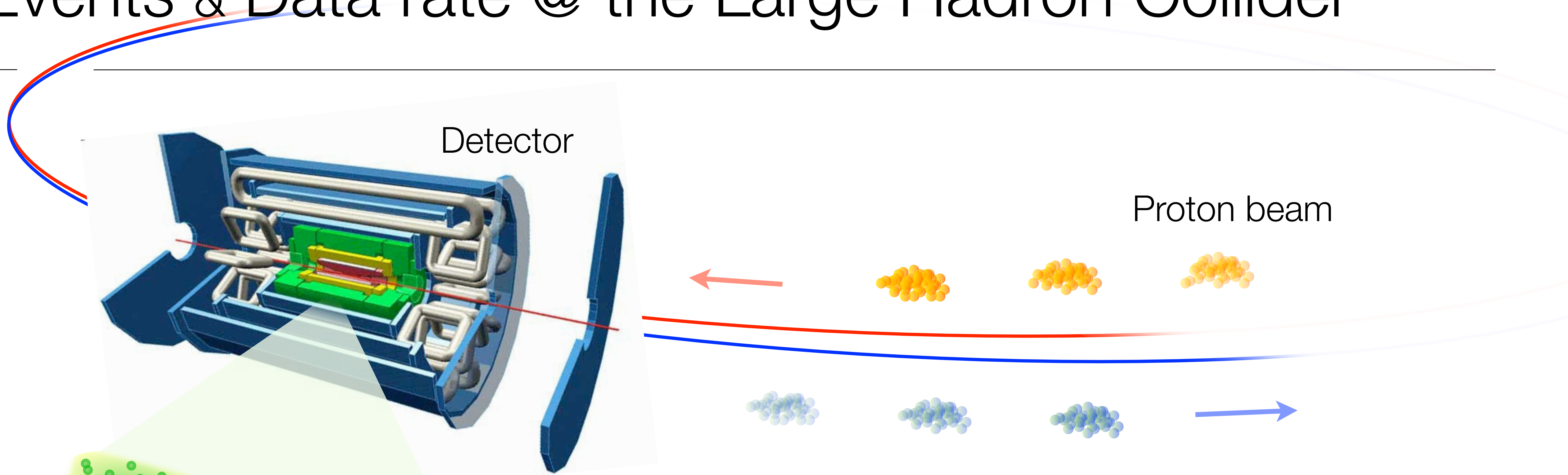
[Storage rate: 1000 Hz]

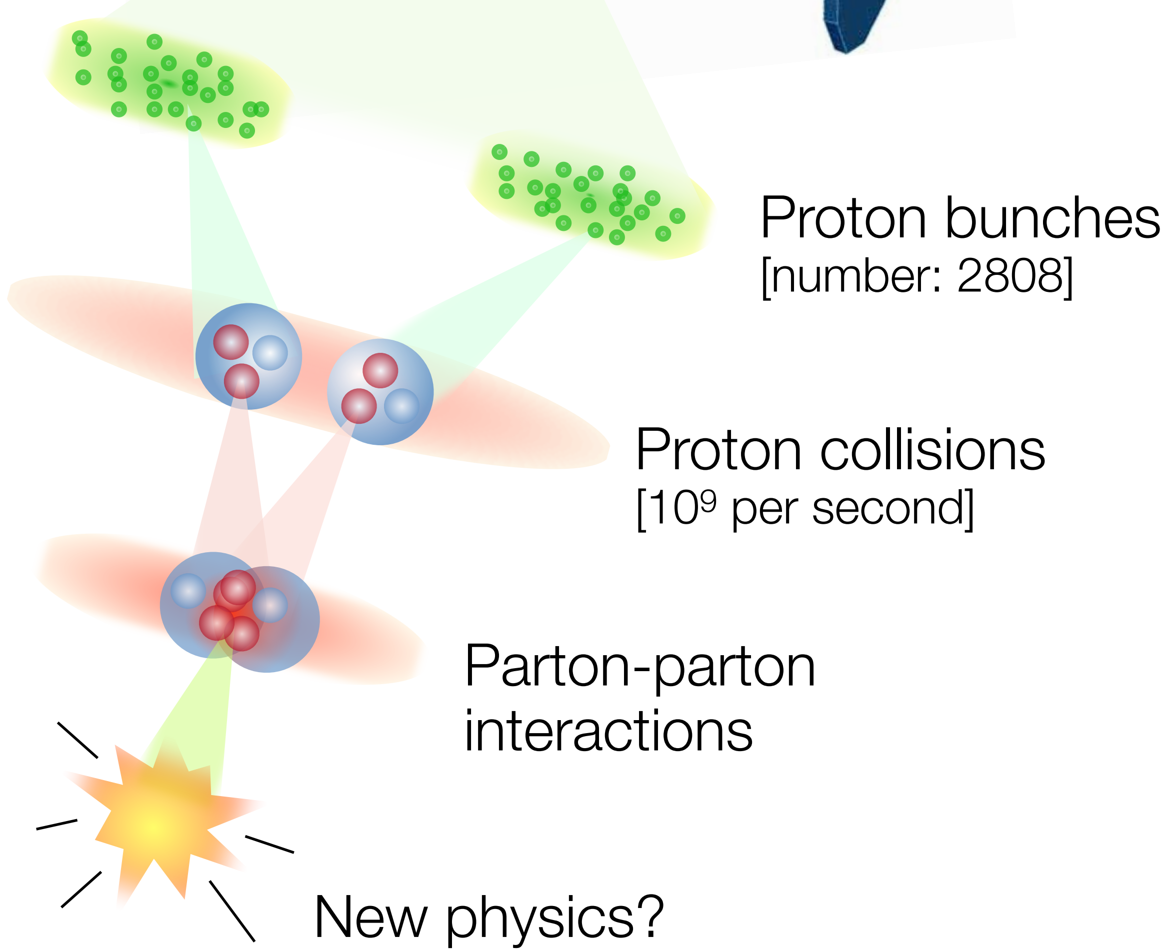
10 Events/min
[$m_H \approx 100$ GeV]

with 0.2% $H \rightarrow \gamma\gamma$
1.5% $H \rightarrow ZZ$

Trigger !

Events & Data rate @ the Large Hadron Collider



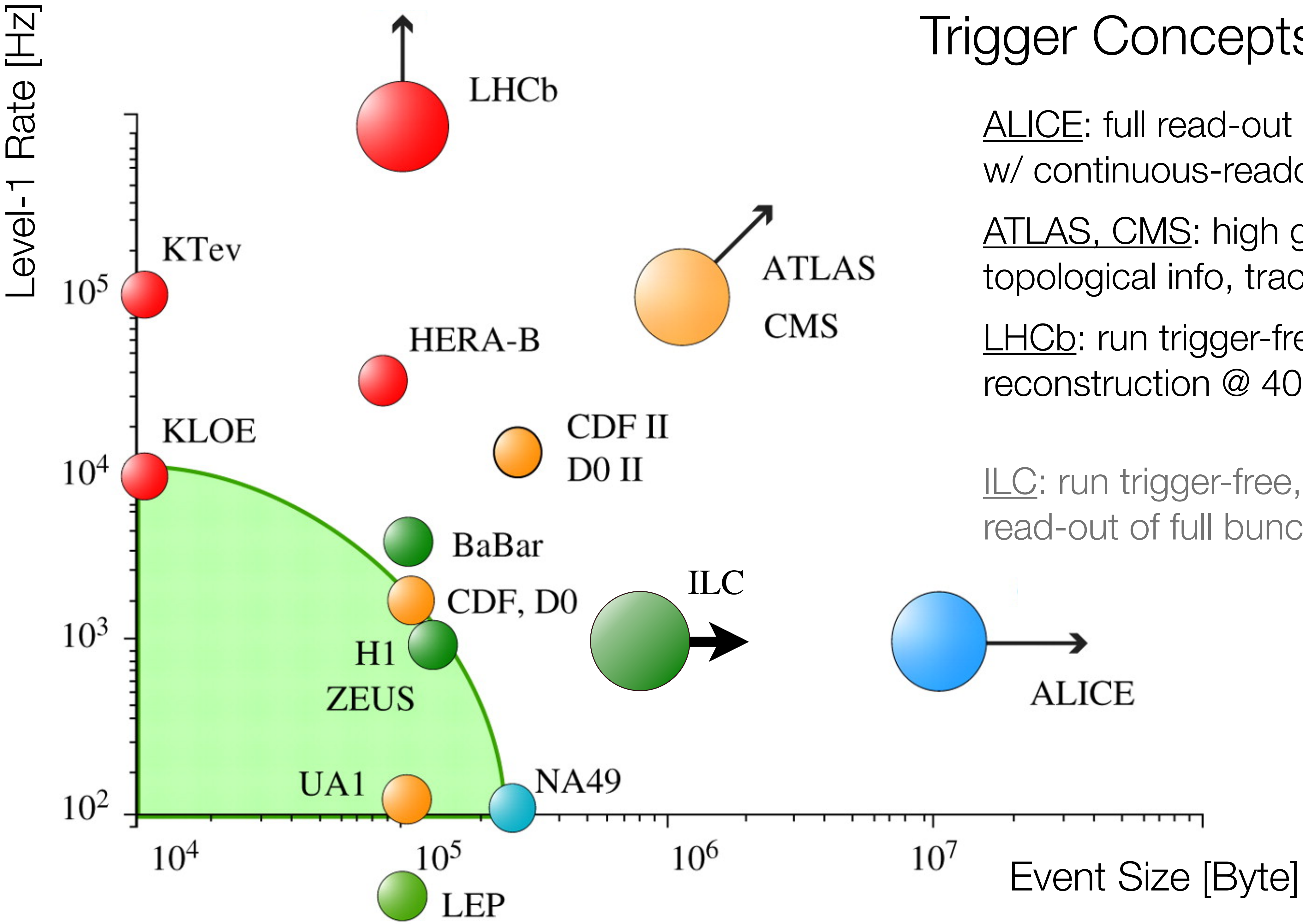


Collision rate : 40 MHz

Event Size : 1.5 MByte

Data Volume : 60 TByte/s

Overview on Operating Conditions



Trigger Concepts:

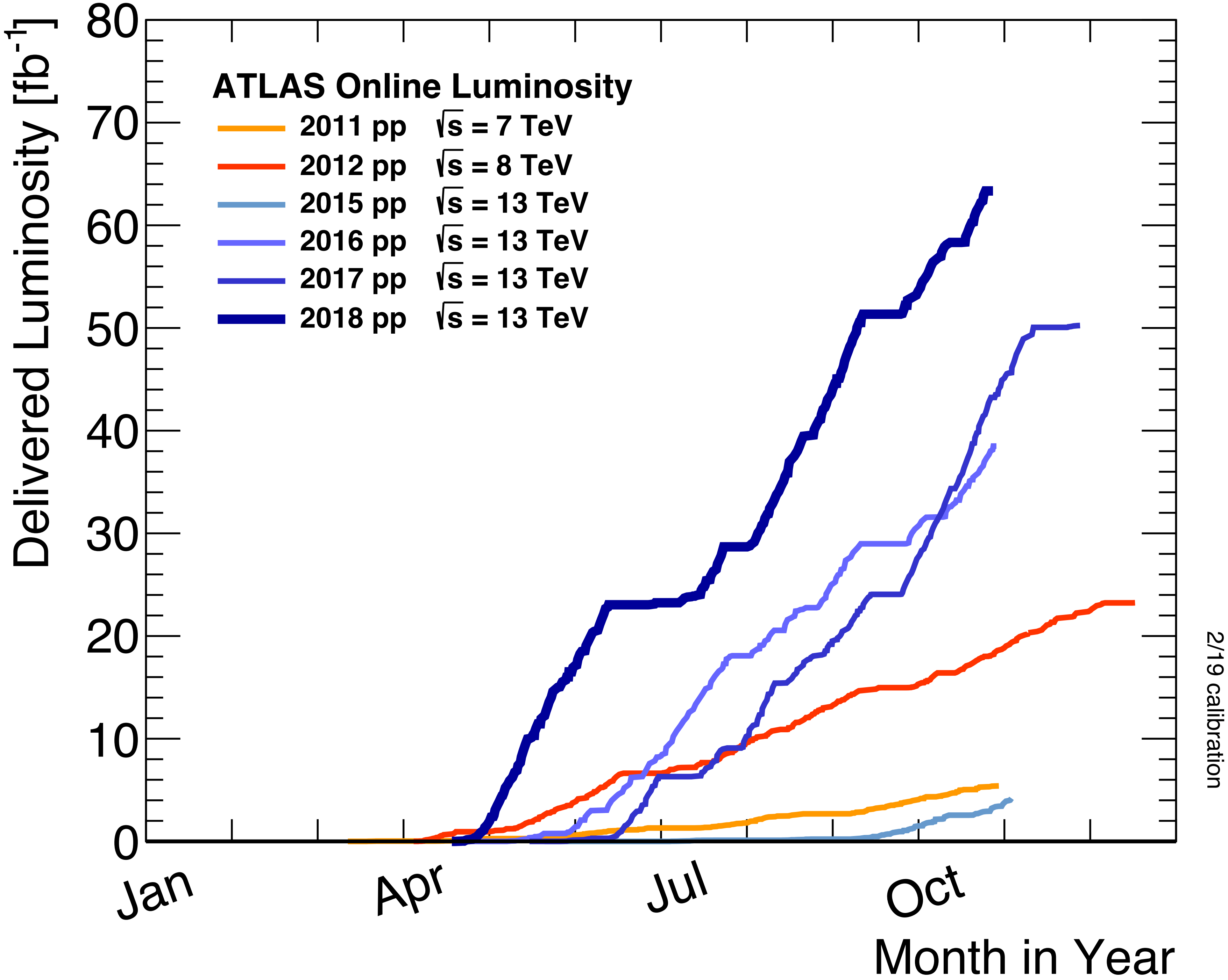
ALICE: full read-out @ 50 kHz w/ continuous-readout of TPC …

ATLAS, CMS: high granularity, topological info, tracking @ L1/HLT, …

LHCb: run trigger-free, full event reconstruction @ 40 MHz …

ILC: run trigger-free, s/w trigger, read-out of full bunch trains …

LHC Run-2 Performance



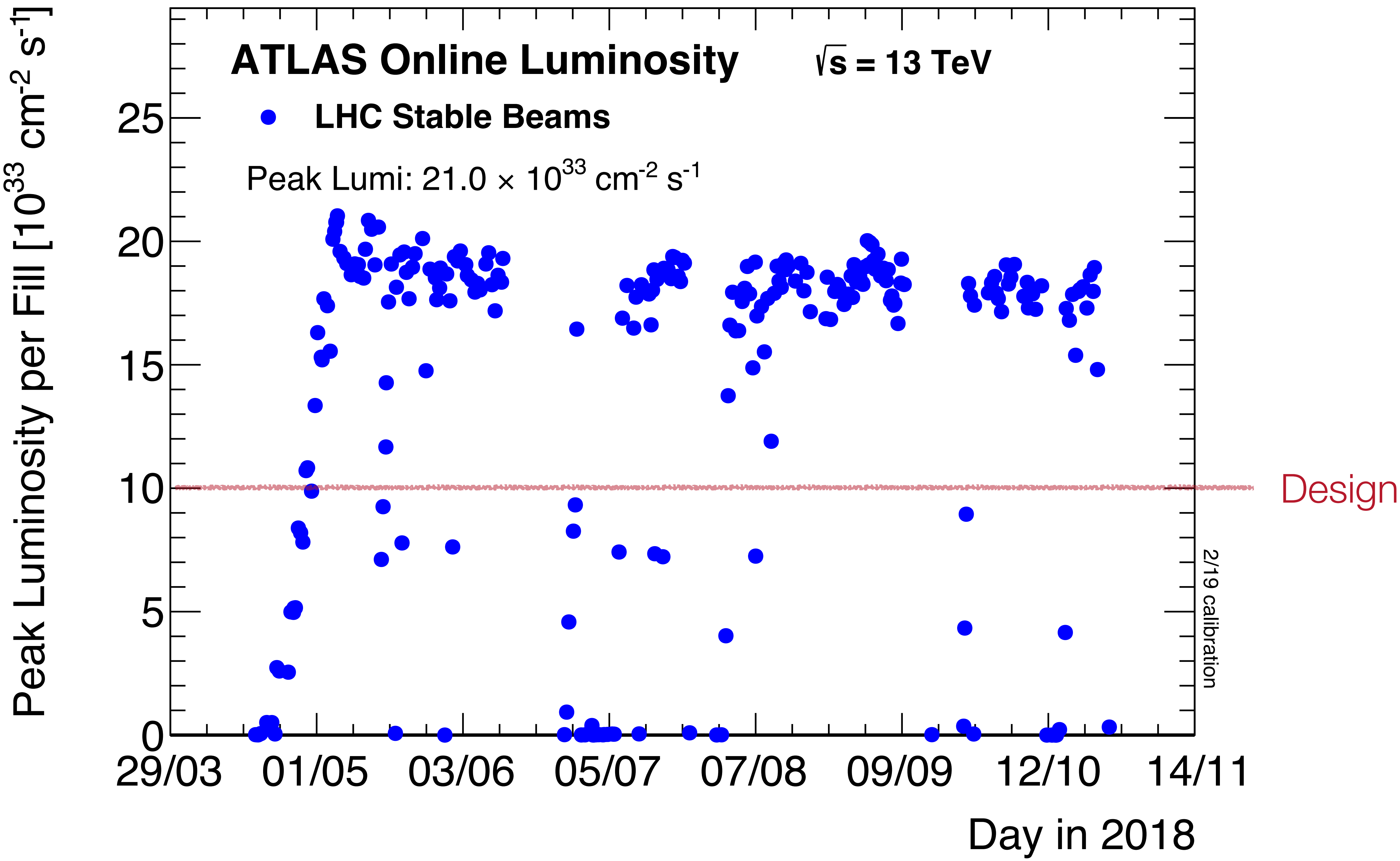
Luminosities:
[recorded]

2011: 5.1 fb^{-1}
2012: 21.3 fb^{-1}

2015: 3.9 fb^{-1}
2016: 35.6 fb^{-1}
2017: 46.9 fb^{-1}

2018: 60.6 fb^{-1}

LHC Run-2 Performance

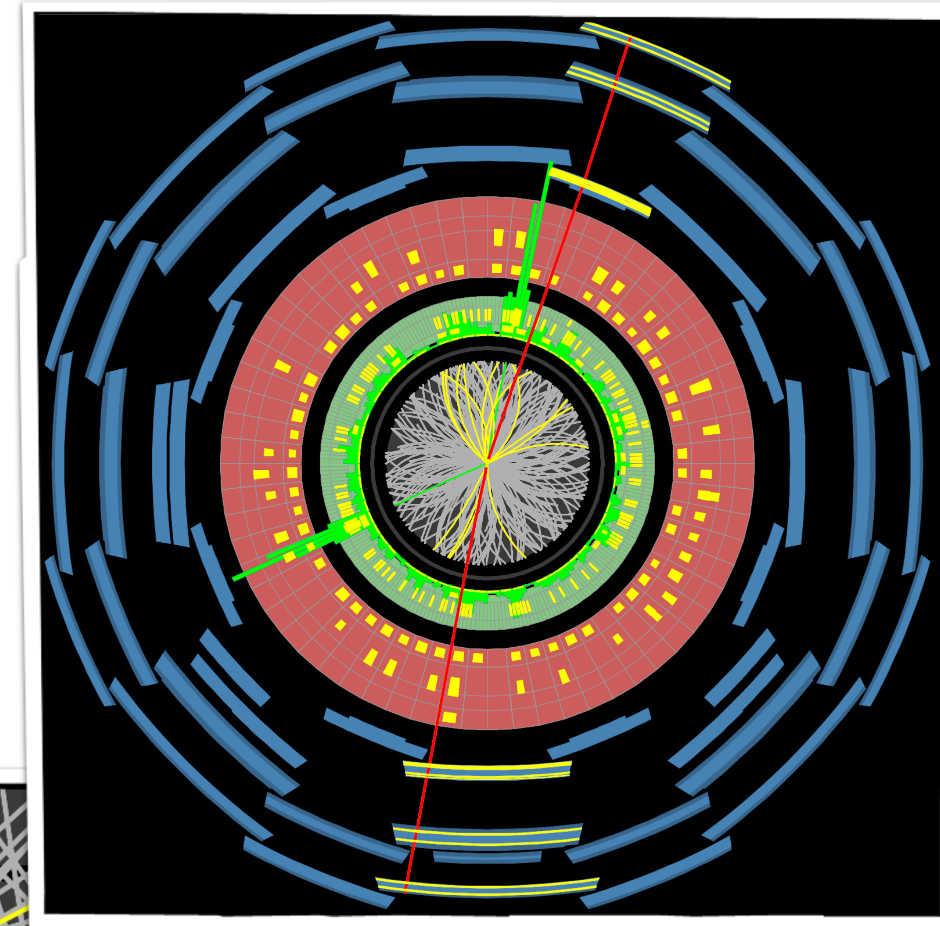


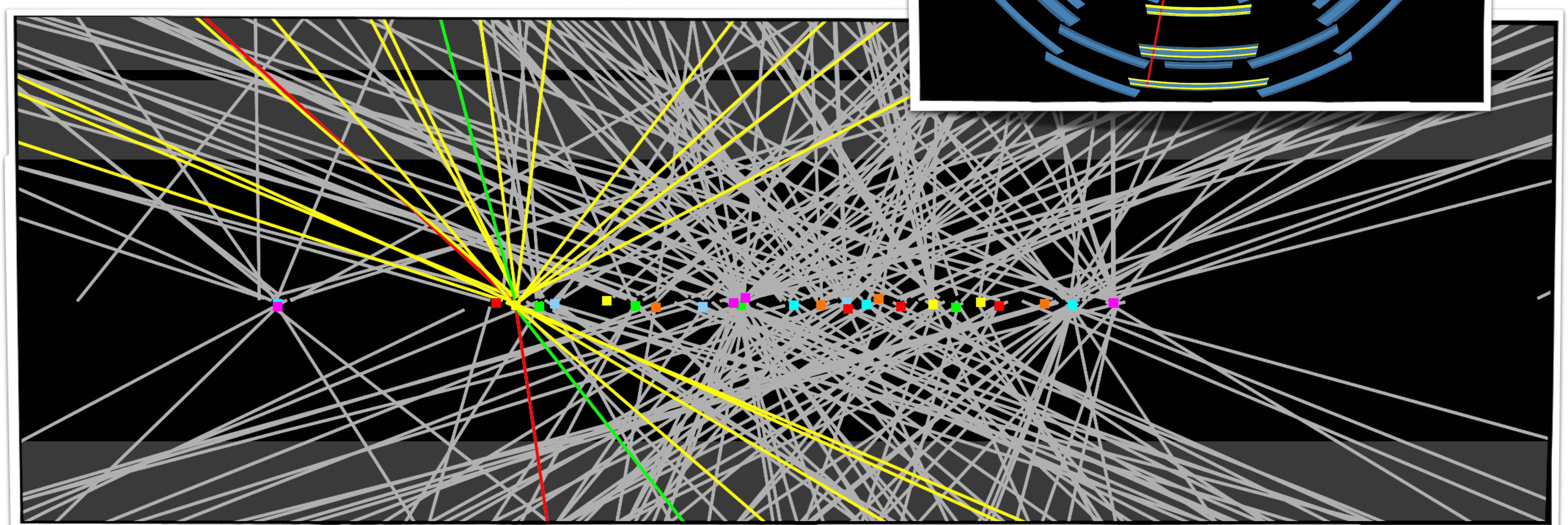
LHC Run-2 Performance

ATLAS Event
with 25 pileup vertices

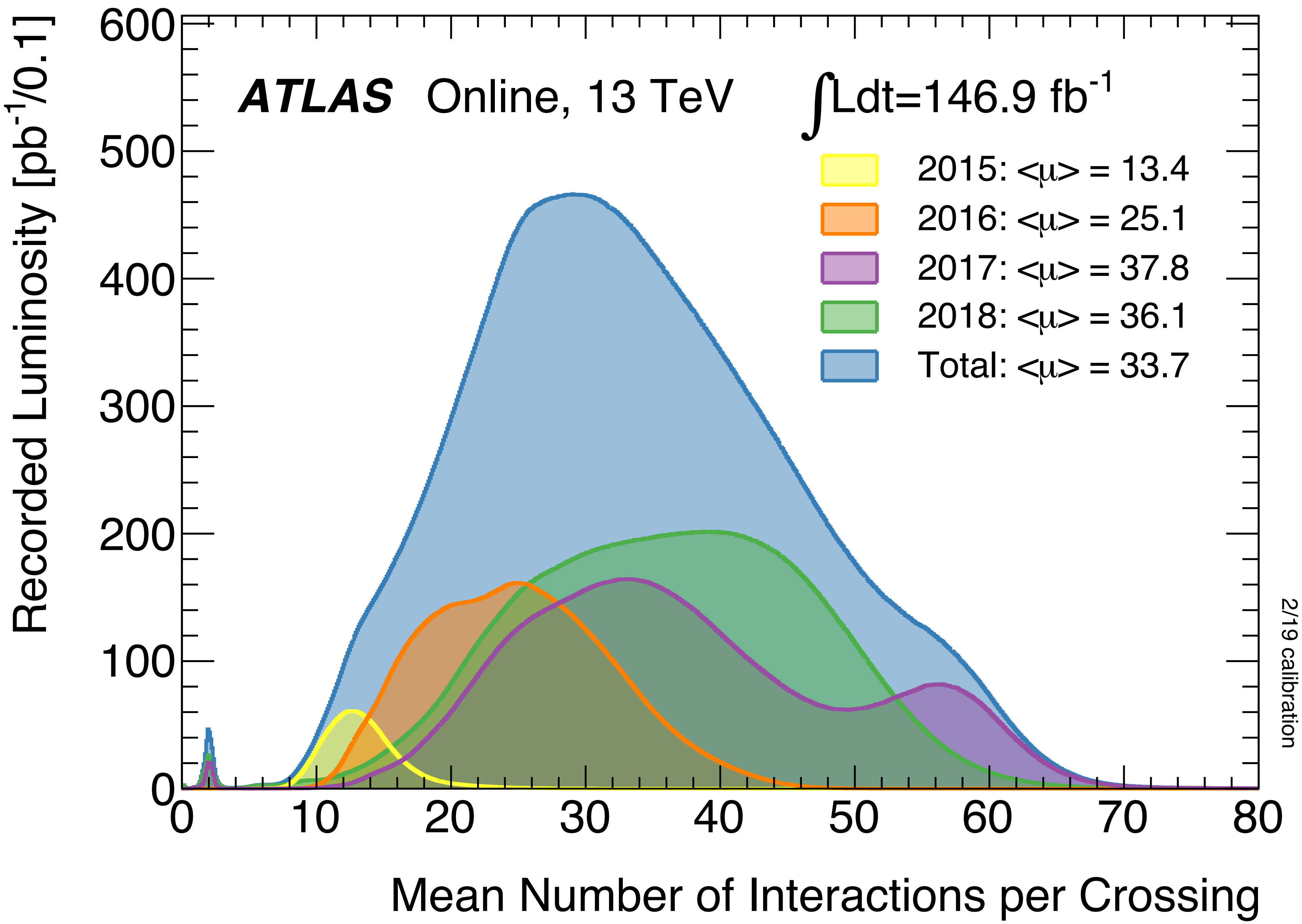
[$\sqrt{s}$ = 13 TeV; 2016 Data]

H ➛ ZZ ➛ ee μμ candidate event

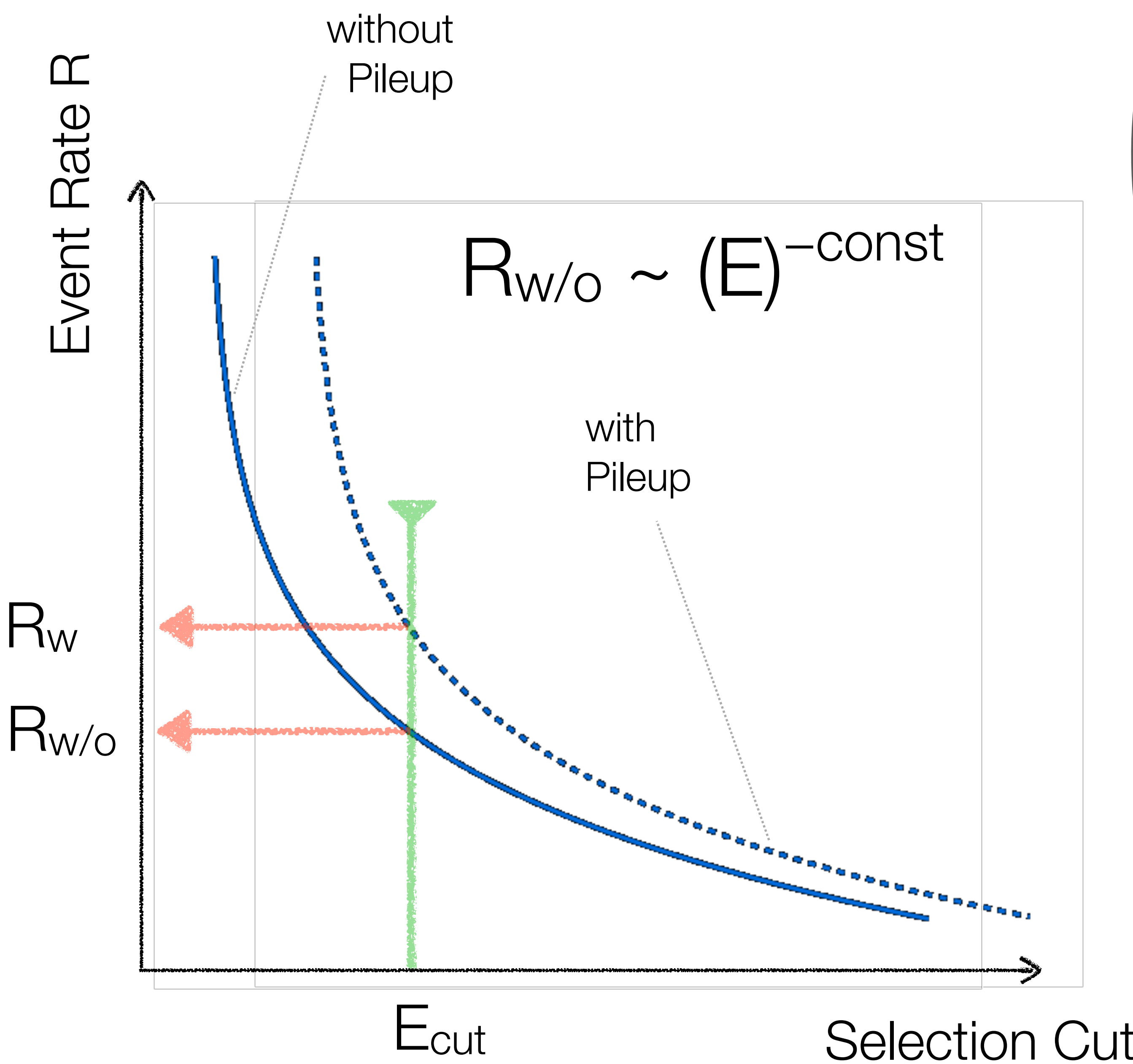


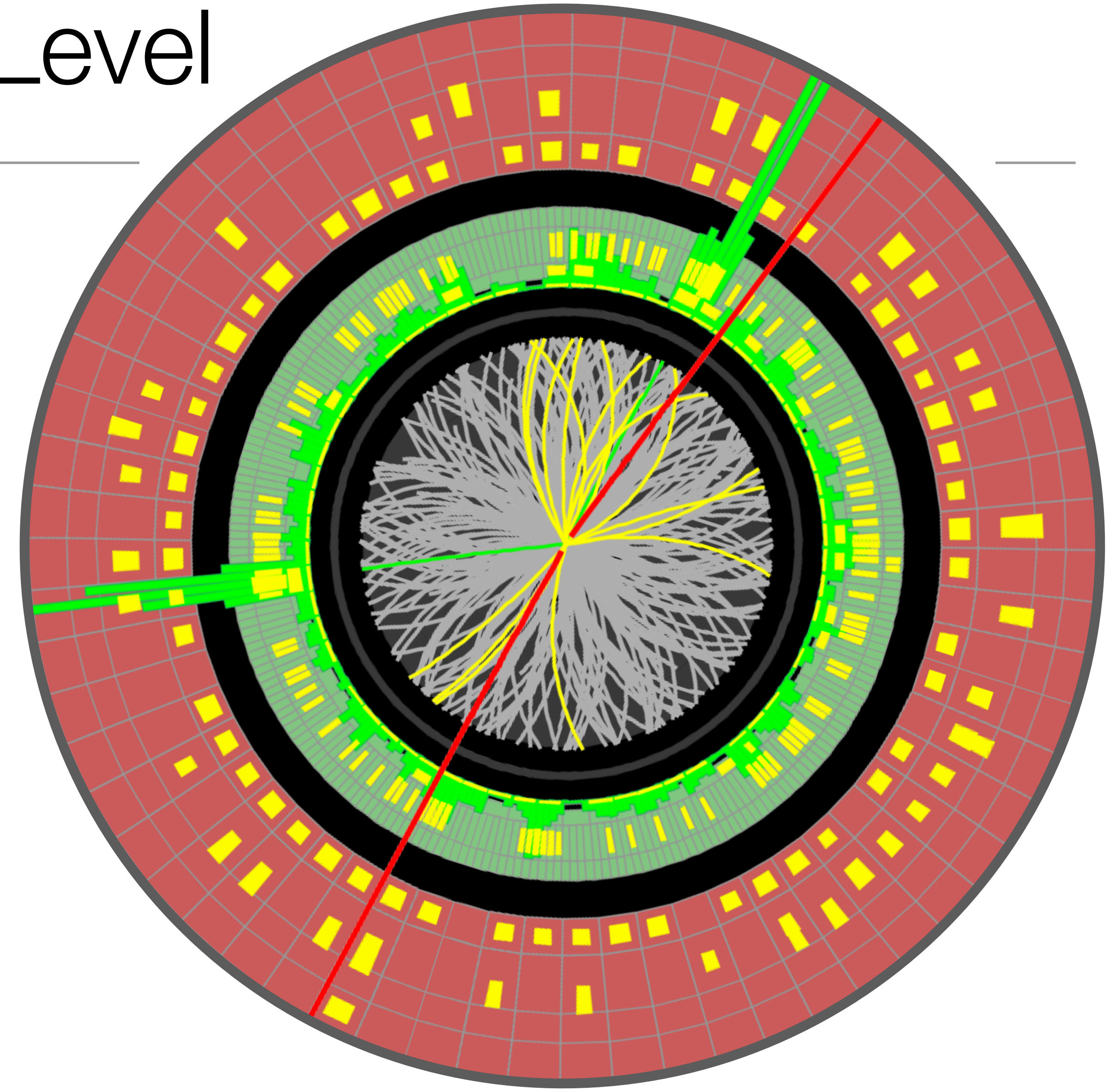


LHC Run-2 Performance – Pileup



Pileup Mitigation at Trigger Level

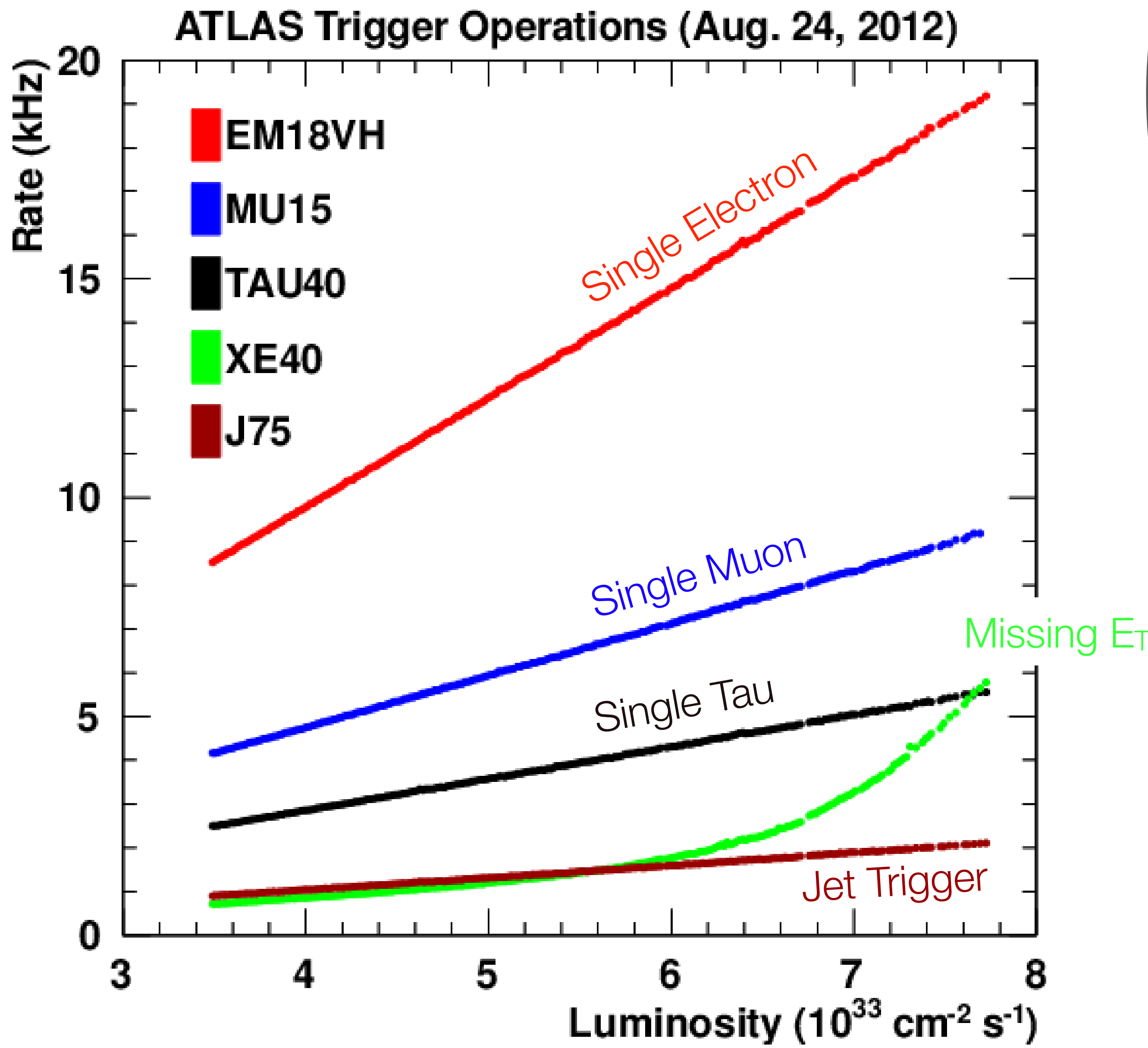


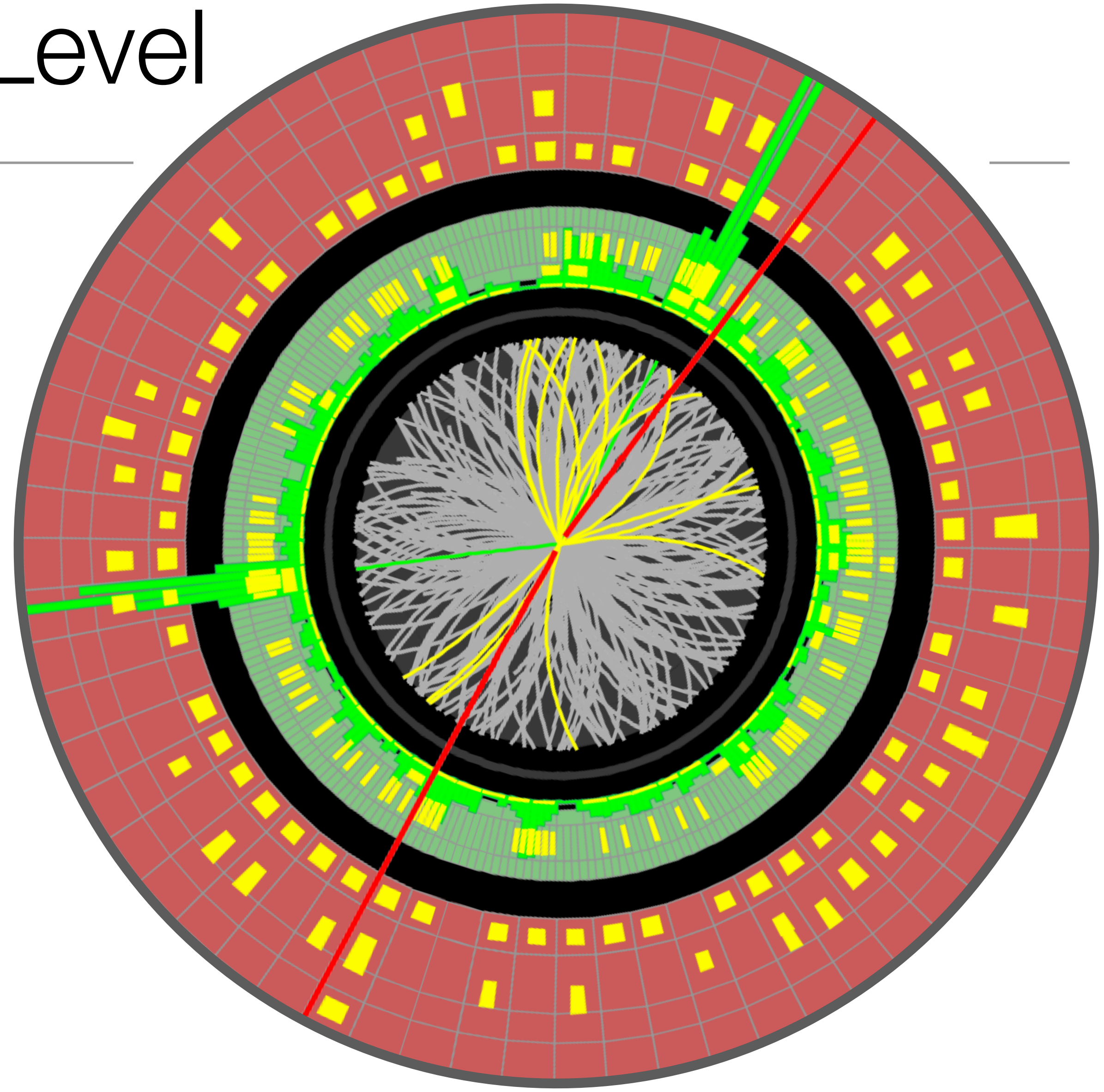


Pileup dependence:

$$R_w \sim R_{w/o} [\mathscr{L} + b\mathscr{L}^2 + \ldots]$$

Pileup Mitigation at Trigger Level





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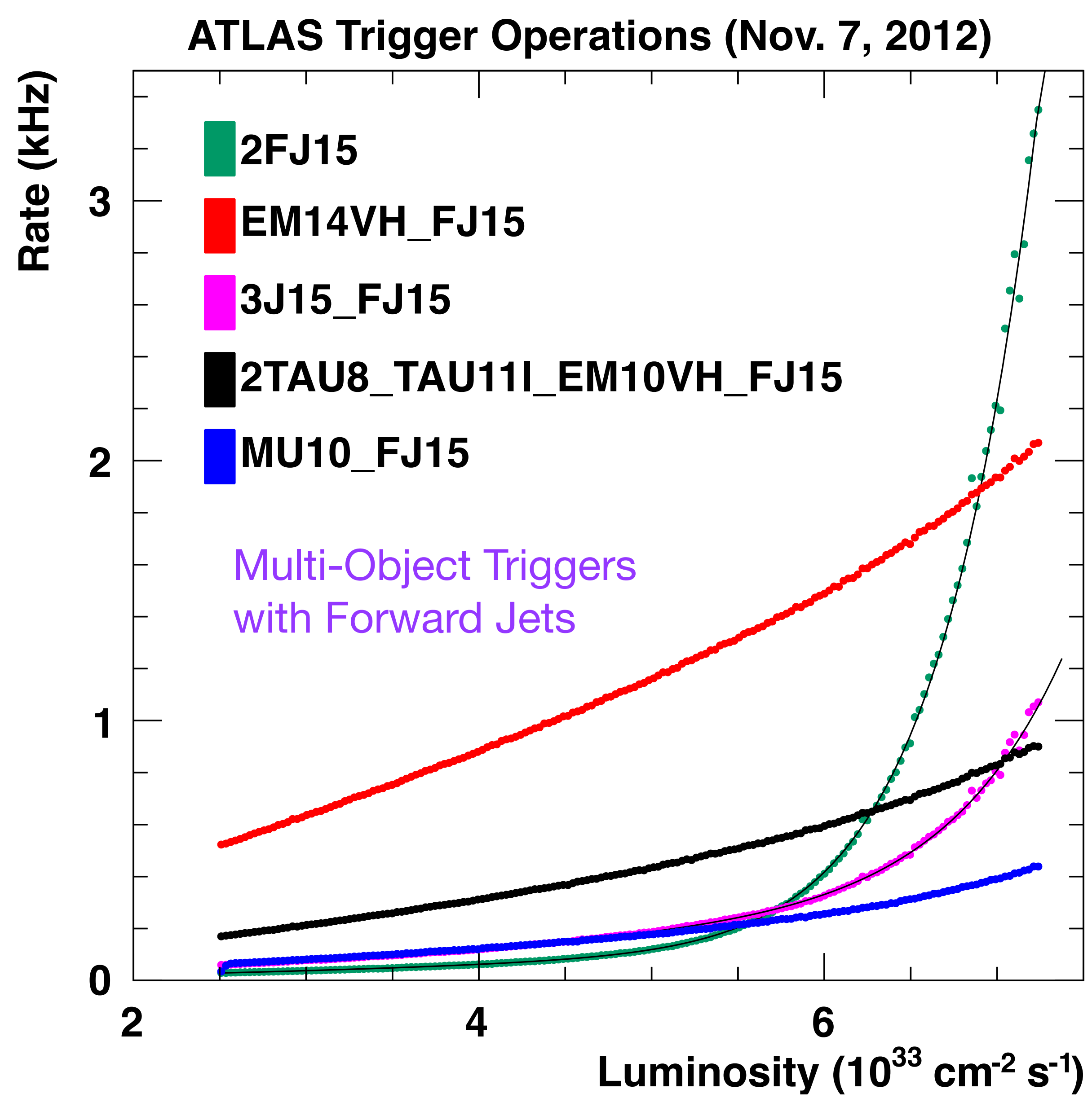

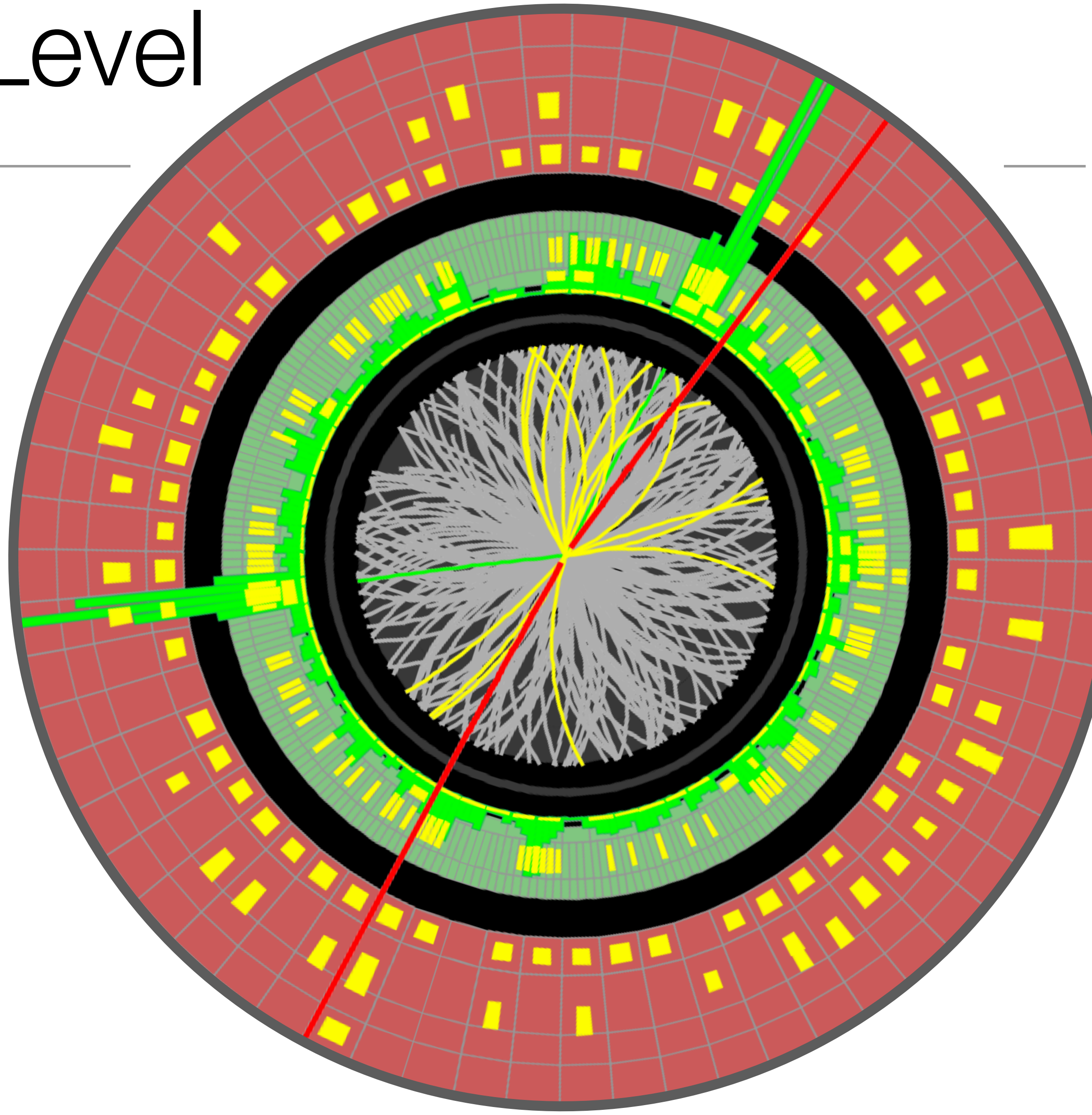

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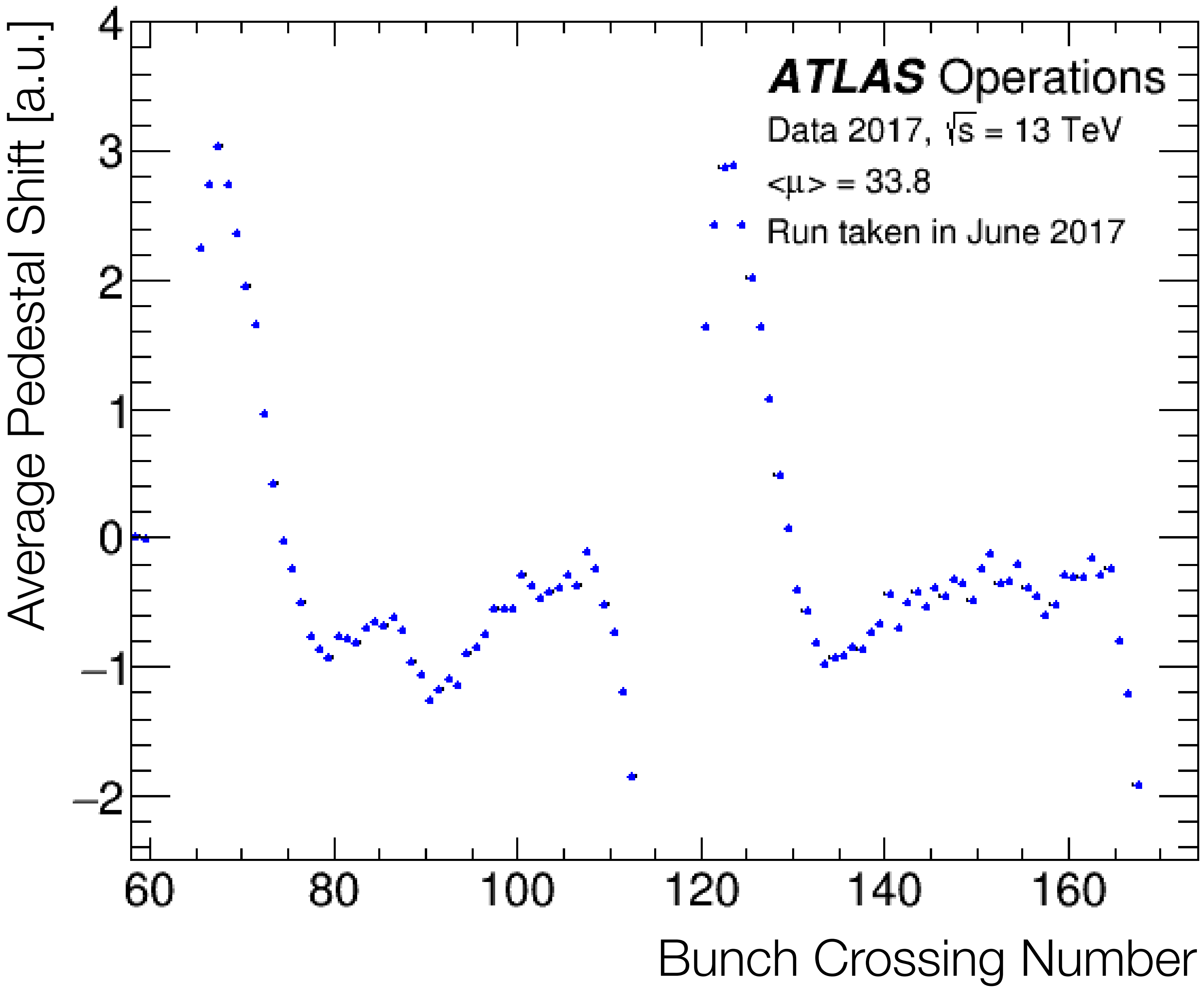

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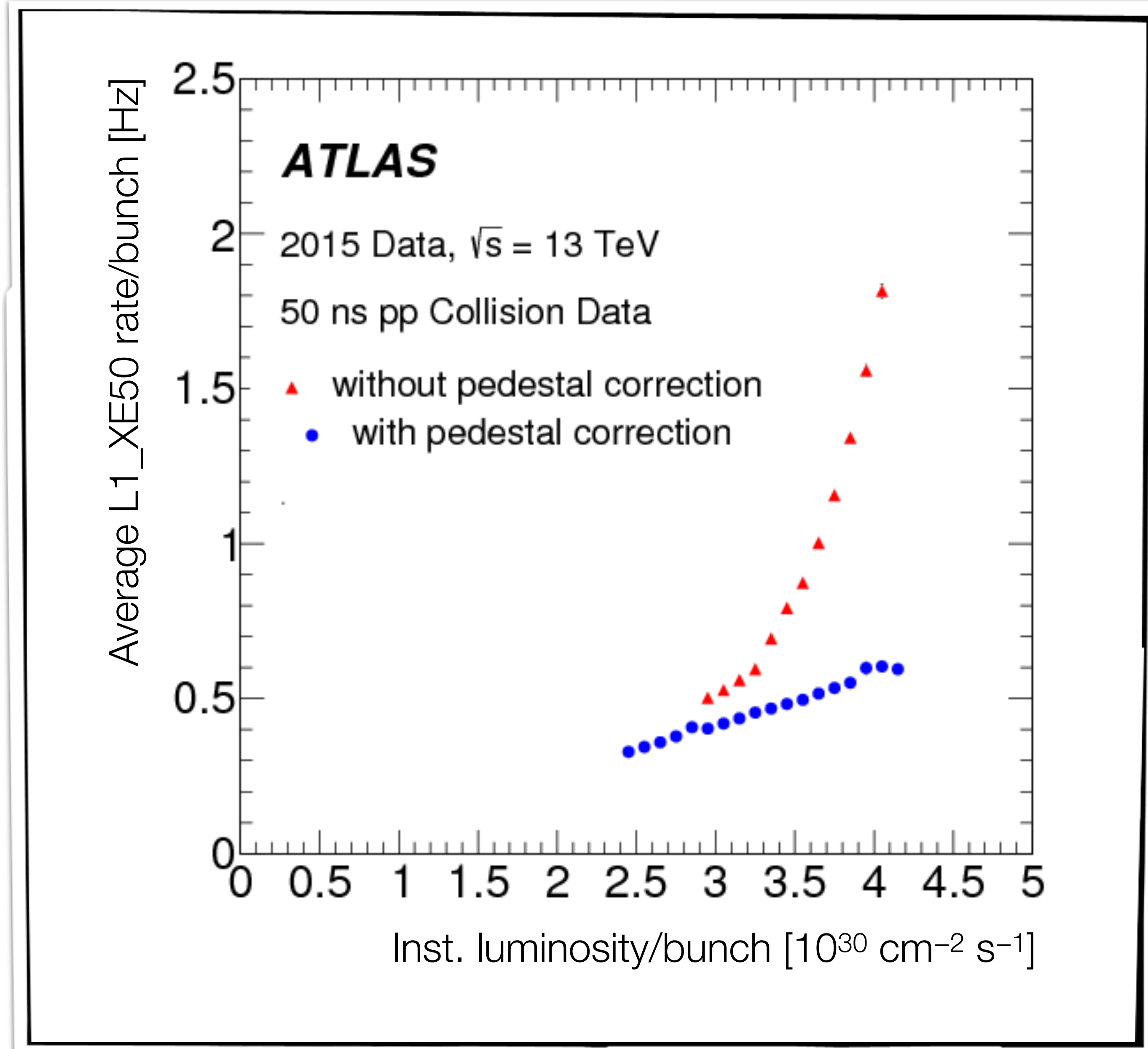
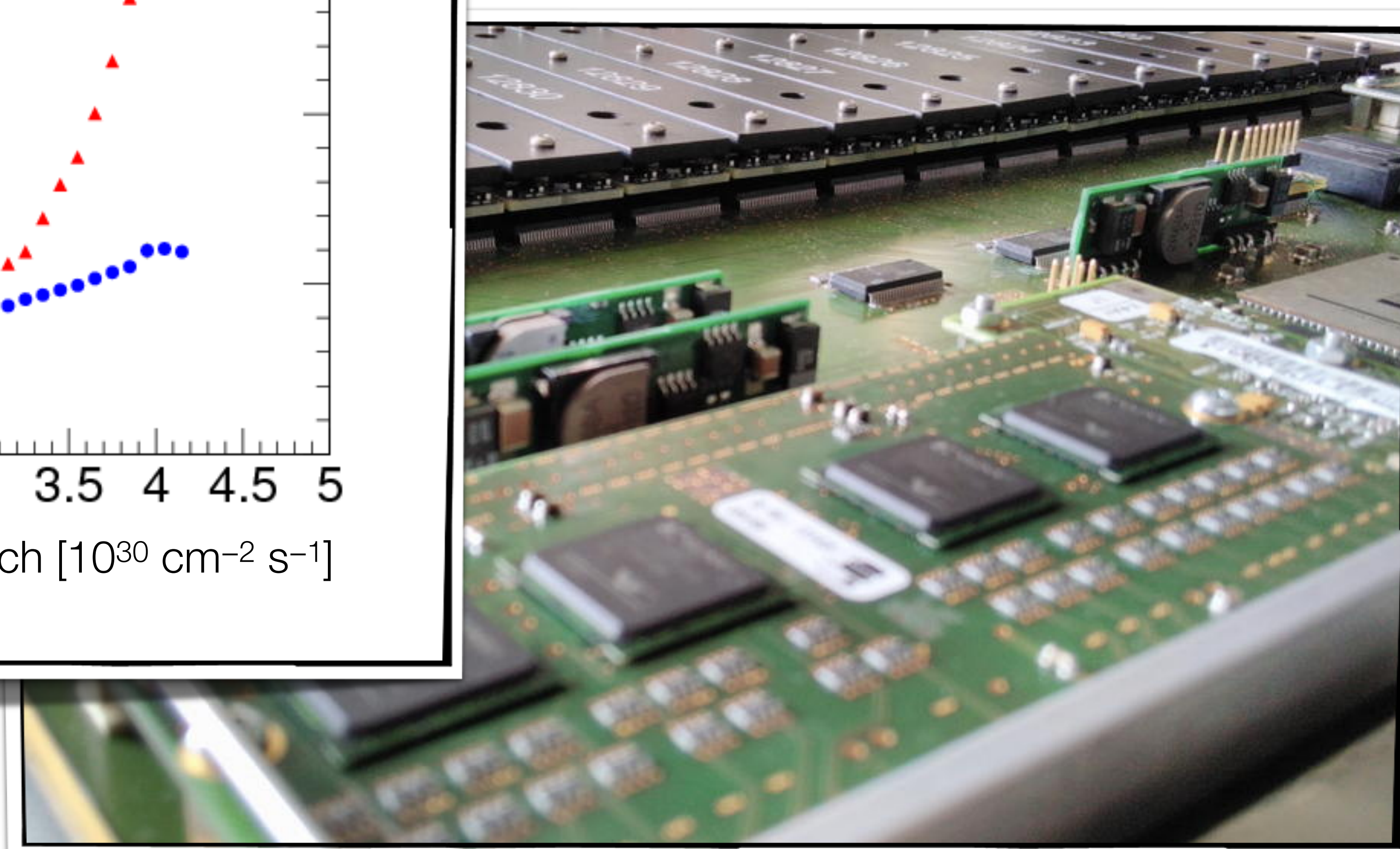
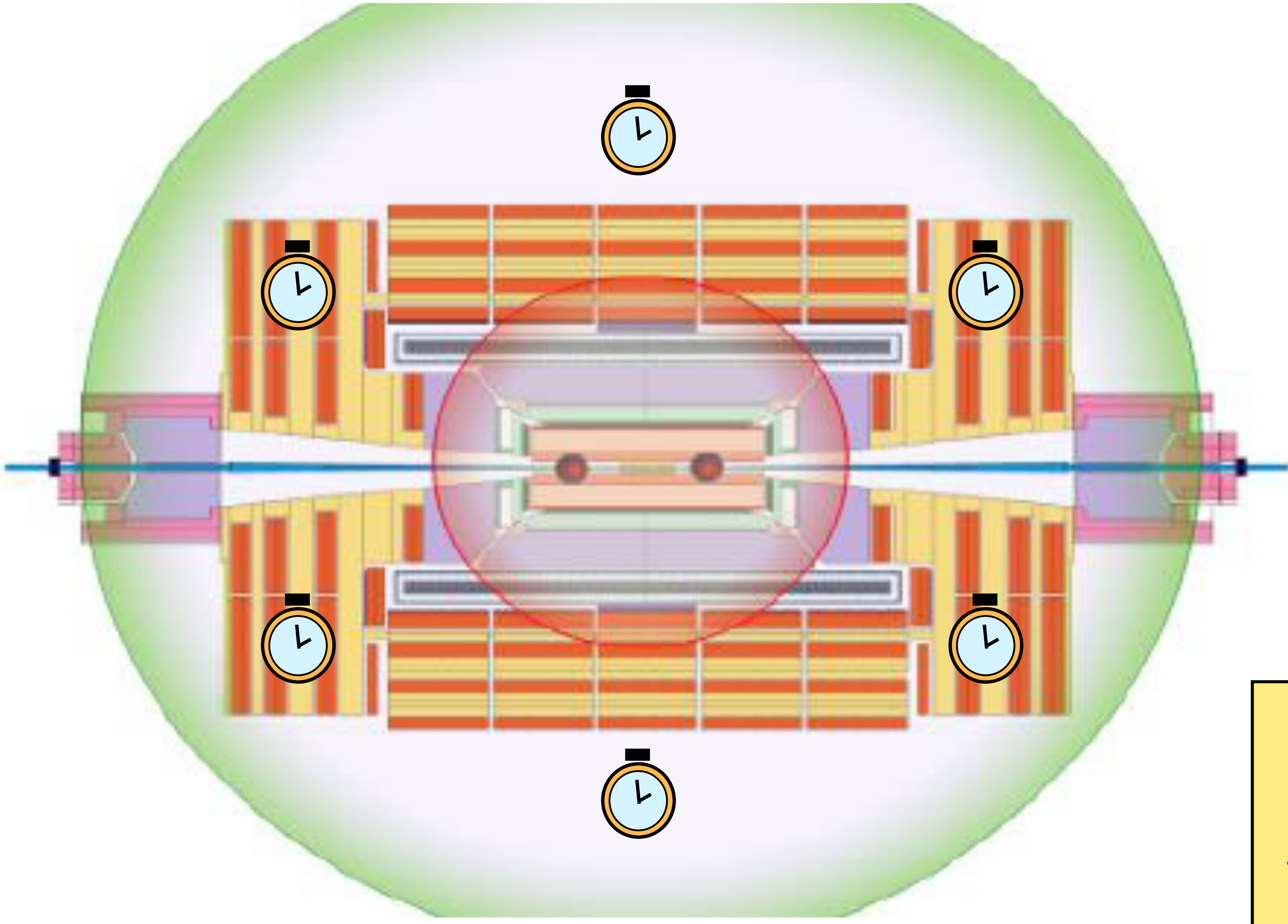




Signal Synchronization



Data within
same bunch crossing
to be processed together

But:

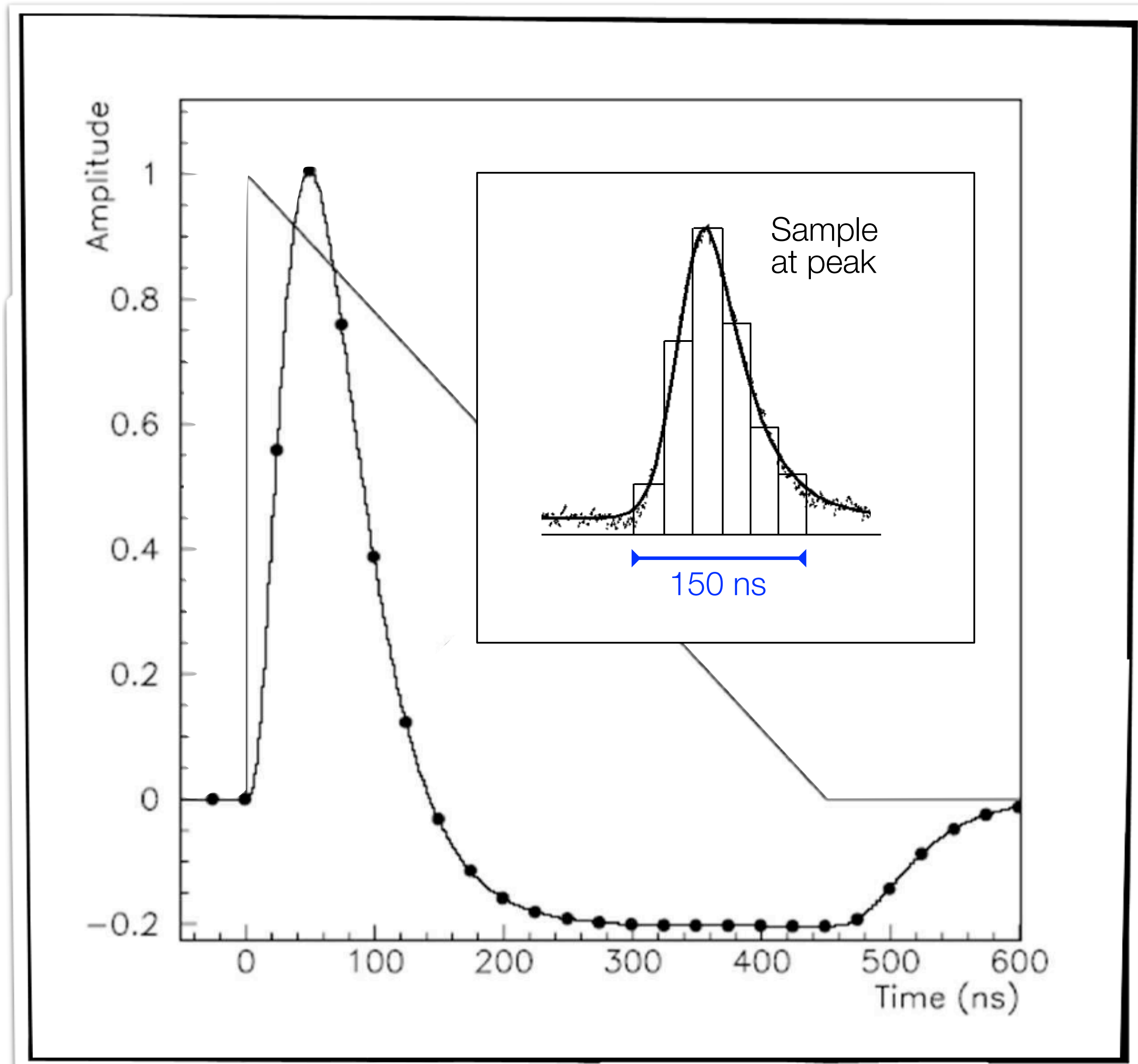
Particle TOF ≫ 25 ns
[c ≈ 0.3 m/ns; 1 m ≙ 3 ns]

Cable delays ≫ 25 ns
[cable lengths: 30 -70 m]
[v_{signal} ≈ 0.66 c; 1 m ≙ 5 ns]

Requires
signal synchronization
with programmable delays

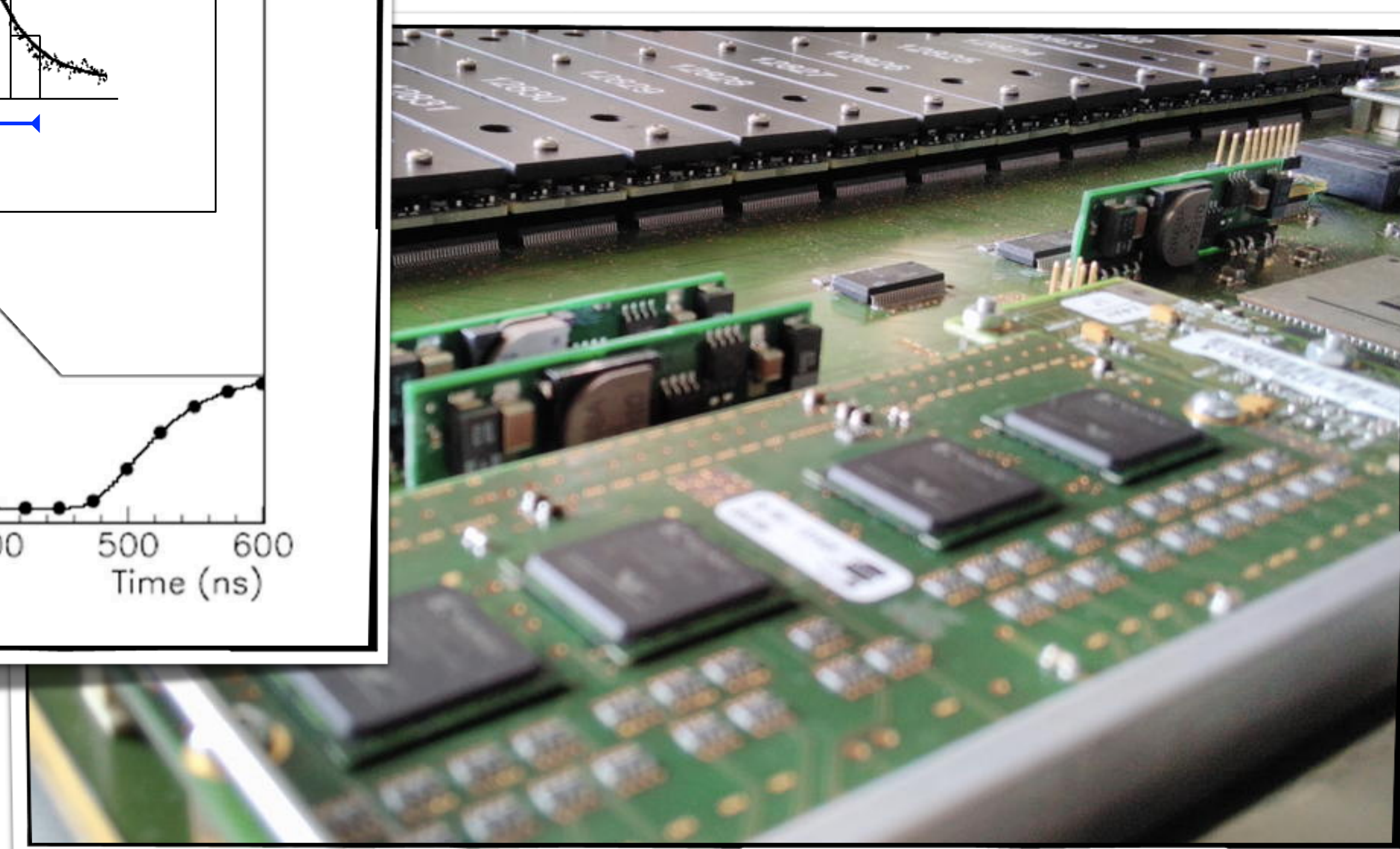
With ns-precision!

Signal Synchronization



Timing
precision guarantee
correct energy determination …

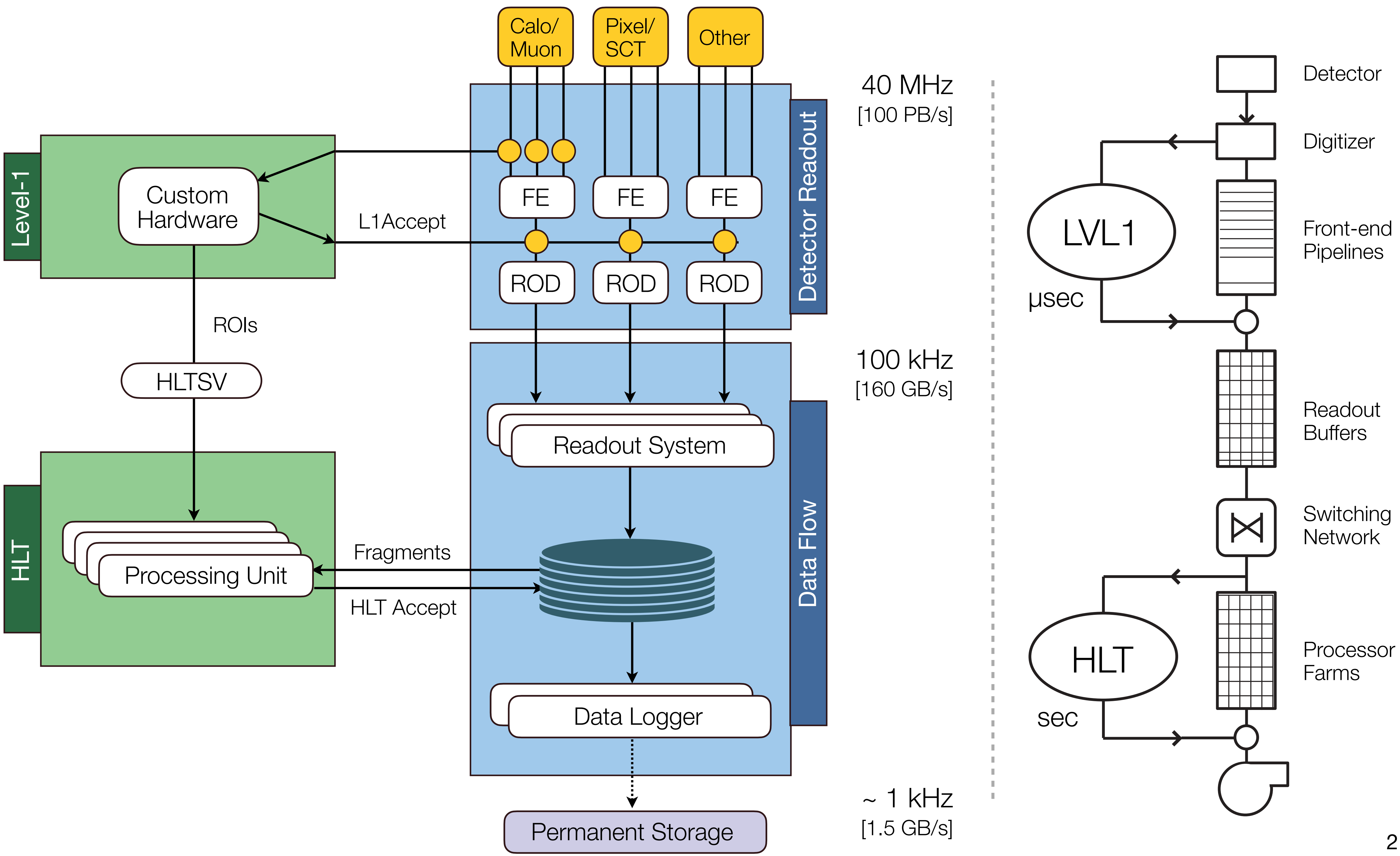
[e.g. ATLAS L1Calo Trigger]



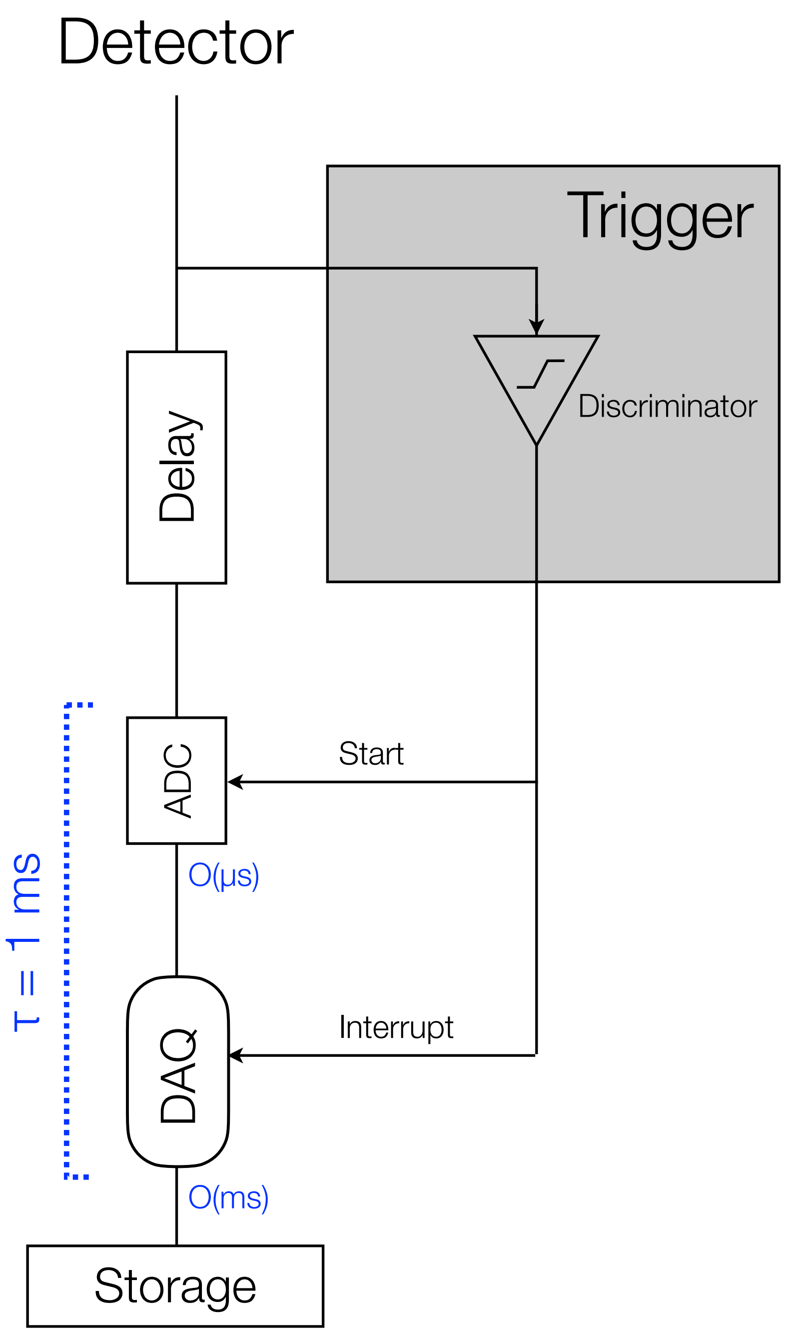
Part 2

“Concepts, Dead Time & Buffering”

Typical DAQ Example – ATLAS @ Run-2



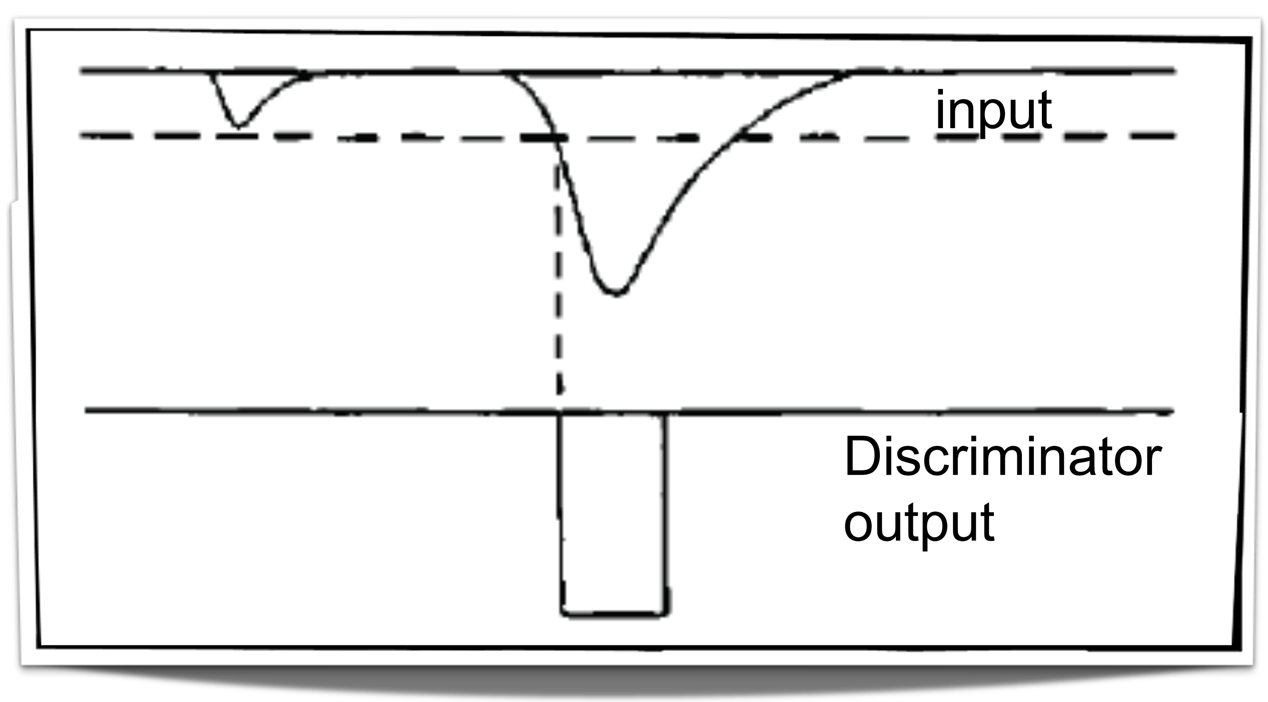
Simple Trigger & DAQ System



Simple
Trigger & DAQ system

Detection
Signal digitization
Signal processing & storage

Started by fast trigger signal
[e.g. Discriminator]



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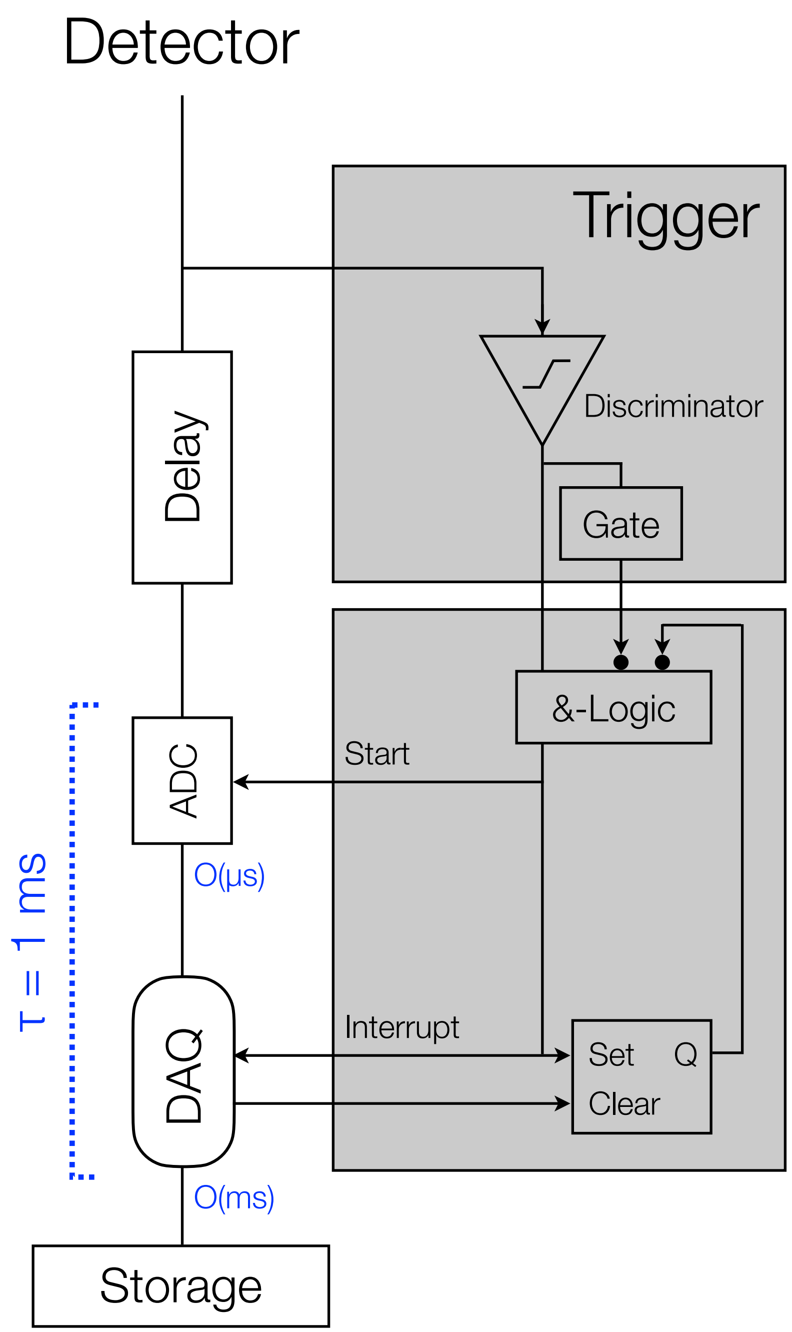

Simple
Trigger & DAQ system

Detection
Signal digitization
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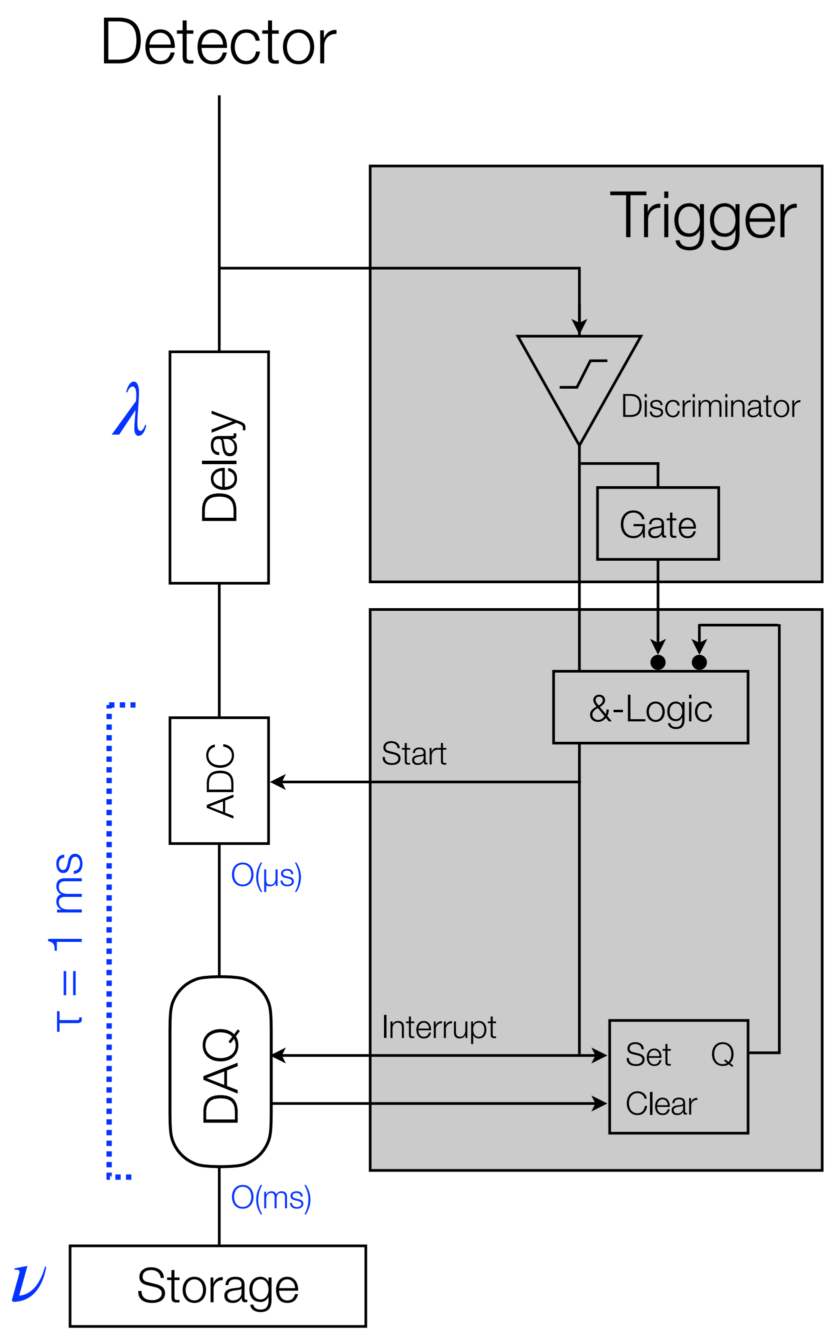
Started by fast trigger signal
[e.g. Discriminator]

Busy-Logic:

Avoids triggers while processing

Defines
➥ Dead Time

DAQ Efficiency & Dead Time



Input event rate : $\lambda = \tau_{\text{inp}}^{-1}$

DAQ output rate : ν

Processing time : τ

DAQ busy : $\nu\tau$

DAQ free : $1 - \nu\tau$

Hence:

$$\nu = \lambda \cdot (1 - \nu\tau) \rightarrow \nu = \lambda(1 + \lambda\tau)^{-1}$$

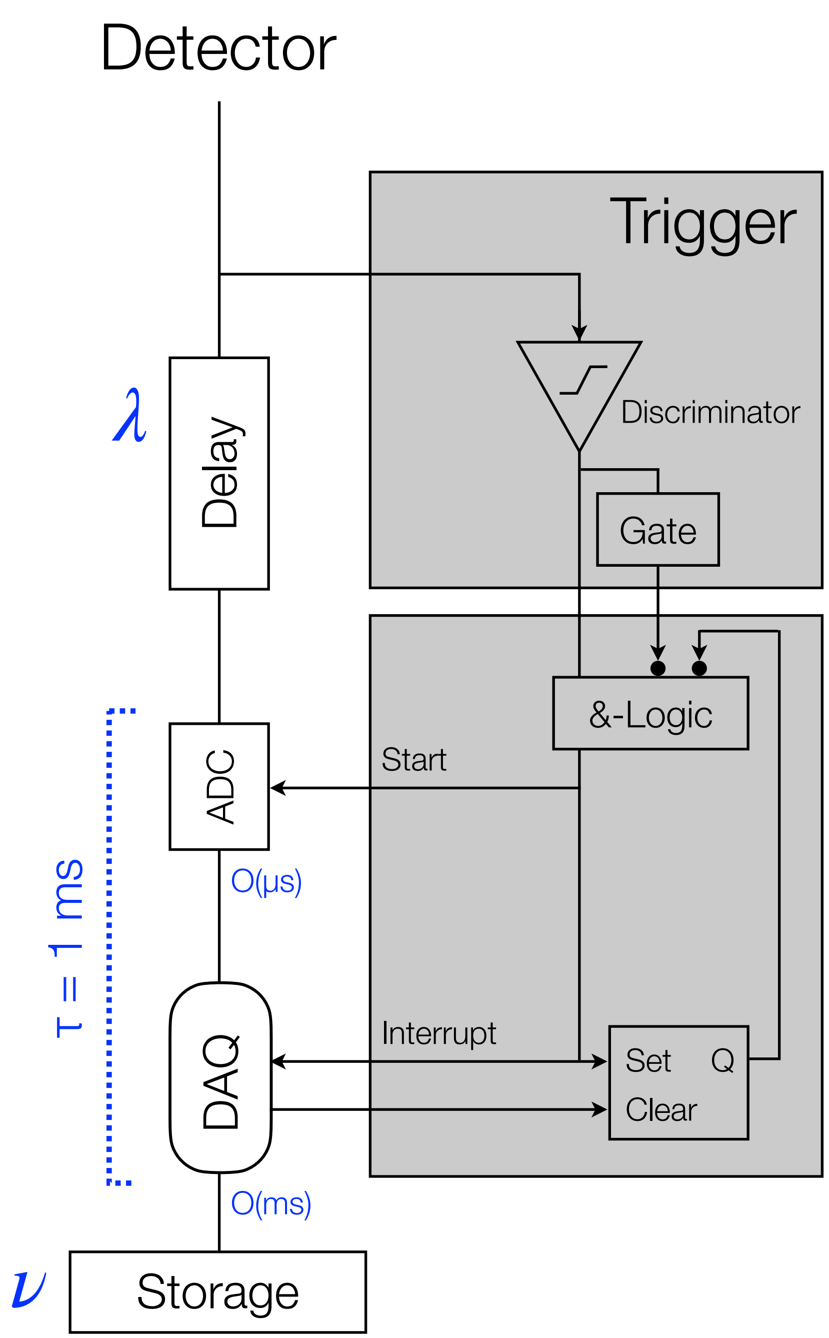
$[\nu < \lambda]$

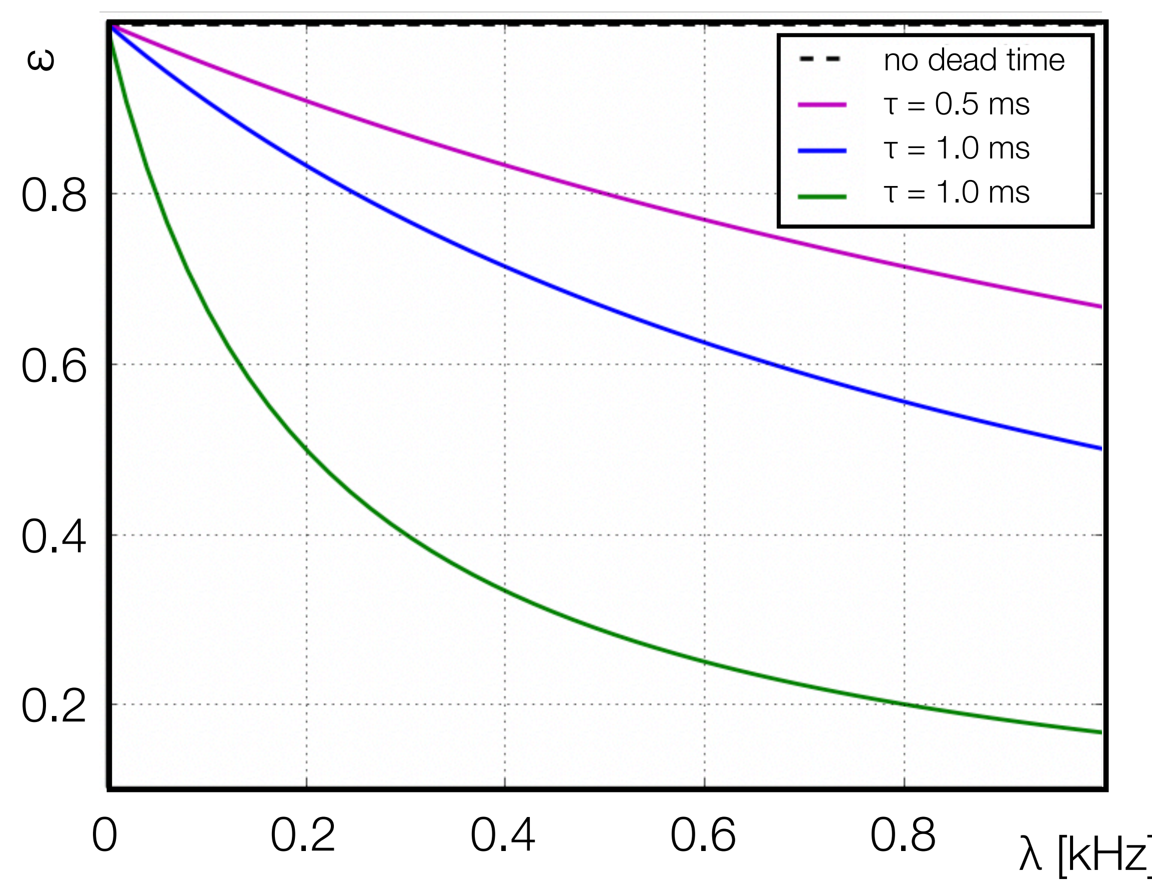
Efficiency : $\epsilon = \nu/\lambda = (1 + \lambda\tau)^{-1}$

Rel. dead time : $\mathrm{DT} = 1 - \epsilon$

$$= \lambda\tau\,(1 + \lambda\tau)^{-1}$$

DAQ Efficiency & Dead Time



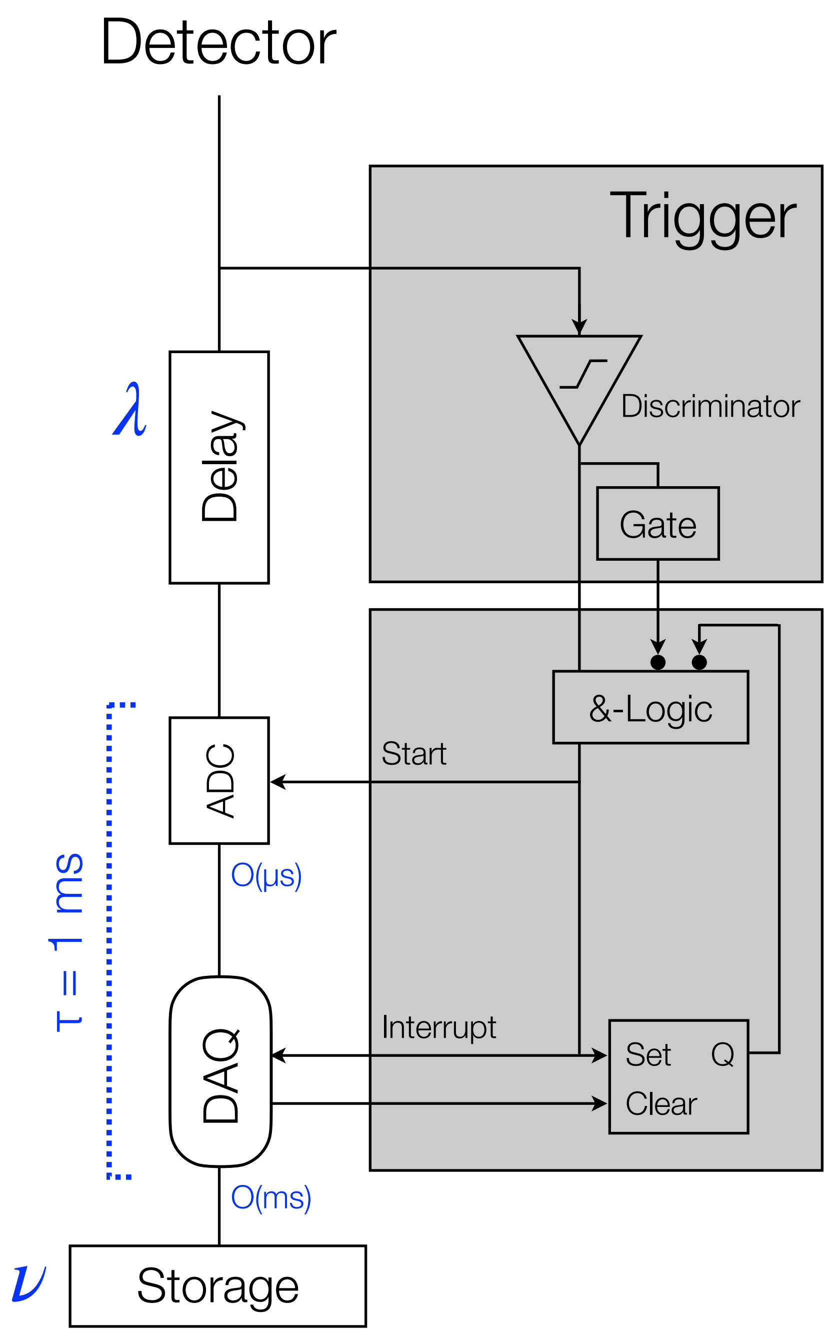


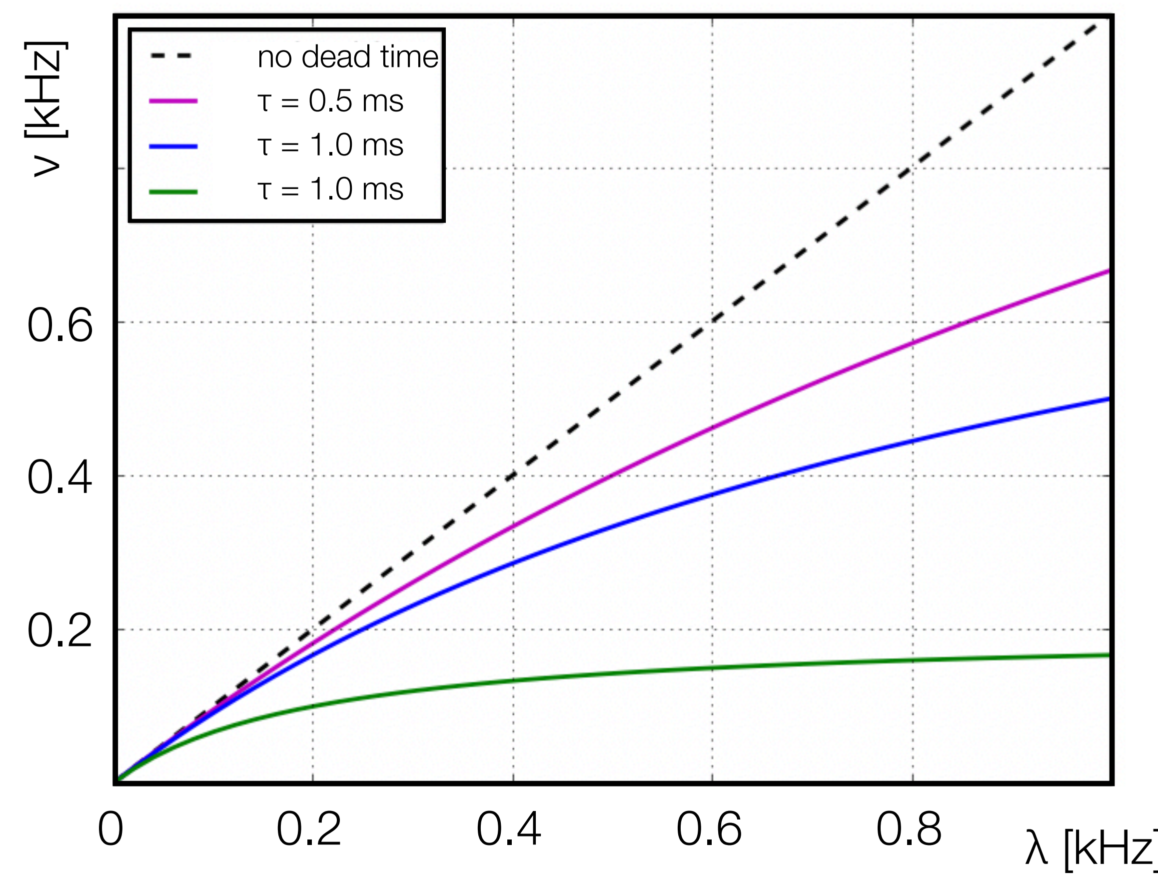
Efficiency : $\epsilon = \nu/\lambda = (1 + \lambda\tau)^{-1}$

Rel. dead time : $\mathrm{DT} = 1 - \epsilon$

$= \lambda\tau\,(1 + \lambda\tau)^{-1}$

DAQ Efficiency & Dead Time





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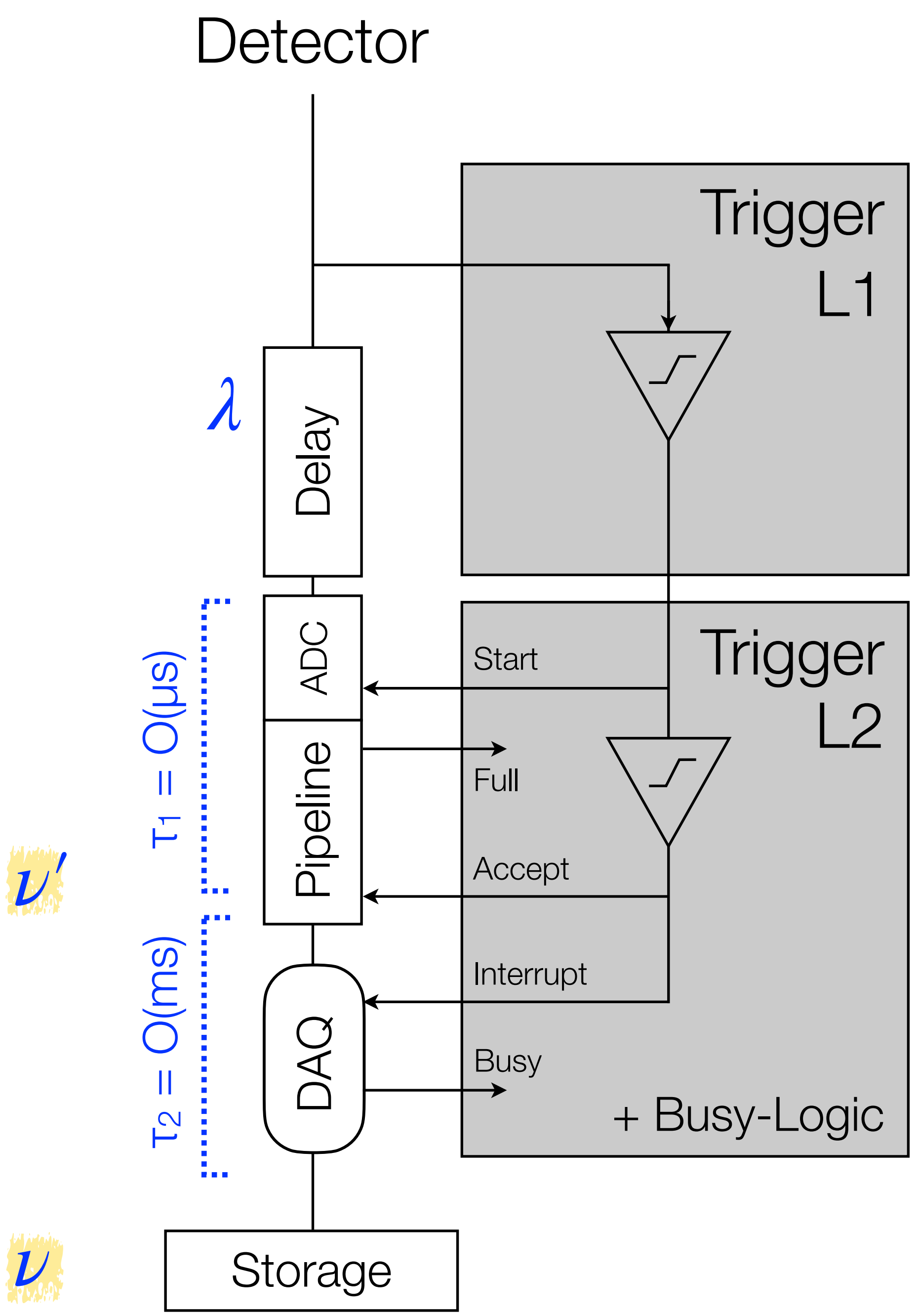
Adding an Extra Trigger Levels



Input event rate : $\lambda = \tau_{\mathrm{inp}}^{-1}$

L1/L2 rates : ν', ν

Processing times : $\tau_1, \tau_2, \tau = \tau_1 + \tau_2$

$$\epsilon = \nu/\lambda = (1 + \lambda\tau)^{-1}$$

$$\epsilon' = \nu'/\lambda = ?$$

DAQ free : $1 - \nu\tau - K\nu\tau_1$

Seen rate : $\nu' = \nu + K\nu$

K L2 Rejection Factor

→

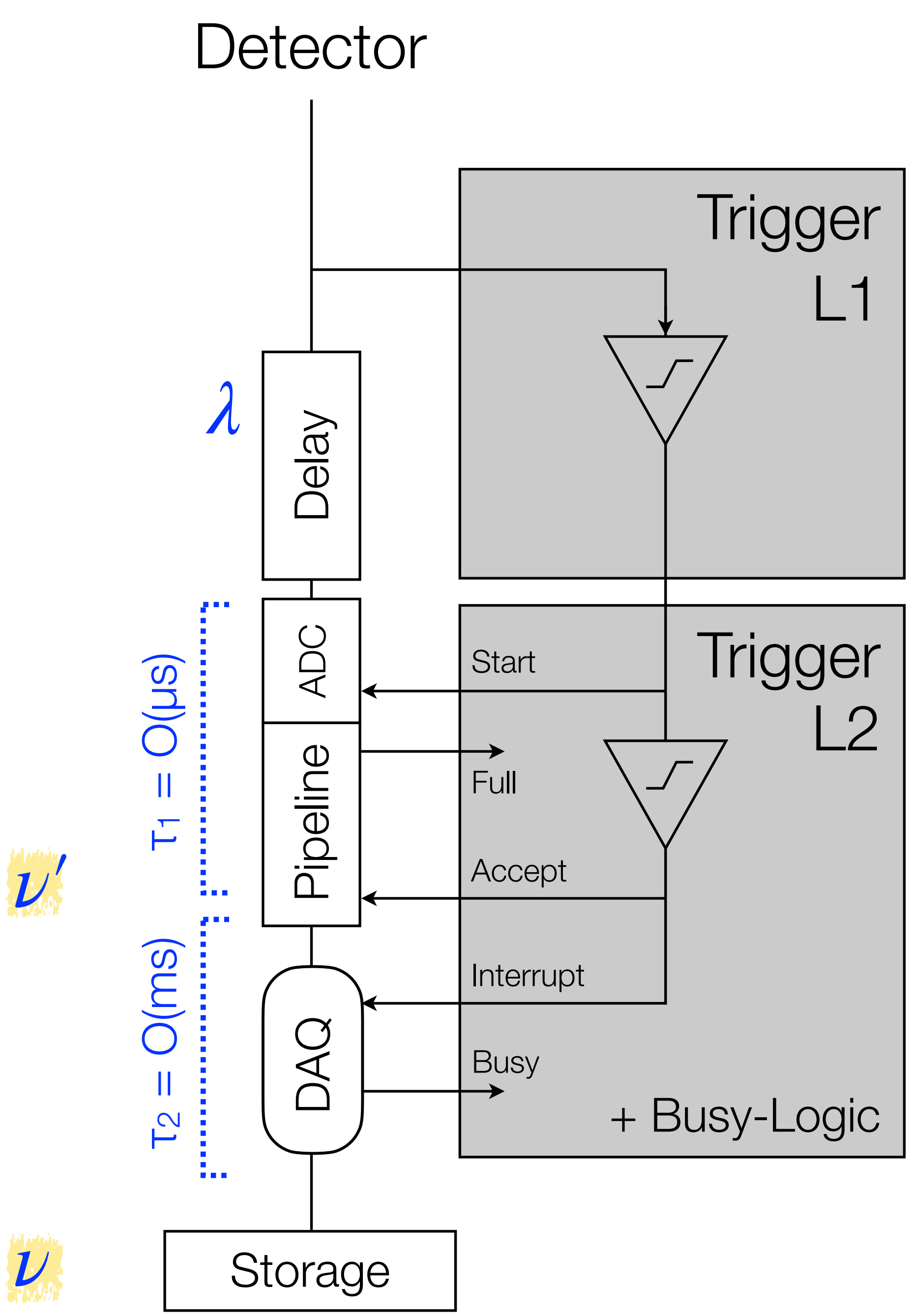
$$\nu' = \lambda\,(1 - \nu\tau - K\nu\tau_1)$$

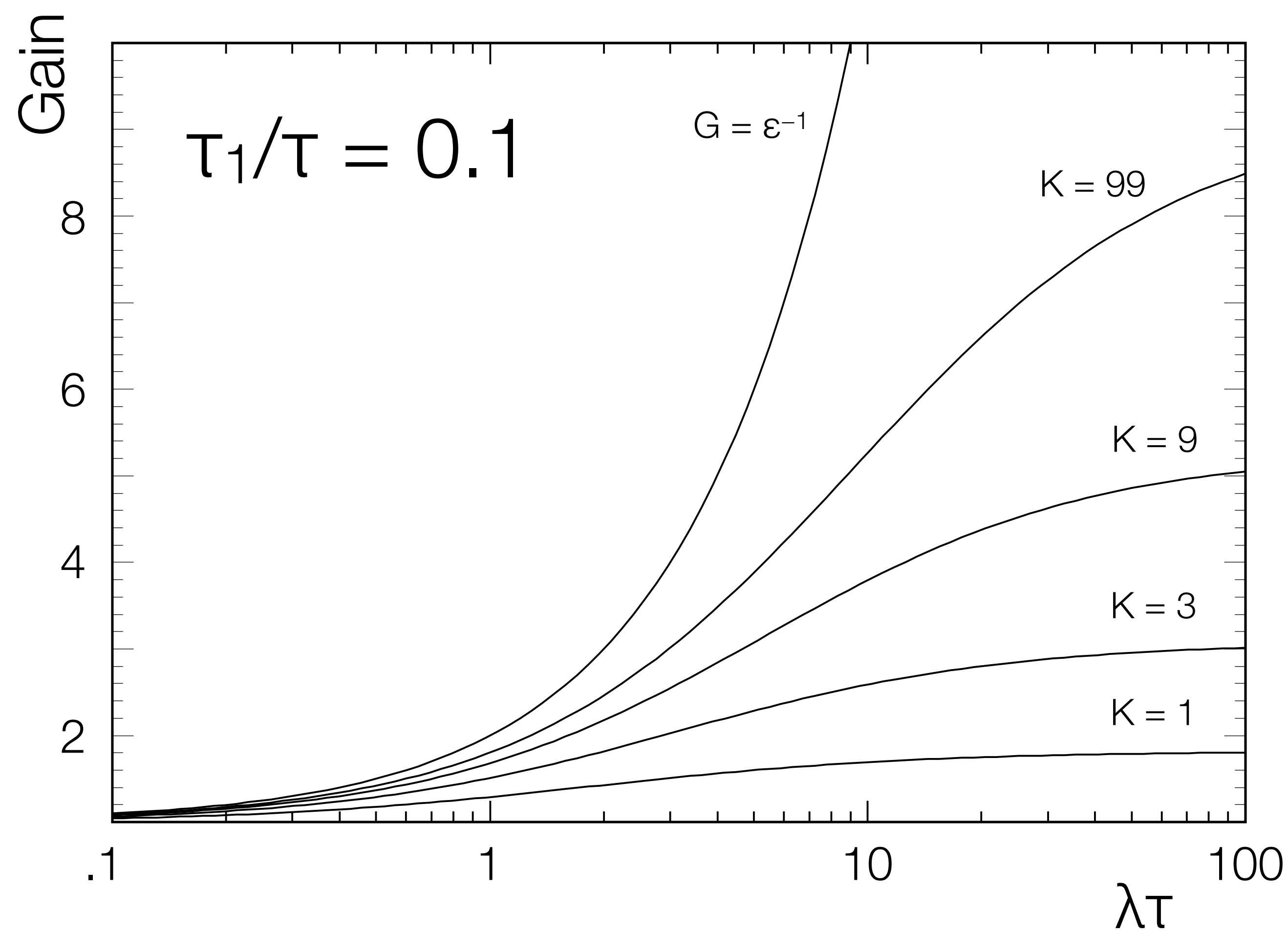
[…]

$$\epsilon' = (1 + \lambda\tau)^{-1}\left(\frac{K+1}{1 + K(1+\lambda\tau_1)/(1+\lambda\tau)}\right)$$

ϵ × Gain (G)

Adding an Extra Trigger Levels





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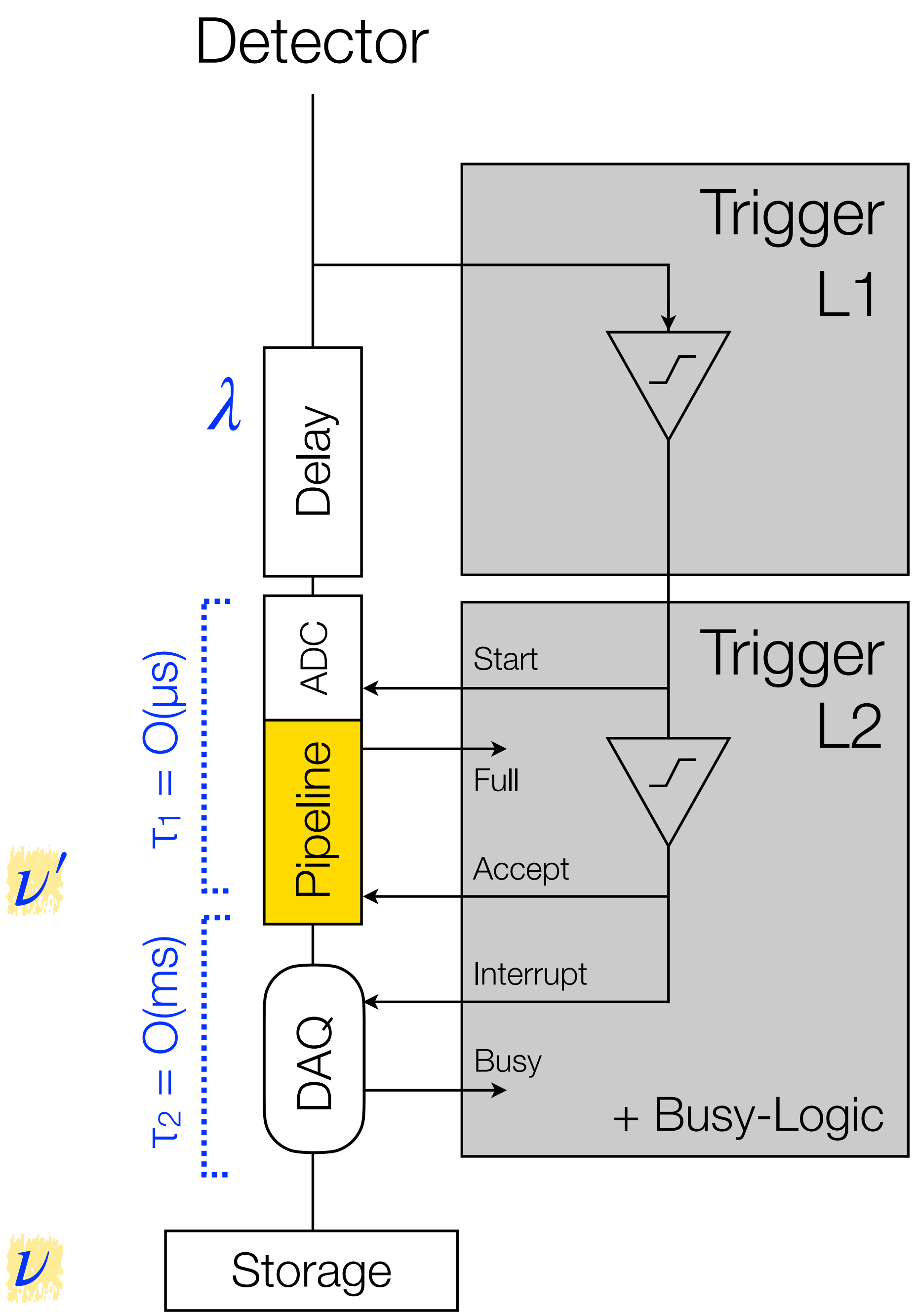

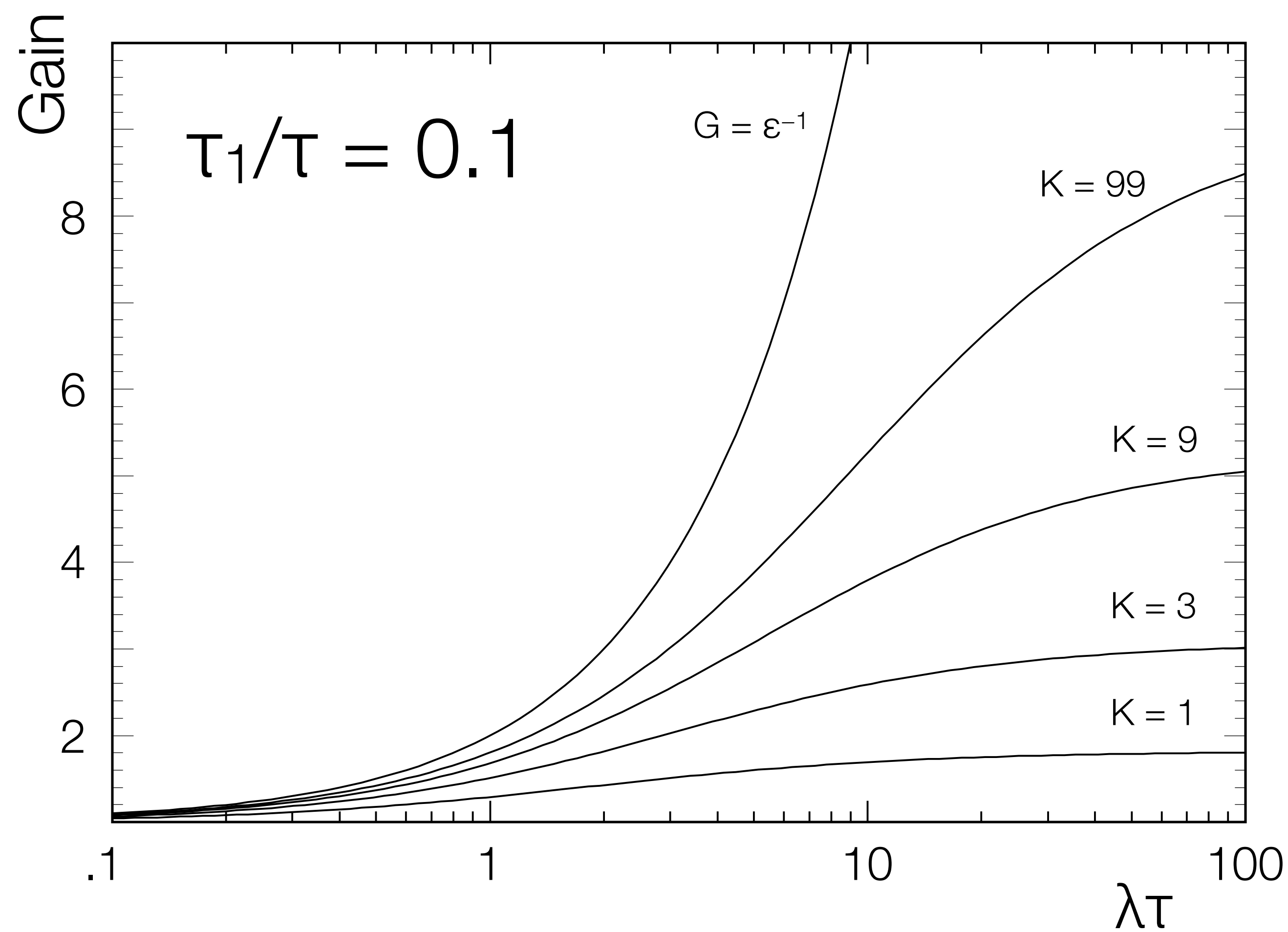

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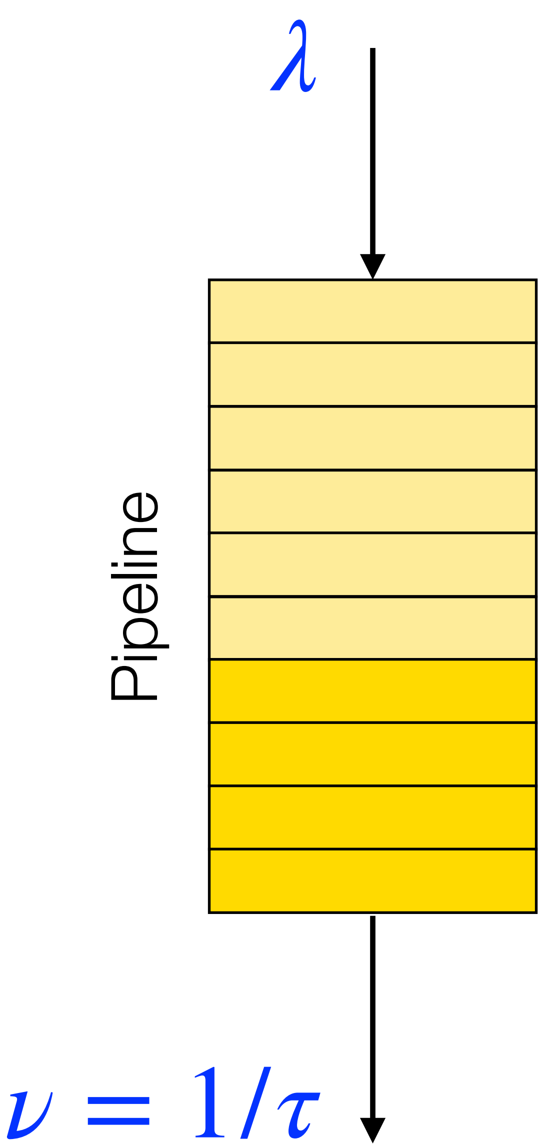
De-Randomizing Using Pipelines



Probability of n filled buffers: P_n

Steady state: $\mathrm{d}P_n = 0$

$$\mathrm{d}P_n = [\lambda P_{n-1} + \nu P_{n+1} - (\lambda + \nu)P_n]\mathrm{d}t$$

$$\mathrm{d}P_0 = [\nu P_1 - \lambda P_0]\mathrm{d}t \ , \ \mathrm{d}P_N = [\lambda P_{N-1} - \nu P_N]\mathrm{d}t$$

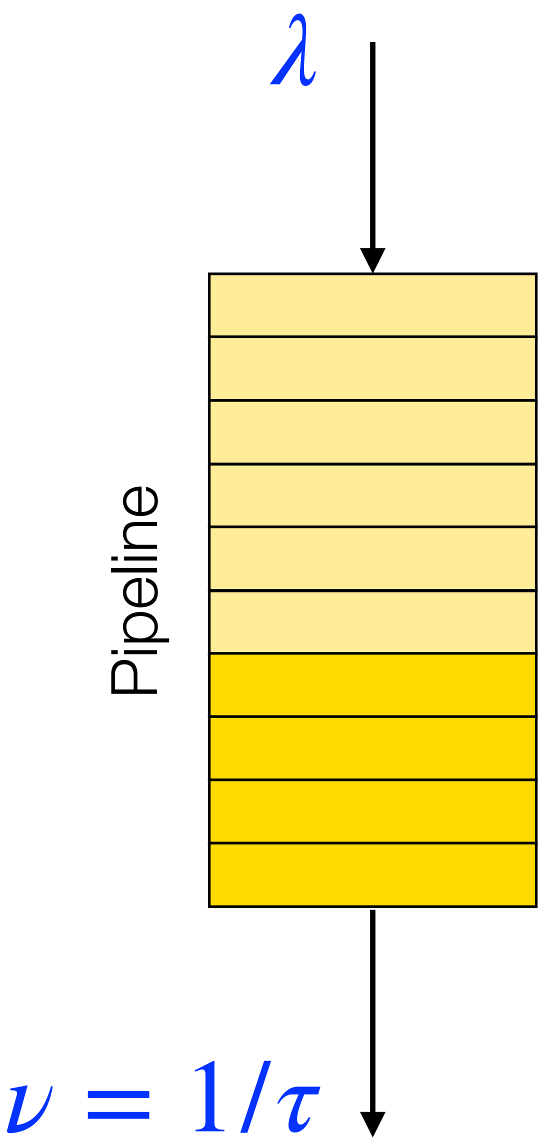
$$P_n = (\lambda/\nu)^n P_0 = (\rho)^n P_0 \qquad \text{[with } \rho = \lambda/\nu = \lambda\tau\text{]}$$

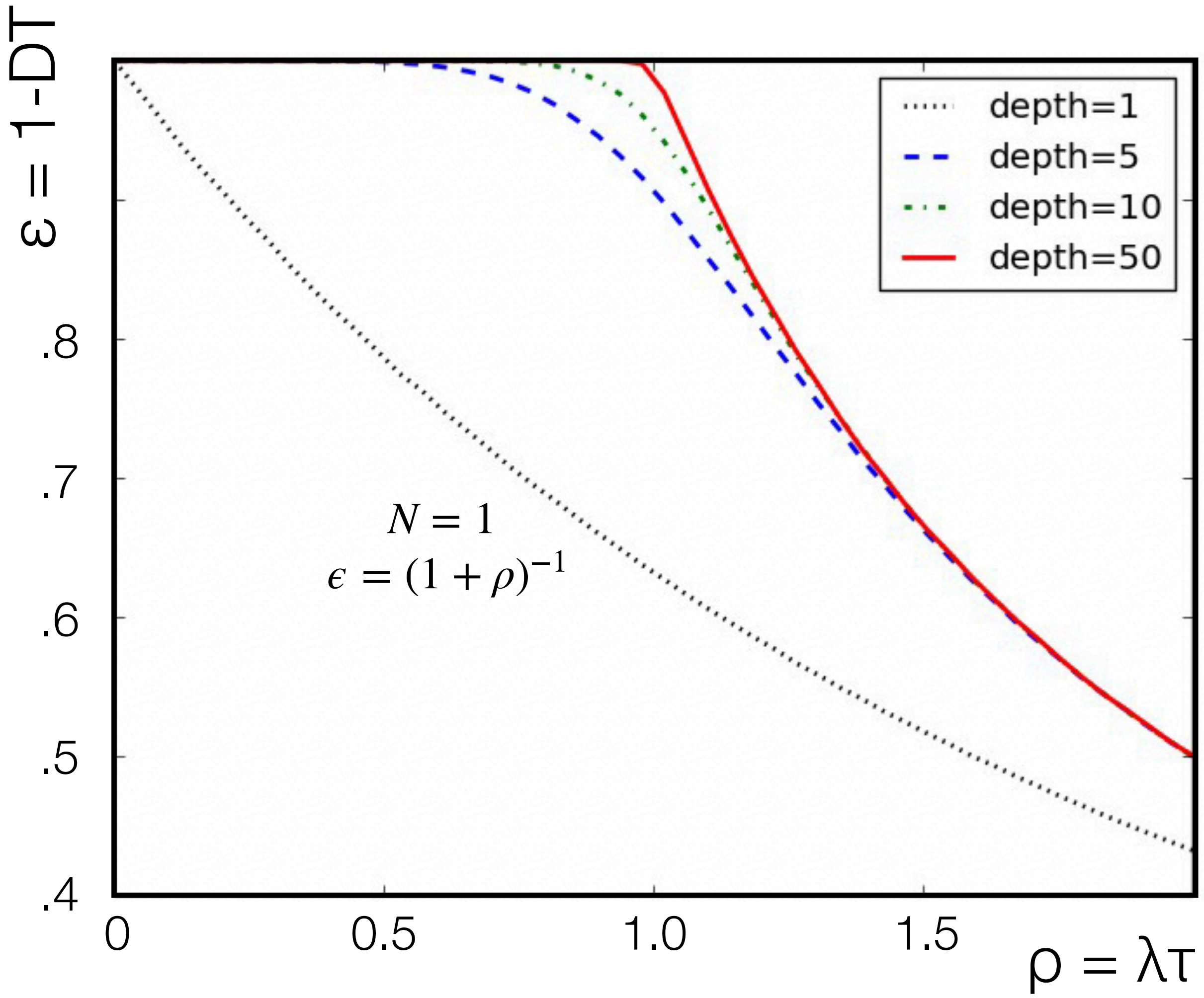
Using $\Sigma P_n = 1$ yields:

$$\mathrm{DT} = P_N = \begin{cases} P_n = \dfrac{(1-\rho)\rho^N}{1-\rho^{N+1}} & \text{for } \rho \neq 1 \\ P_n = \dfrac{1}{N+1} & \text{for } \rho = 1 \end{cases}$$

$\rho = \lambda\tau$

De-Randomizing Using Pipelines





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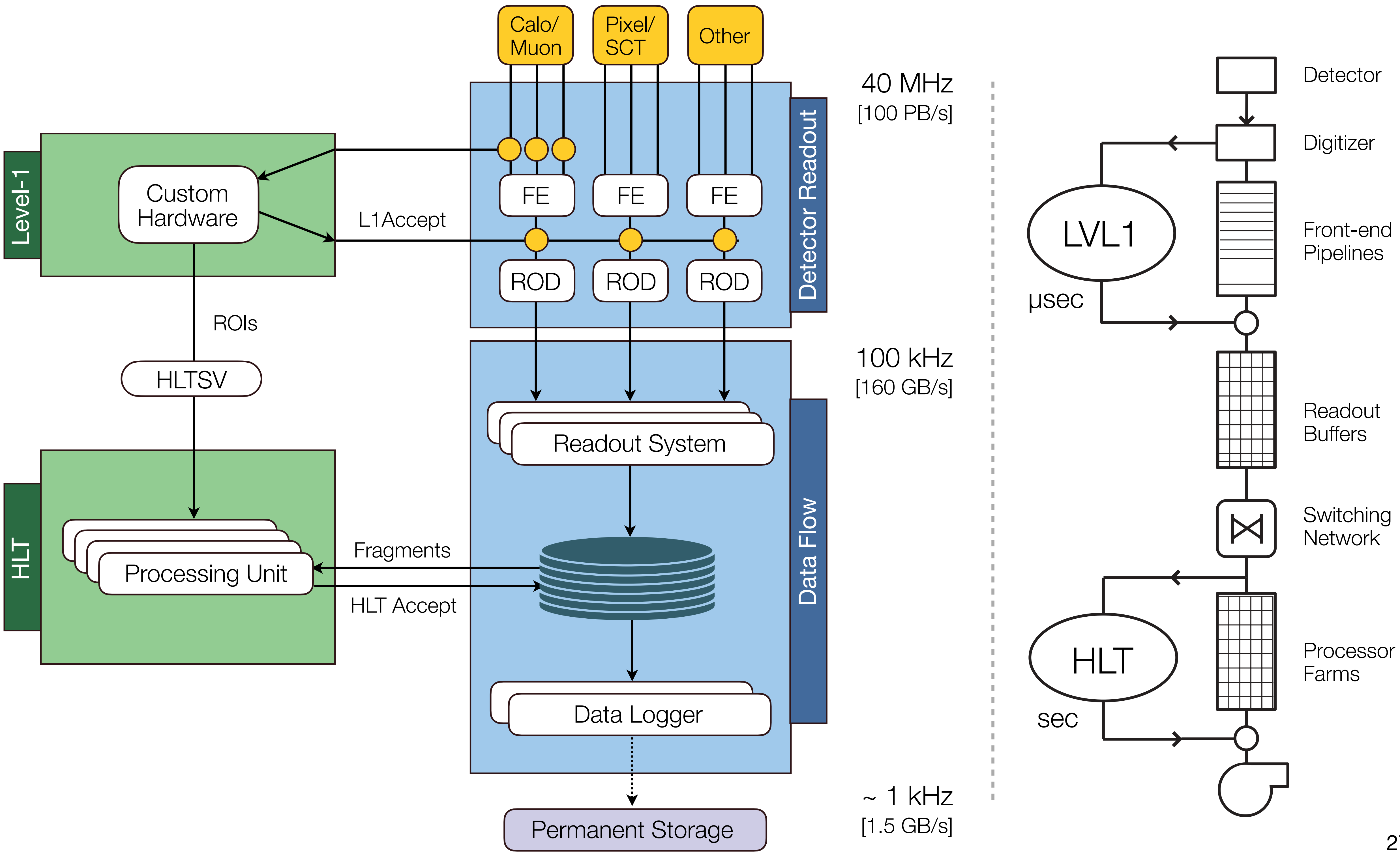
$\rho = \lambda\tau$

Typical DAQ Example – ATLAS @ Run-2



Some Rates, Latencies & Dead Times

LVL1 dead time:

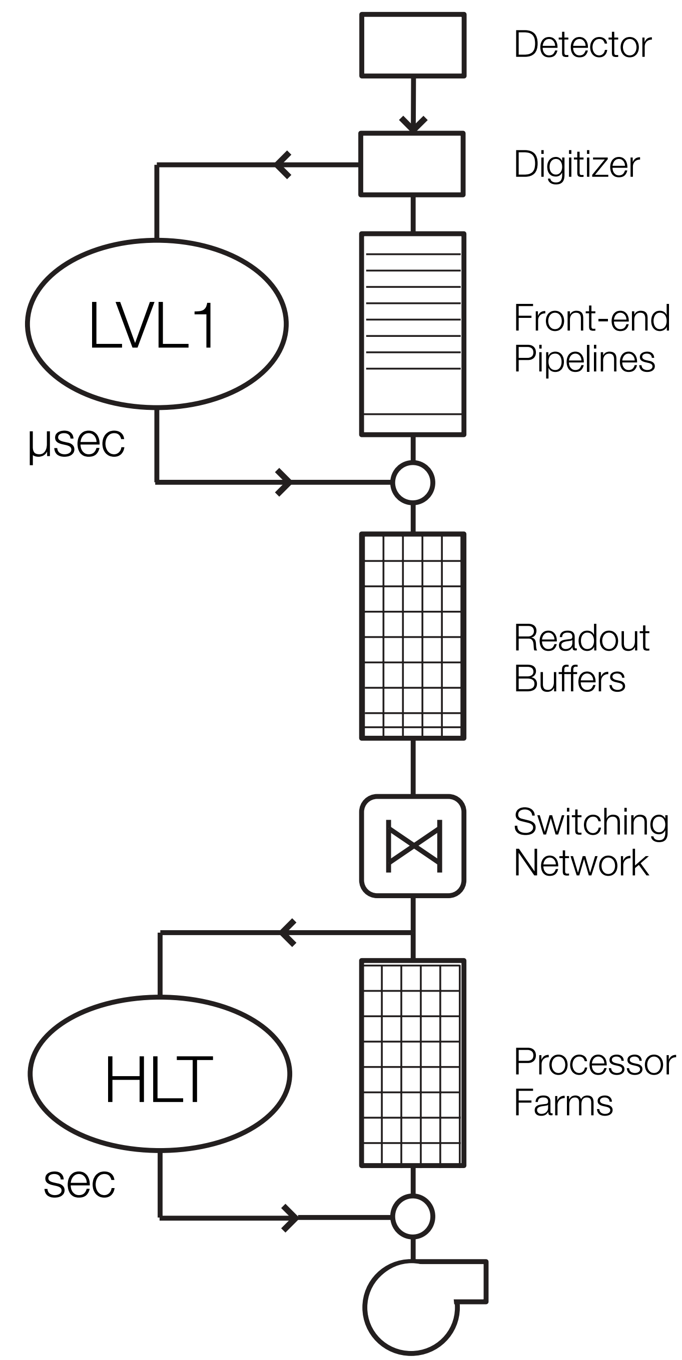
DT = r/o Rate × busy after L1A

e.g. H1: 50 Hz × 2 ms (L1)

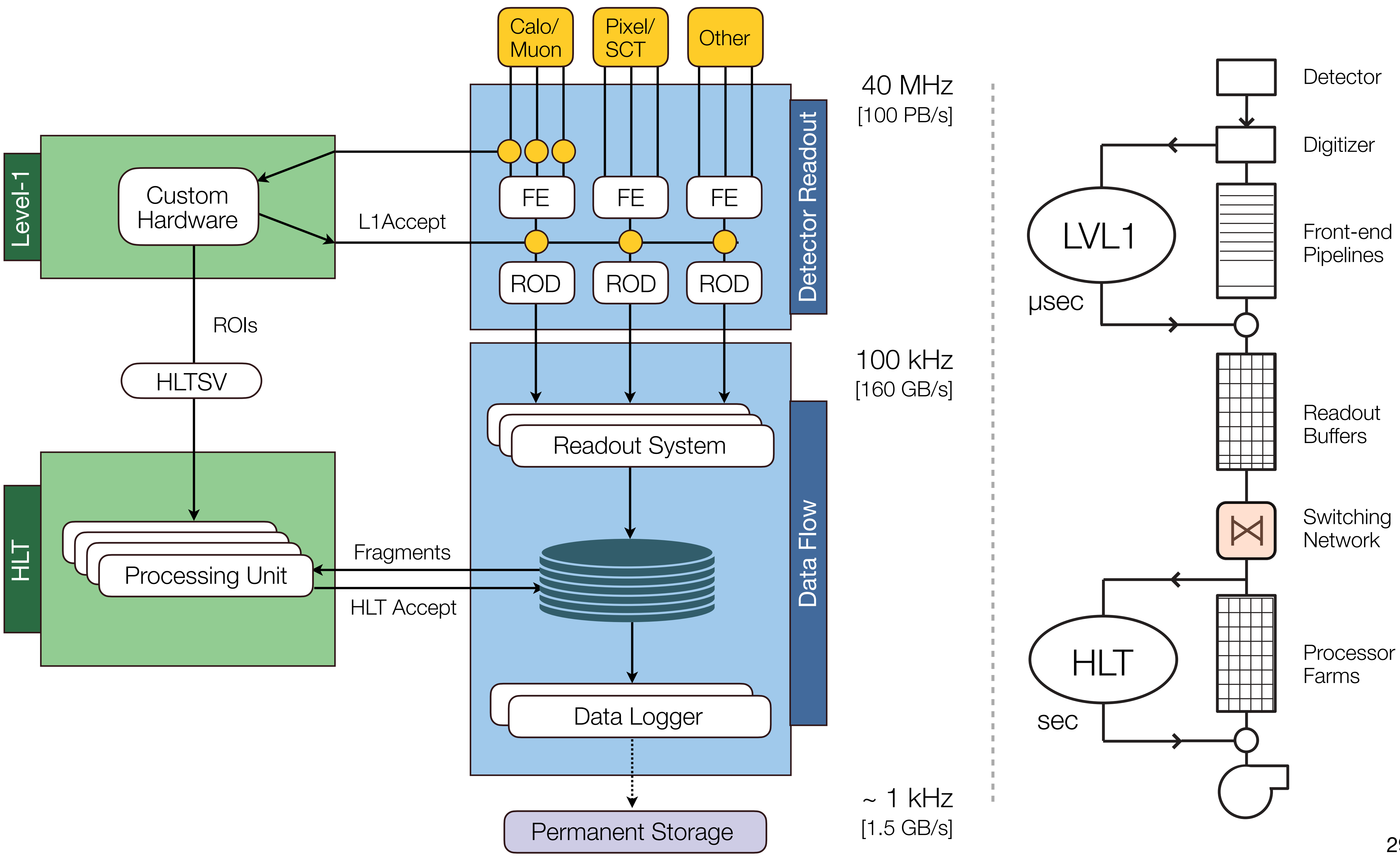
ATLAS: 100 kHz × 125 ns (L1)

Experiment	Rate	Rate⁻¹	Latency (First level)	L1 DT (First level)
LEP	90 kHz	11 μs	few μs	1.5%
HERA (H1)	10 MHz	96 ns	4 μs	10 %
Tevatron (Run1)	250 kHz	4 μs	4 μs	5 %
Tevatron (Run2)	7.6 MHz	132 ns	4 μs	5 %
ATLAS	40 MHz	25 ns	2.5 μs	0.1%
ILC	3 MHz	337 ns	– †	0 %

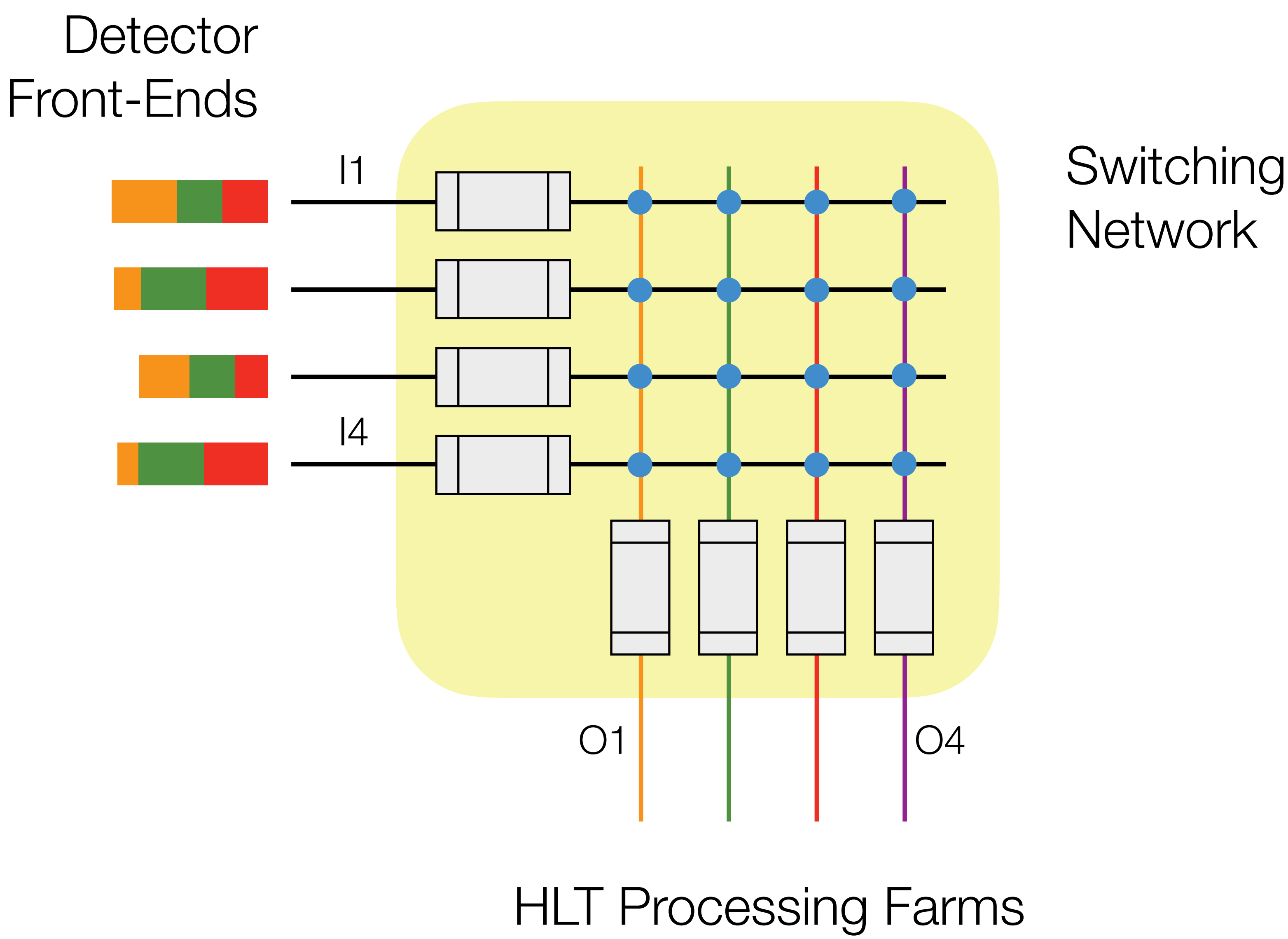
† Trigger-less readout in gab between bunch trains

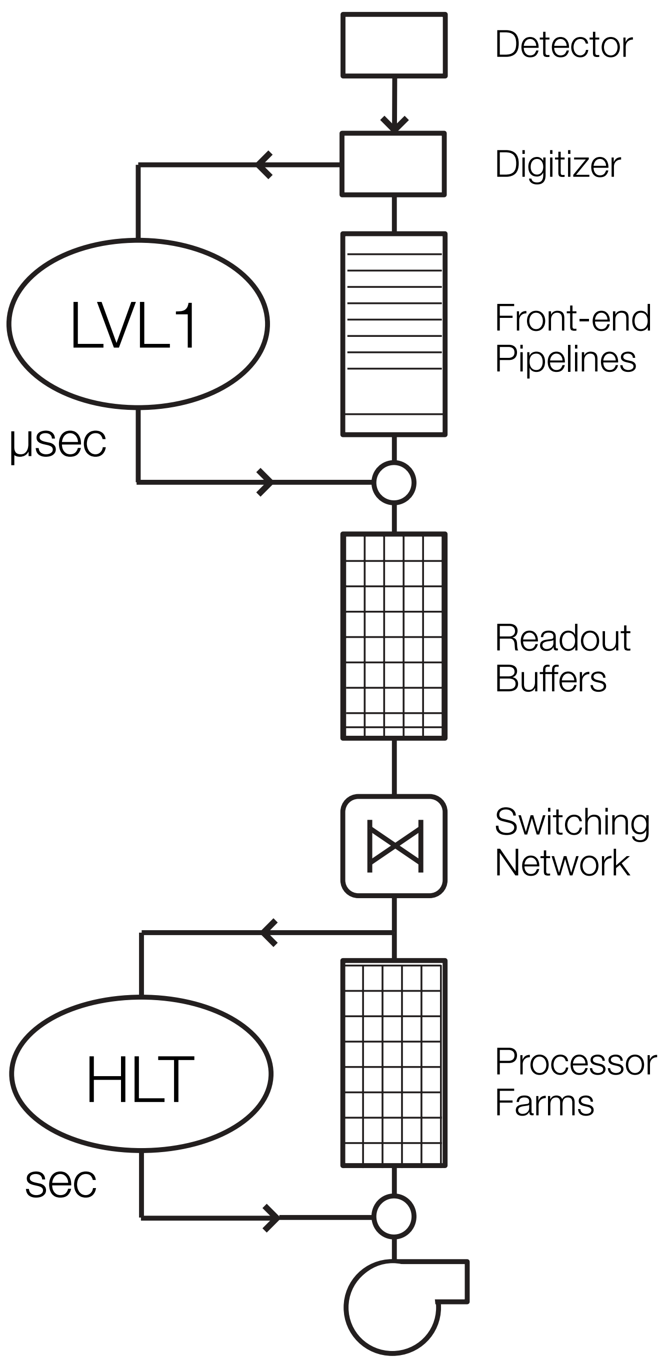


Typical DAQ Example – ATLAS @ Run-2

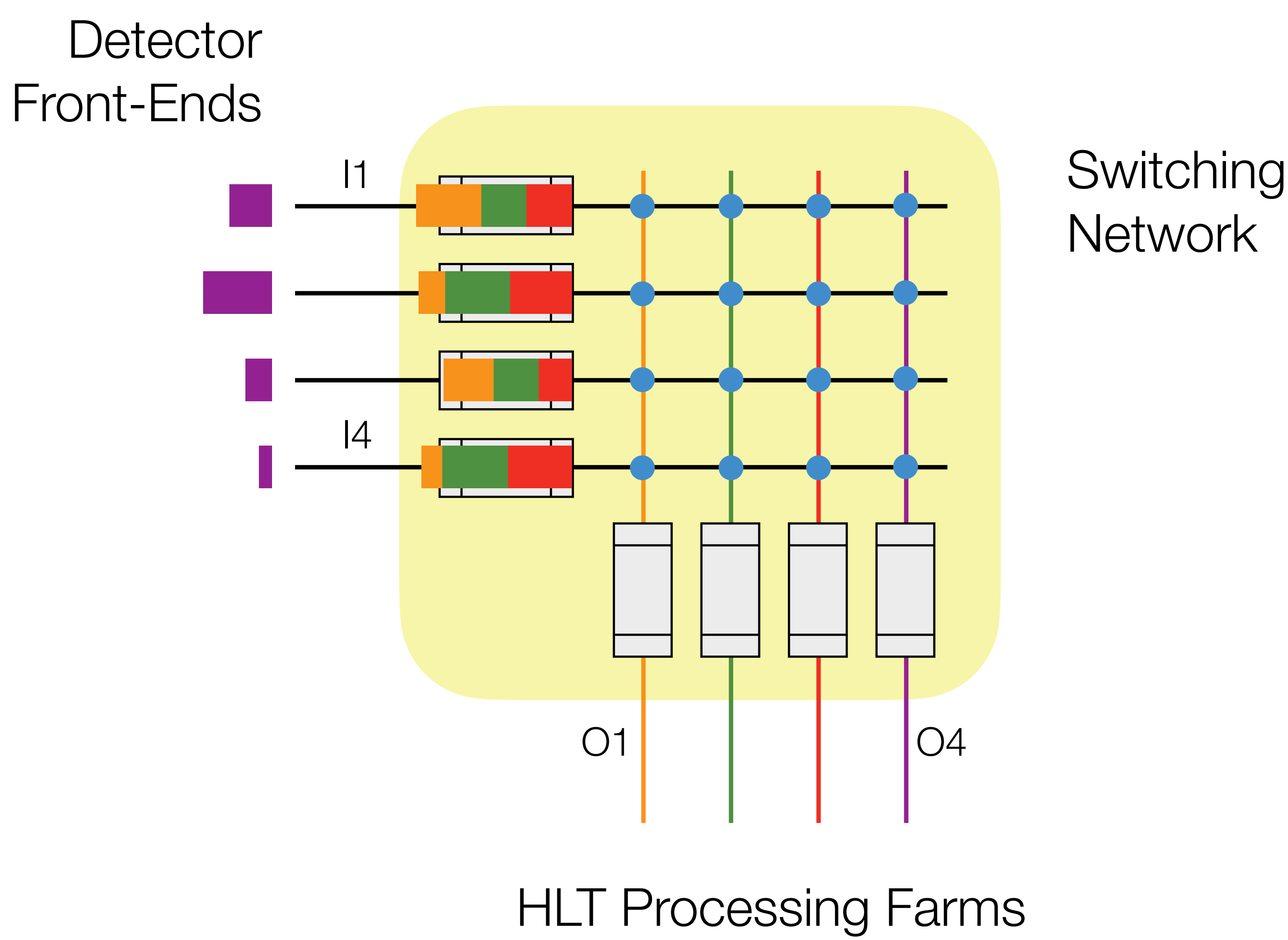


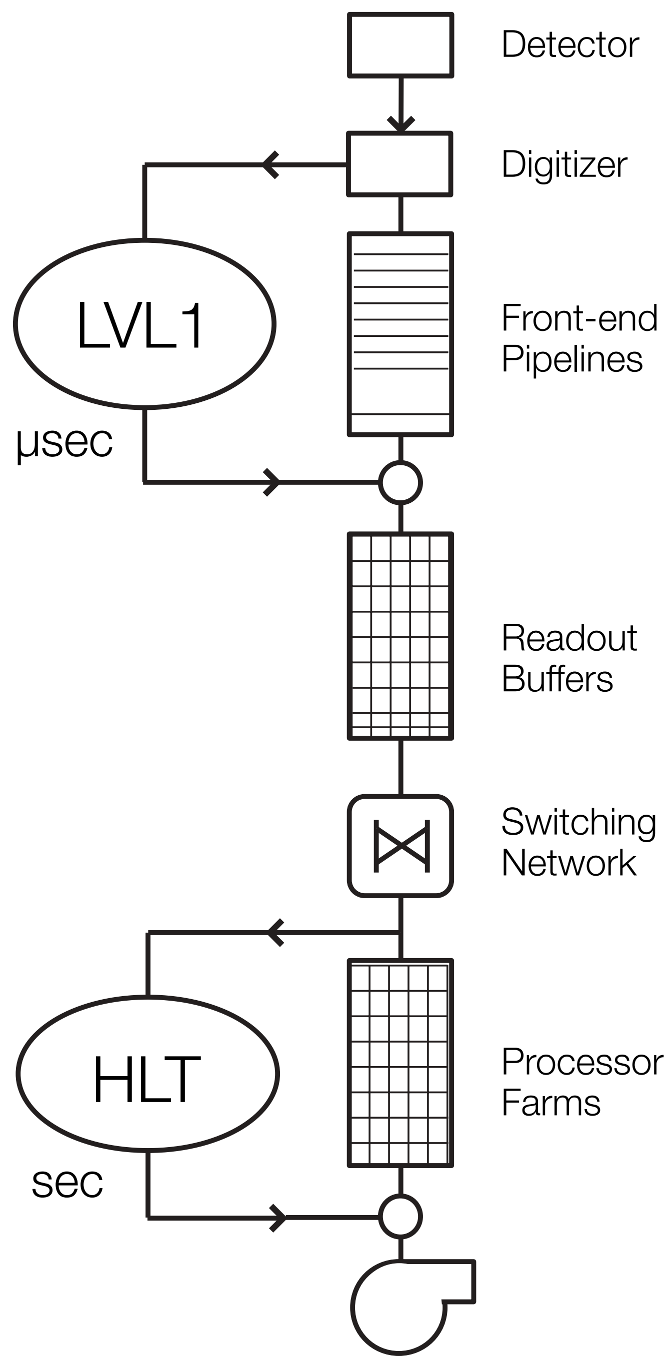
DAQ Switching Network



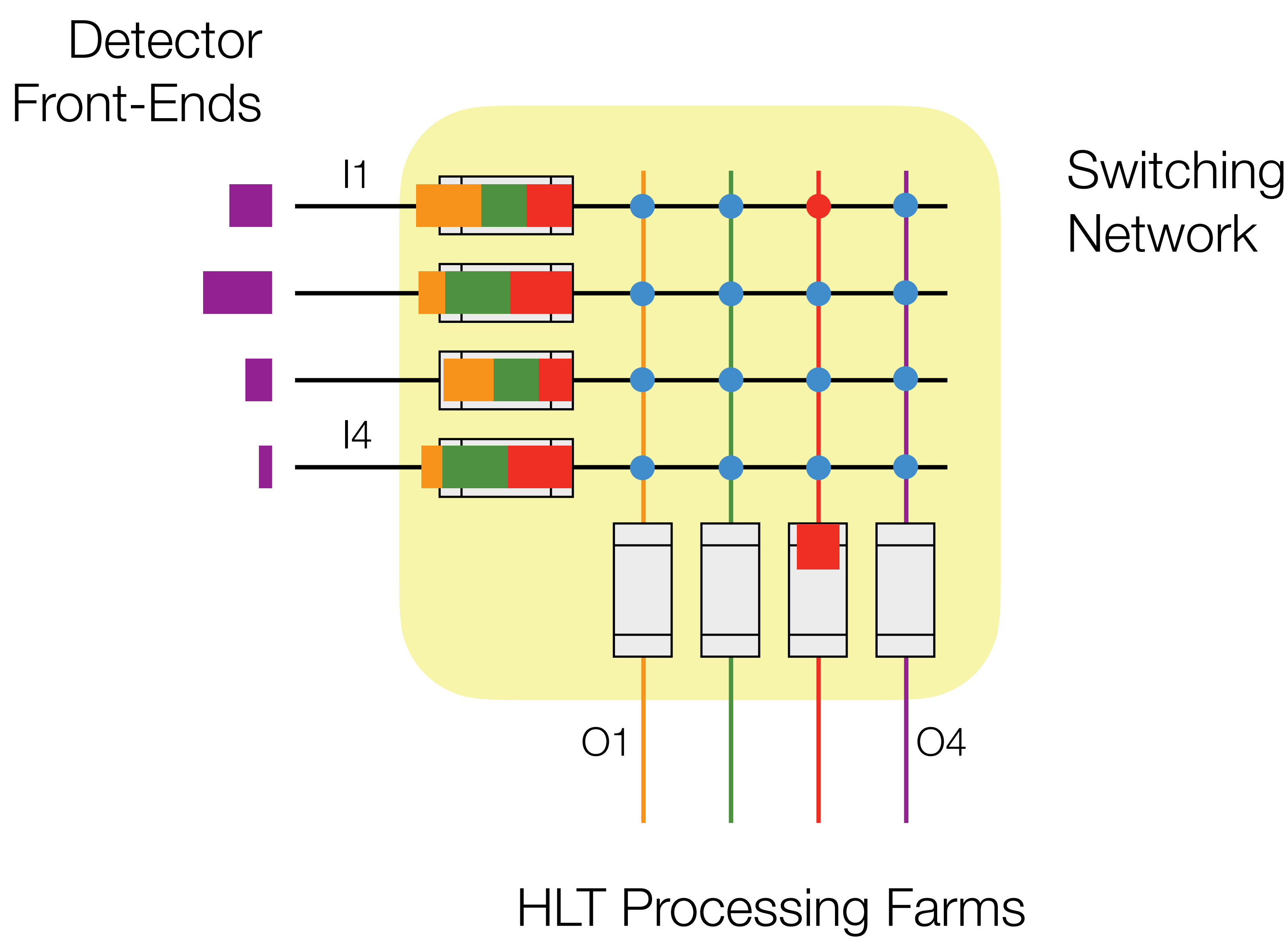


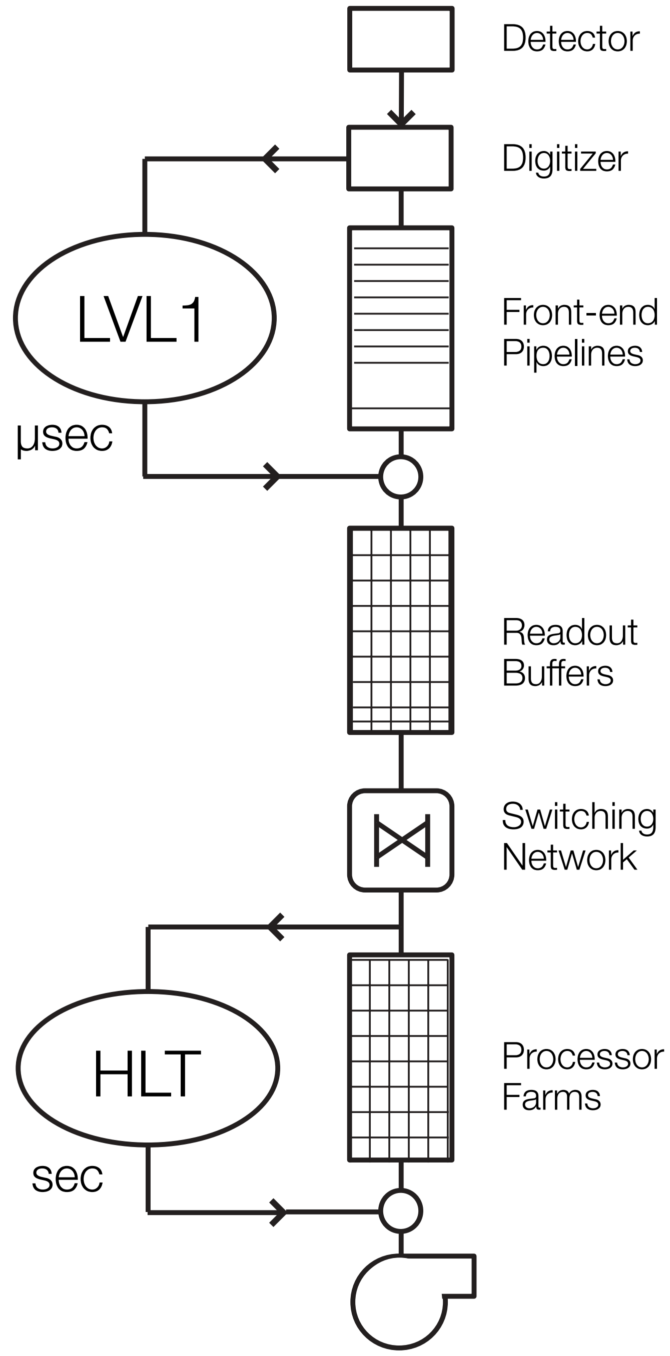
DAQ Switching Network



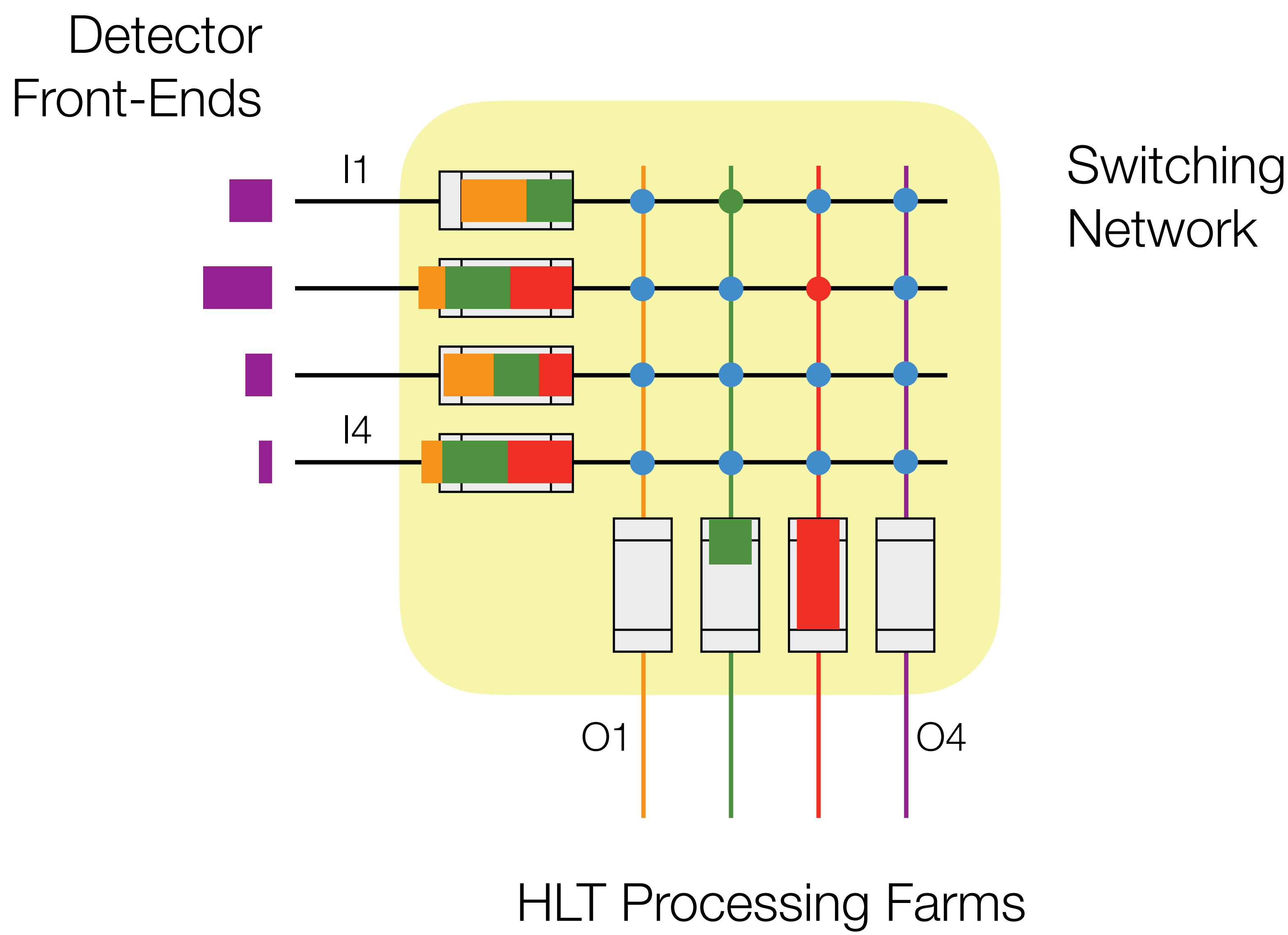


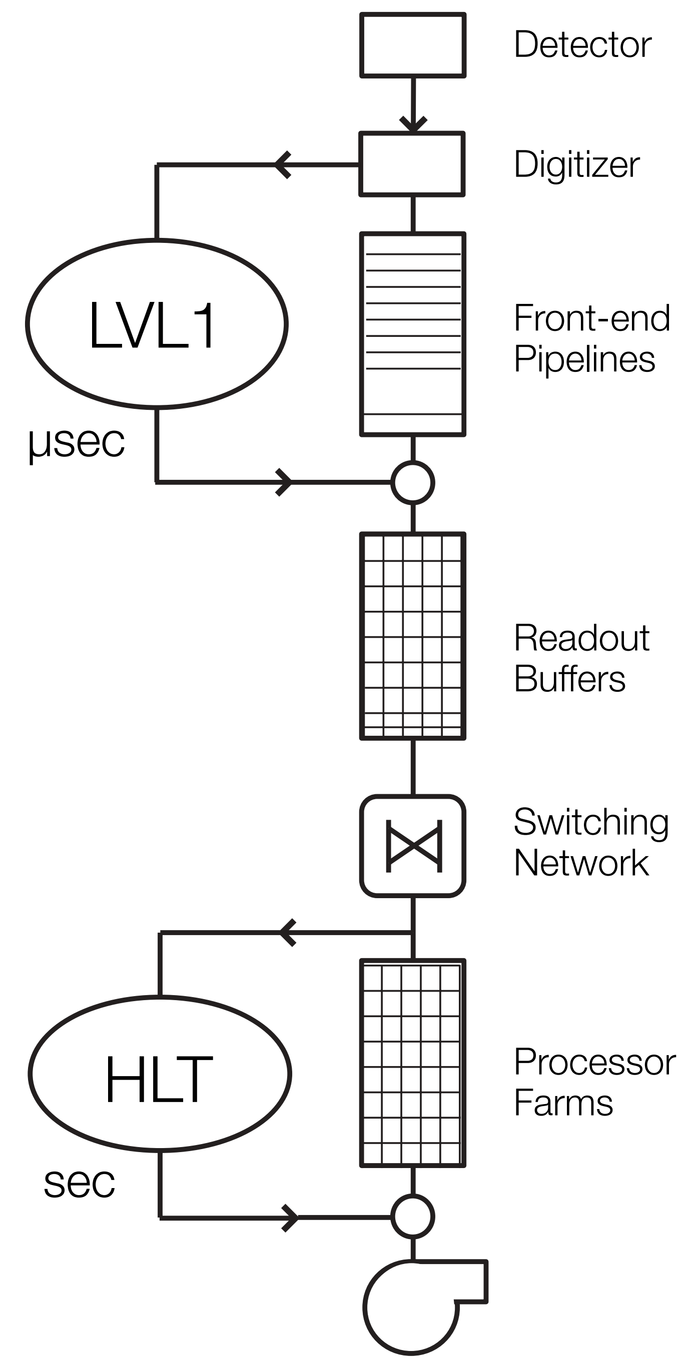
DAQ Switching Network



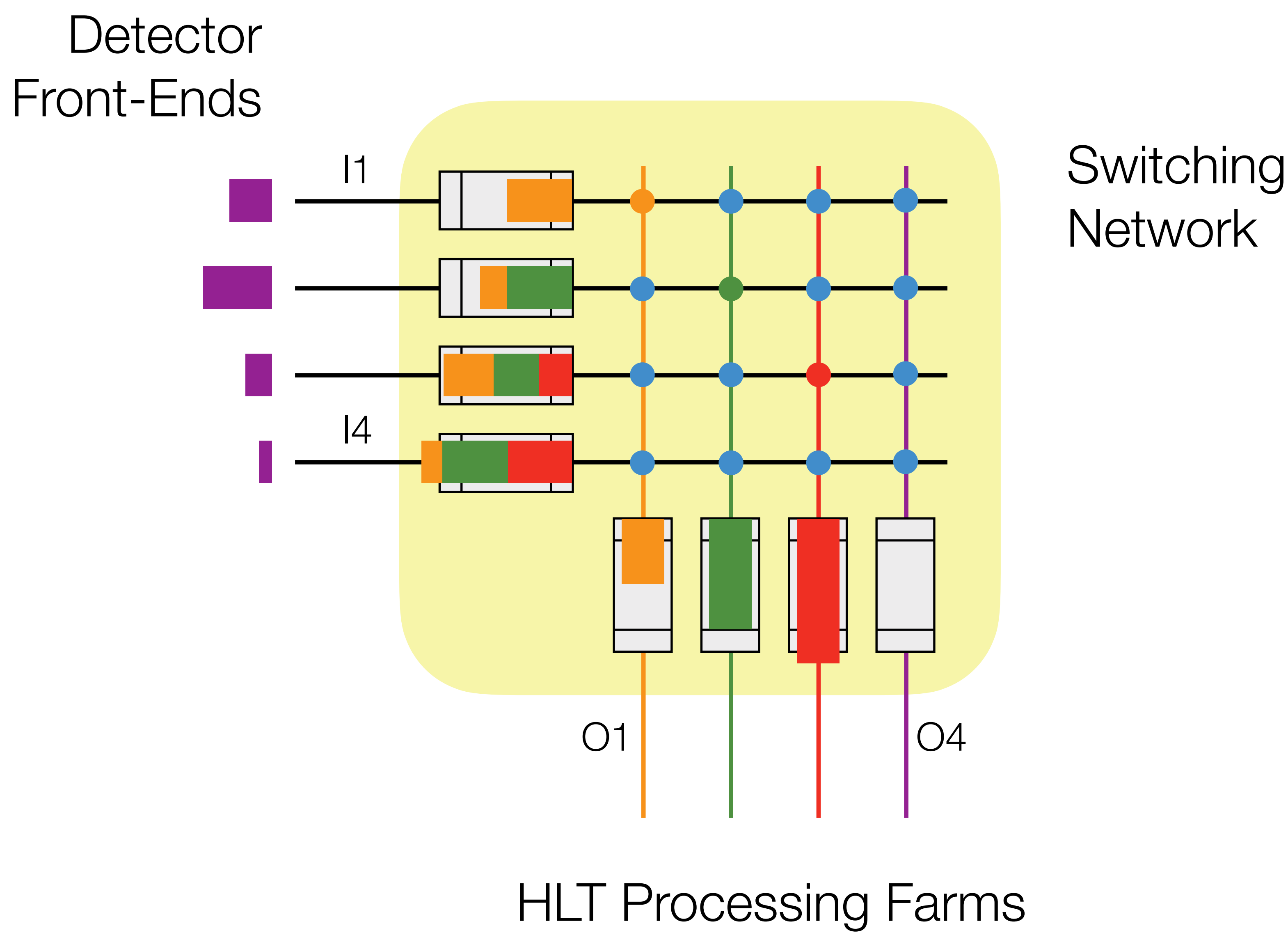


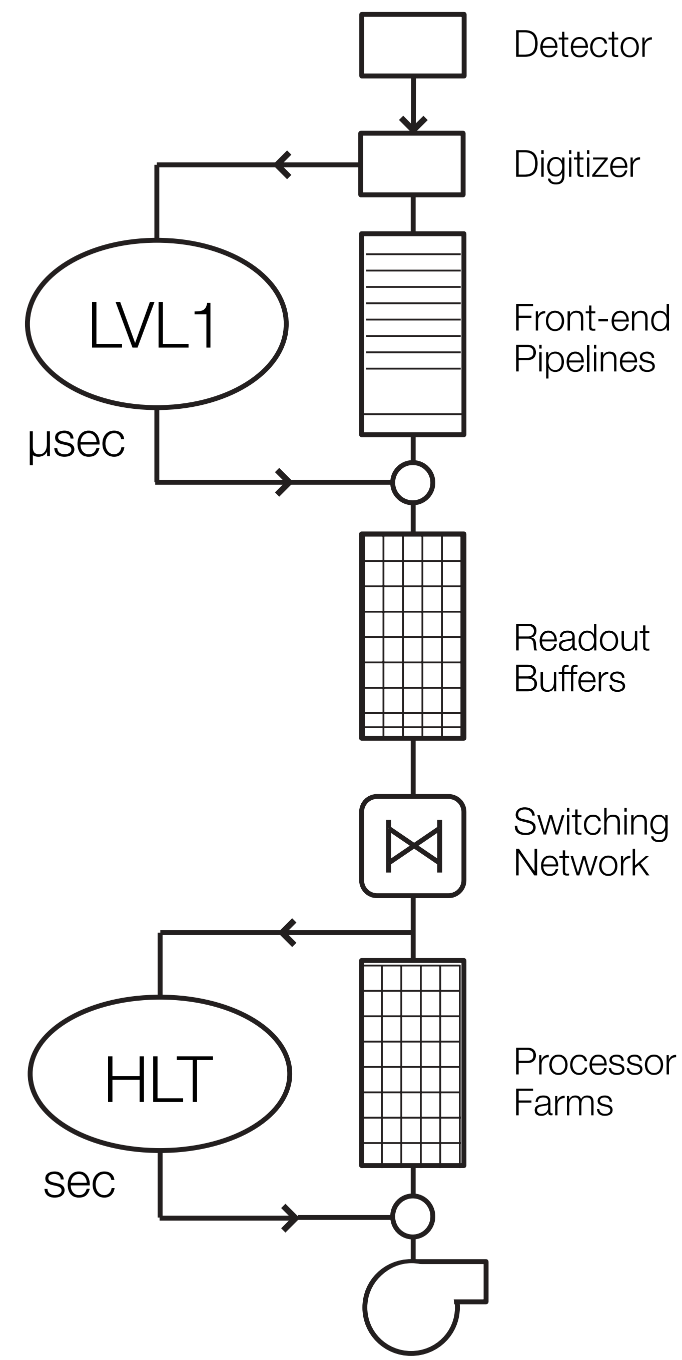
DAQ Switching Network



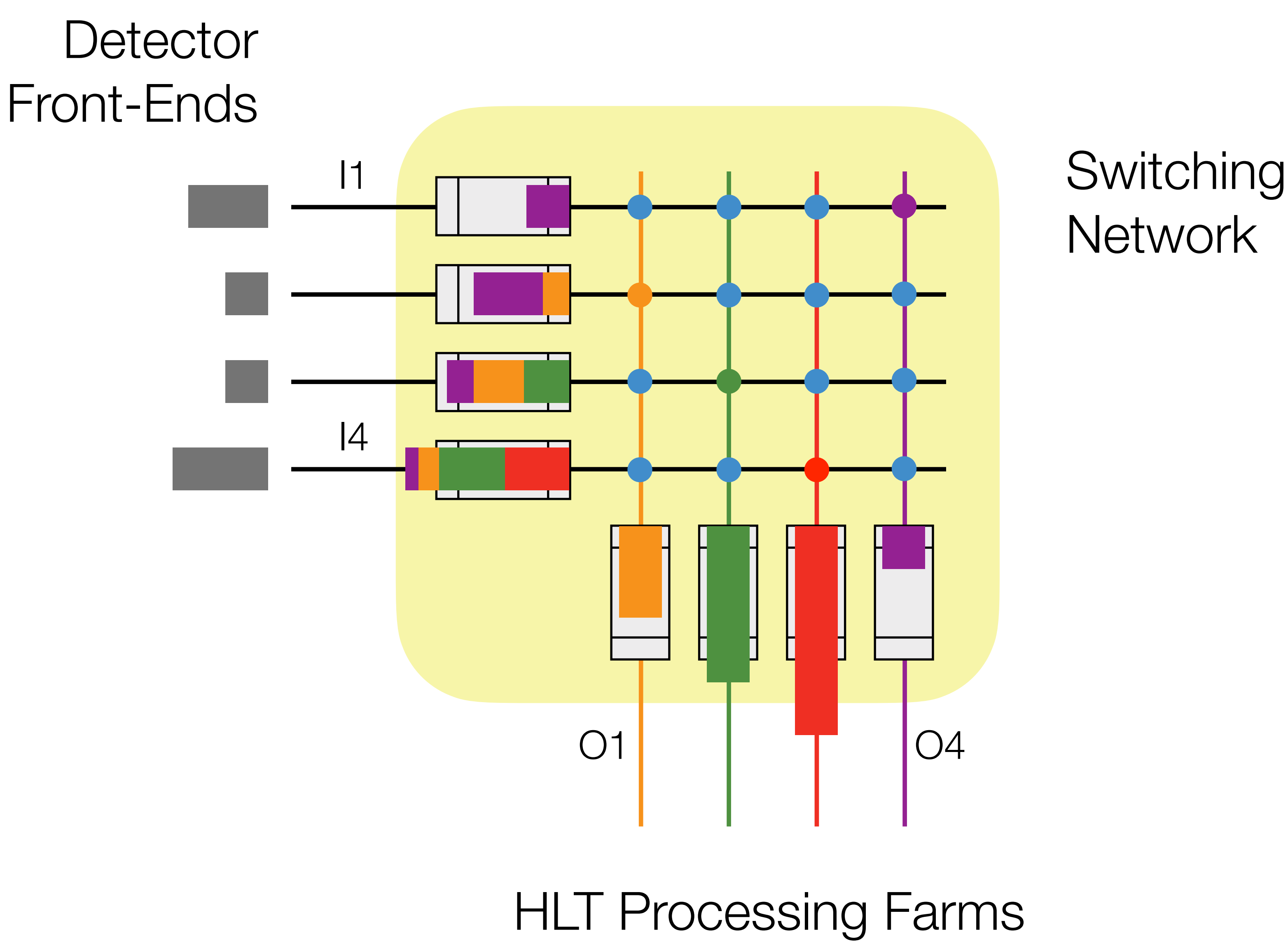


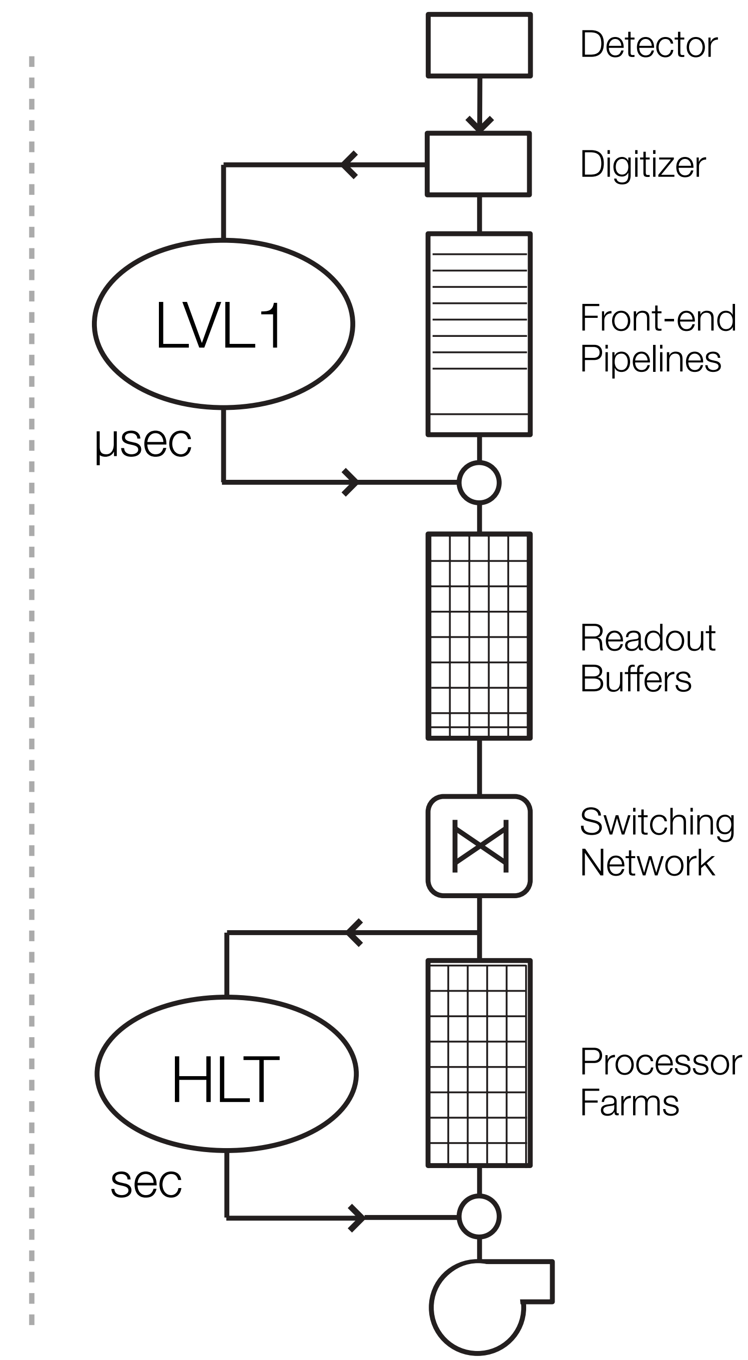
DAQ Switching Network



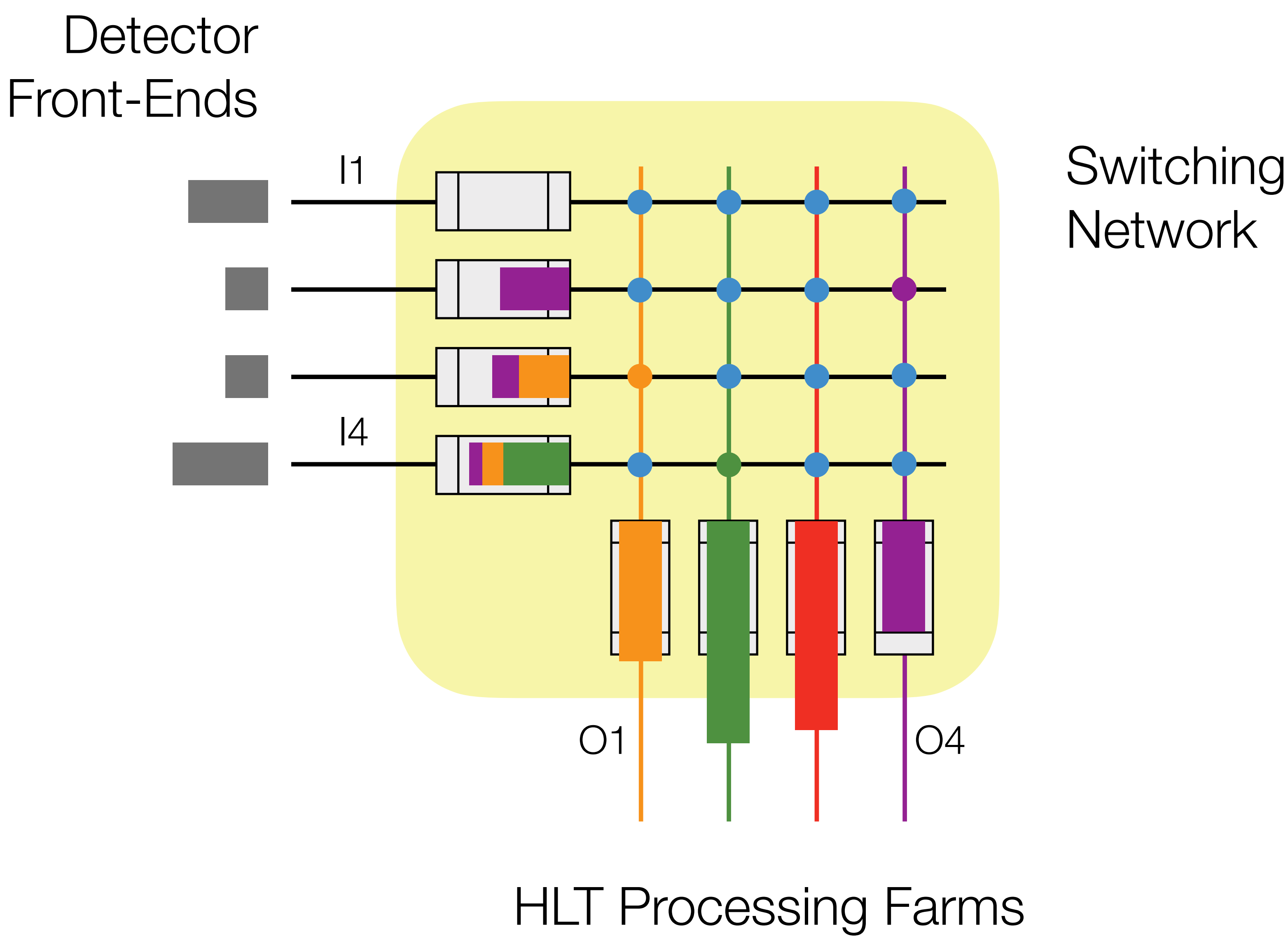


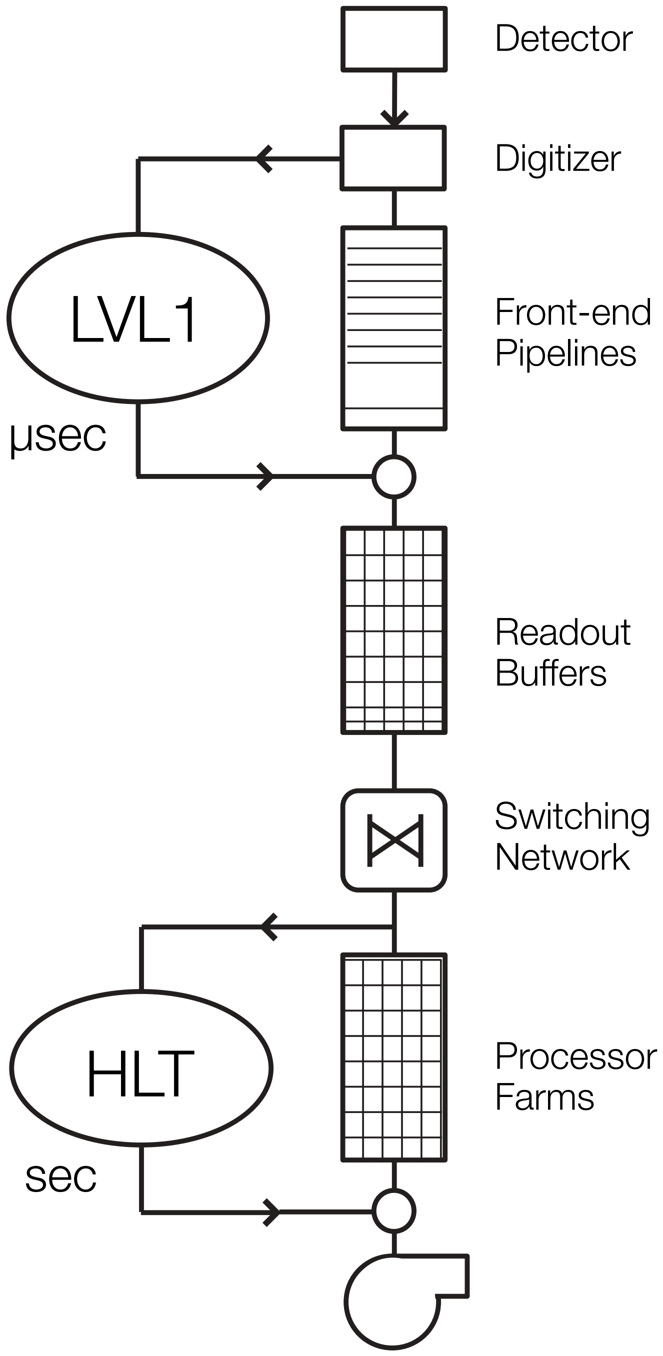
DAQ Switching Network



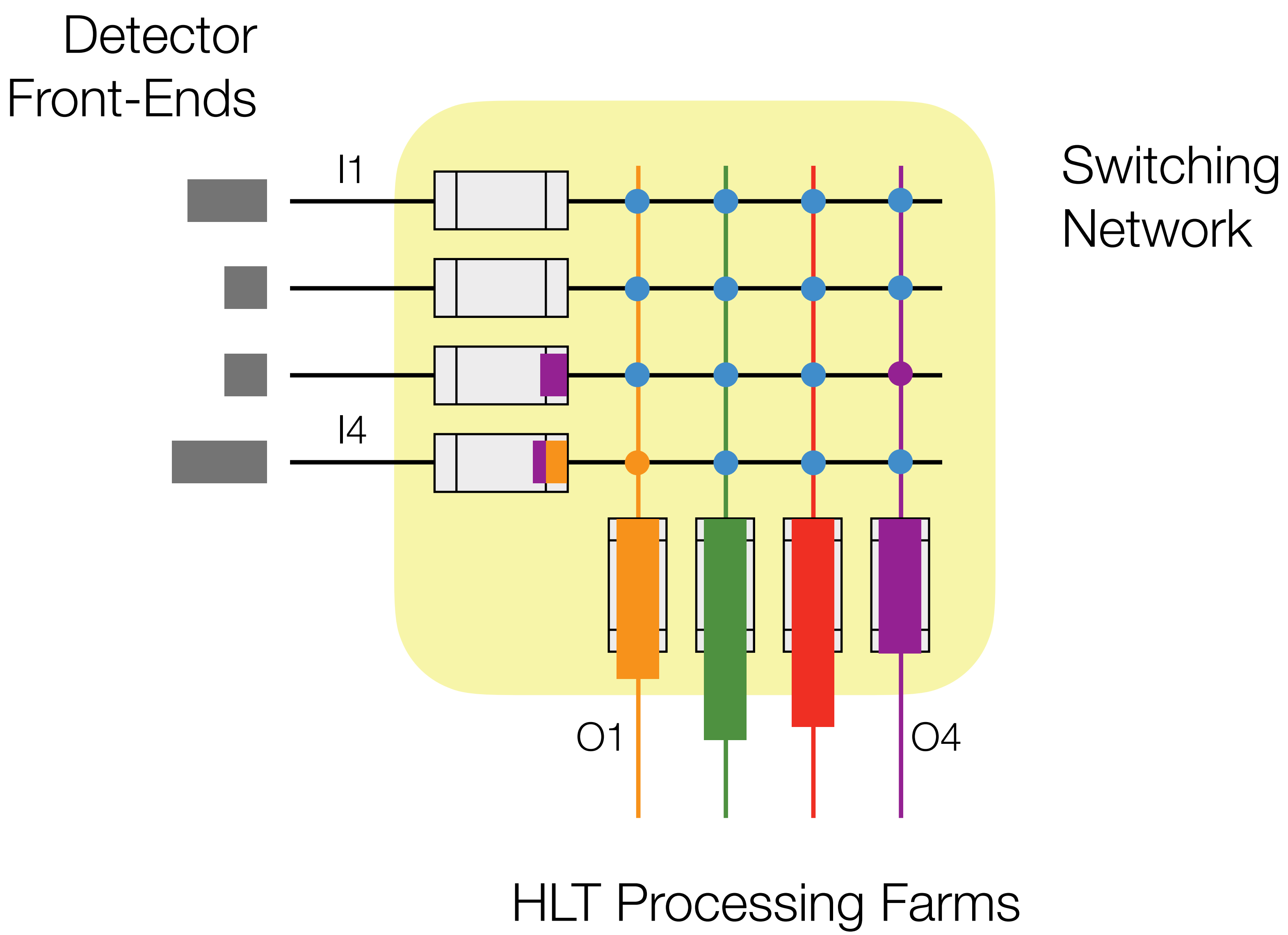


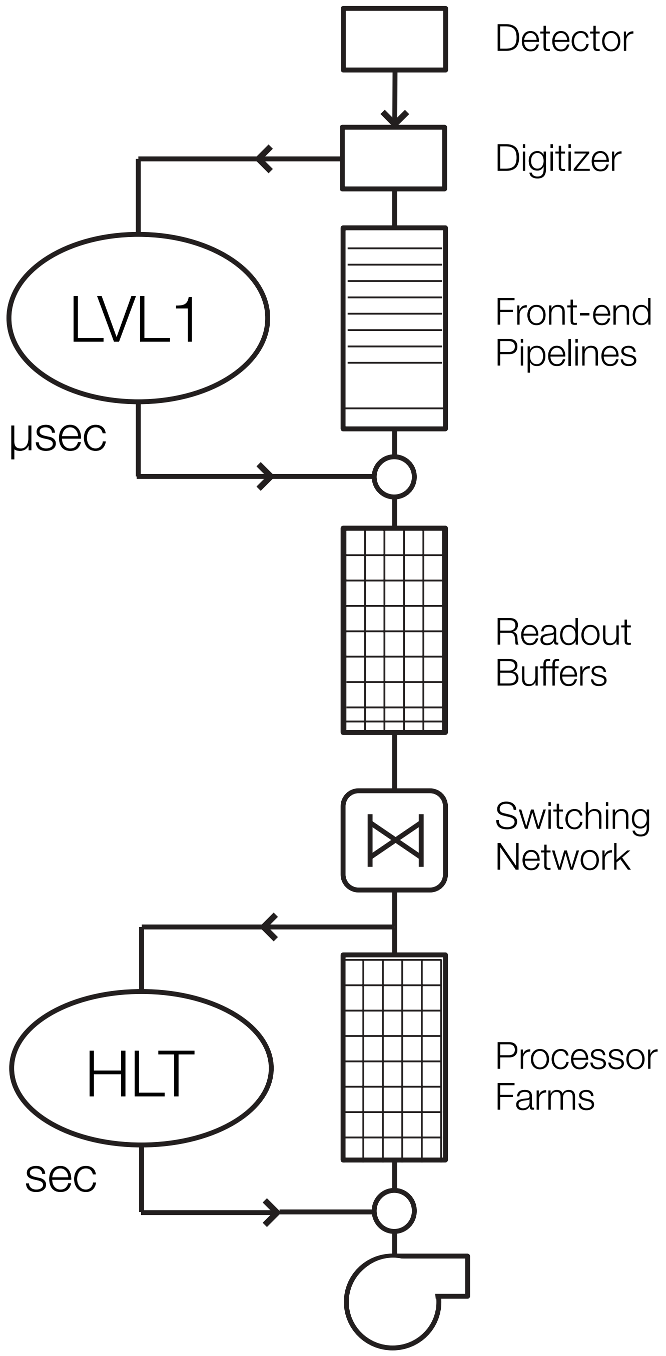
DAQ Switching Network



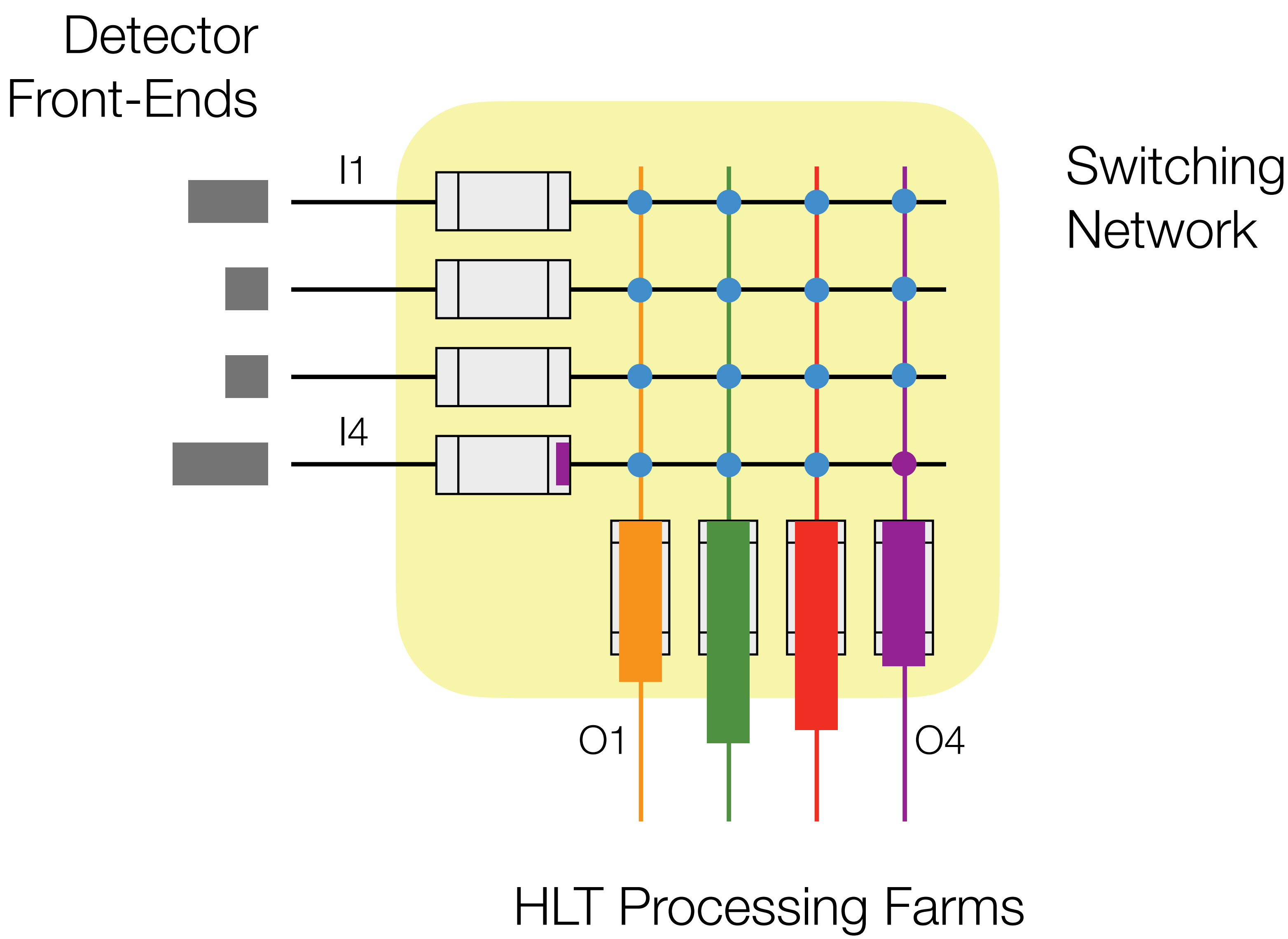


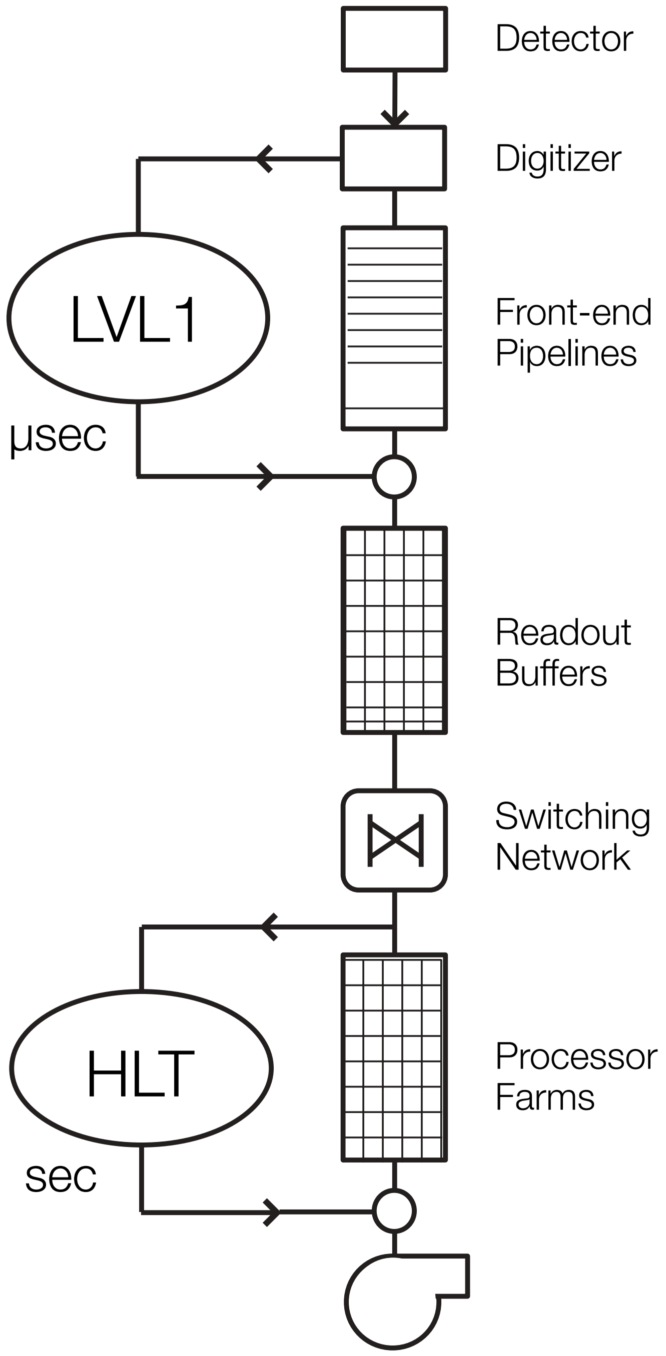
DAQ Switching Network



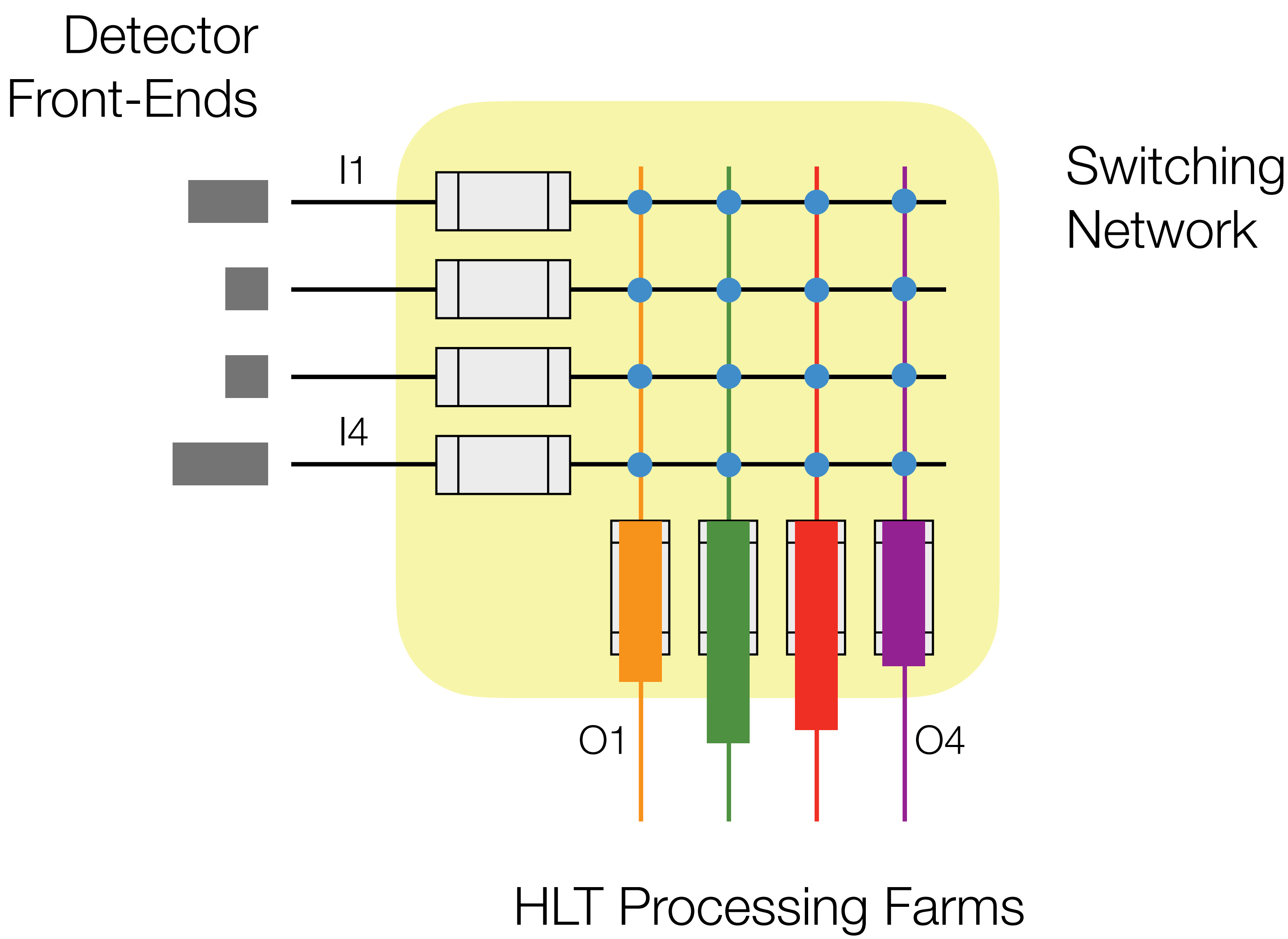


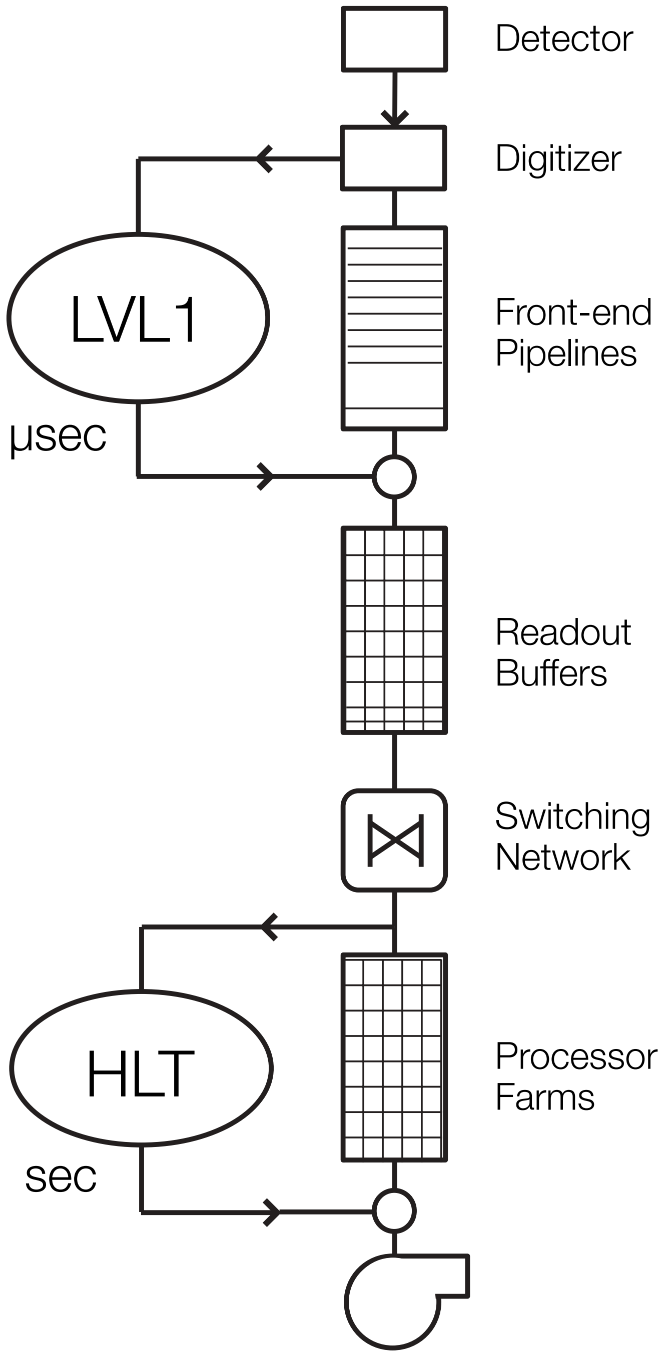
DAQ Switching Network





DAQ Switching Network





Part 3

"Realizing Trigger Systems"

Fast & Parallel Processing

Task Parallelism

Data Parallelism

Data Pipelining

Multicore Processors

GPUs

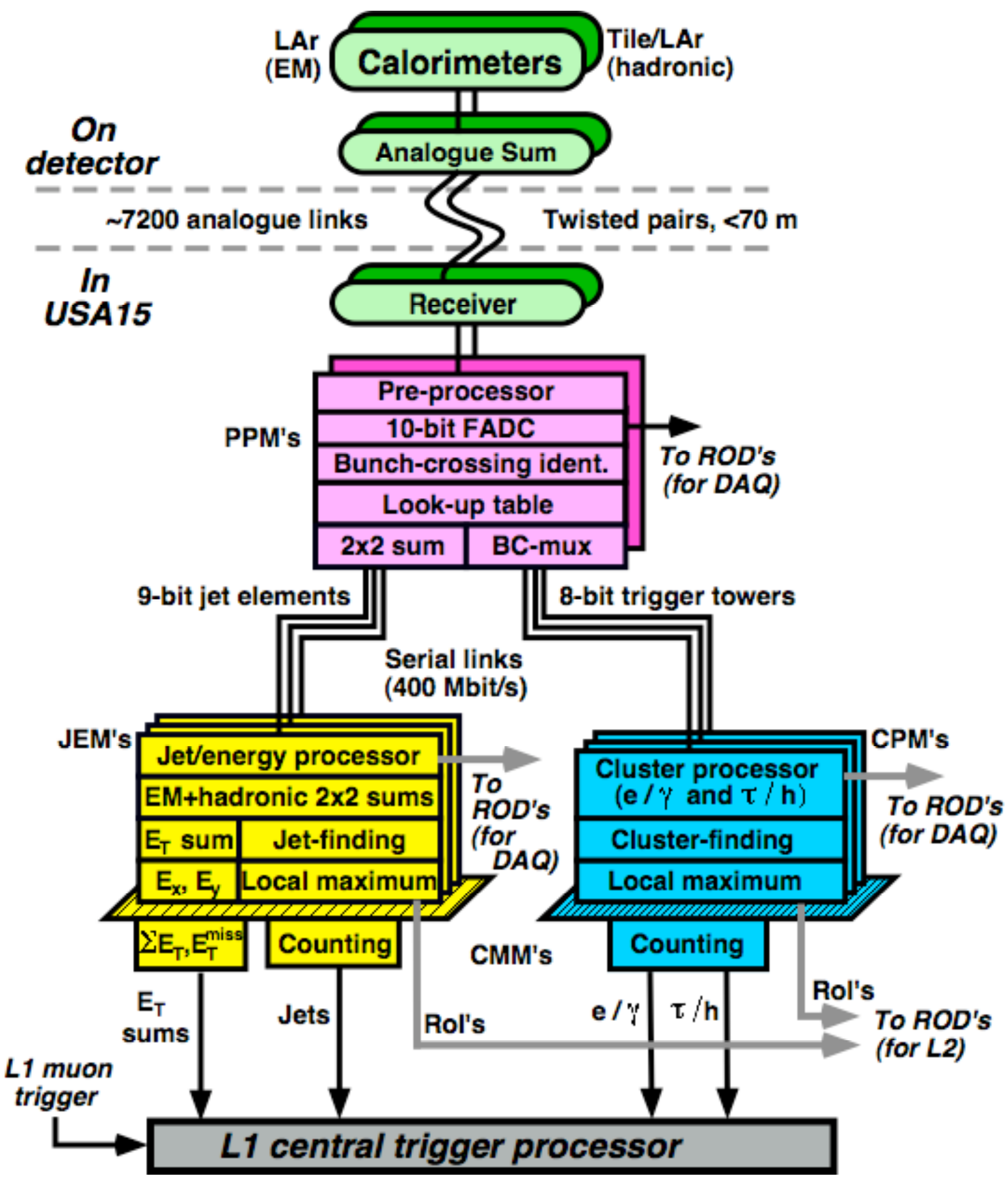
FPGAs

...

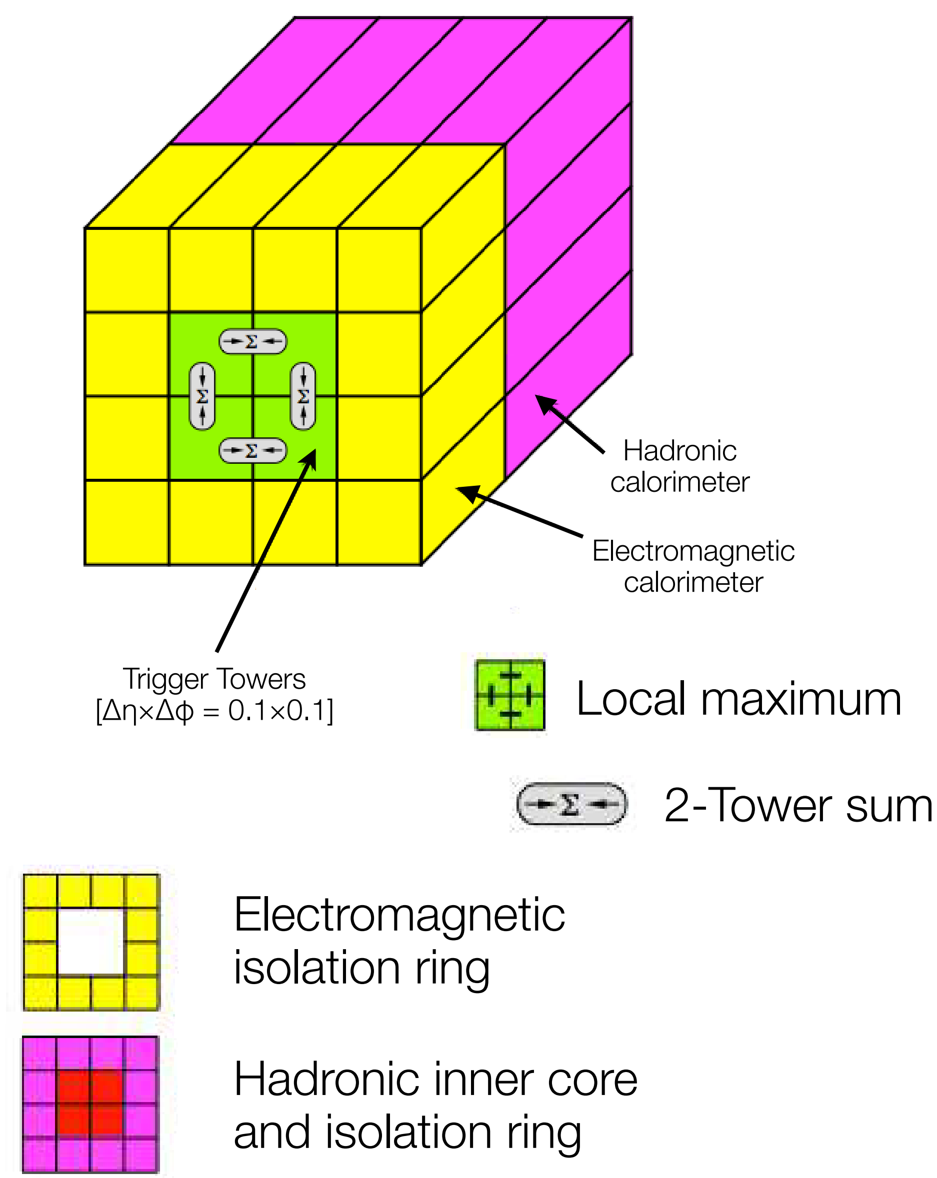
Different technologies to do in-situ signal analysis

[Choice depends on requirements]

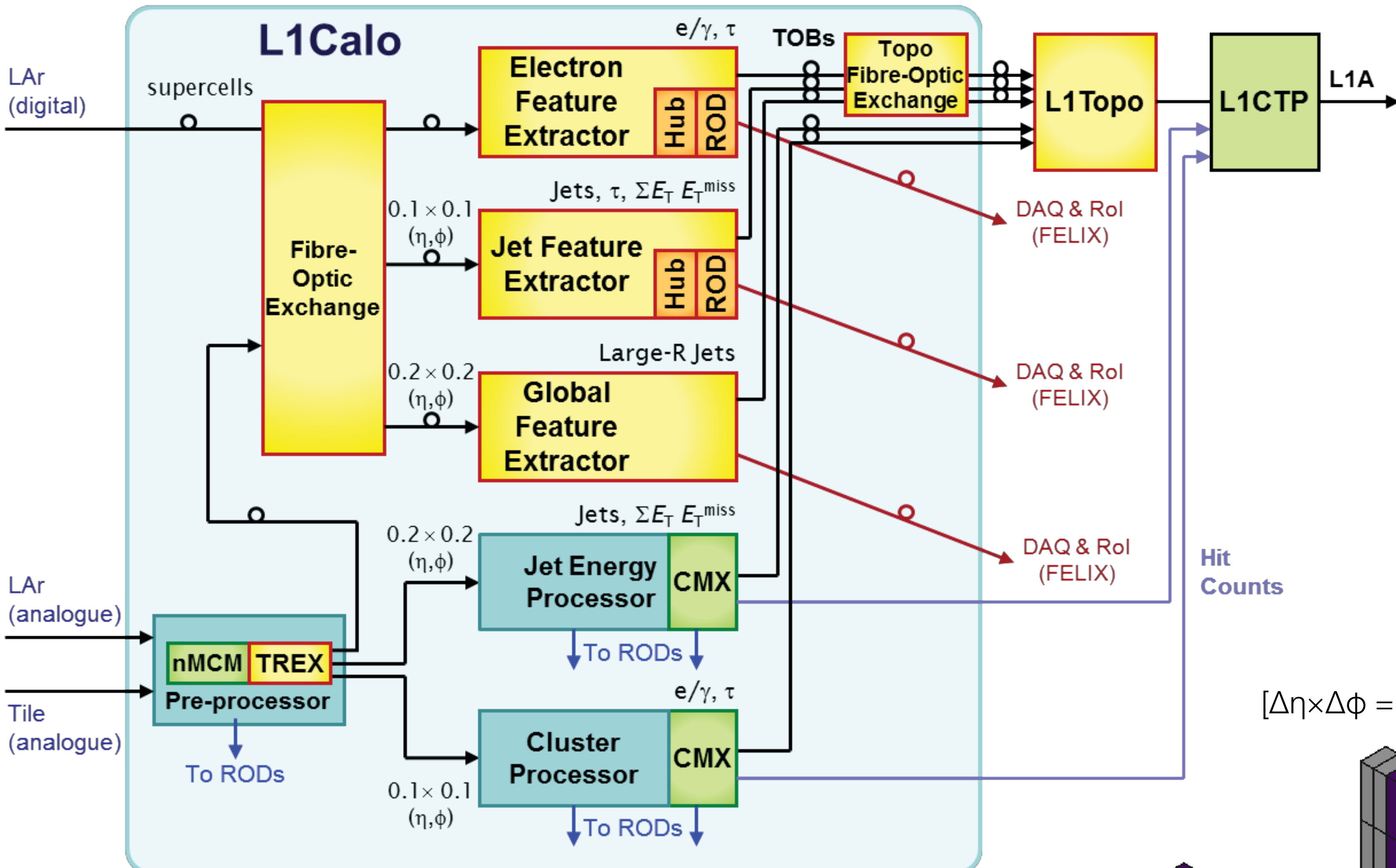
Calorimeter Trigger – ATLAS Run-1 & Run-2

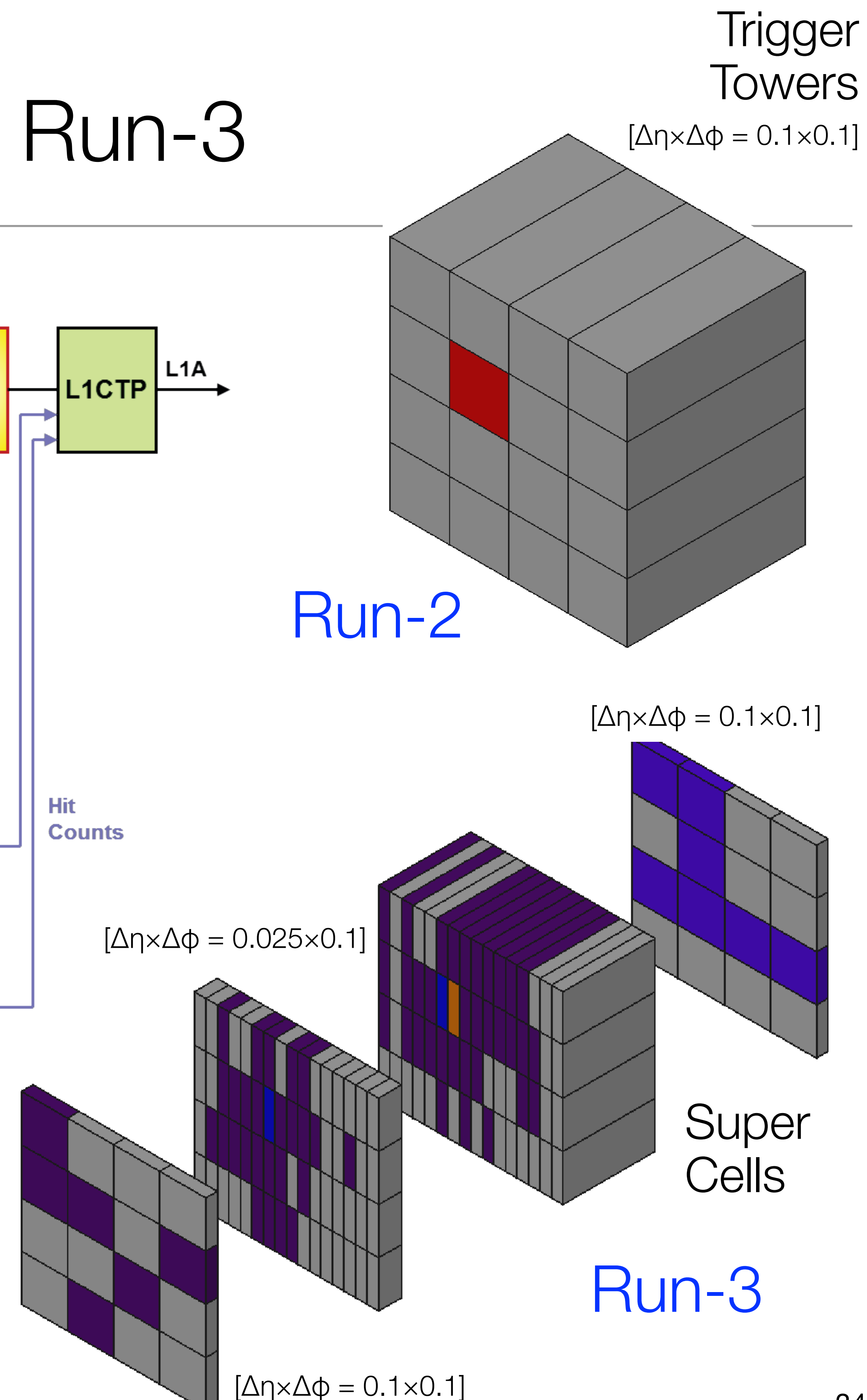


e/γ Identification



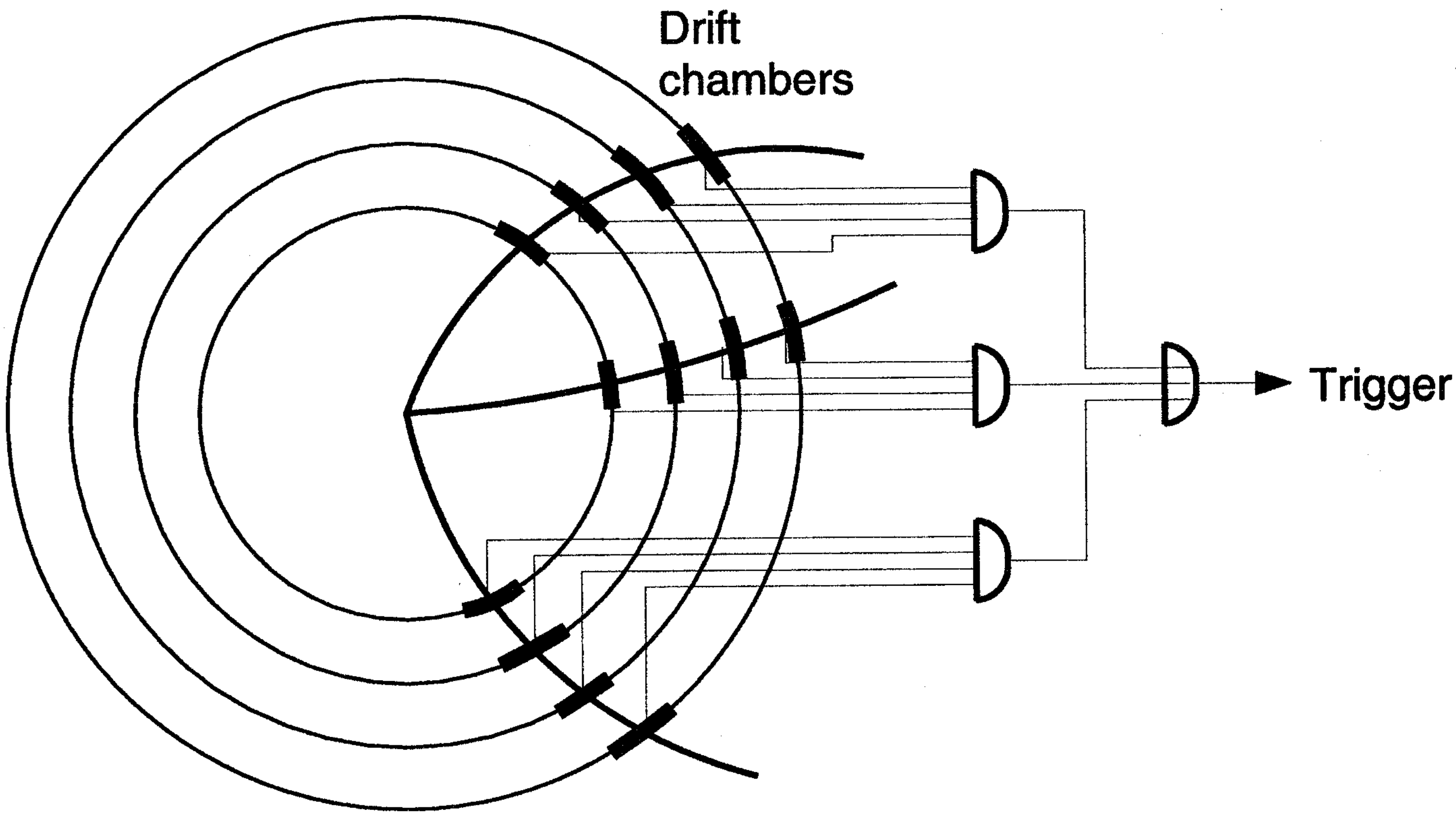
Calorimeter Trigger – ATLAS Run-3



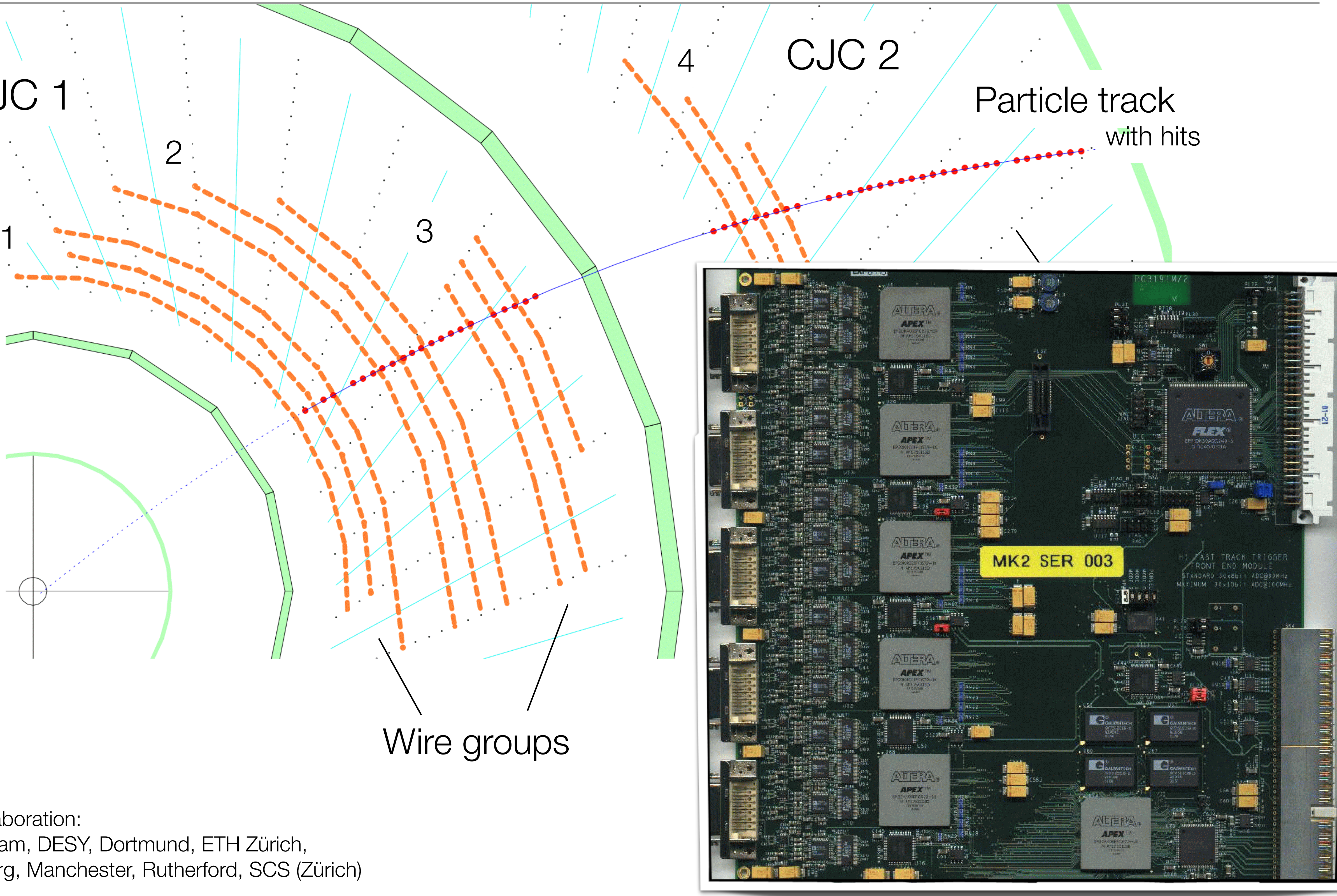


Toward higher granularity …

Tracking Triggers

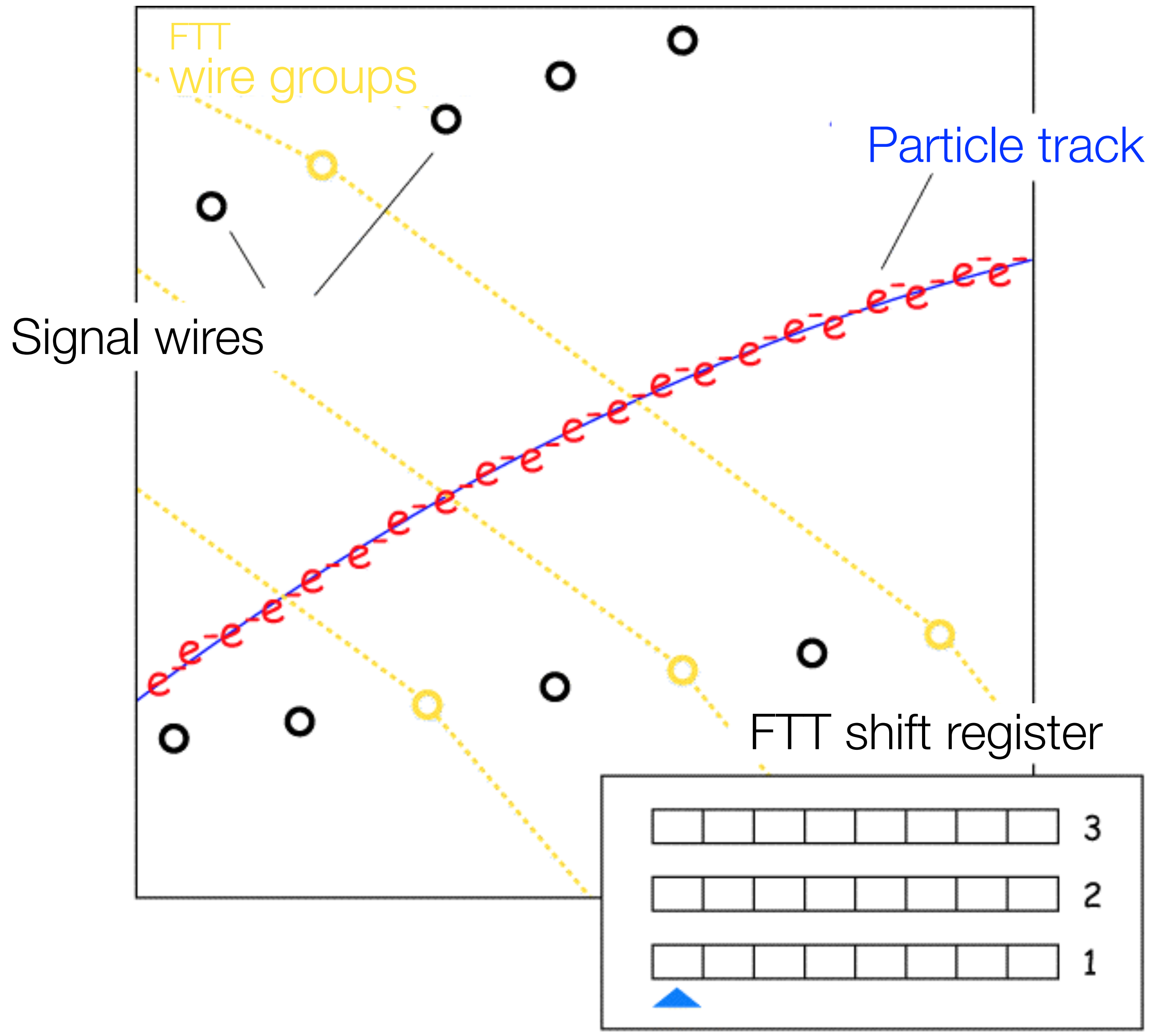


Tracking Triggers – FTT @ H1

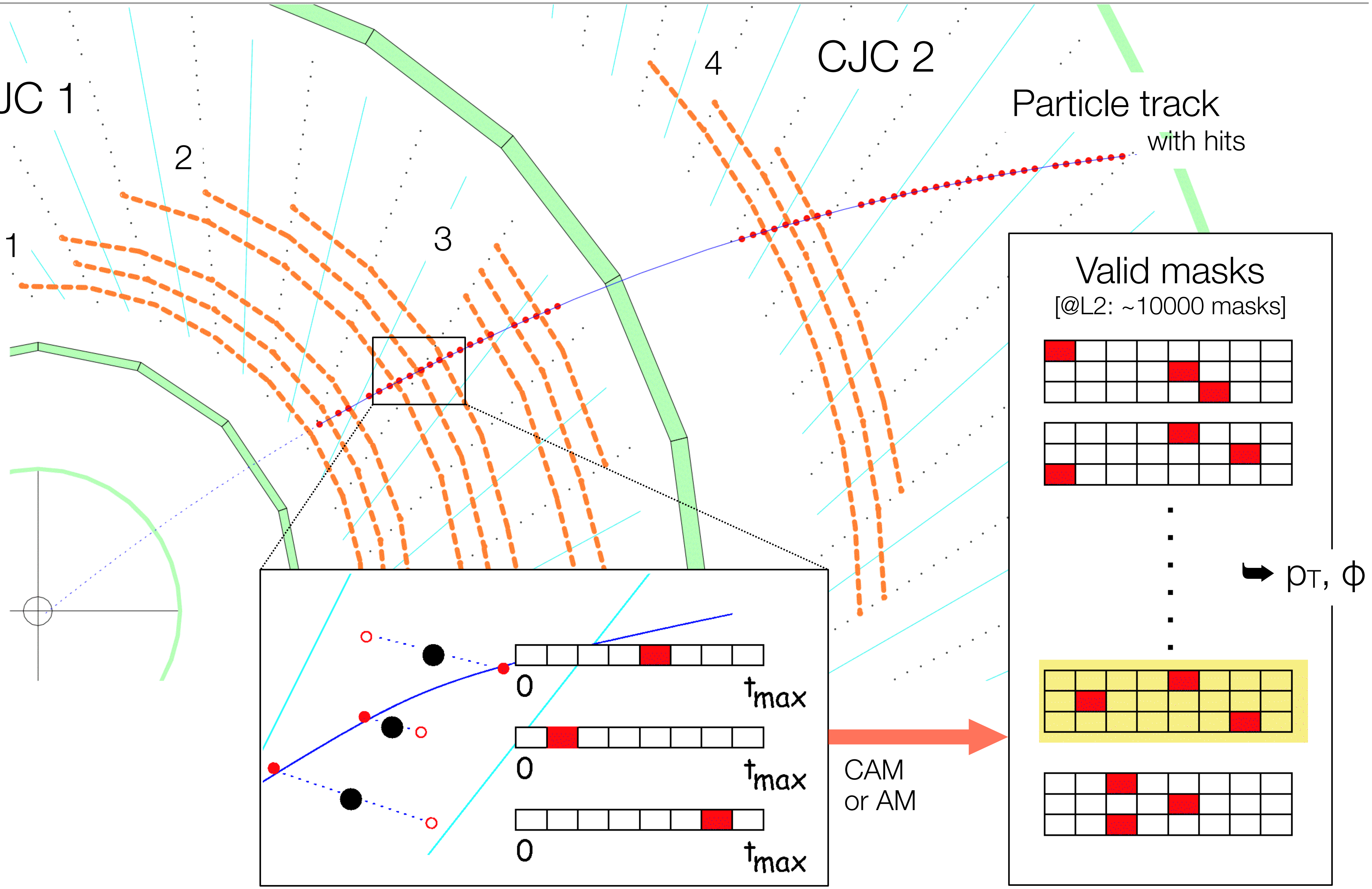


FTT Kollaboration:
Birmingham, DESY, Dortmund, ETH Zürich,
Heidelberg, Manchester, Rutherford, SCS (Zürich)

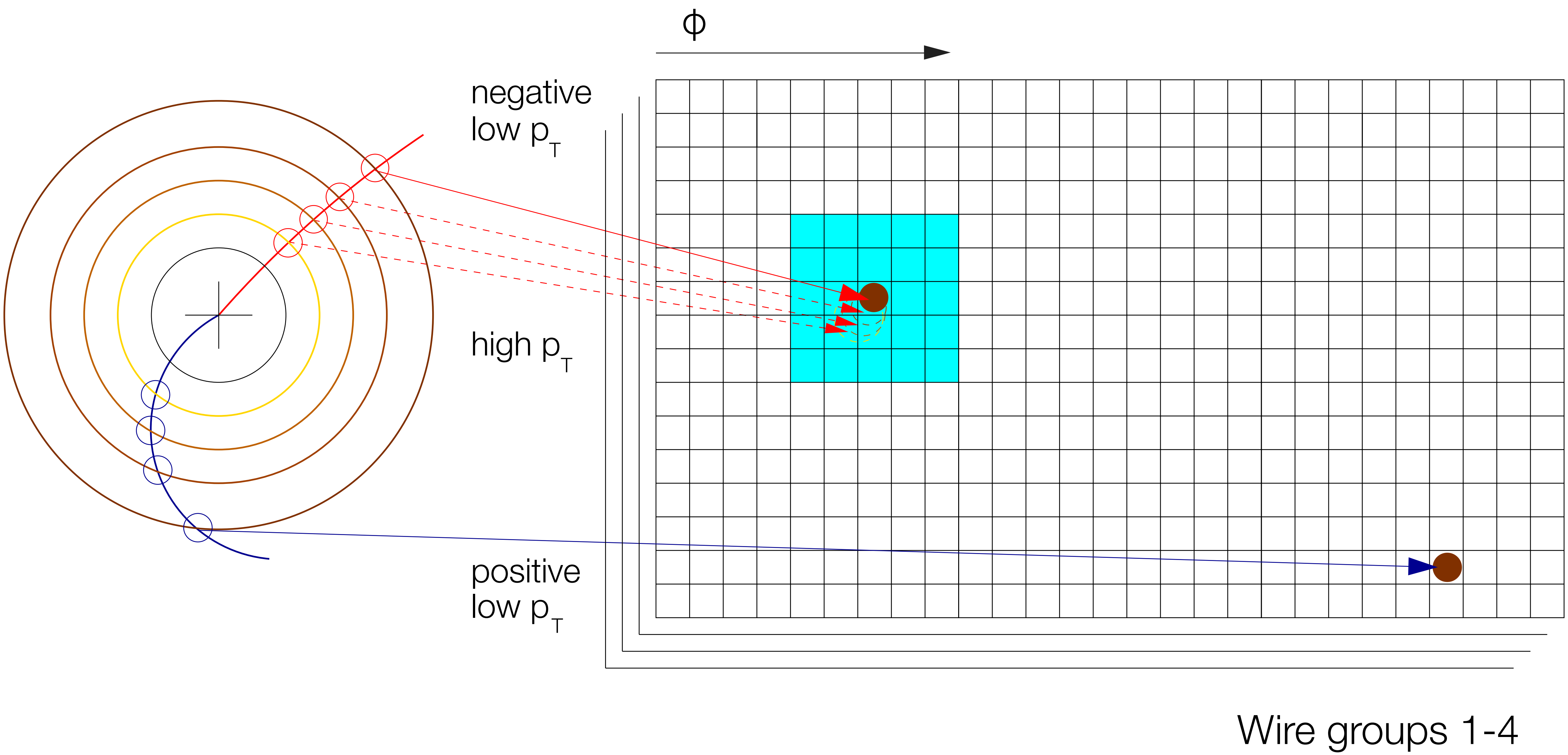
Tracking Triggers – FTT @ H1



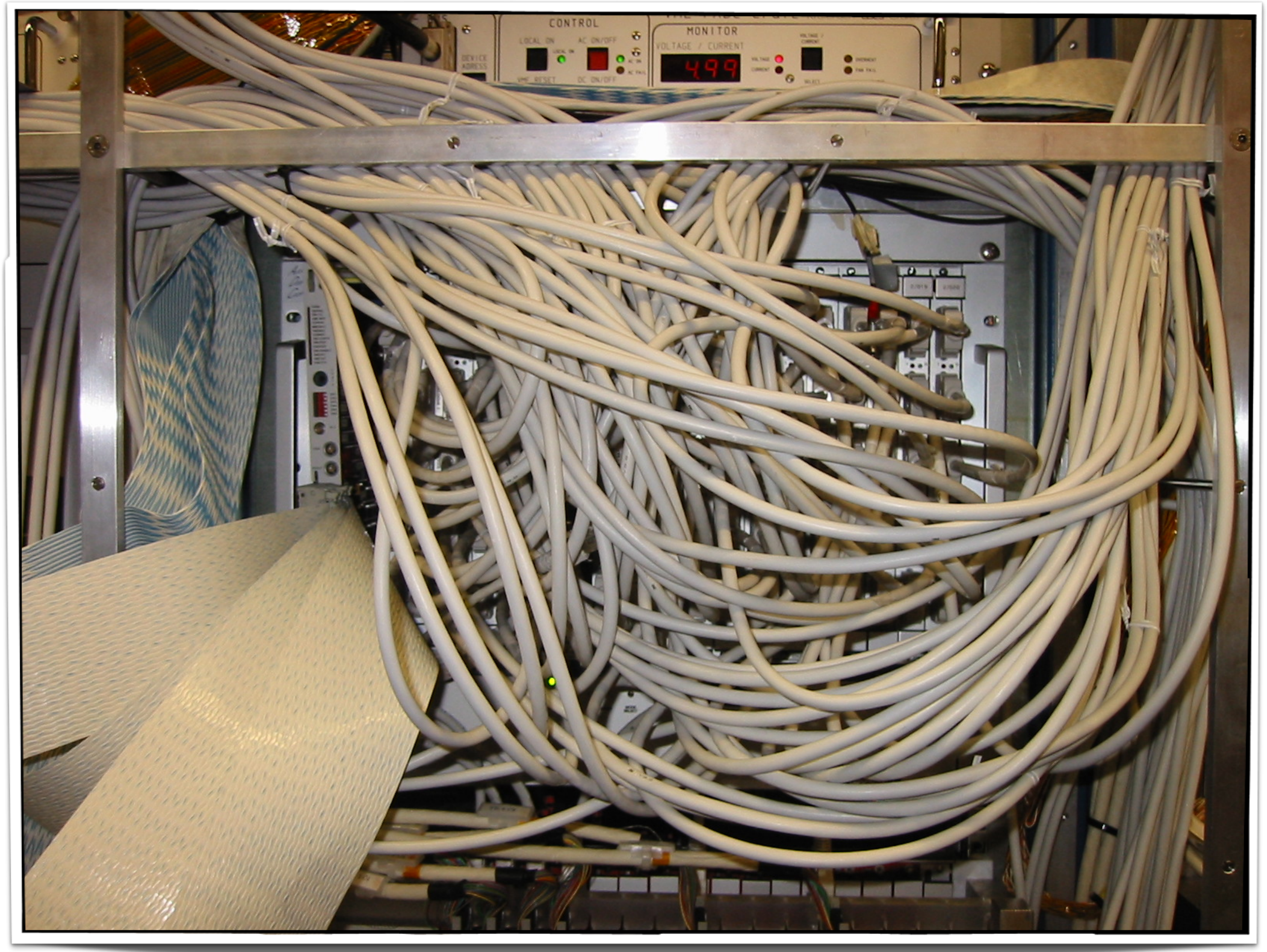
Tracking Triggers – FTT @ H1



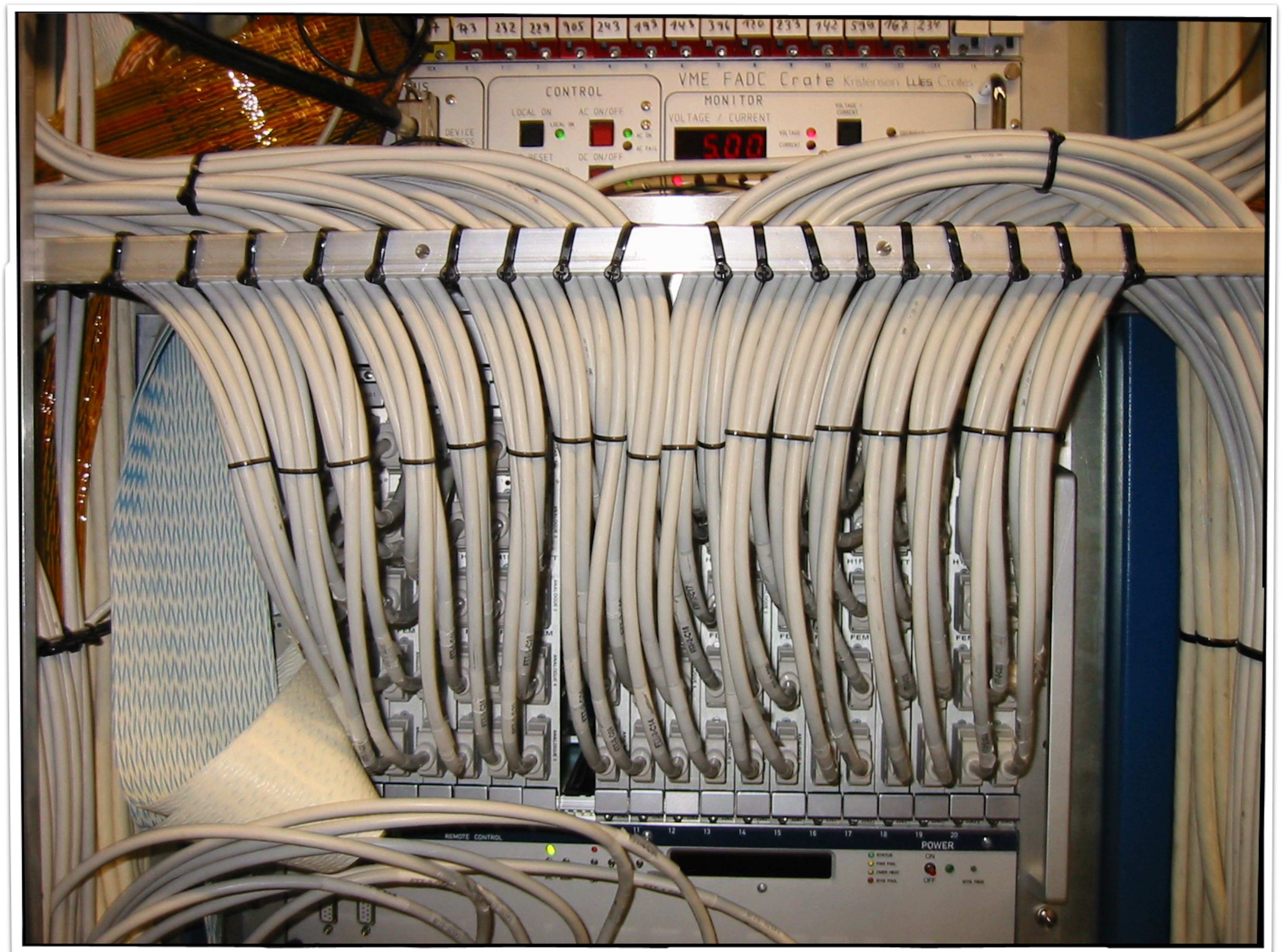
Finding tracks from segments …



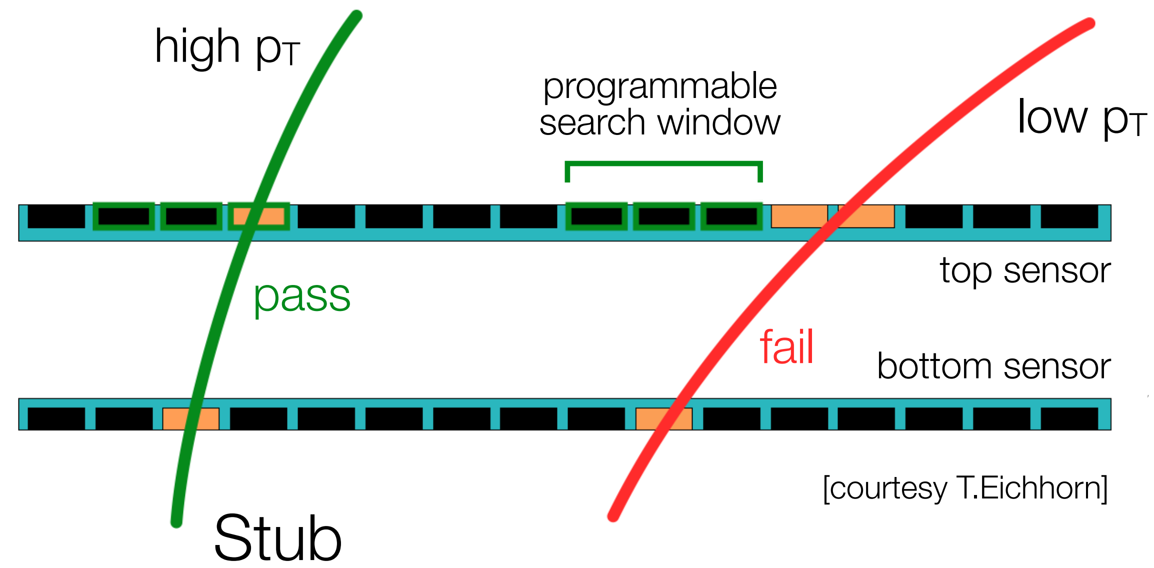
Tracking Triggers – FTT @ H1



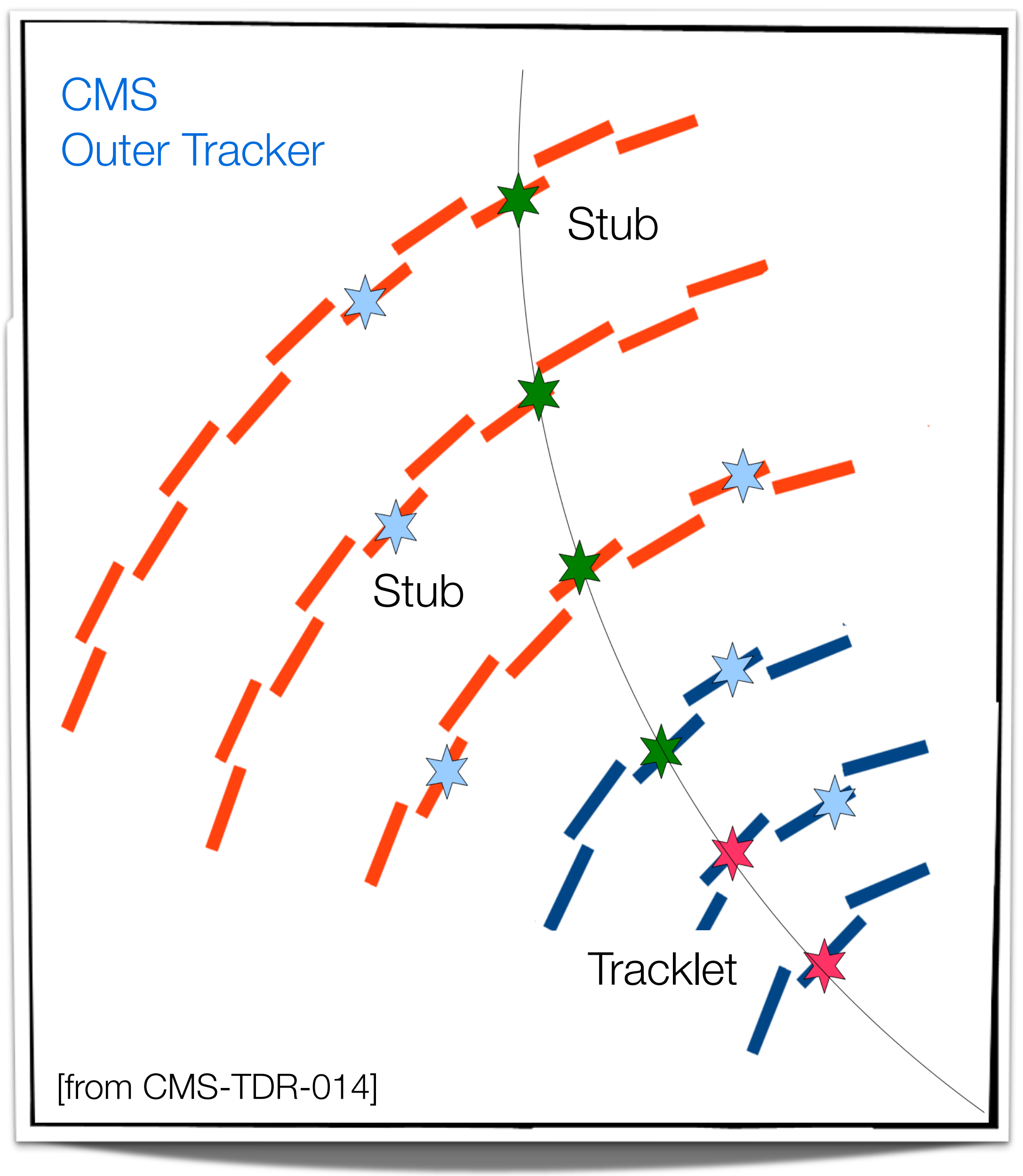
Tracking Triggers – FTT @ H1

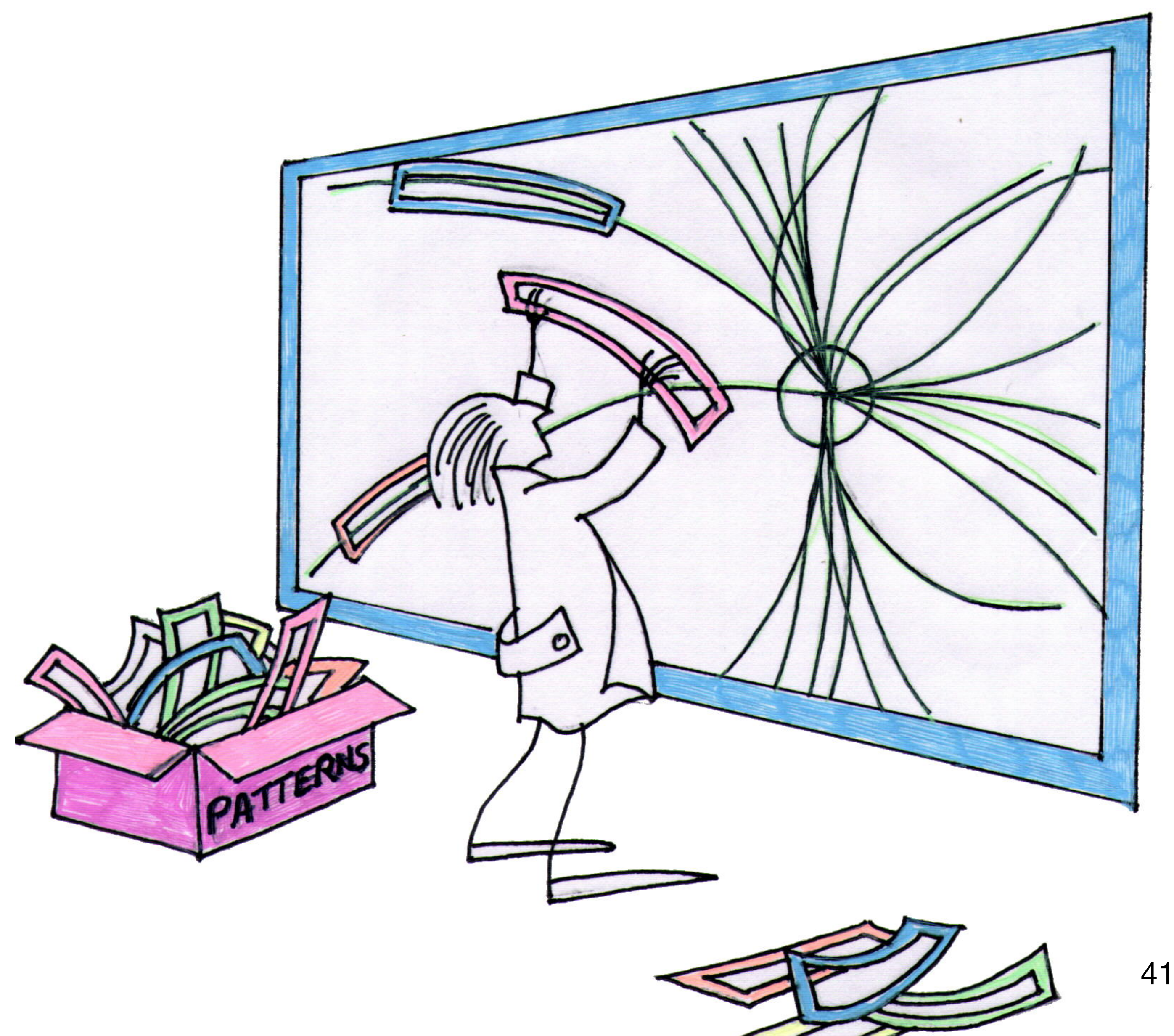


CMS Tracking @ Level-1



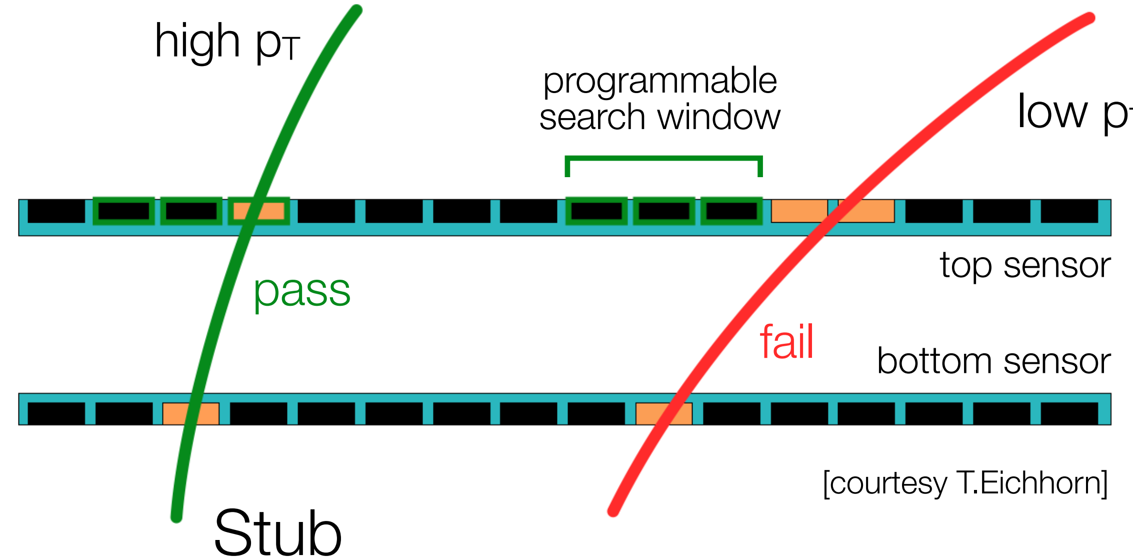
Tracking based on correlated hit pairs (‘stubs’) & tracklets (stub pairs)

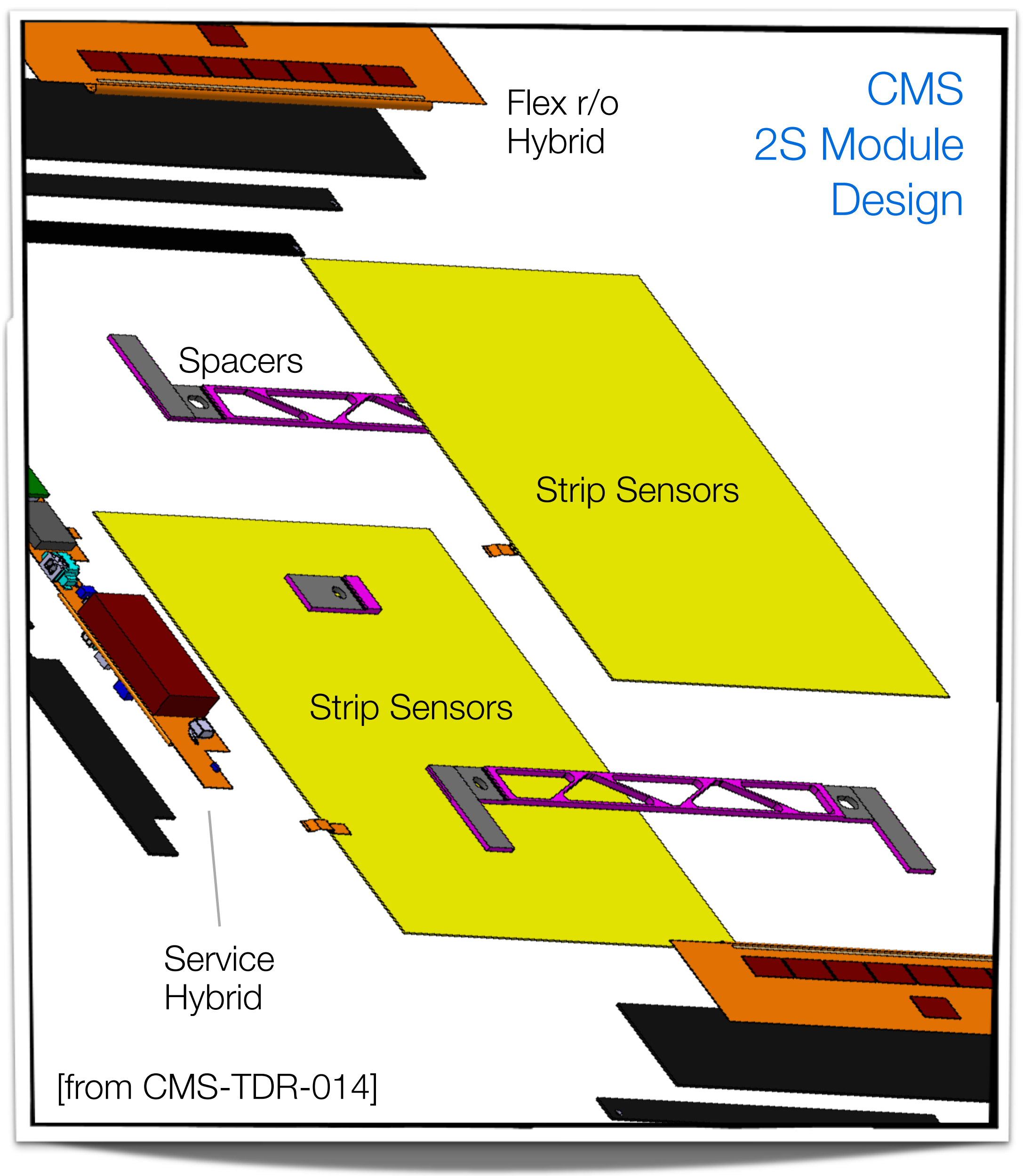


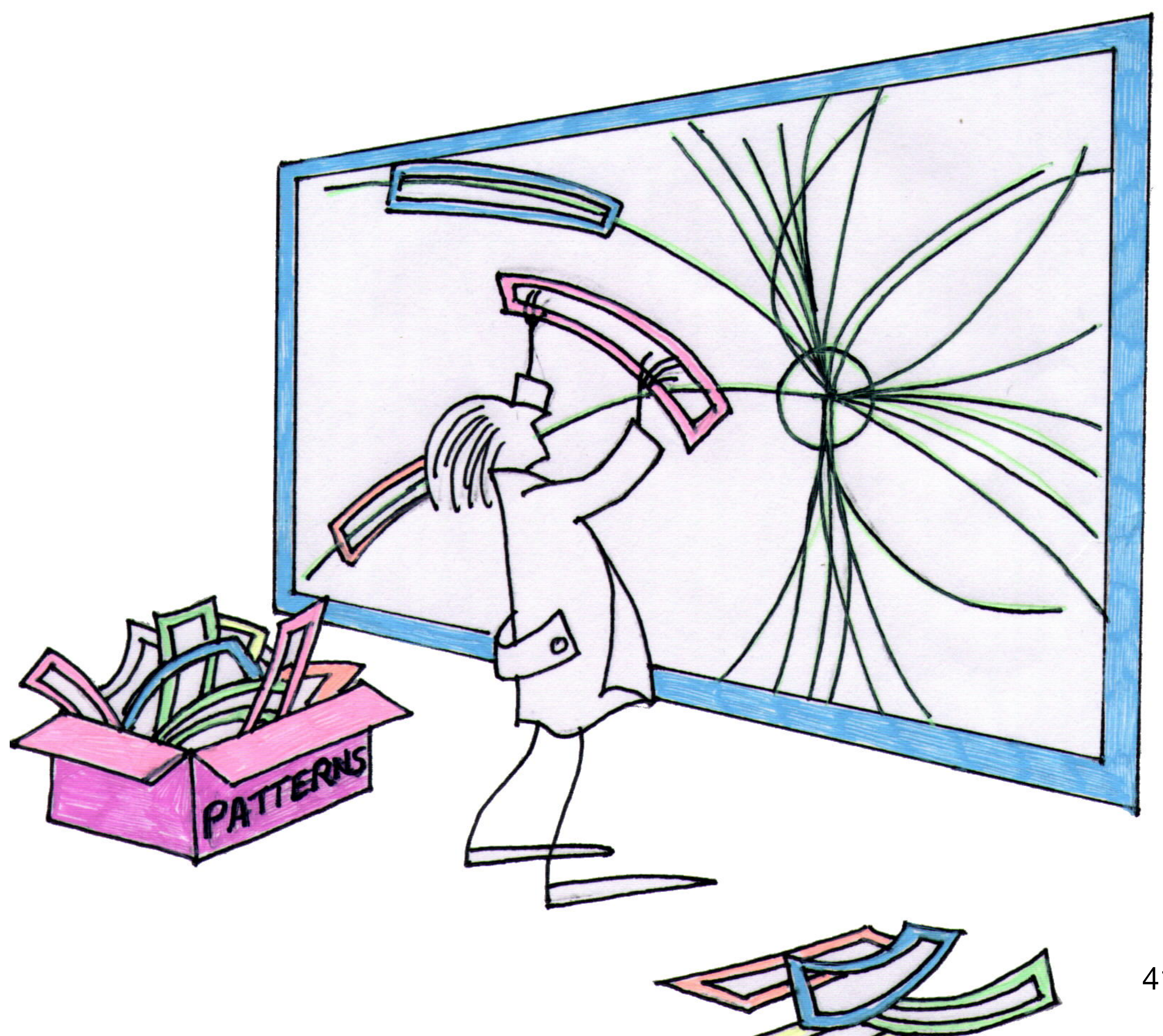


CMS Tracking @ Level-1

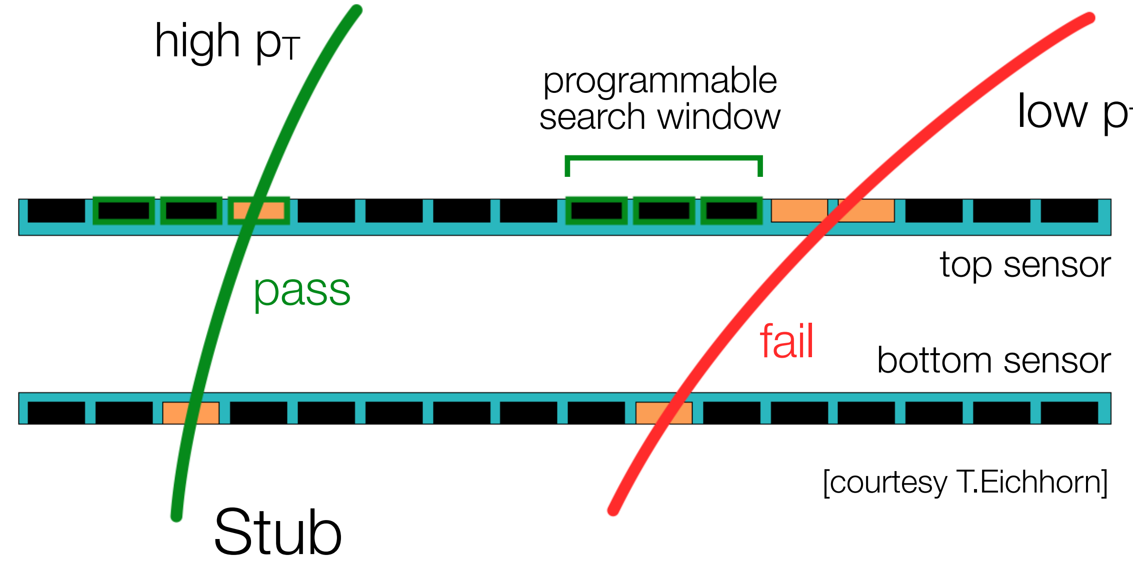
Requires double-sided silicon pixel/strip modules …



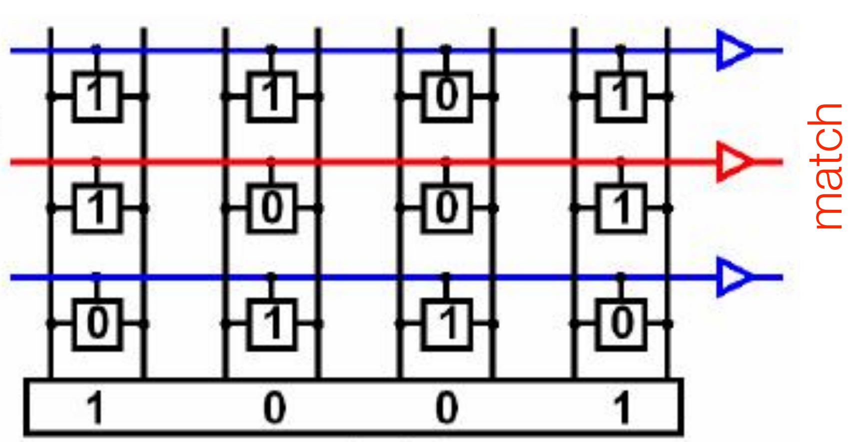


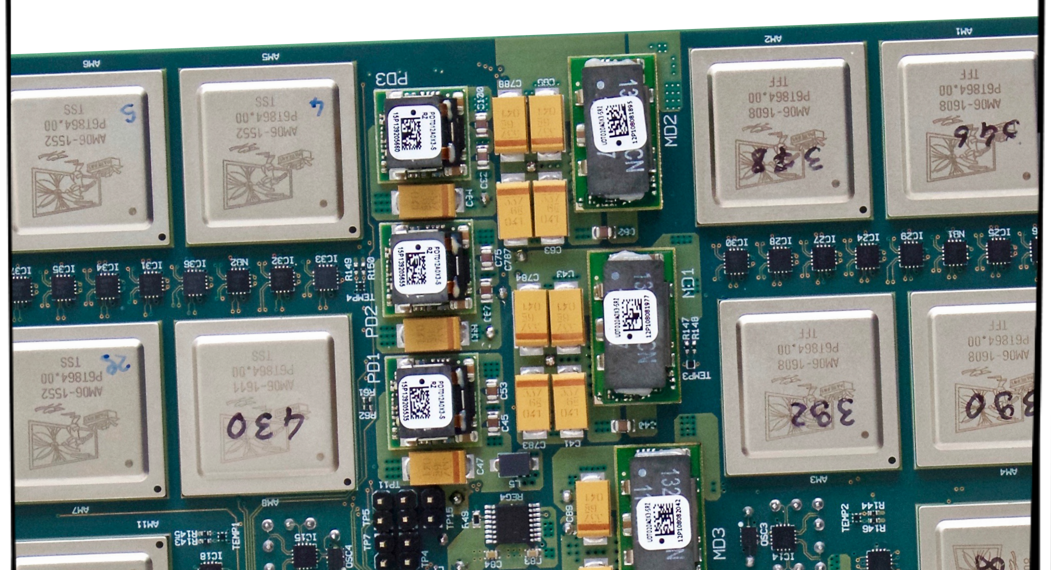


CMS Tracking @ Level-1



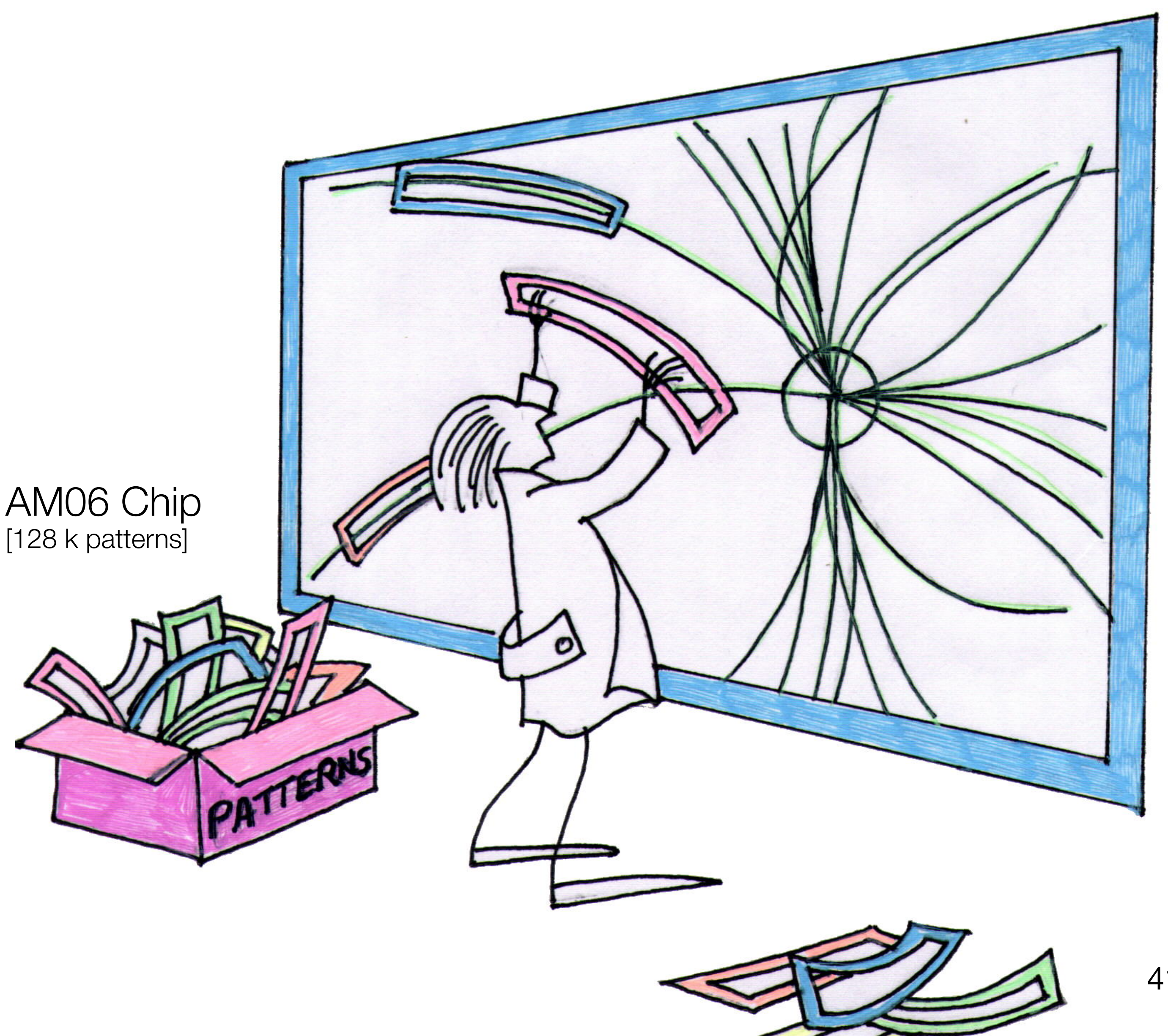
Requires large scale pattern matching …
Use of associative memories (AM) …





PRM Prototype

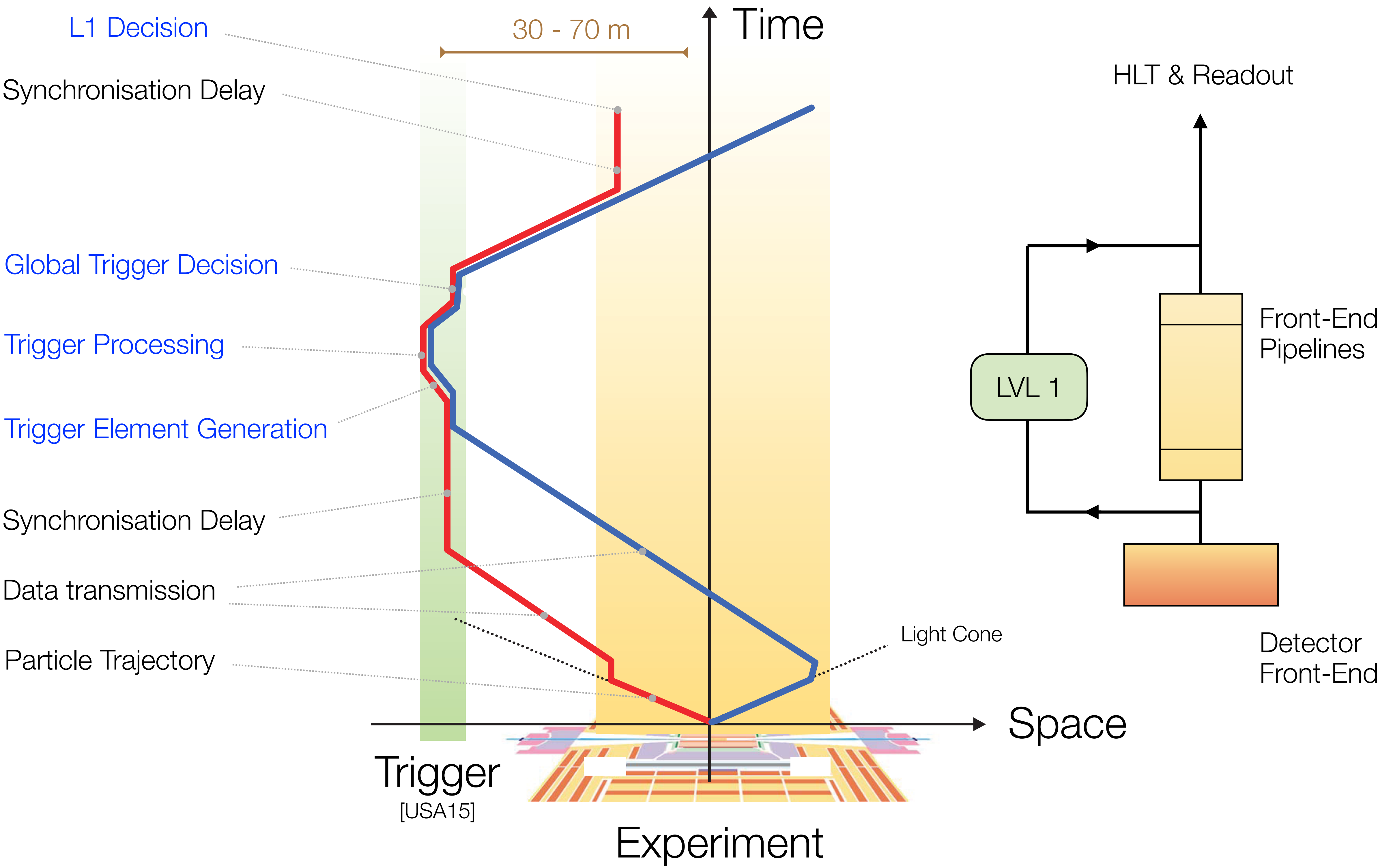
AM06 Chip
[128 k patterns]



Epilogue

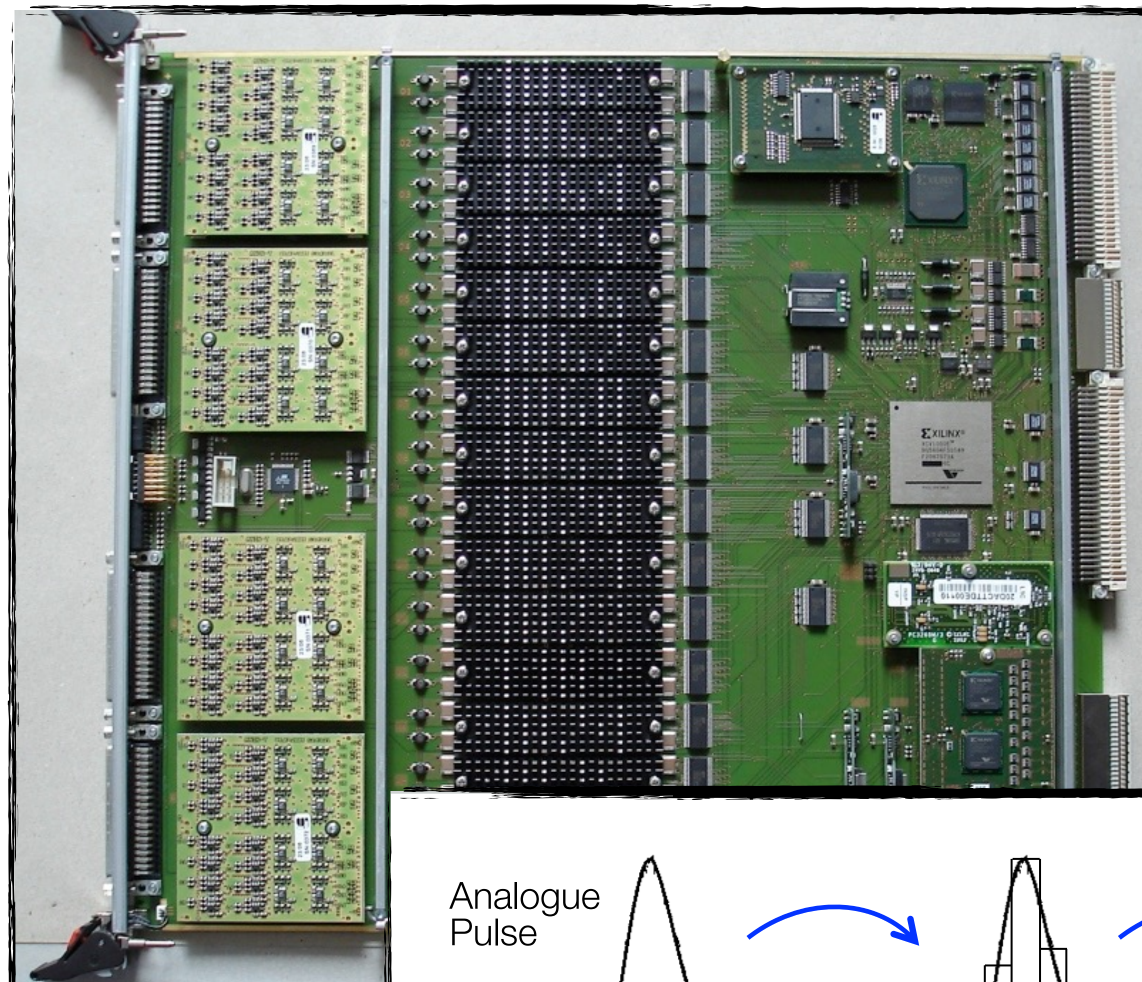
“Synchronization Challenge by Example”

Trigger Real-Time Path [Level-1]



Example: ATLAS L1 Calorimeter Trigger

The L1Calo Pre-Processor System



PreProcessor

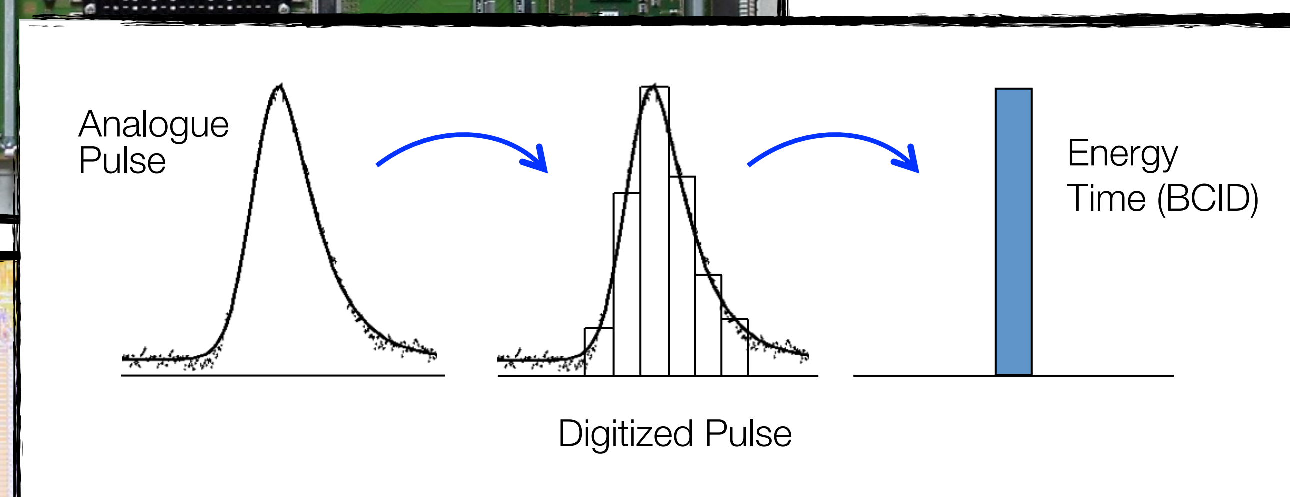
PPr Latency: 0.4 μs
Modules: 124

Input:

About 7000 analogue calorimeter signals

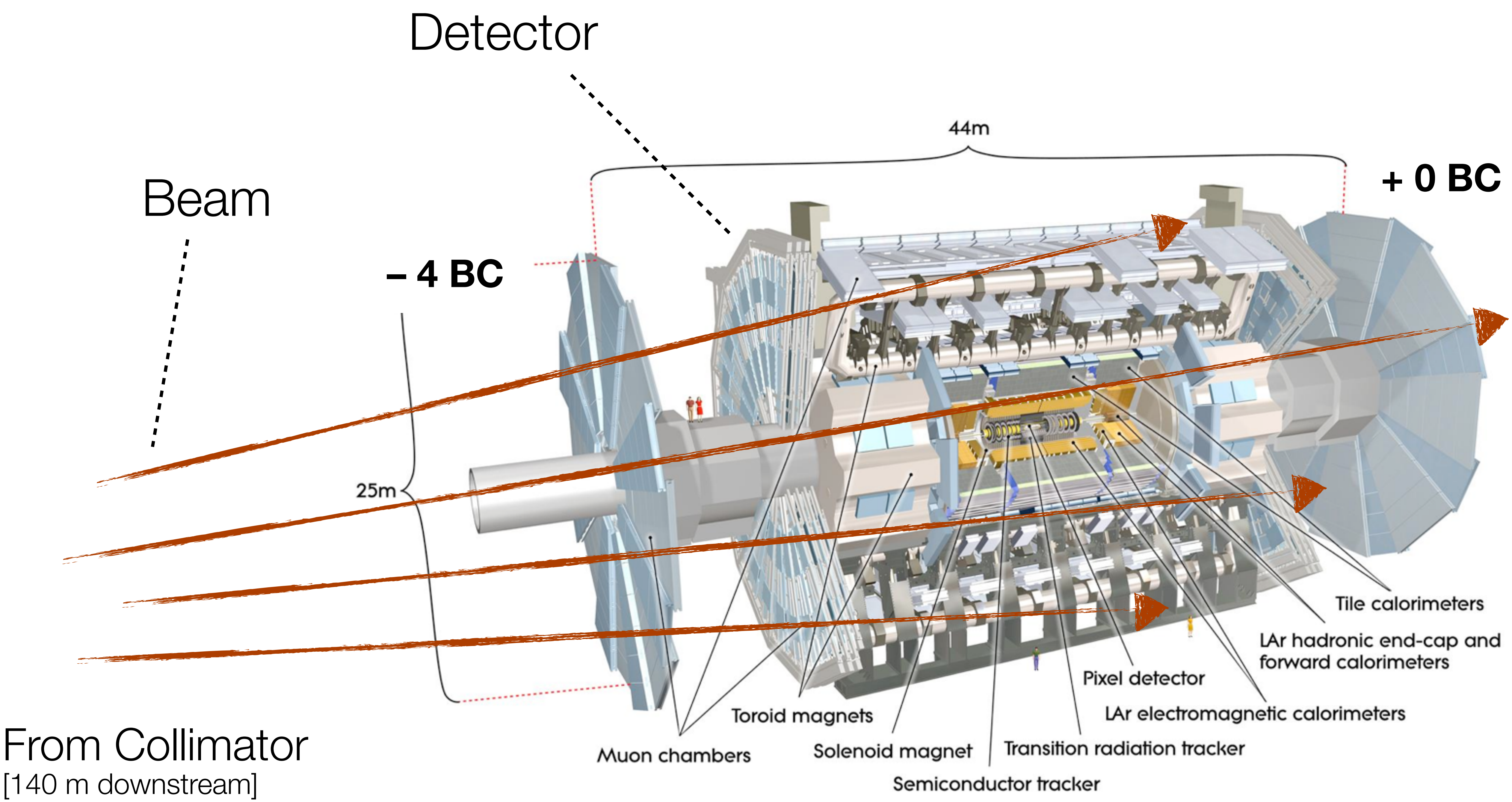
Output:

Digital energy measurement and time stamp



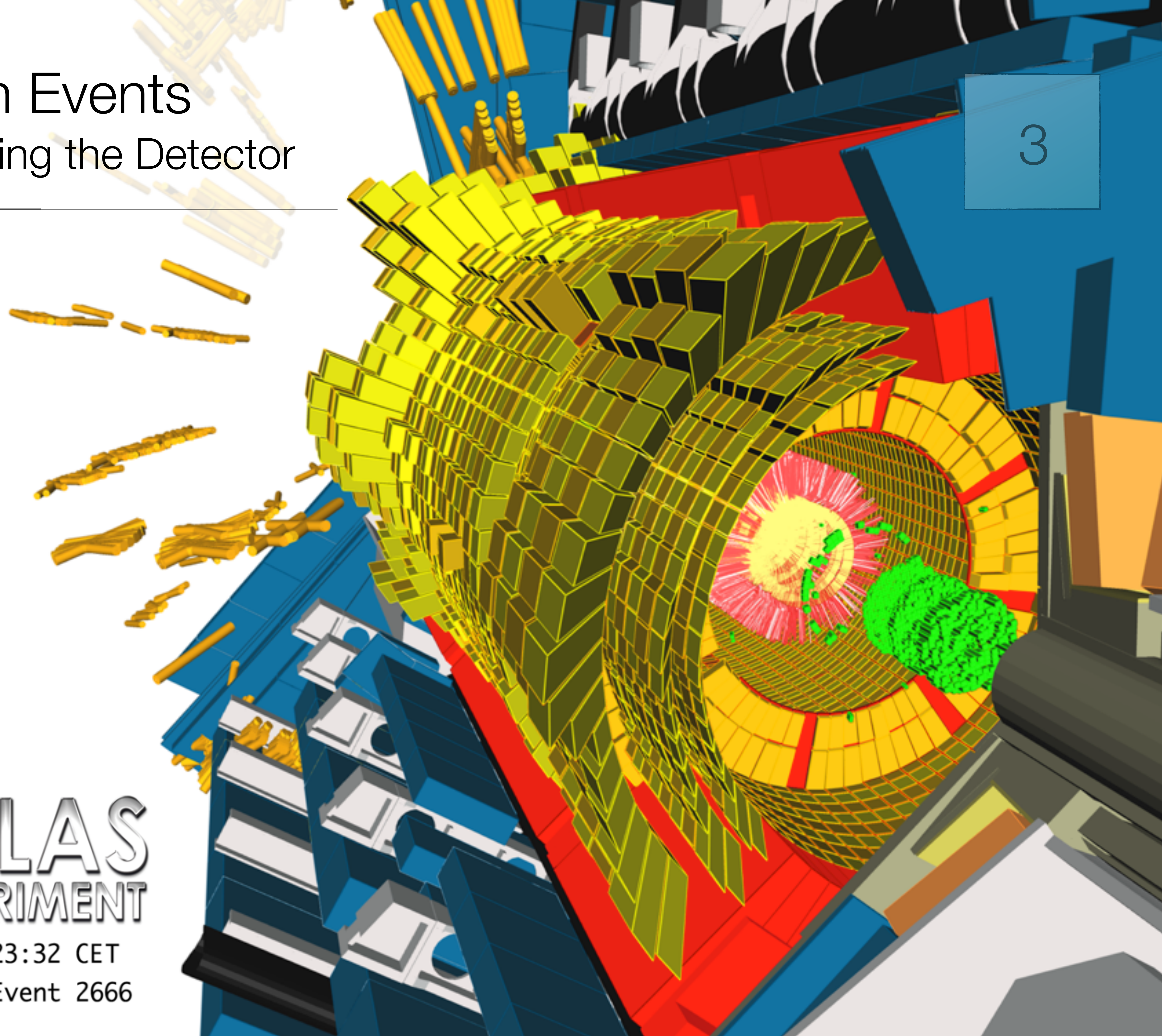
Example: ATLAS L1 Calorimeter Trigger

First Synchronisation in 2010



Splash Events

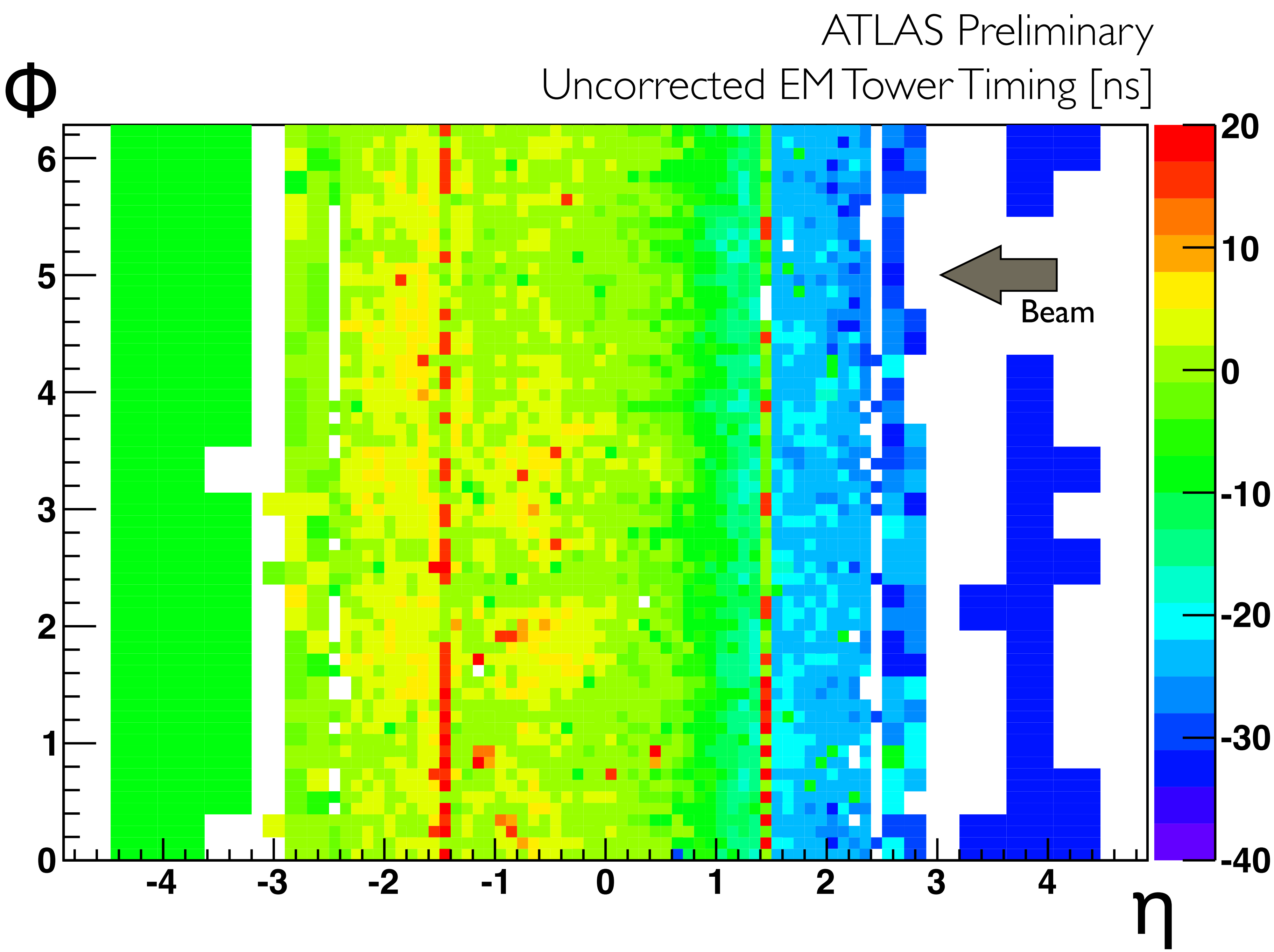
Illuminating the Detector

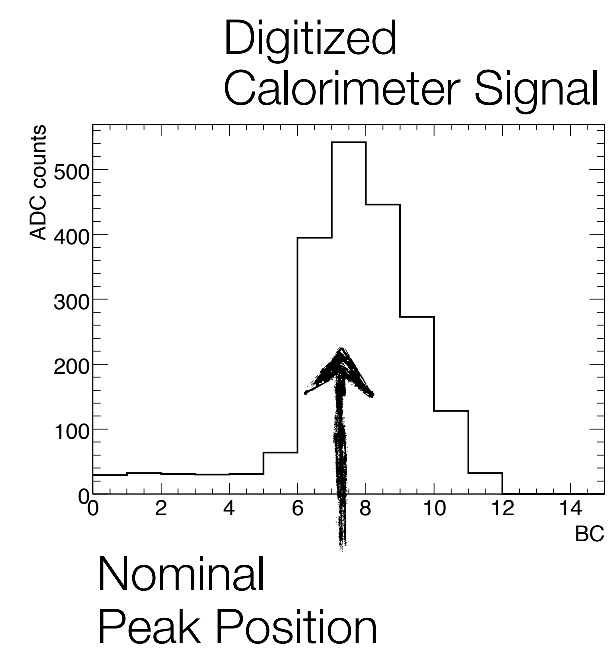


2009-11-20, 23:32 CET
Run 140370, Event 2666

Example: ATLAS L1 Calorimeter Trigger

First Synchronisation in 2010



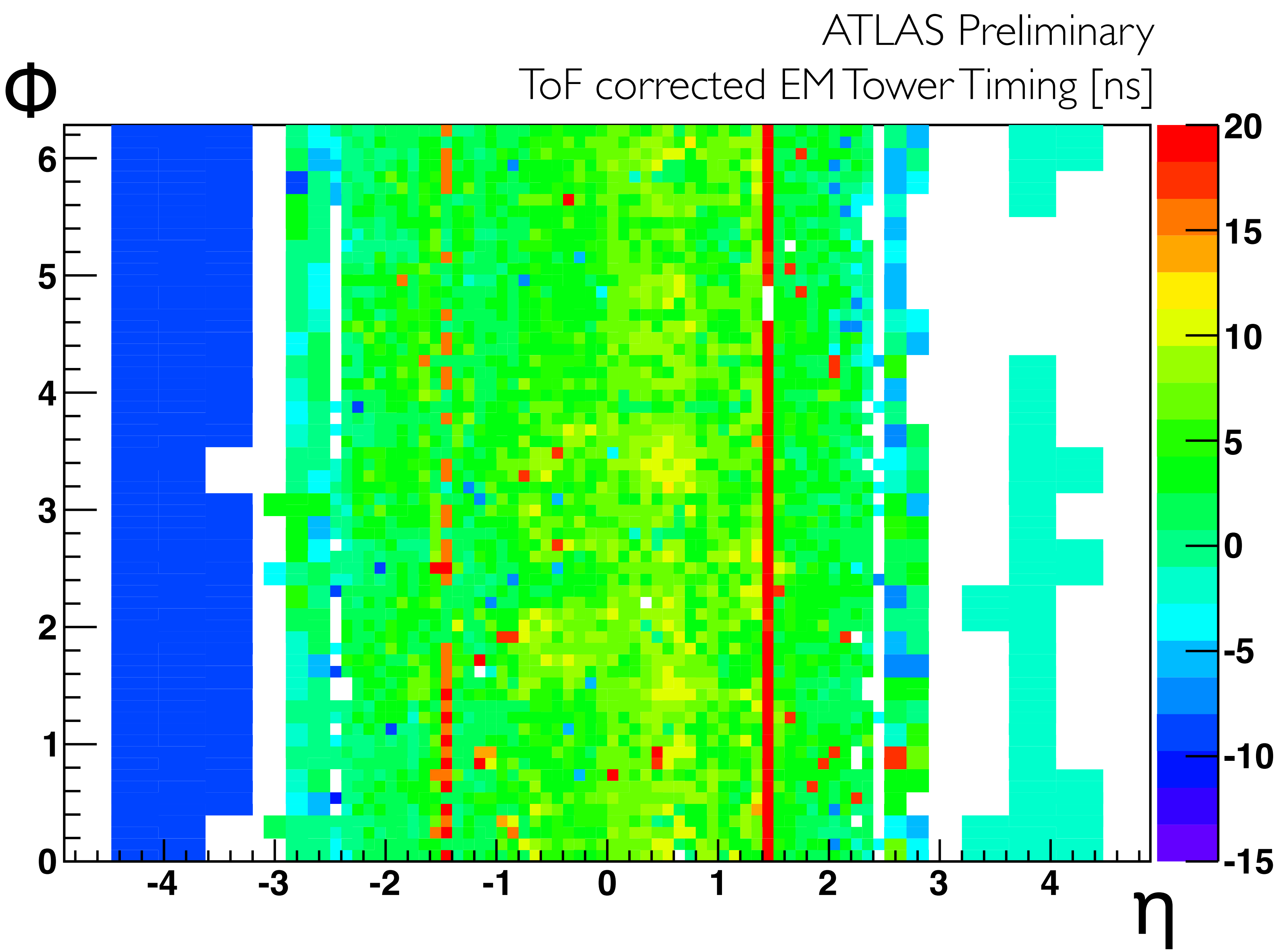


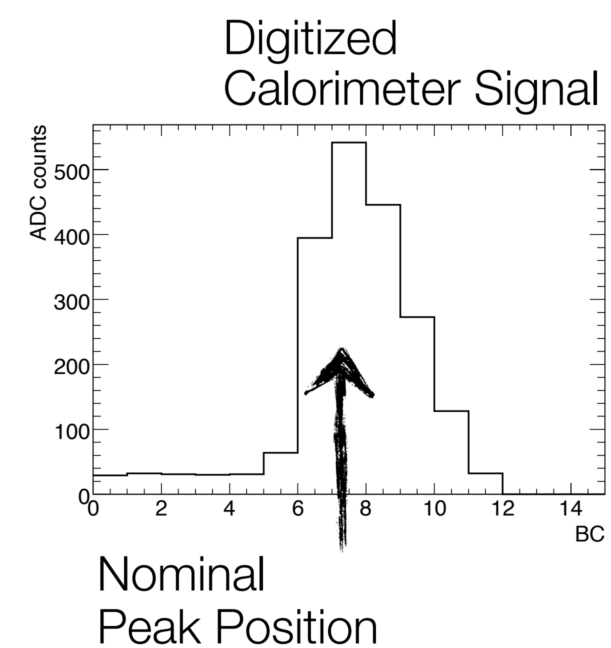
Fine-Timing
via fit to ADC spectra

Timing Asymmetry due to Time-of-Flight ...

Example: ATLAS L1 Calorimeter Trigger

First Synchronisation in 2010



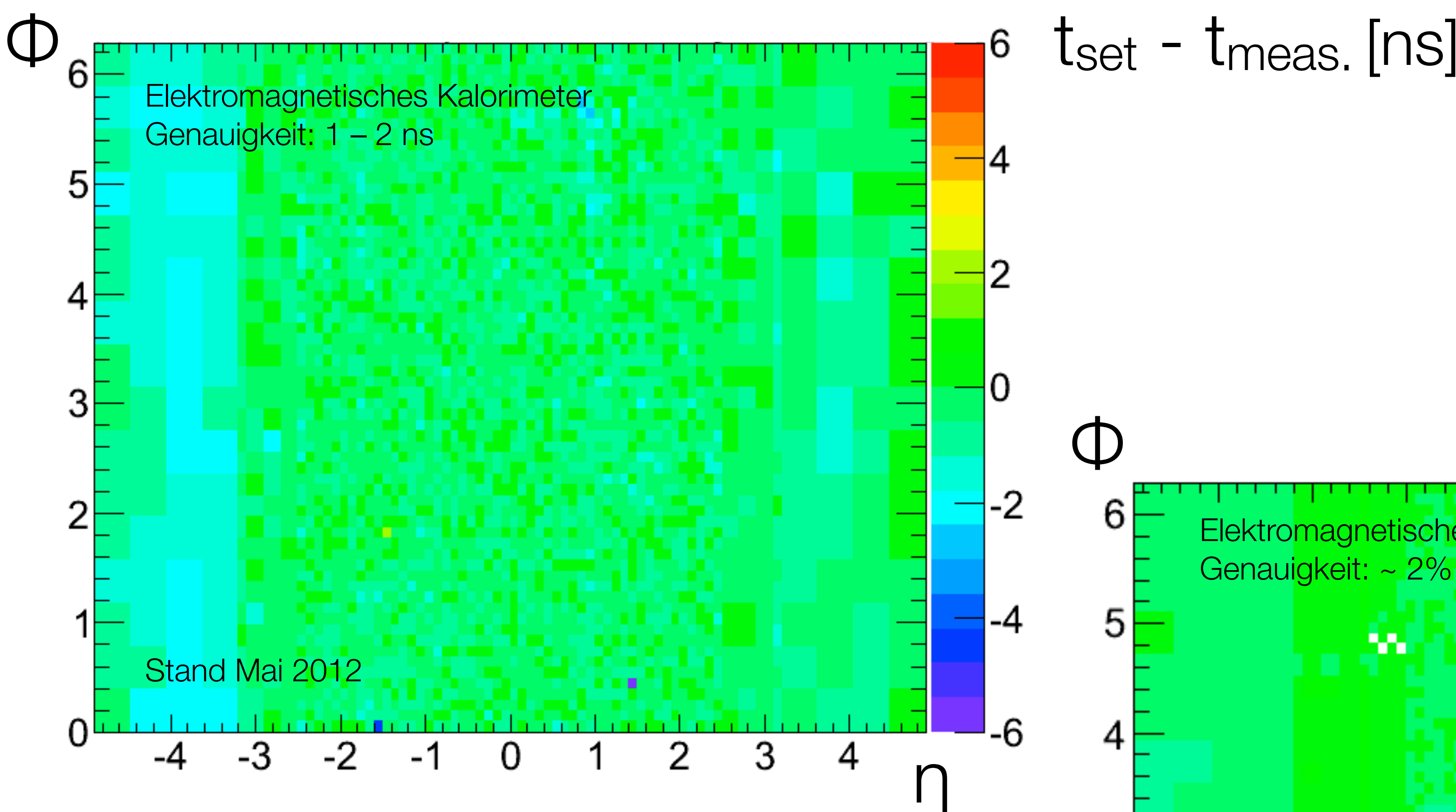


Fine-Timing
via fit to ADC spectra

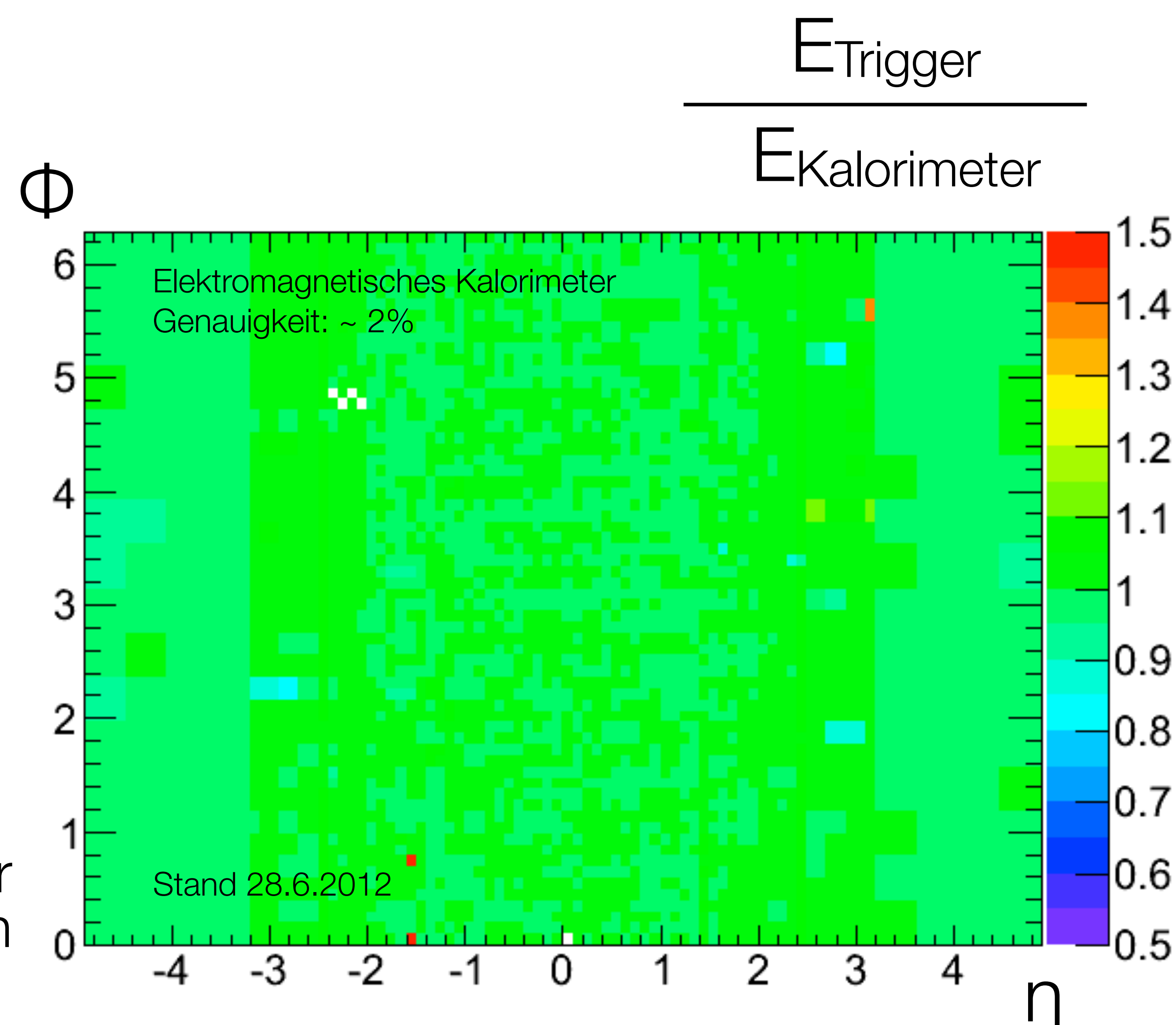
Relative Trigger Timing at ± 10 ns @ Startup !

Example: ATLAS L1 Calorimeter Trigger

Timing & Energy Calibration after Synchronisation



Qualität der
Zeitsynchronisation

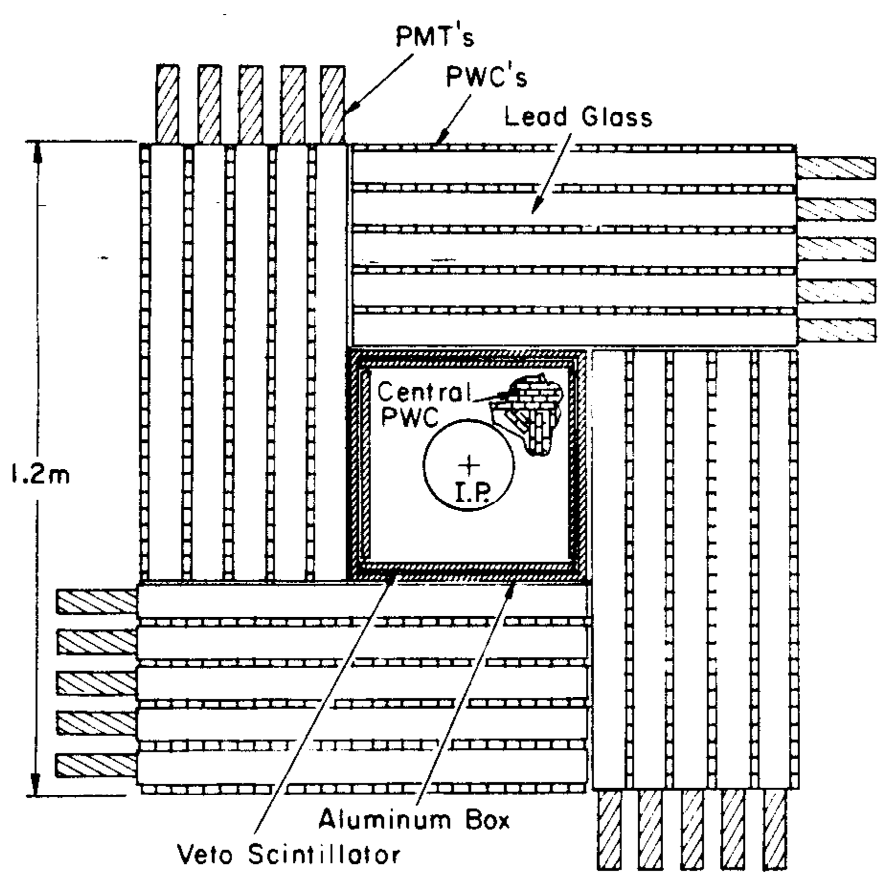


Qualität der
Energiekalibration

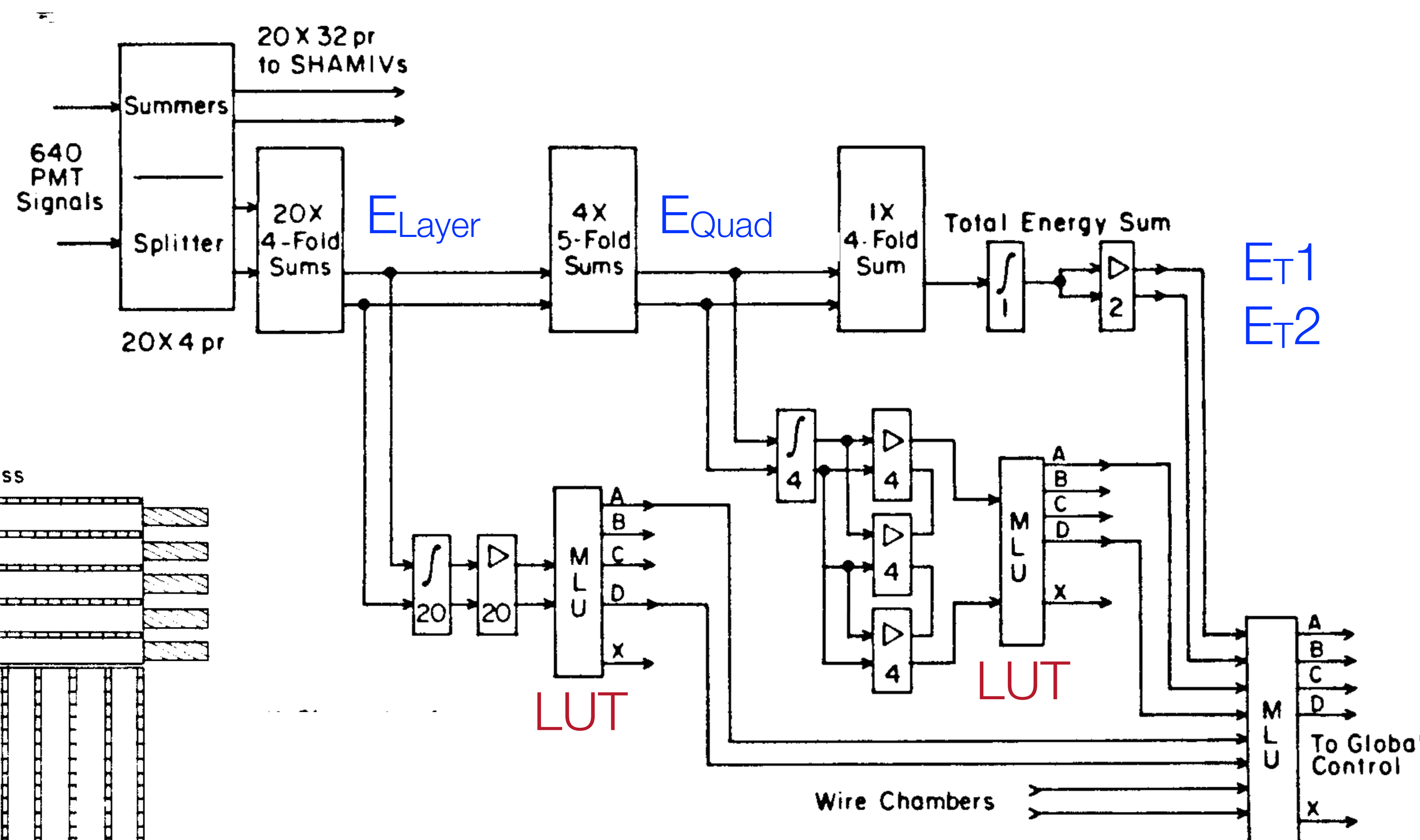
Thanks

Extras

Calorimeter Trigger – ASP Detector



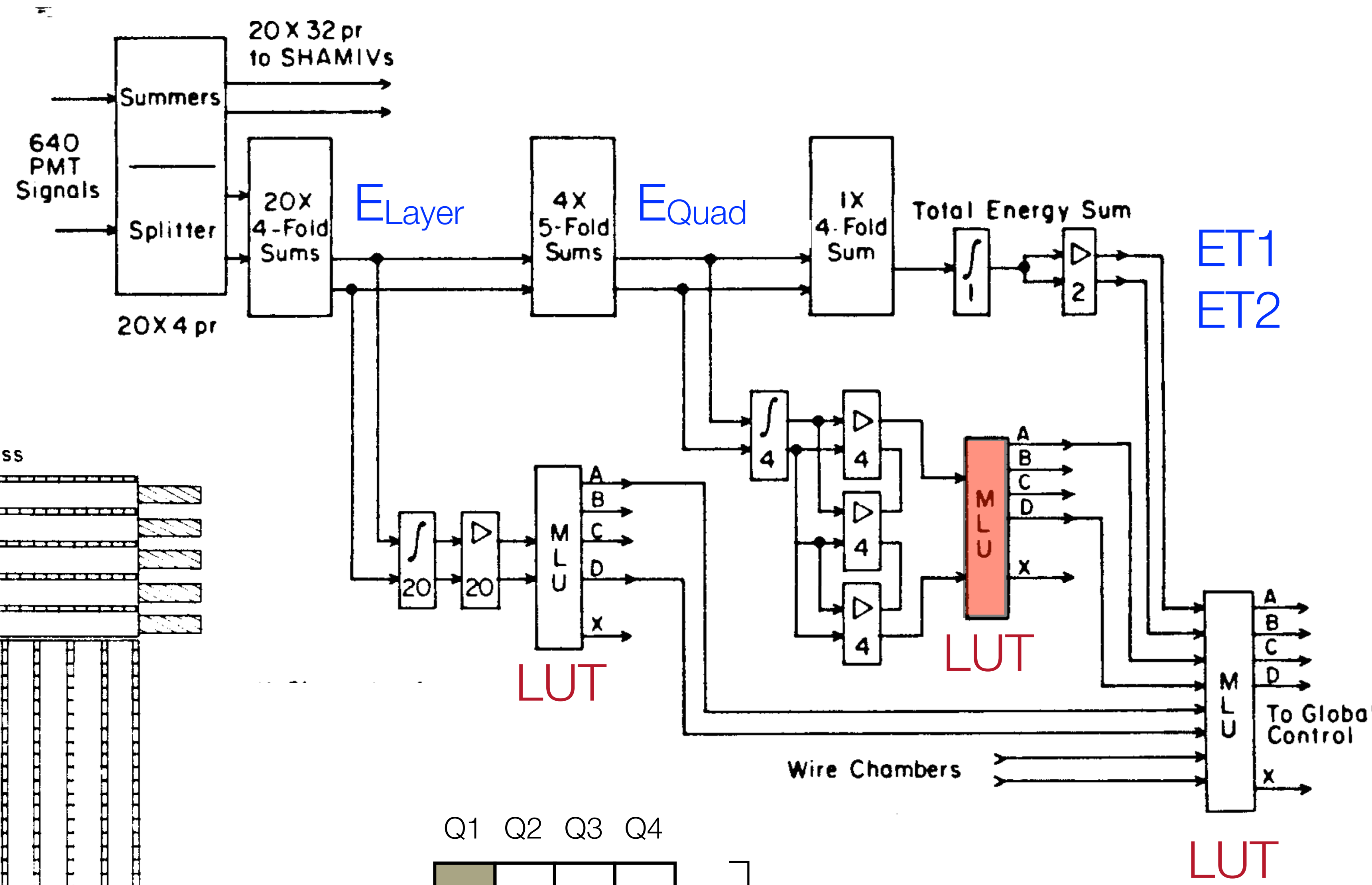
ASP Calorimeter
[Anomalous Single Photon Search]

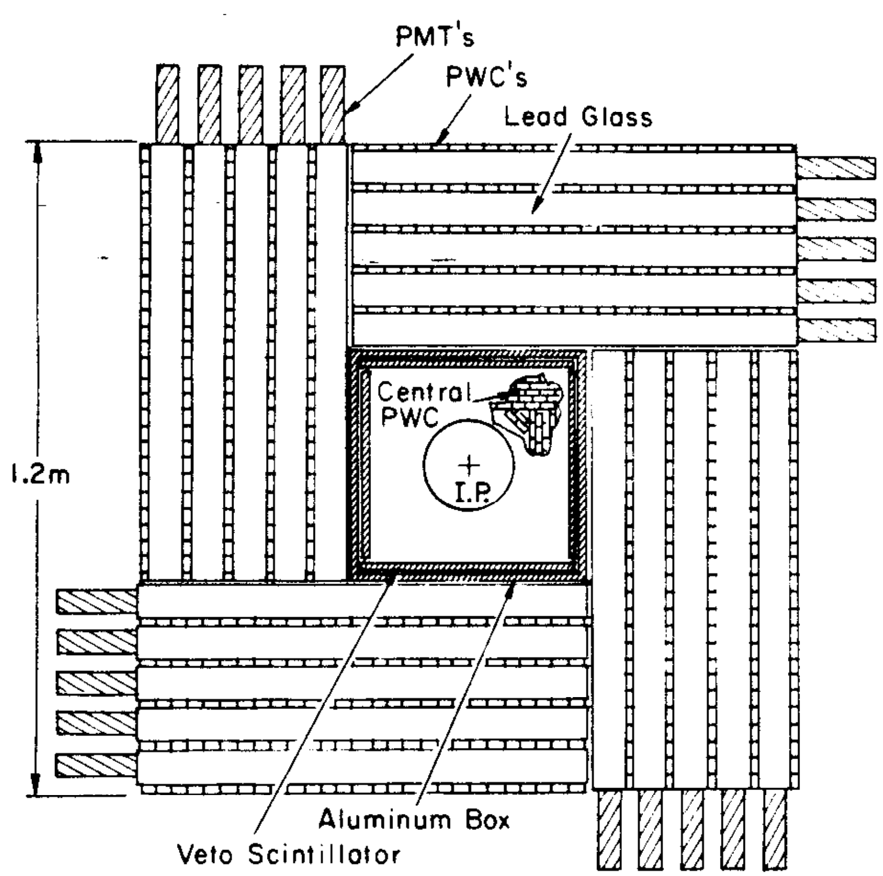


E_{Layer}: Energy per Layer
E_{Quad}: Energy per Quadrant
E_T: Total energy

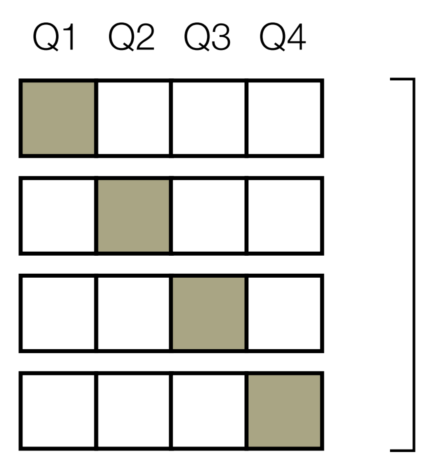
LUT: Look Up Table

Calorimeter Trigger – ASP Detector





ASP Calorimeter
[Anomalous Single Photon Search]



LUT addresses
generating trigger