A brief lecture on

DAQ & Trigger

EDIT-2020 School

DESY, February 2020

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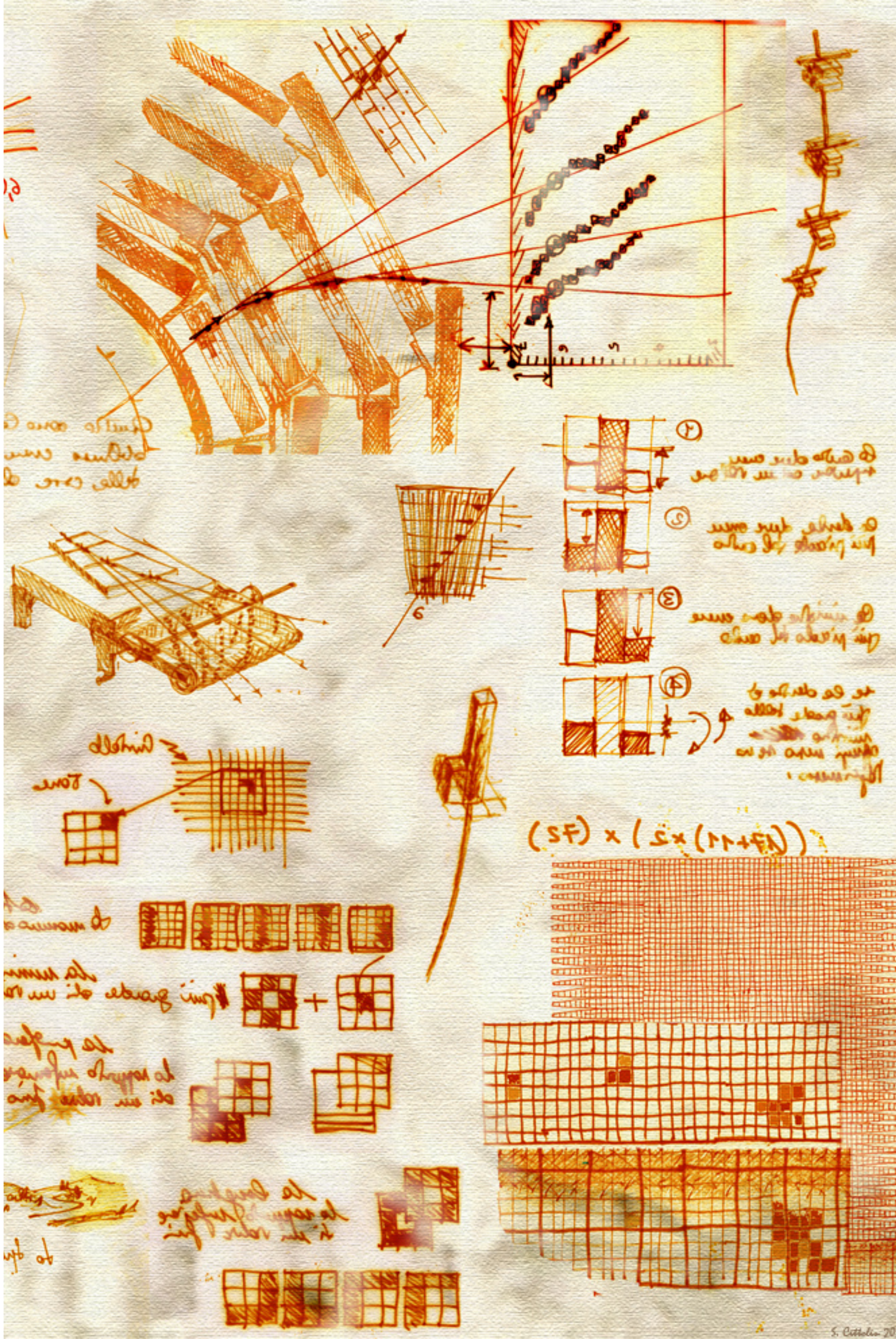
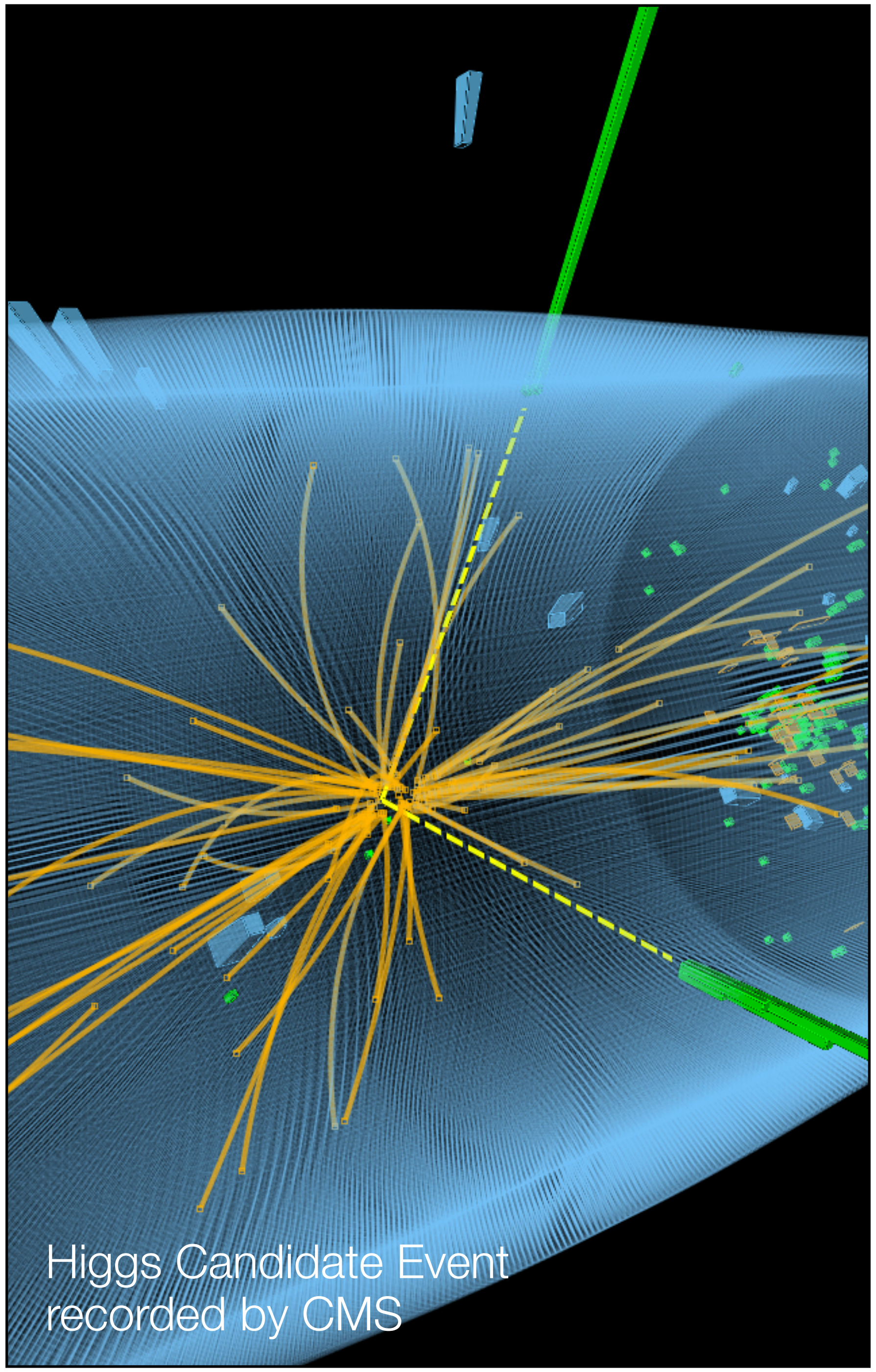
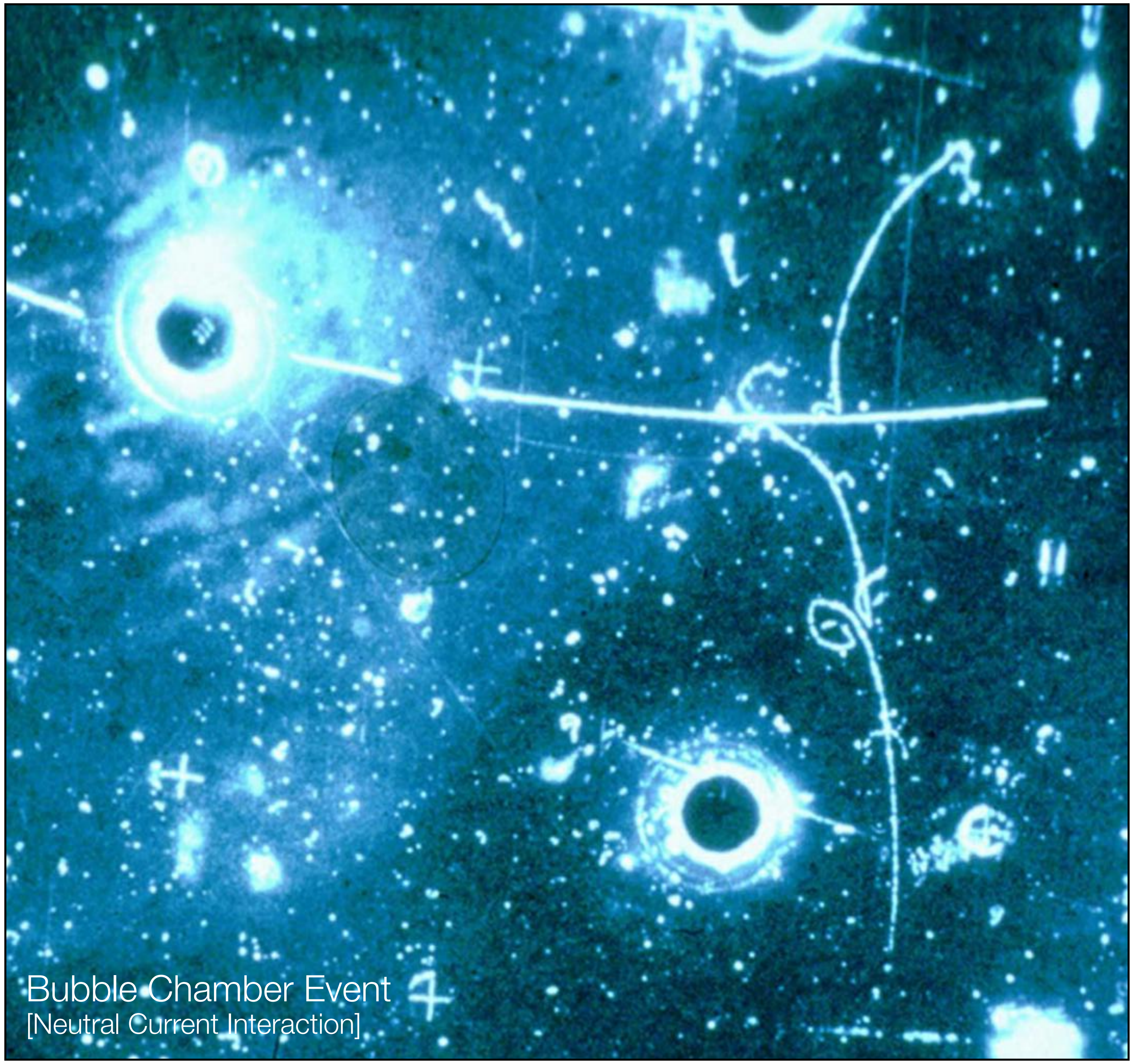


Prologue

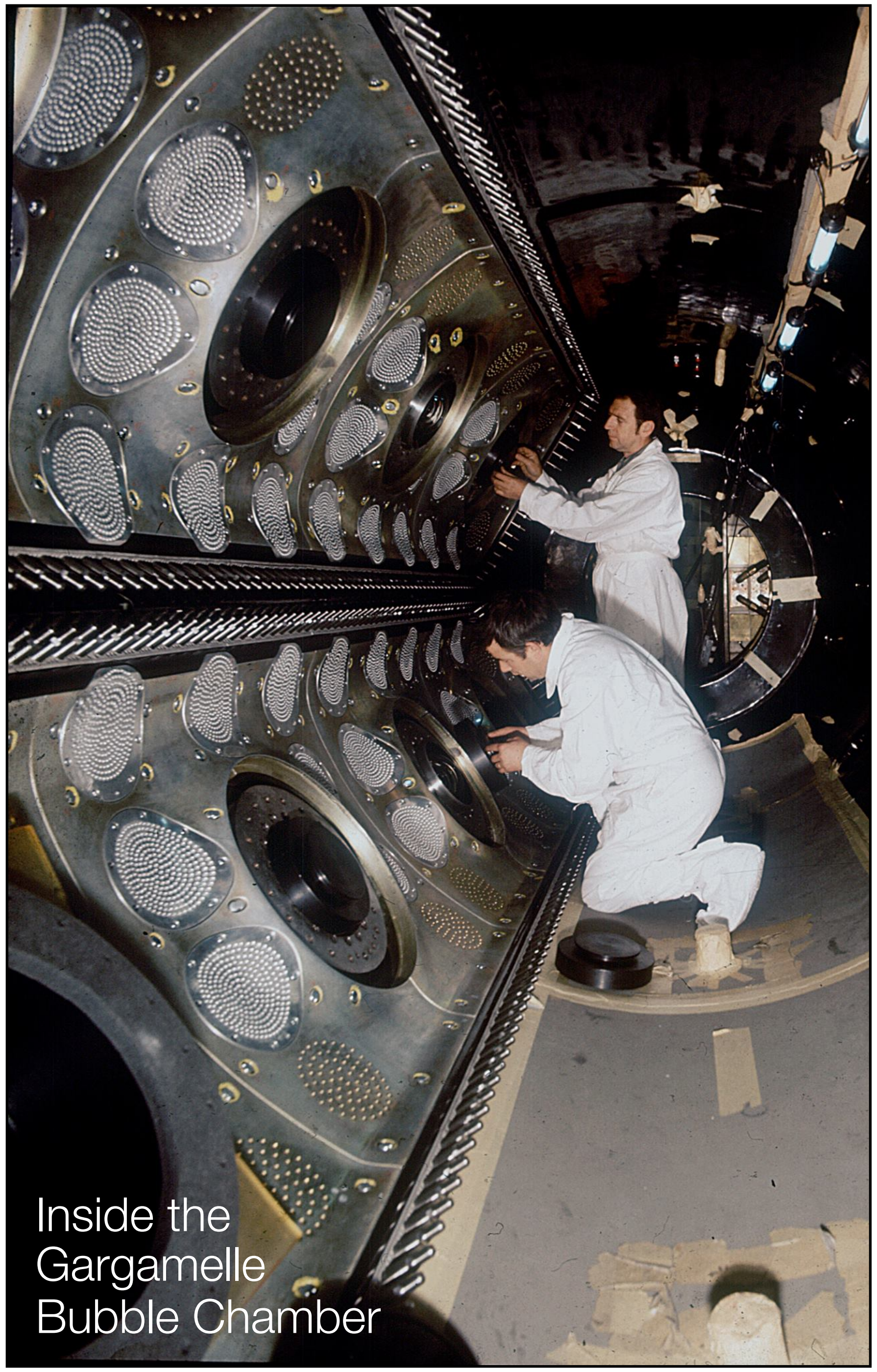
"Introducing the Subject"

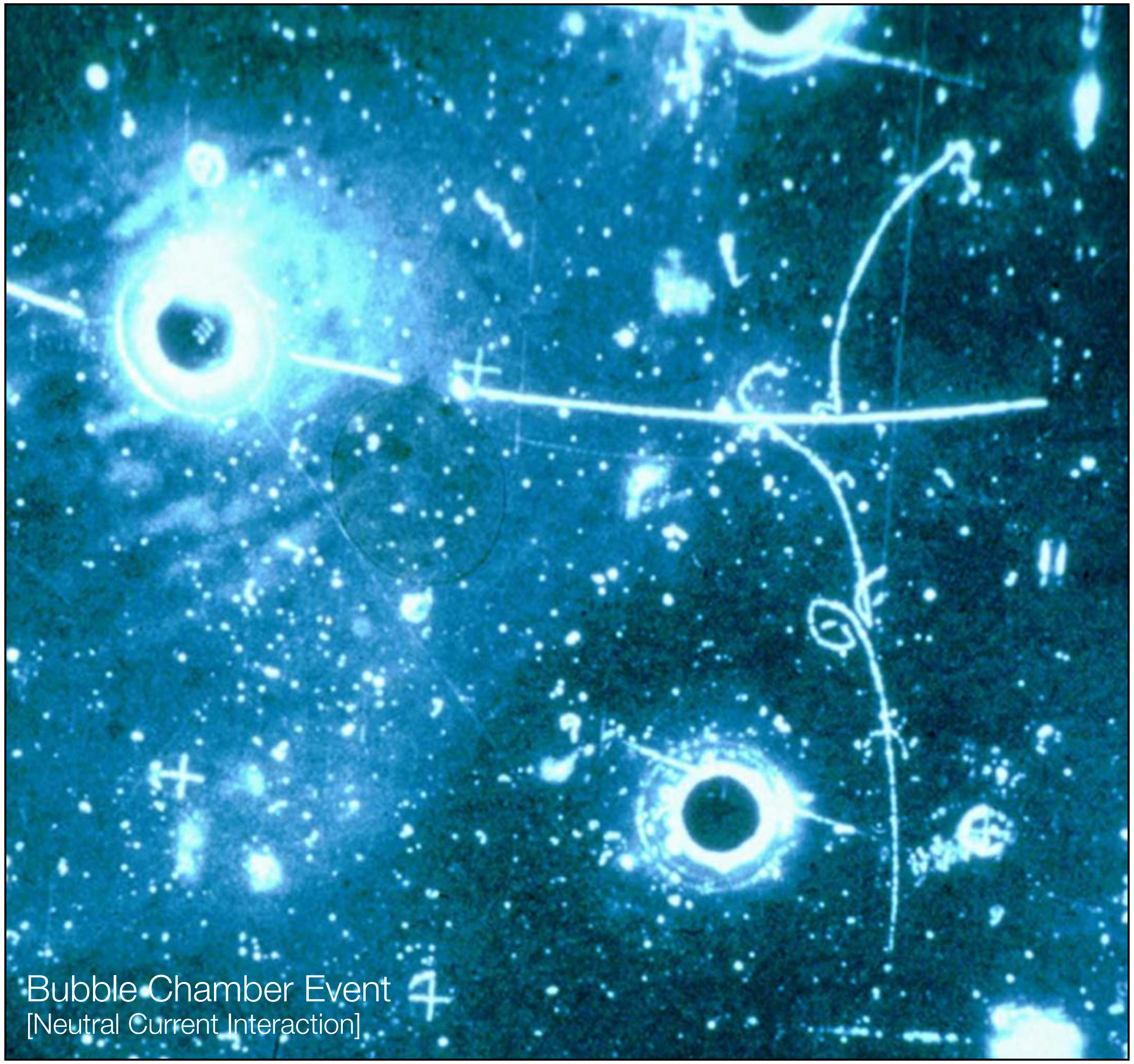
Detecting & Recording Particle Reactions


Higgs Candidate Event
recorded by CMS

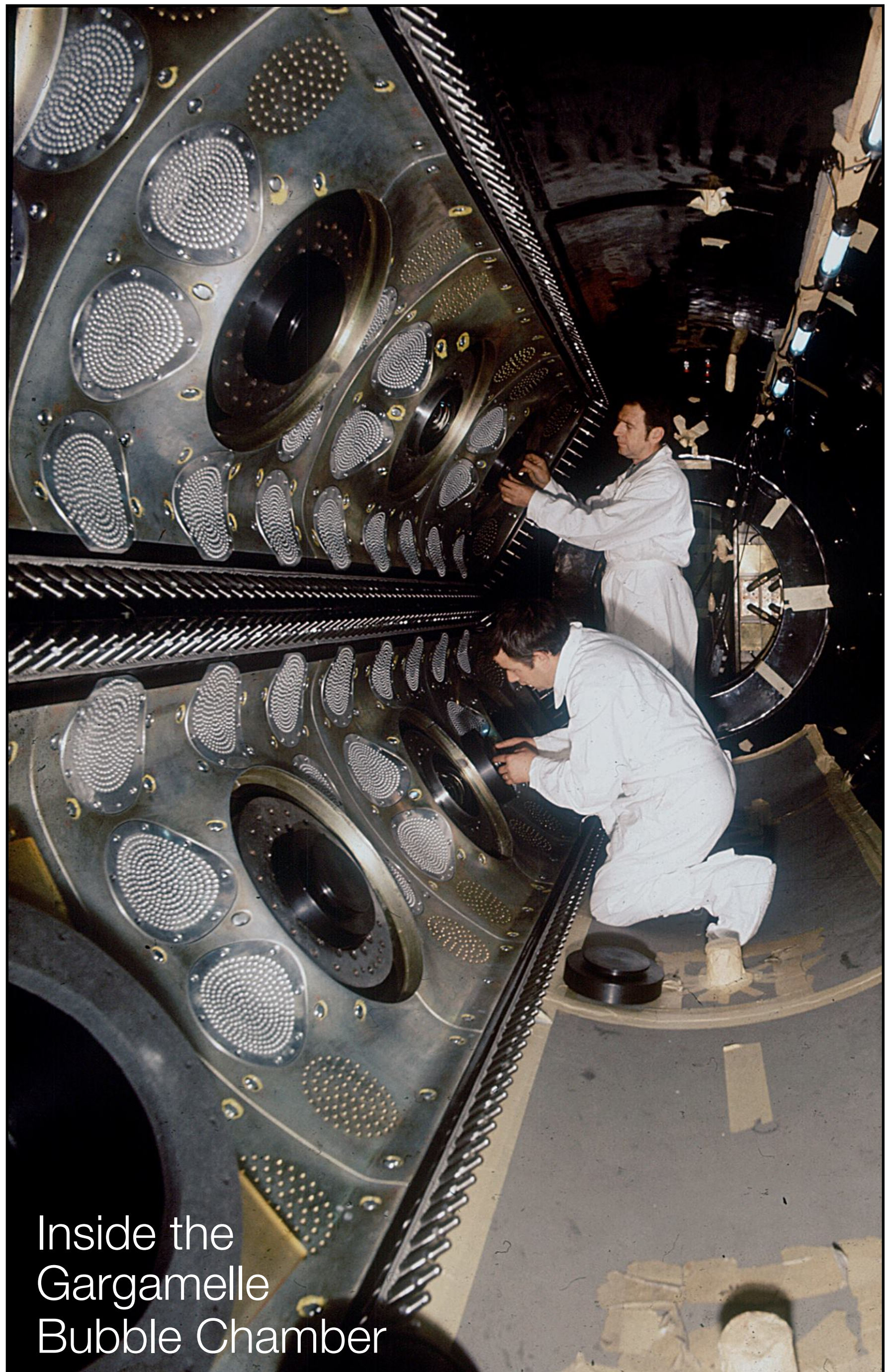

Bubble Chamber Event
[Neutral Current Interaction]

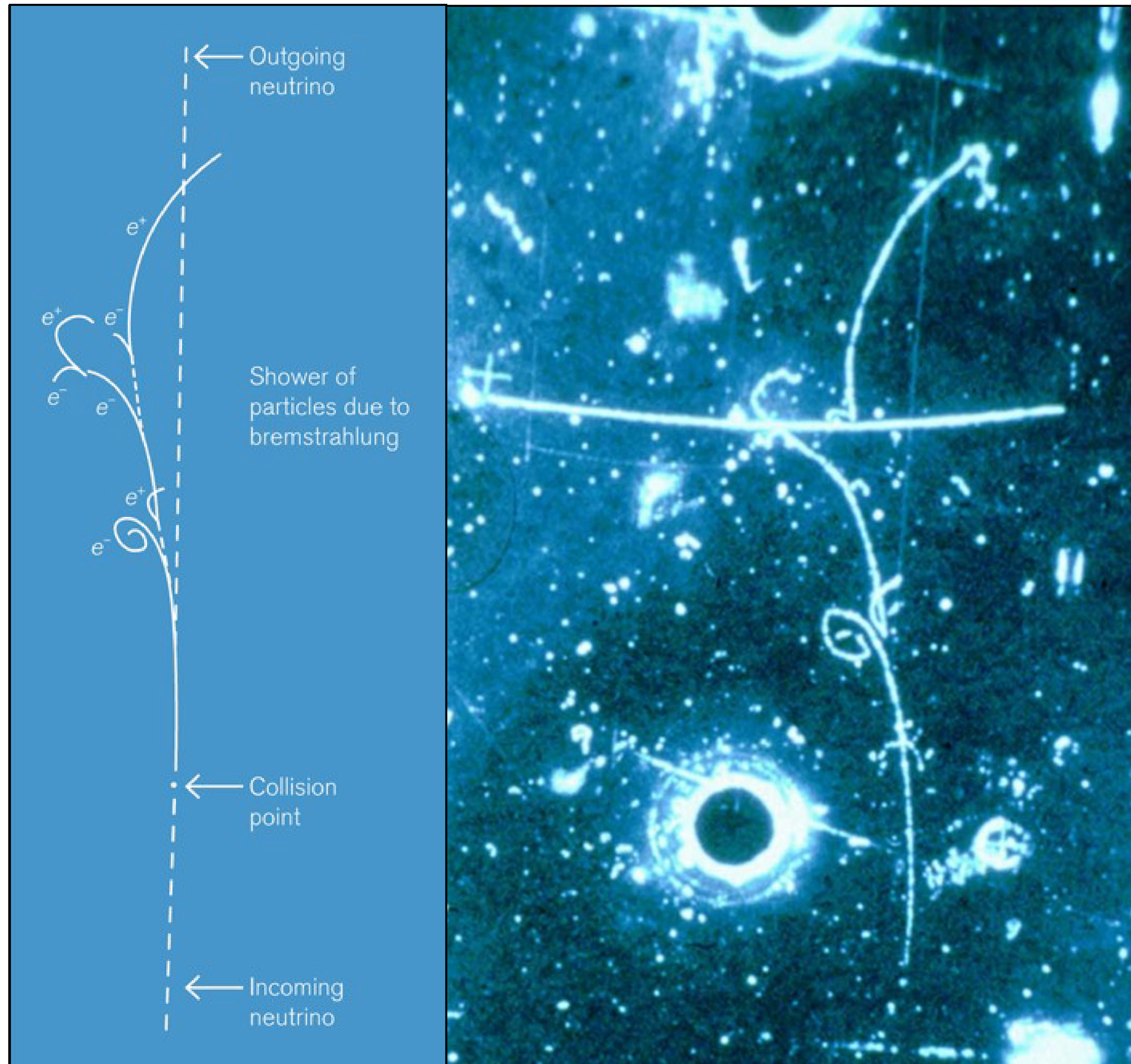
Detecting & Recording Particle Reactions



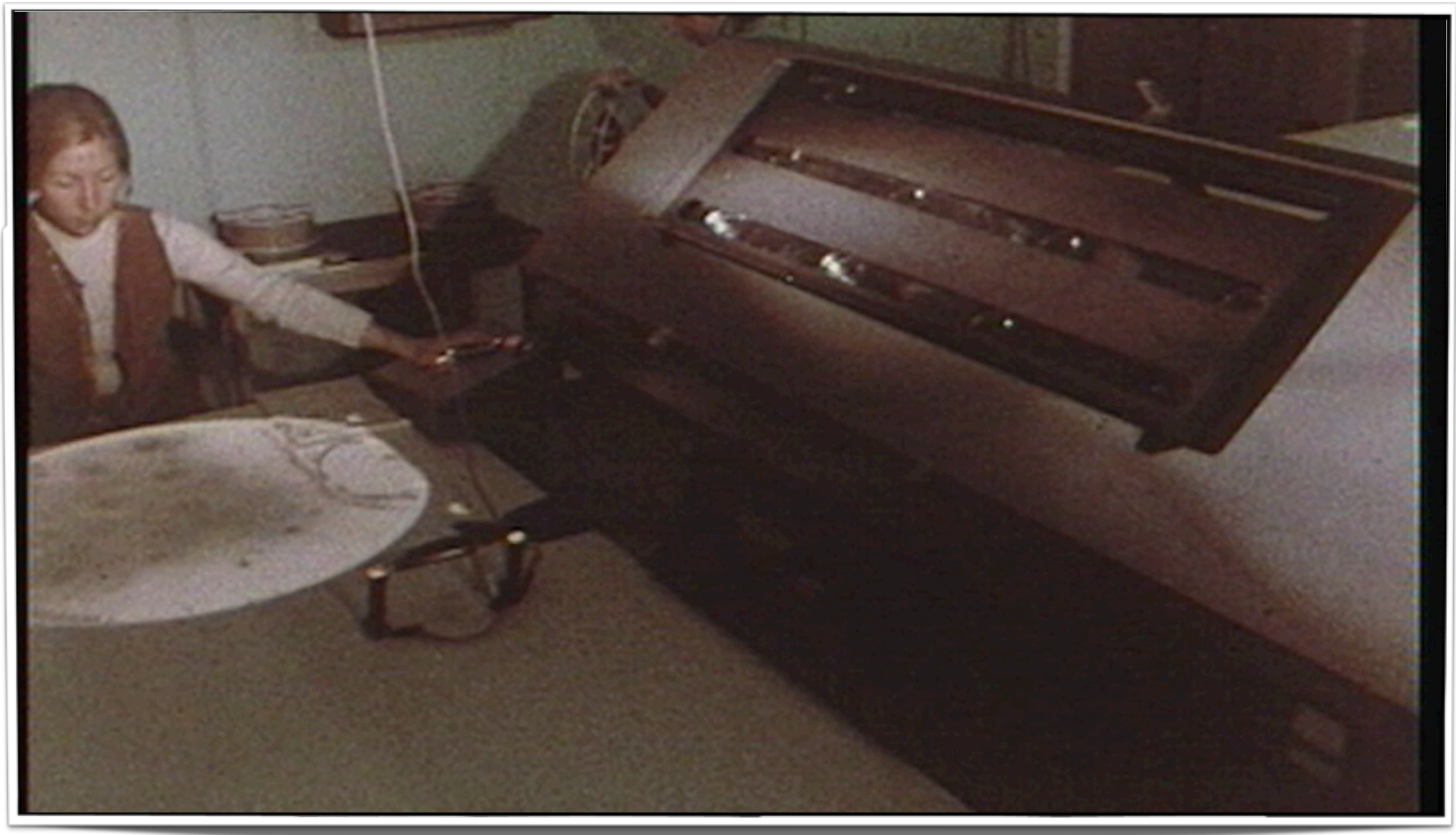


Detecting & Recording Particle Reactions


Inside the Gargamelle Bubble Chamber

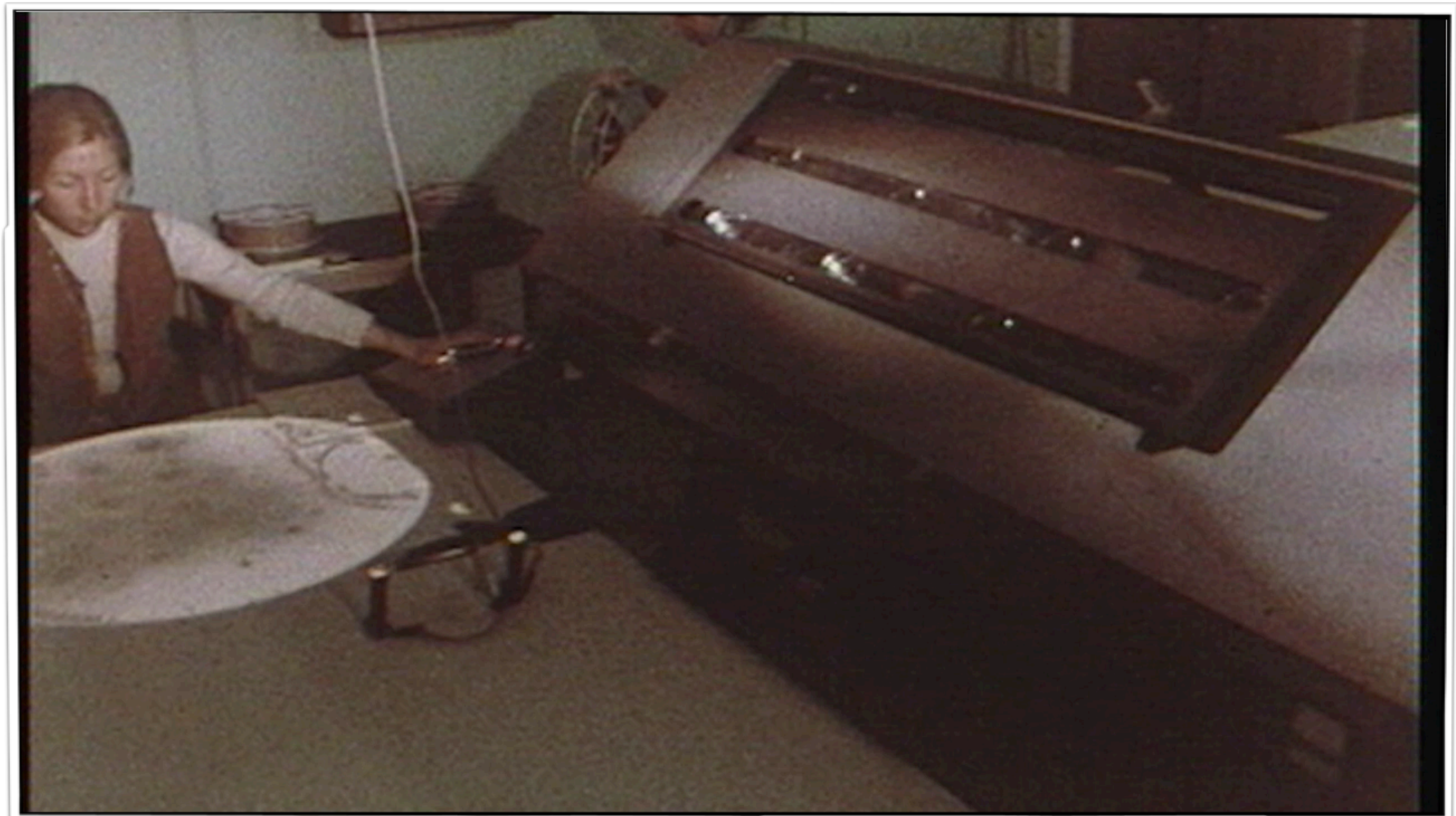


Gargamelle – Selecting Events



[https://videos.cern.ch/record/1069969]

Gargamelle – Selecting Events



[https://videos.cern.ch/record/1069969]

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

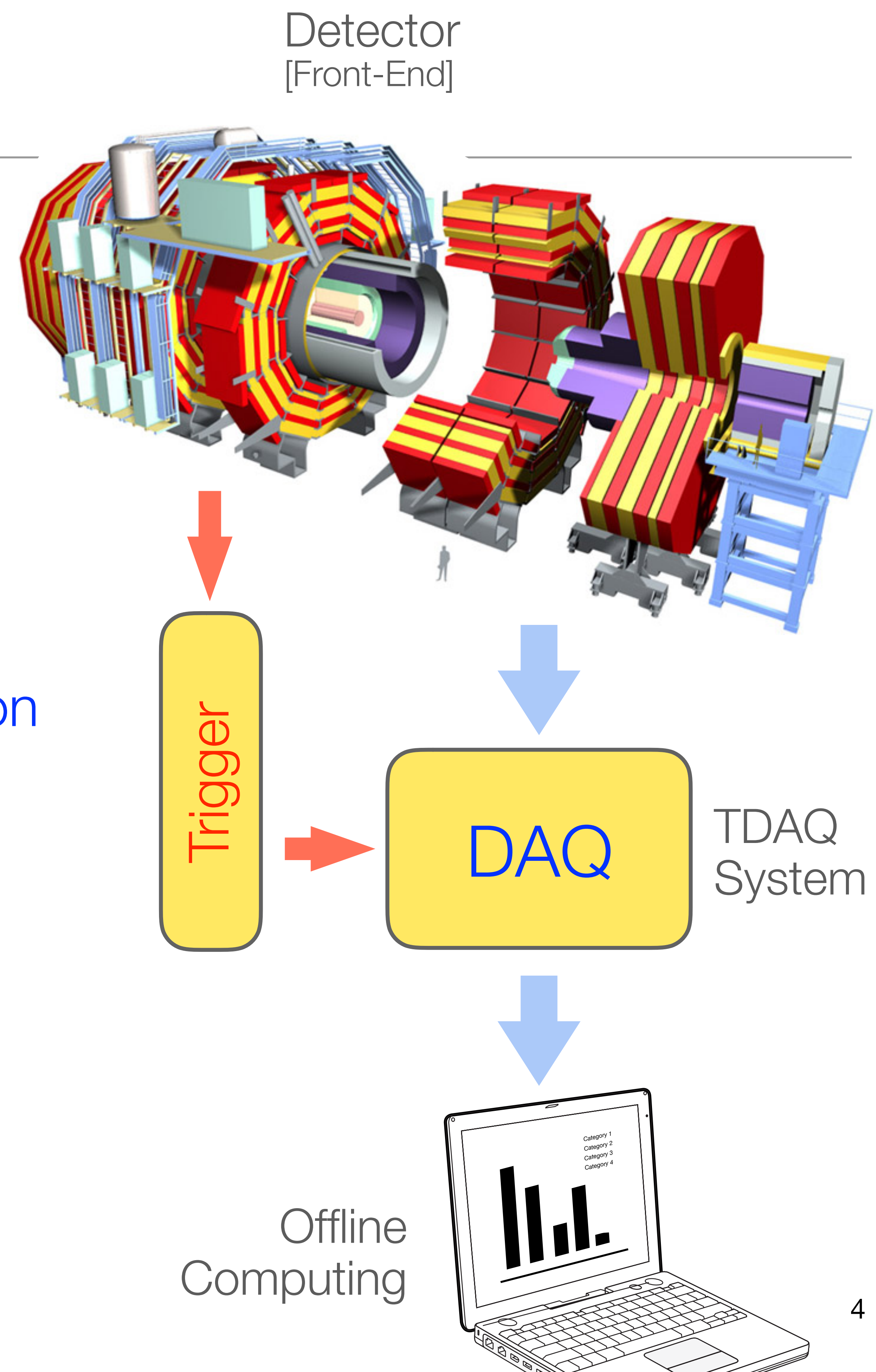
Trigger & DAQ in a Nutshell

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

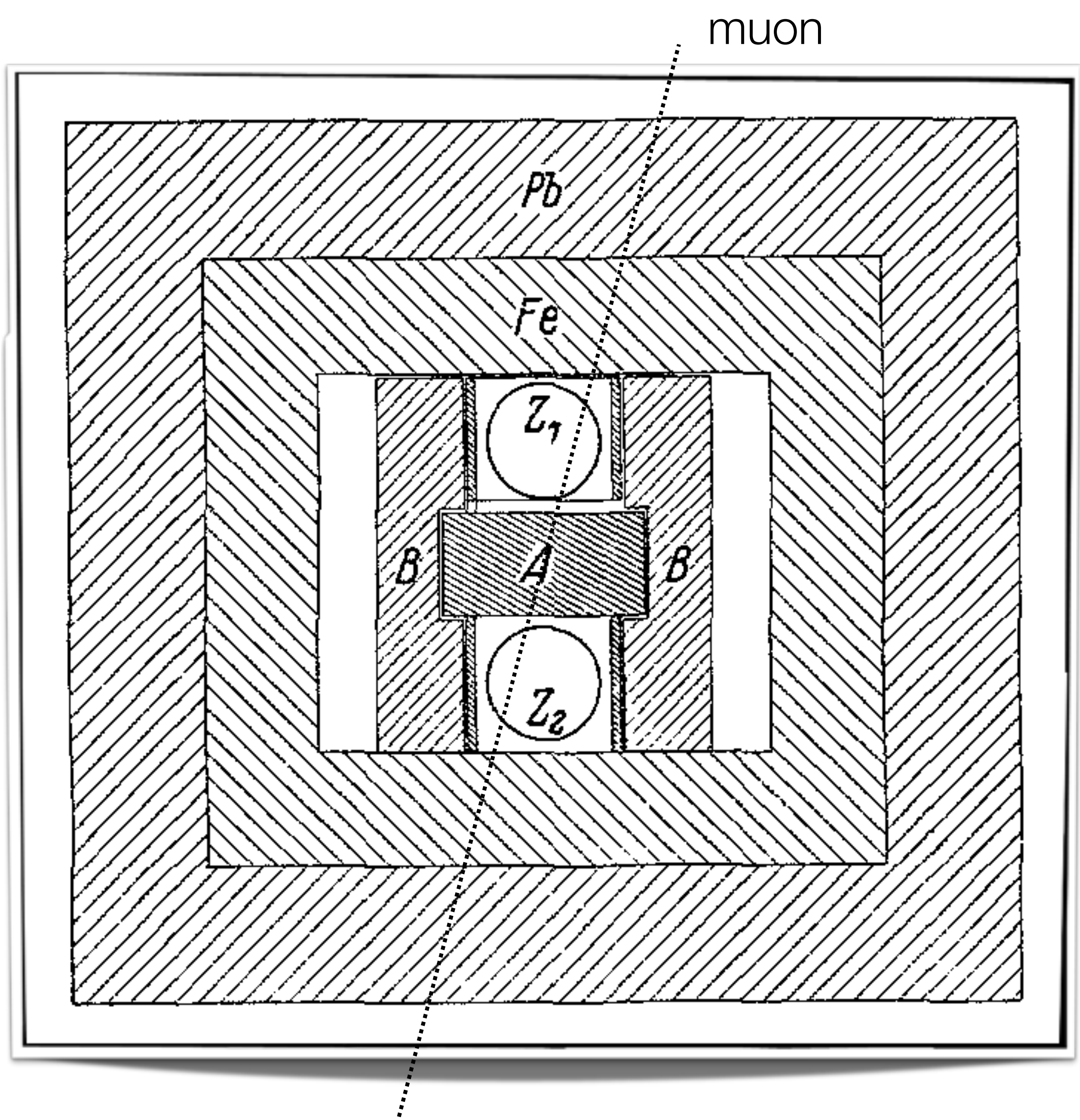
Trigger responsible for real-time selection of the subset of data to be recorded.

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

Often interwoven …



Detecting Coincidences



Bothe, Kohlhörster
Zeitschrift für Physik 56 (1929)

W. Bothe et al.

Studying Cosmic Rays

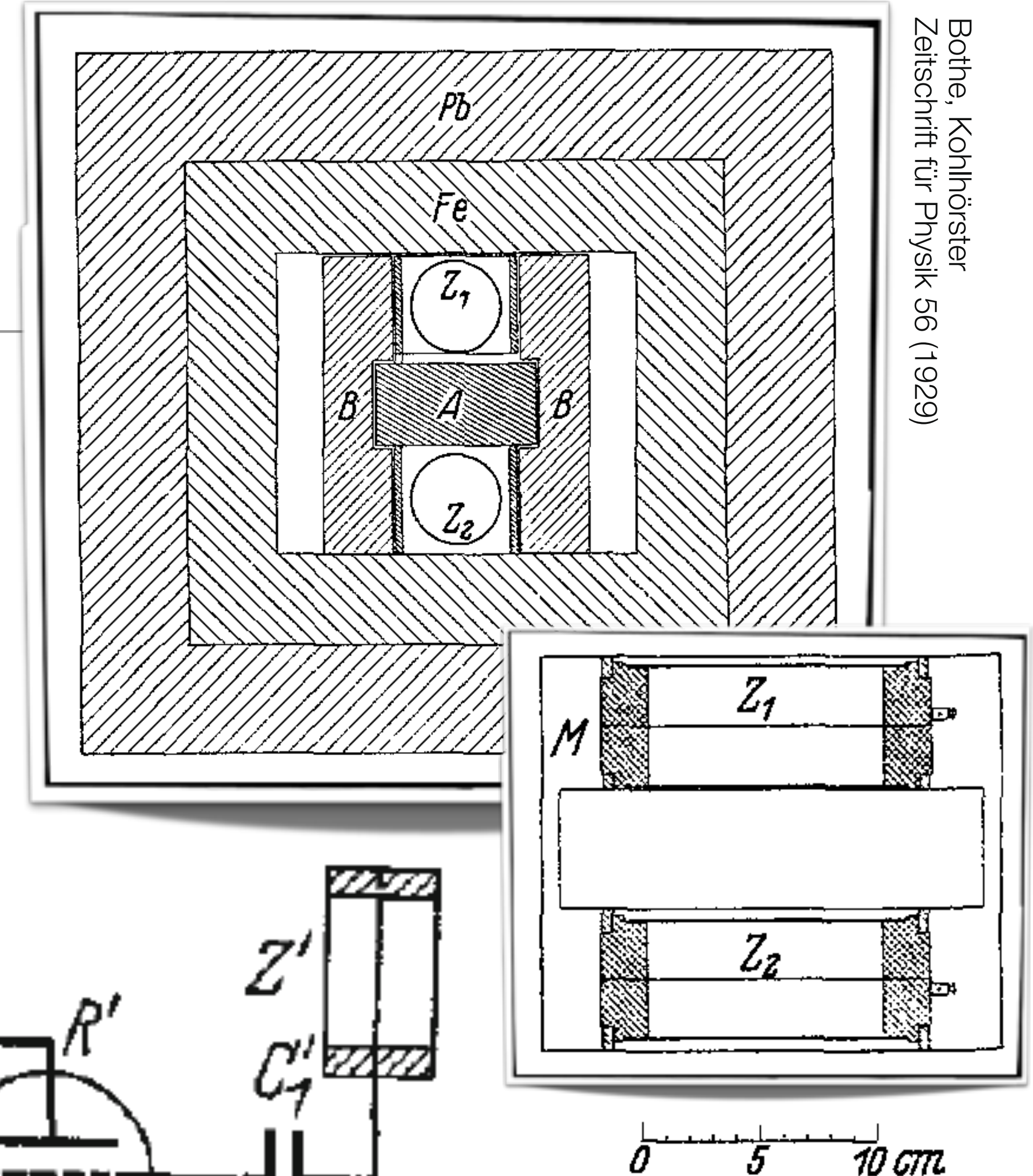
[1929]

Detecting Coincidences

Walter Bothe

Nobel prize 1954

For the coincidence method
and his discoveries made therewith.



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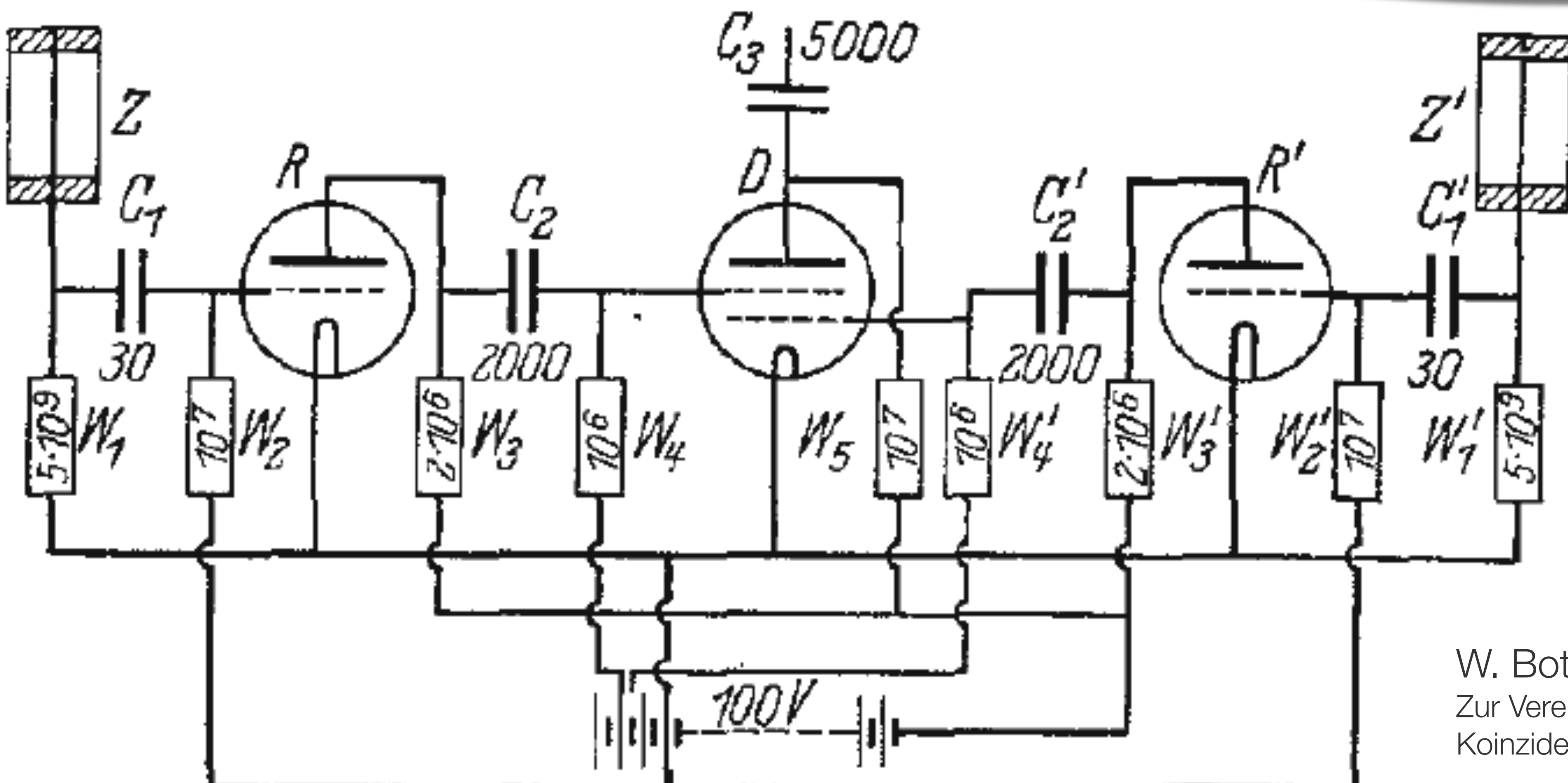
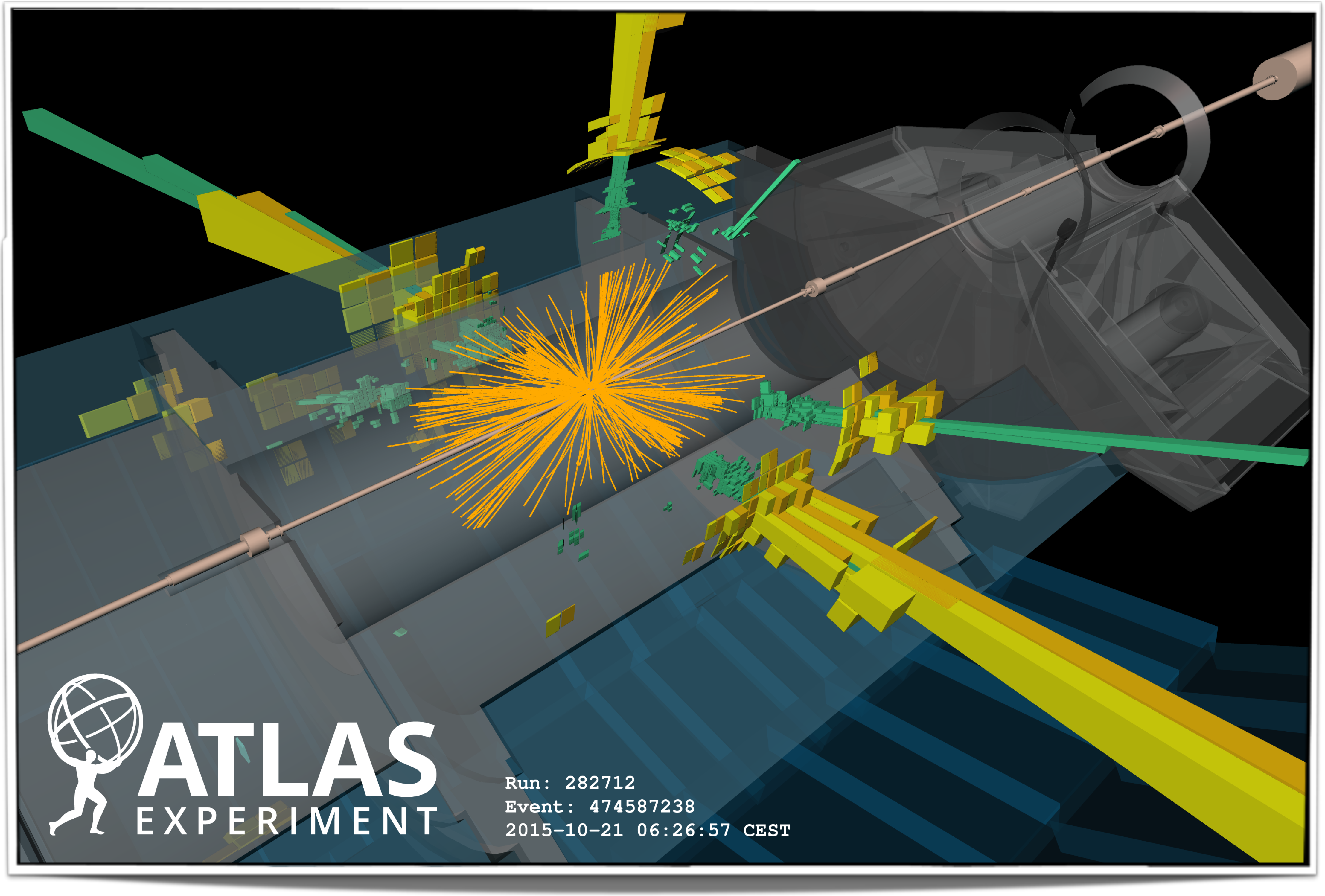


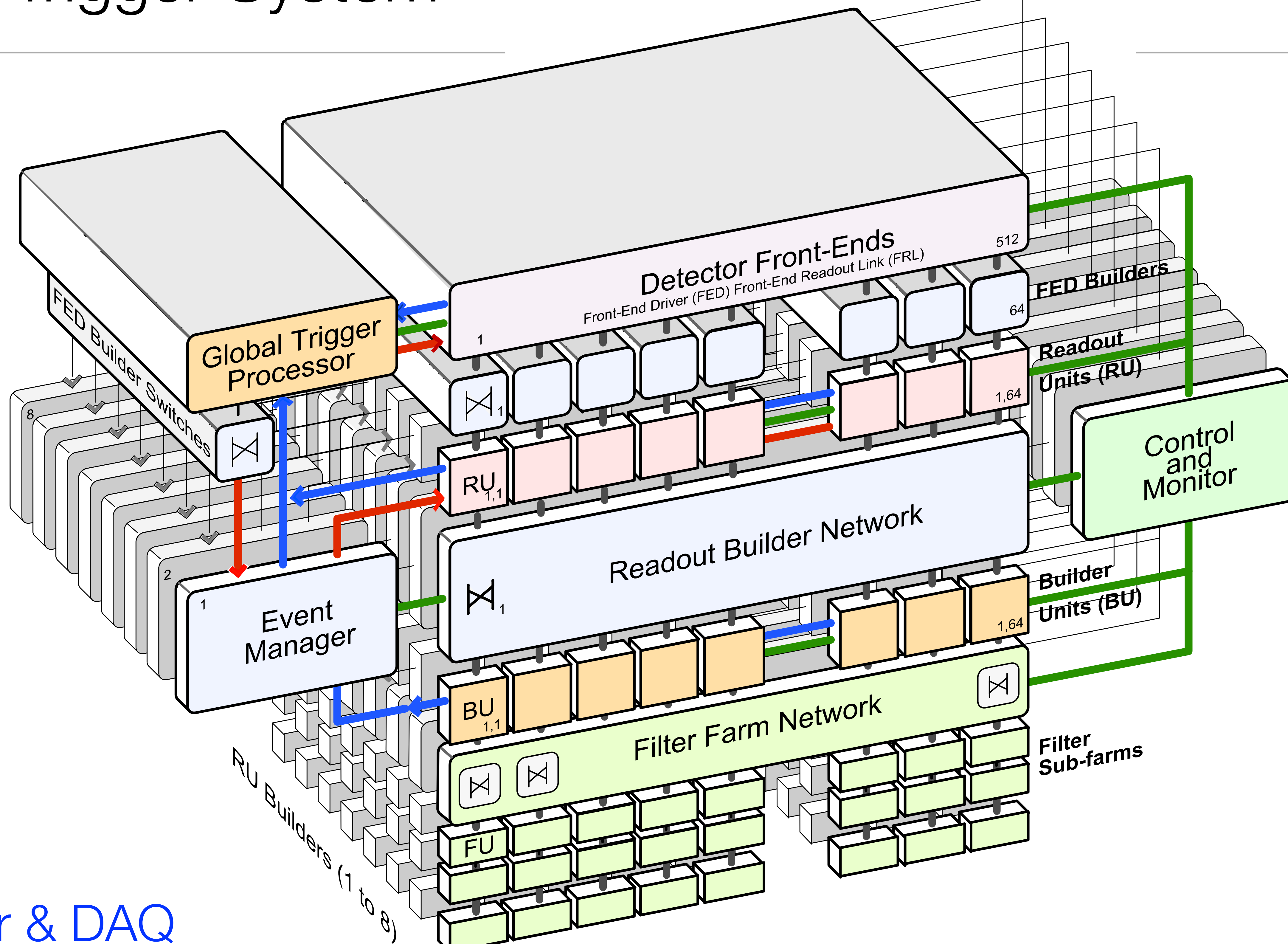
W. Bothe
Zur Vereinfachung von
Koinzidenzzählungen

Zeitschrift für Physik 59 (1930)

ATLAS Multijet Signature



LHC Trigger System

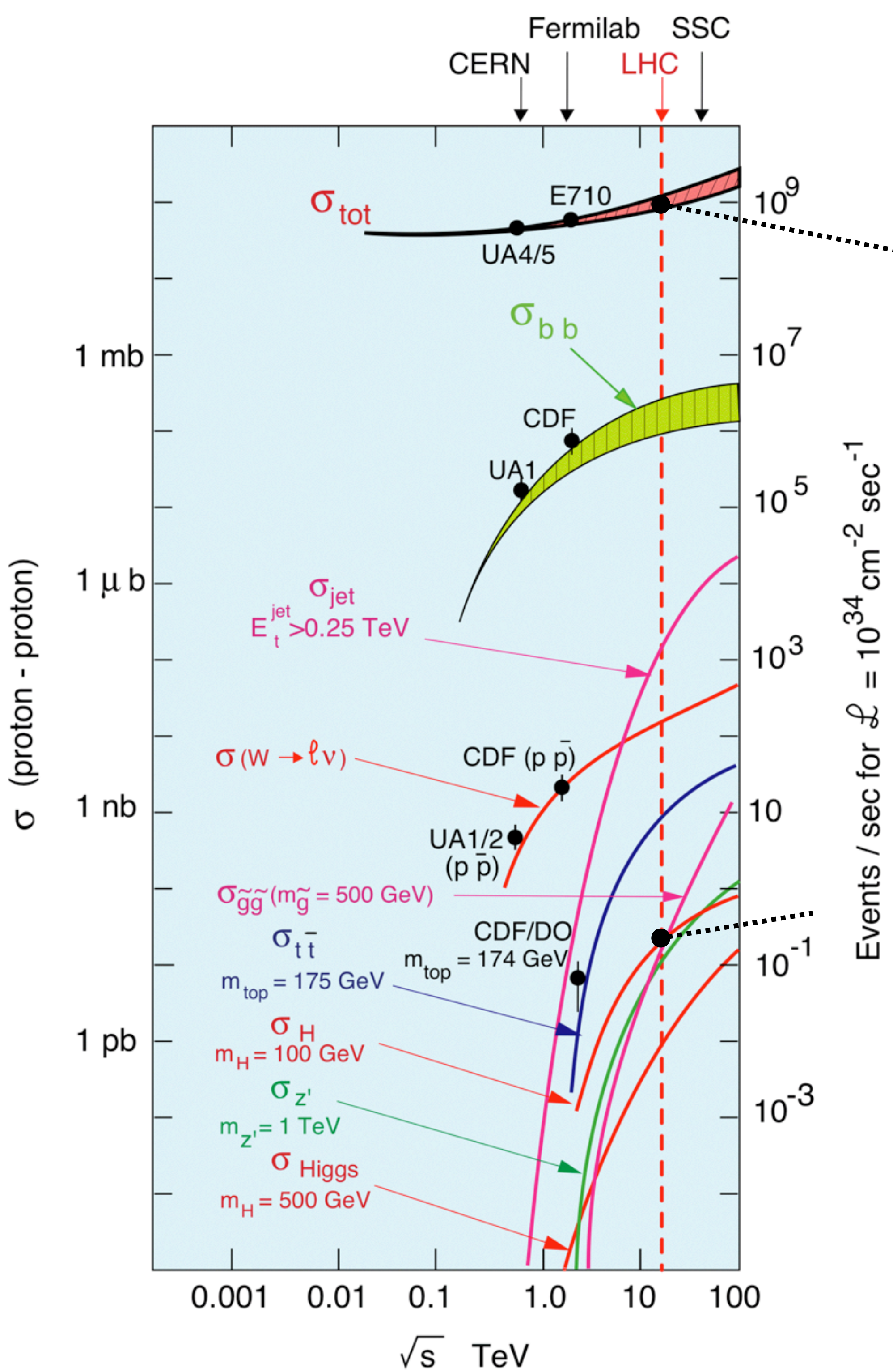


CMS
Trigger & DAQ

Part 1

"The TDAQ Challenges of Today"

LHC Cross Sections and Event Rates



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

~ 10^{10}

Efficient
rate reduction needed

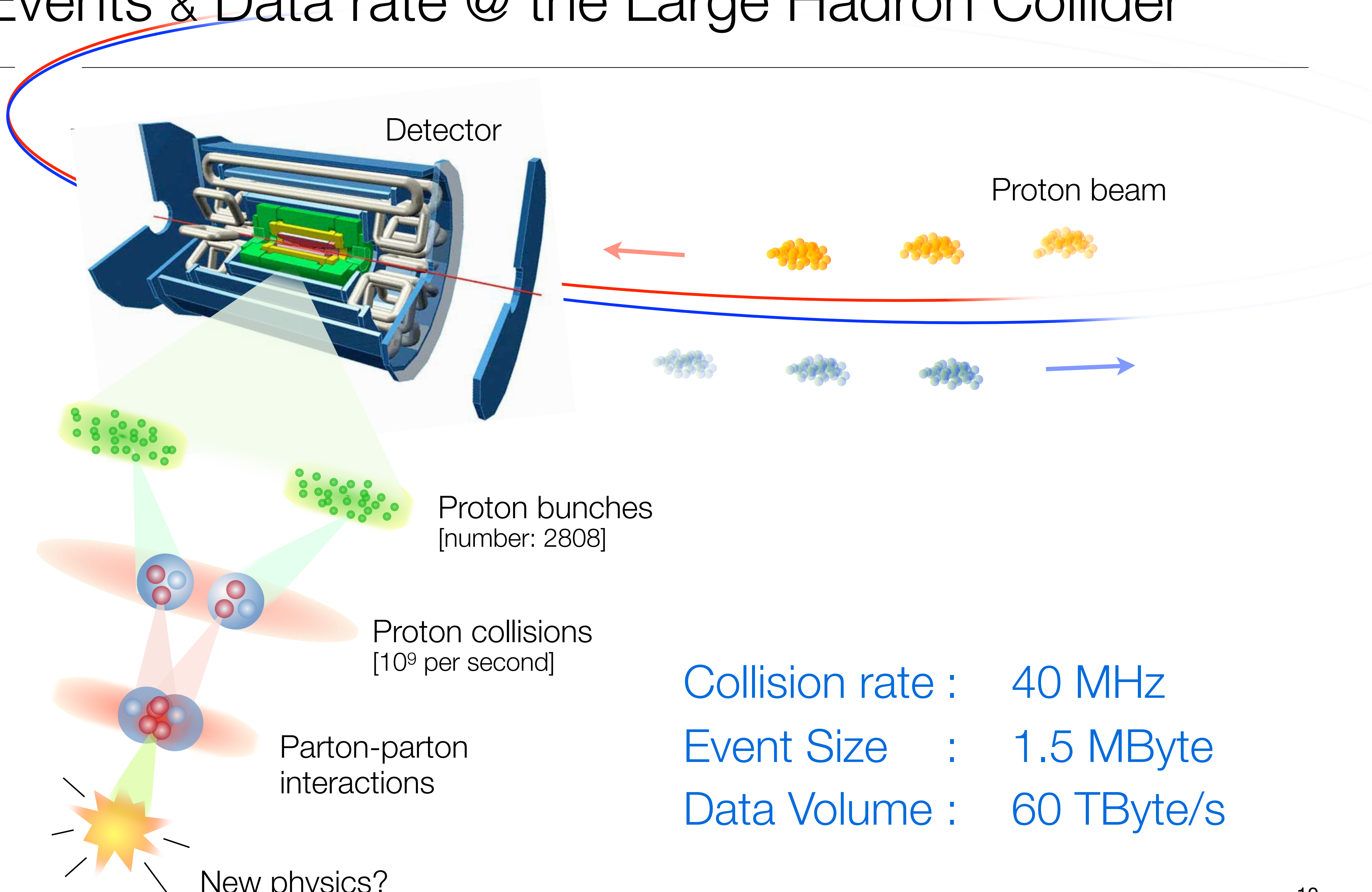
[Storage rate: 100 Hz]

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

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

Trigger !

Events & Data rate @ the Large Hadron Collider

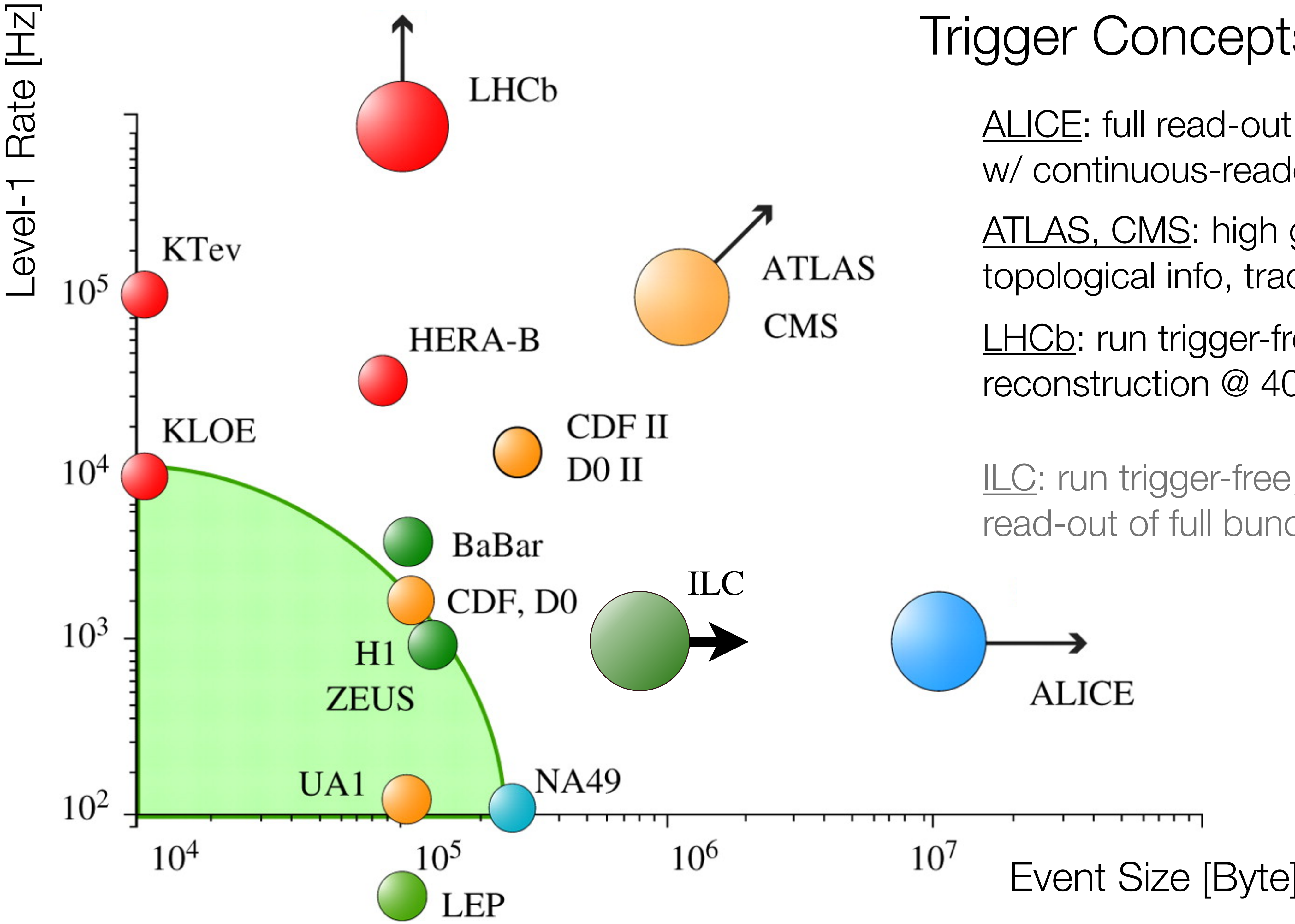


Collision rate : 40 MHz

Event Size : 1.5 MByte

Data Volume : 60 TByte/s

Overview on Operating Conditions



Trigger Concepts:

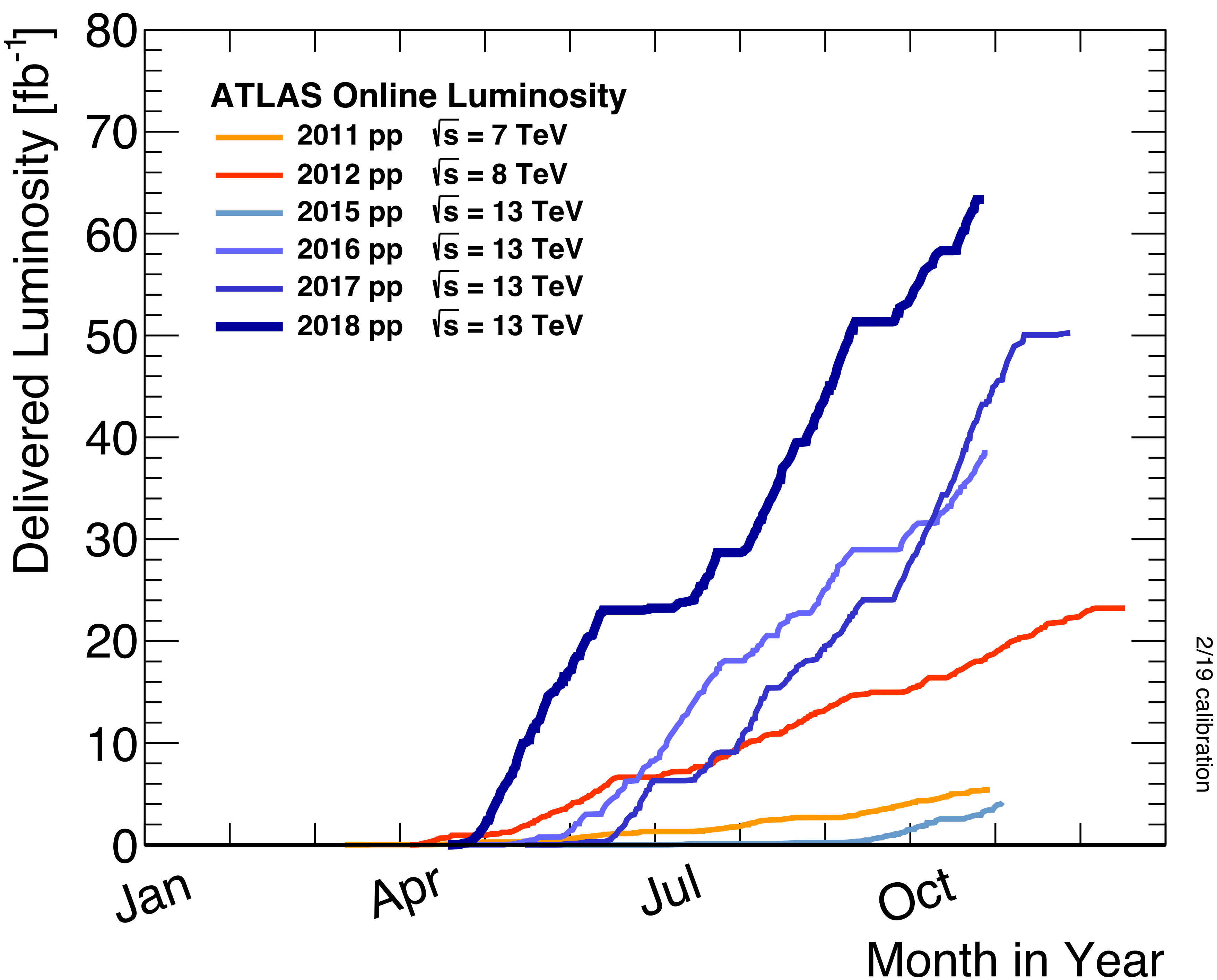
ALICE: full read-out @ 50 kHz w/ continuous-readout of TPC …

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



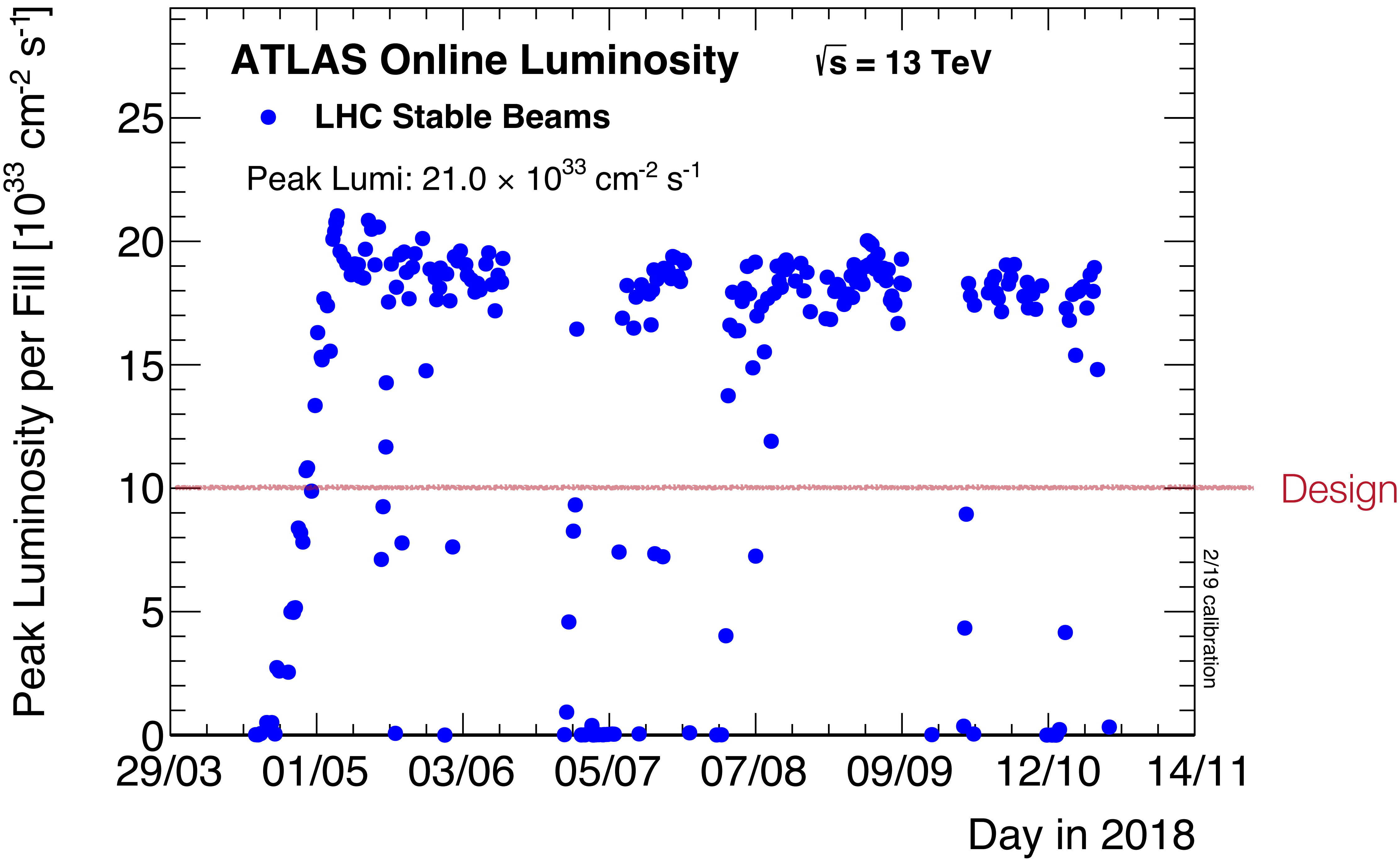
Luminosities:
[recorded]

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

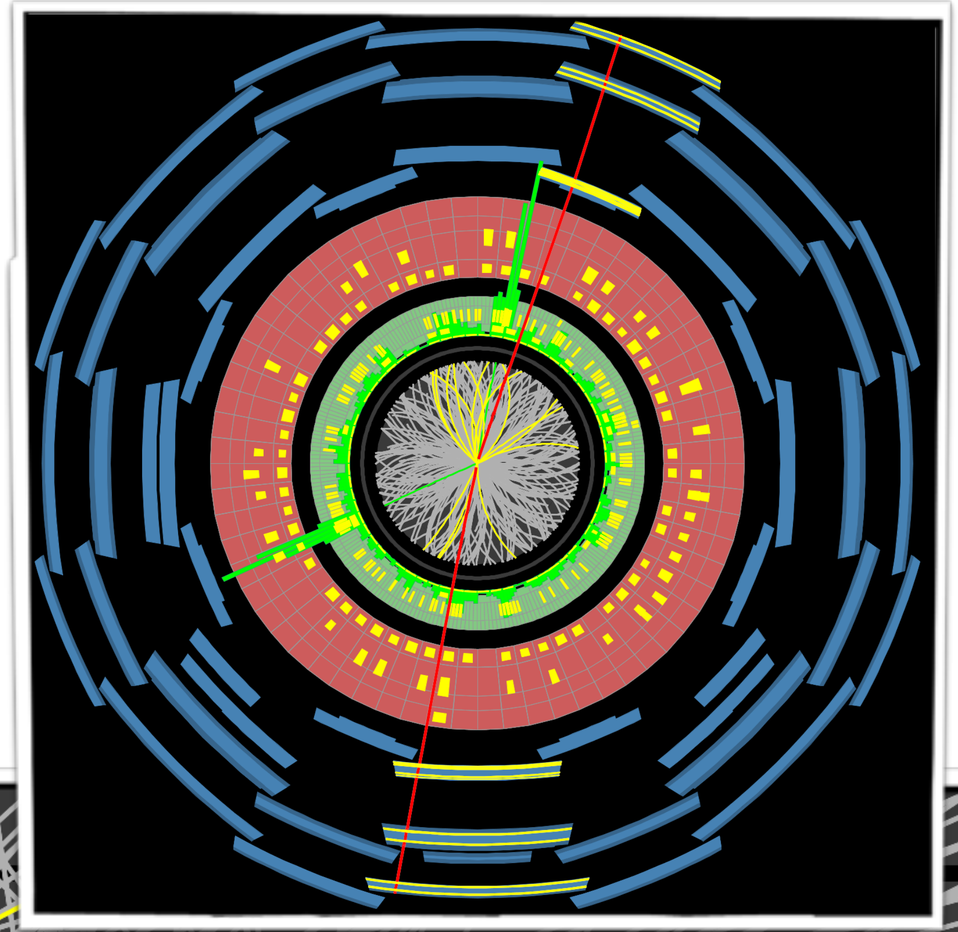


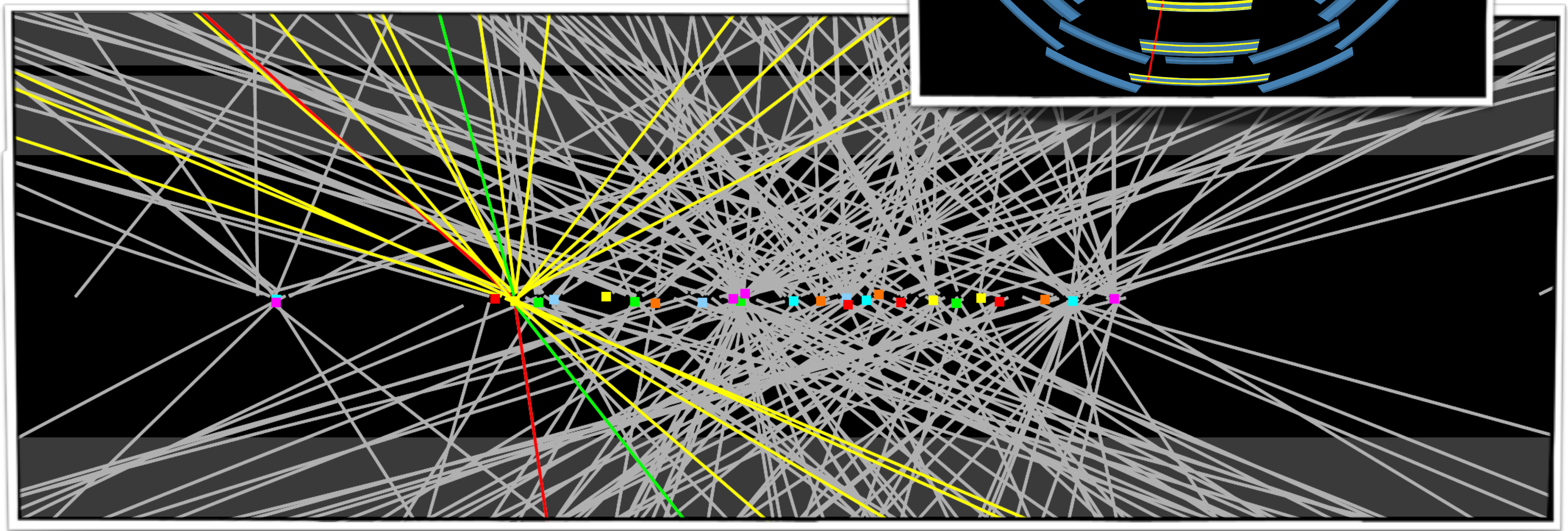
LHC Run-2 Performance

ATLAS Event
with 25 pileup vertices

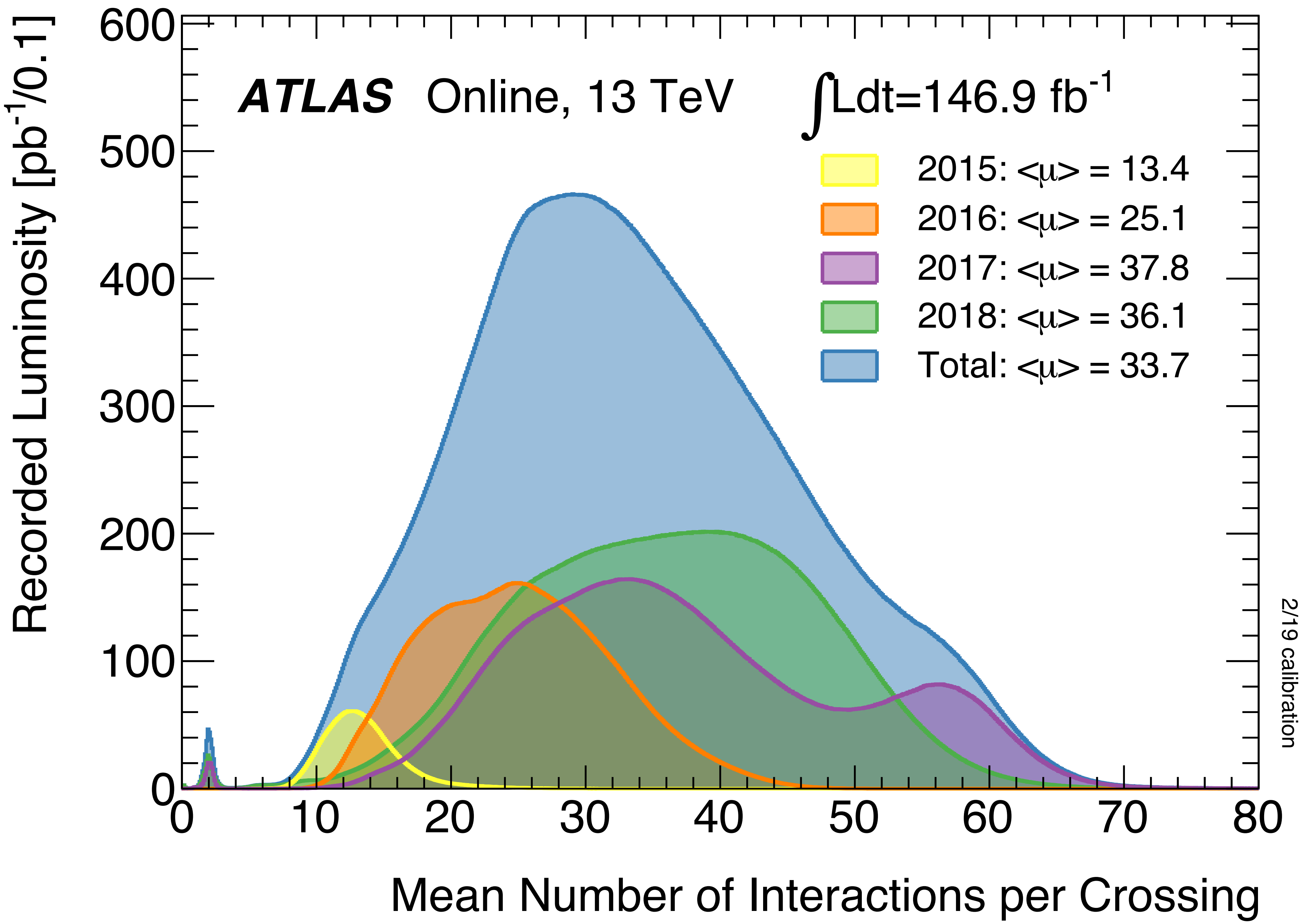
[$\sqrt{s}$ = 13 TeV; 2016 Data]

H ➛ ZZ ➛ ee μμ candidate event

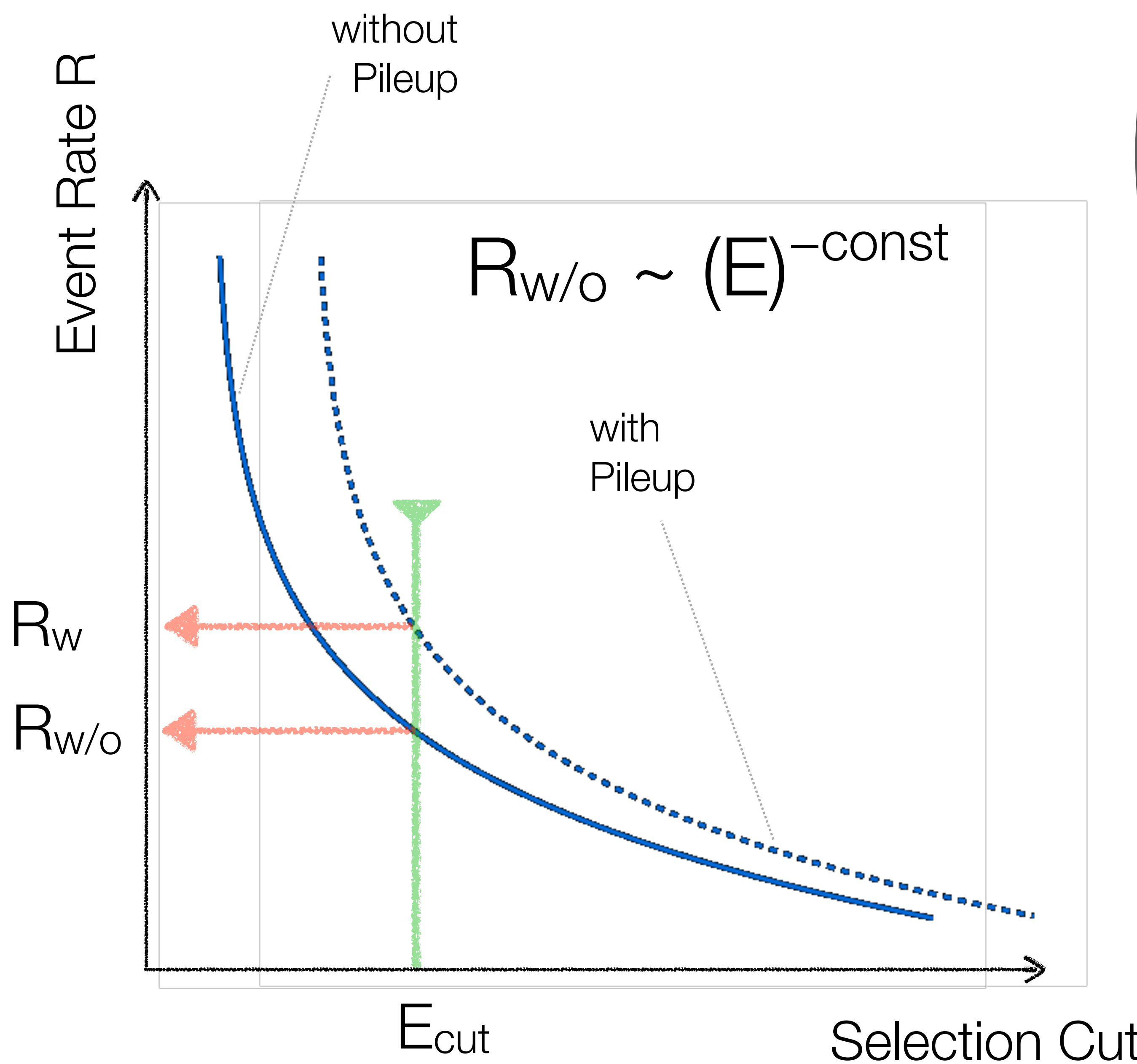


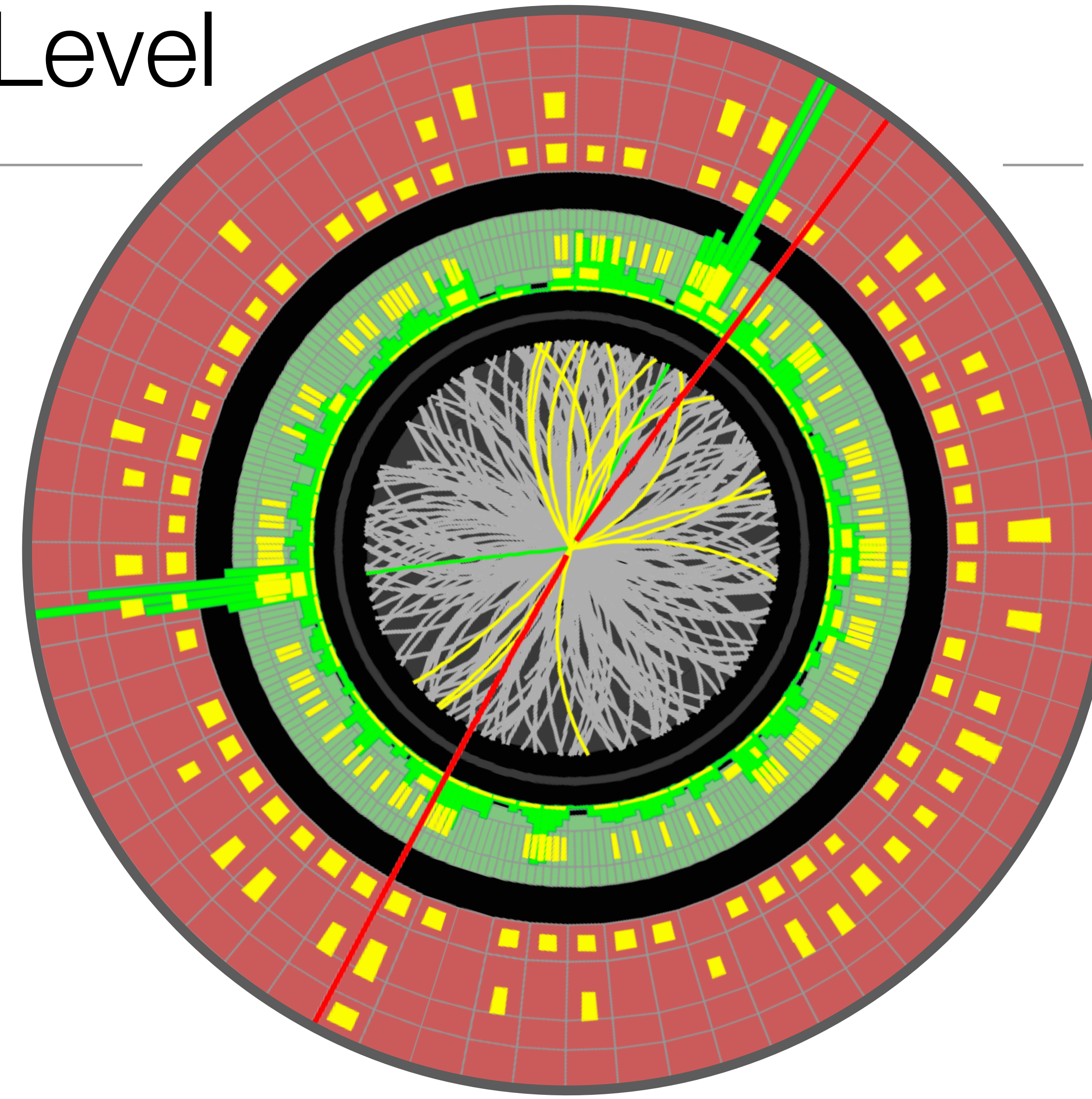


LHC Run-2 Performance – Pileup



Pileup Mitigation at Trigger Level

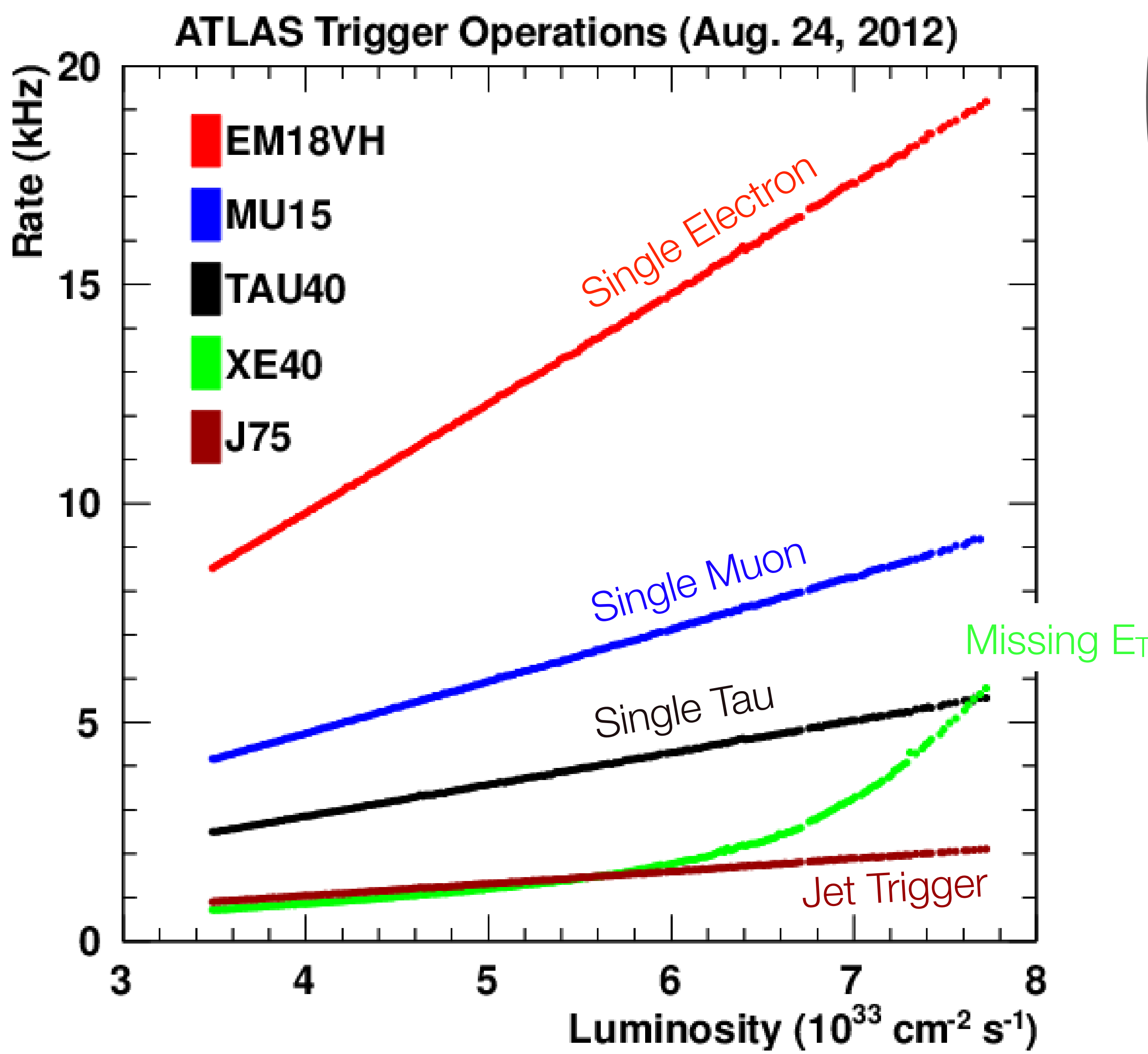


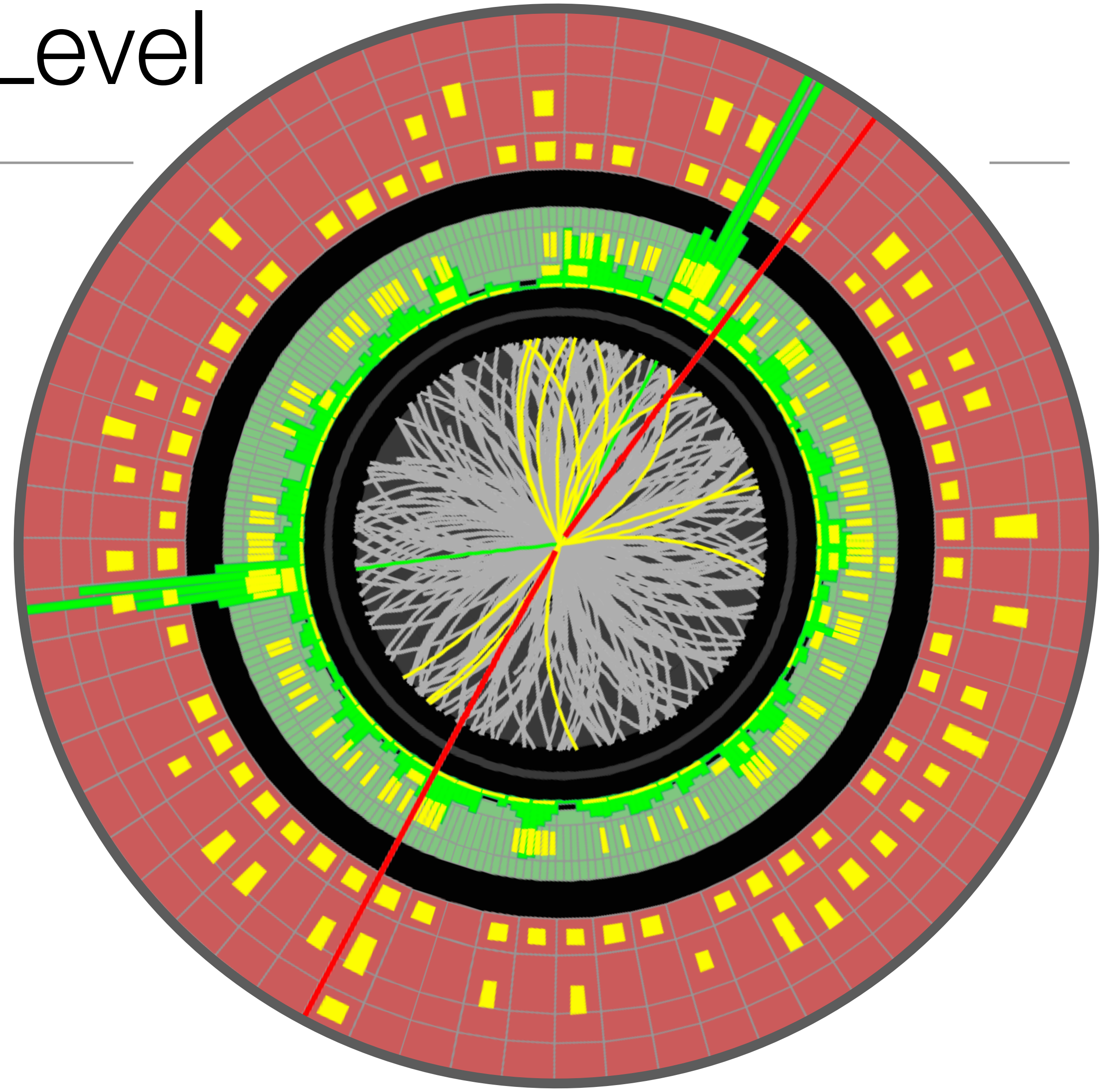


Pileup dependence:

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

Pileup Mitigation at Trigger Level





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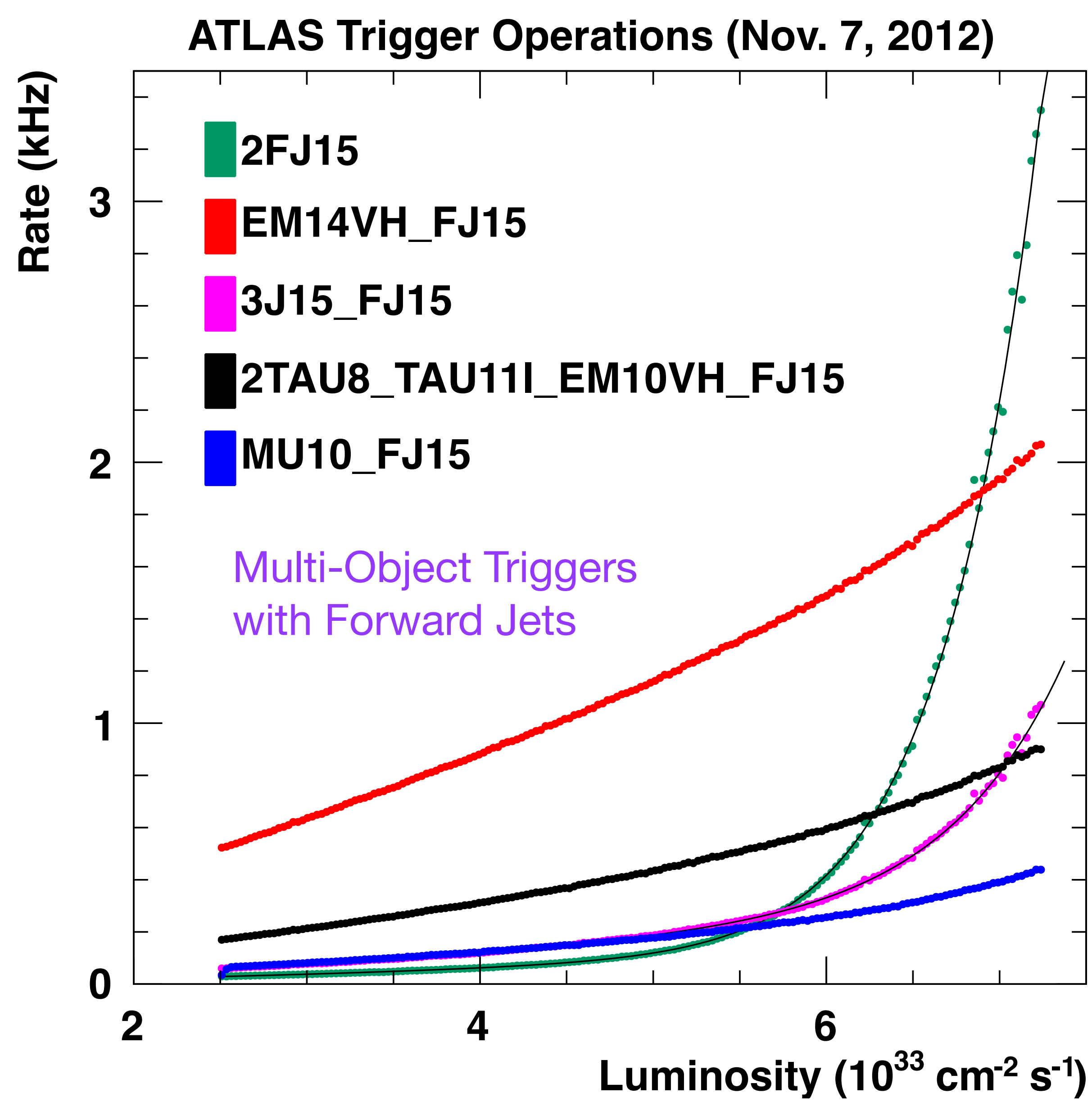

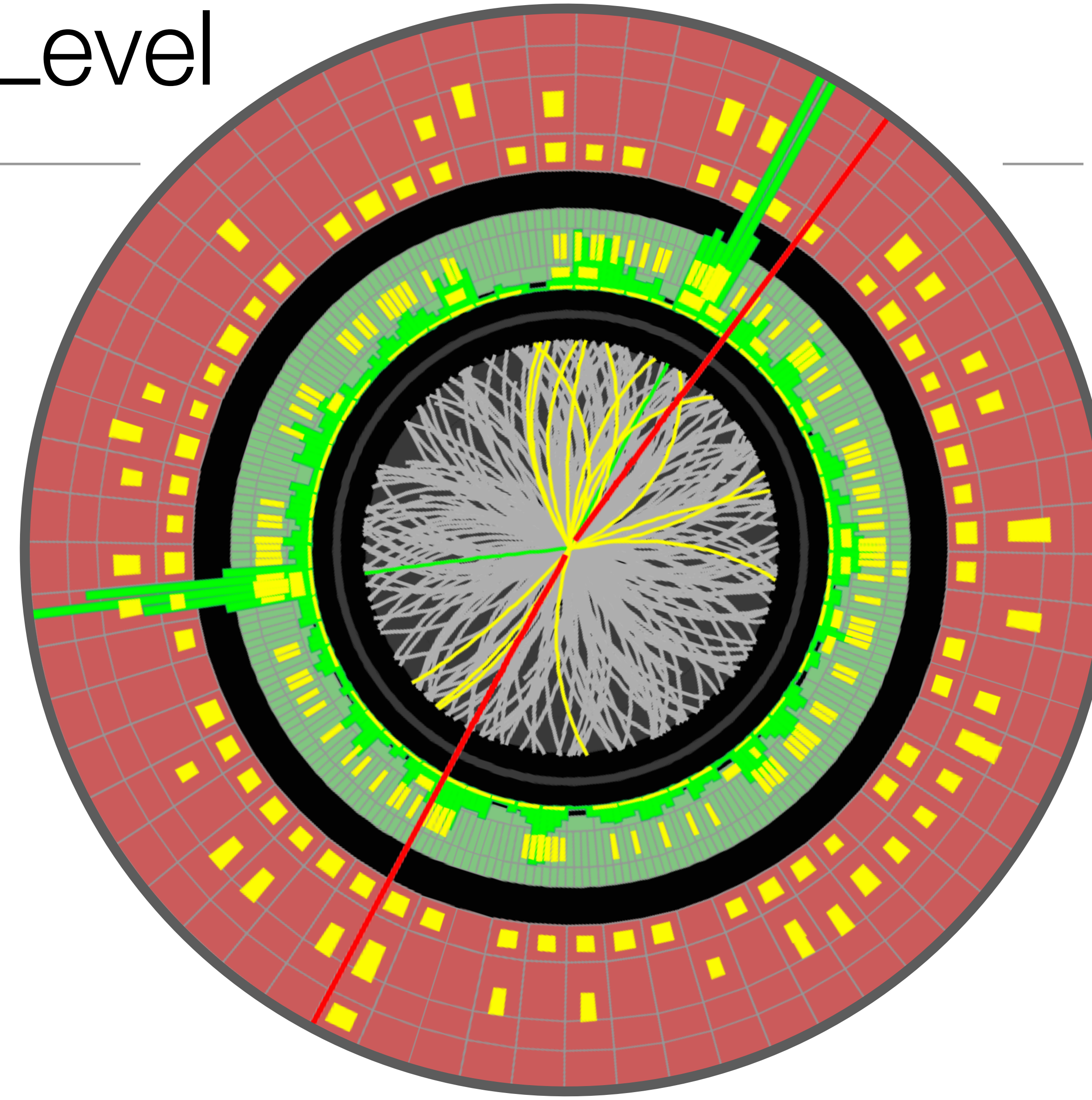

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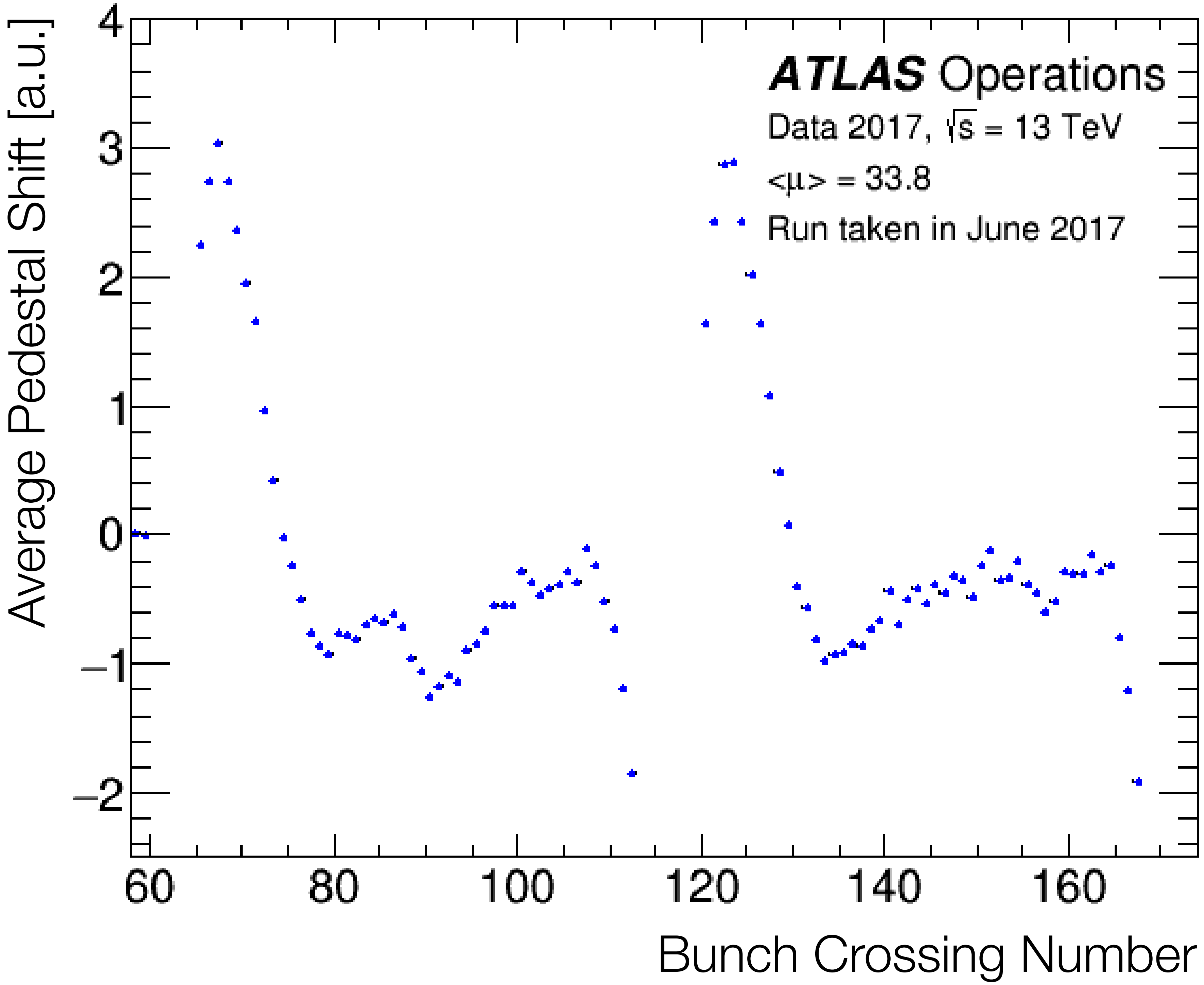

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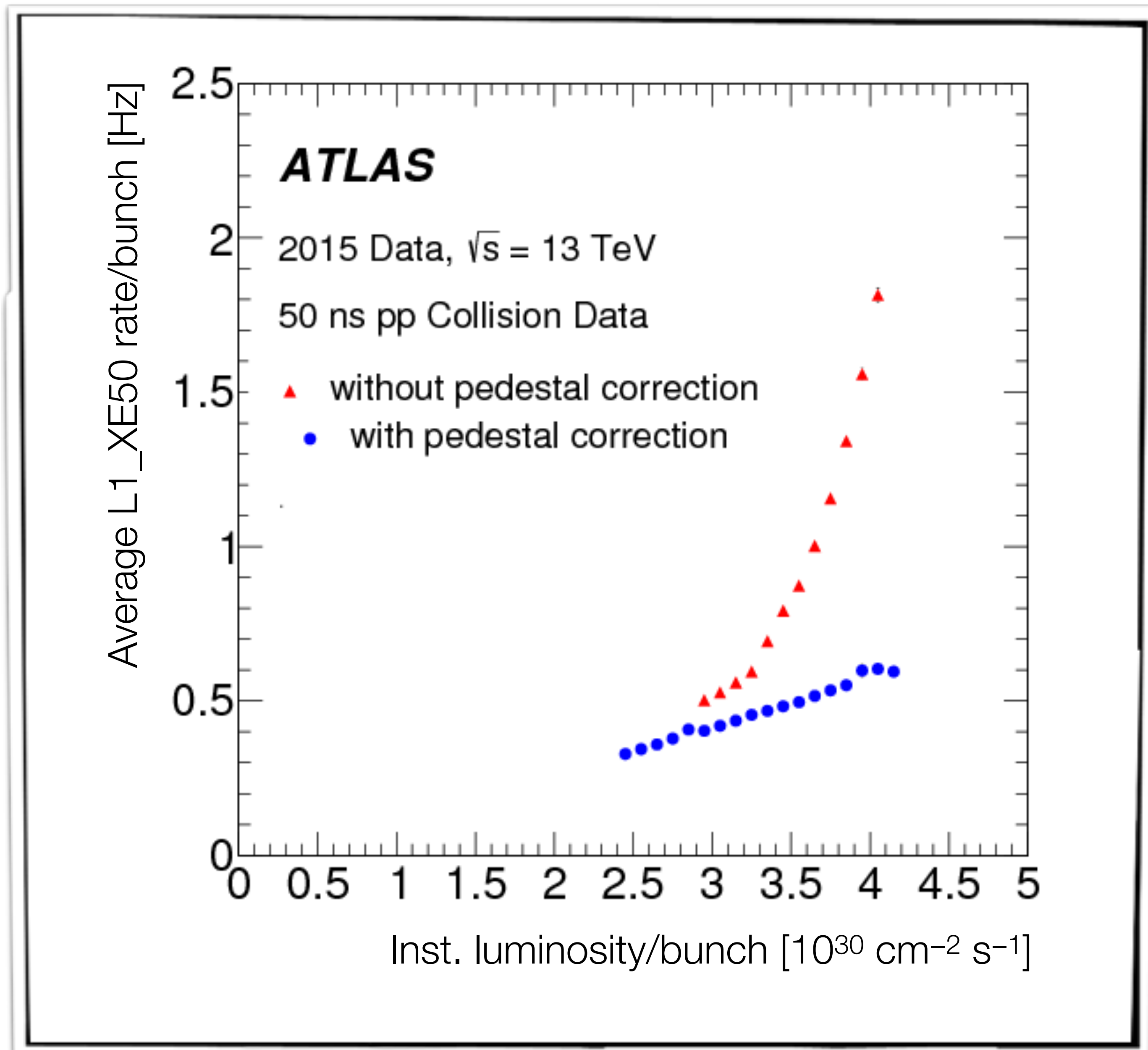
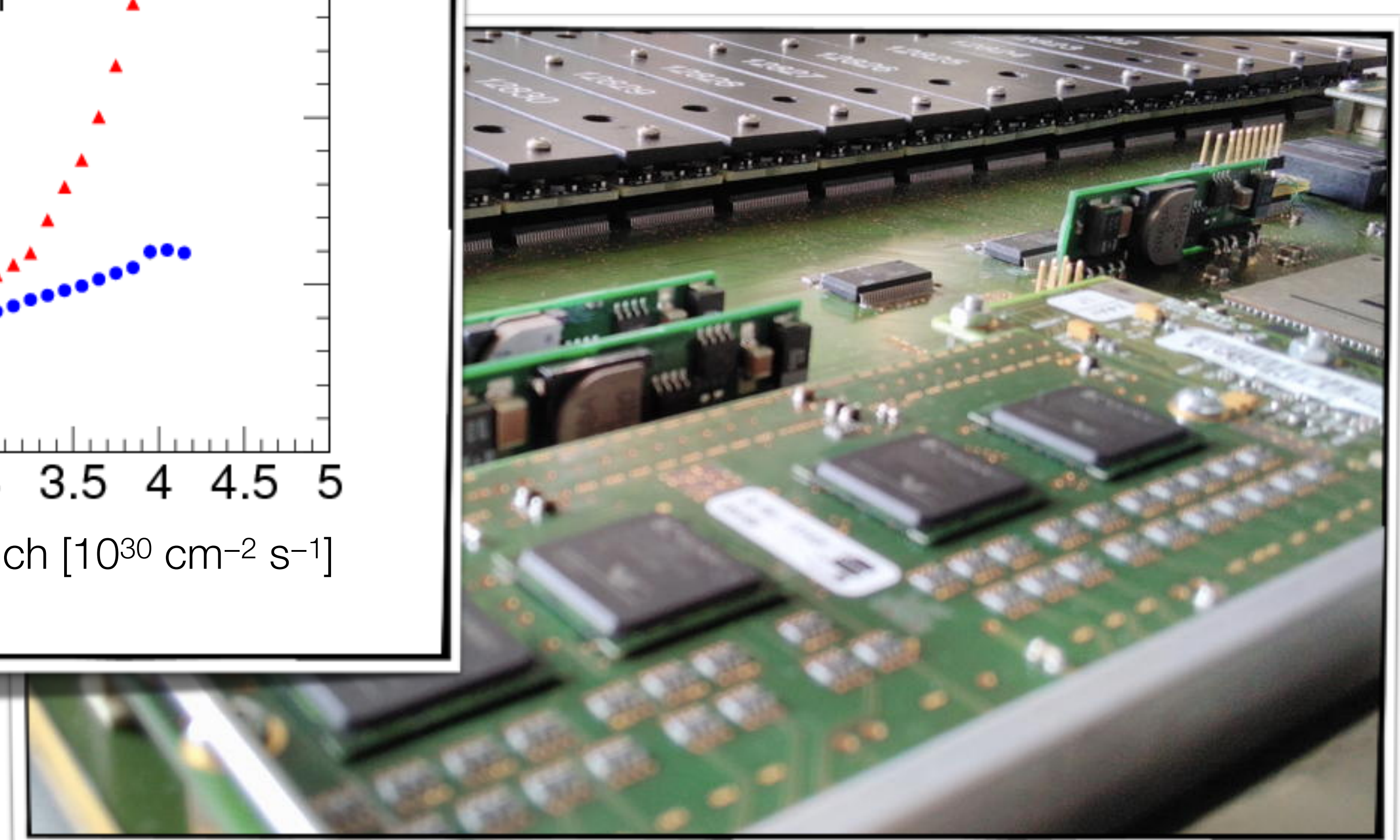
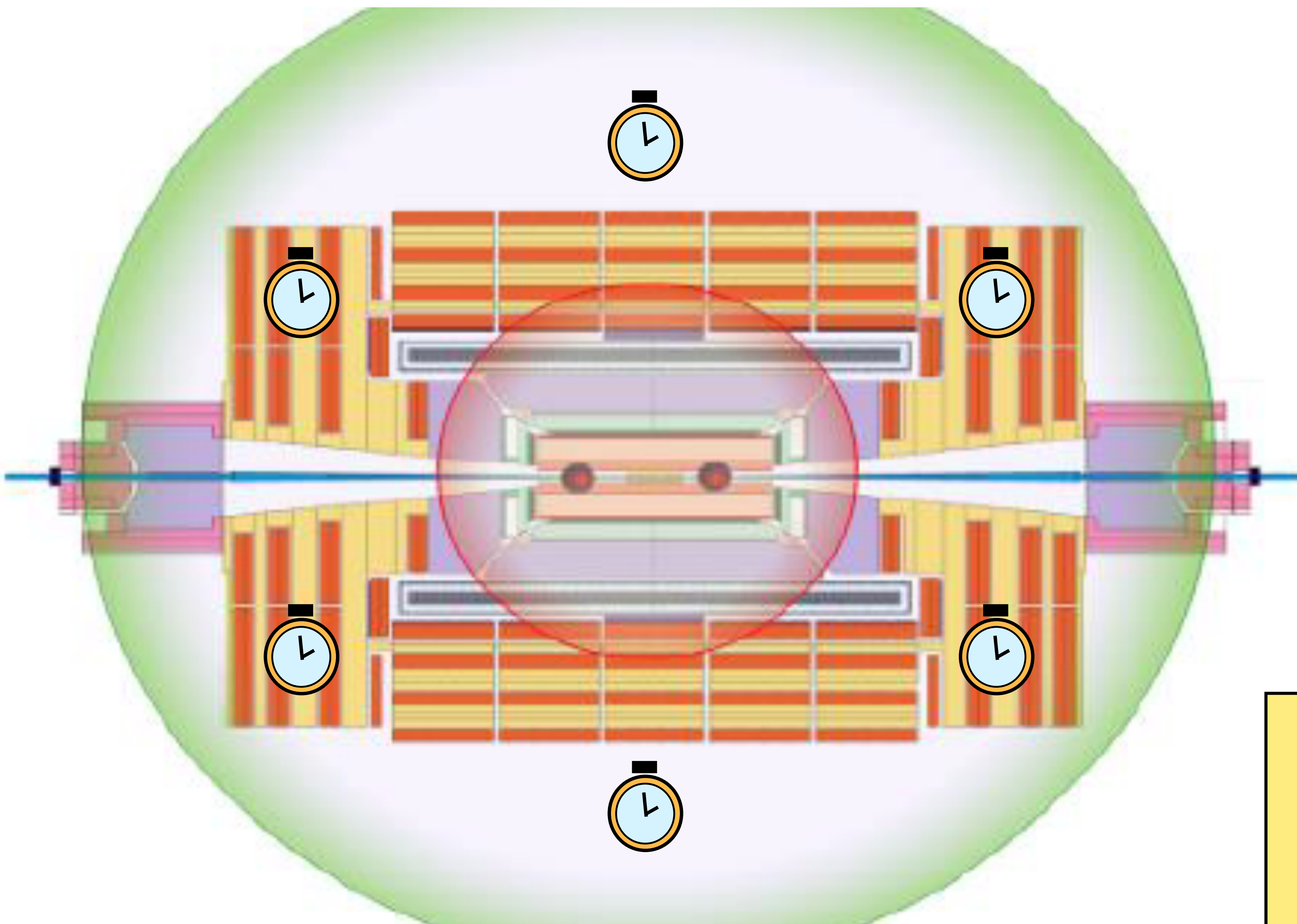




Signal Synchronization



Data within
same bunch crossing
to be processed together

But:

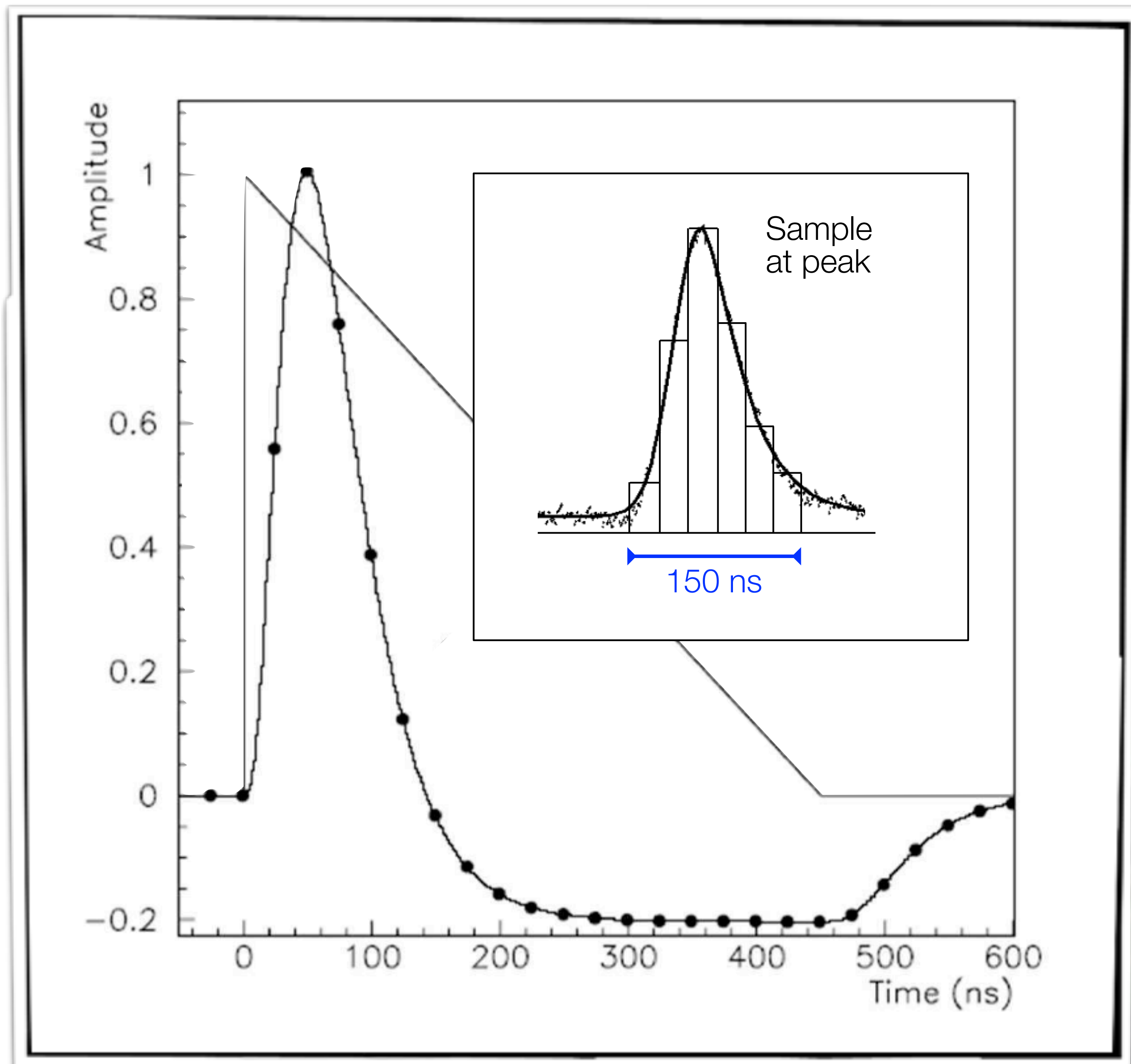
Particle TOF ≫ 25 ns
[c ≈ 0.3 m/ns; 1 m ≙ 3 ns]

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

Requires
signal synchronization
with programmable delays

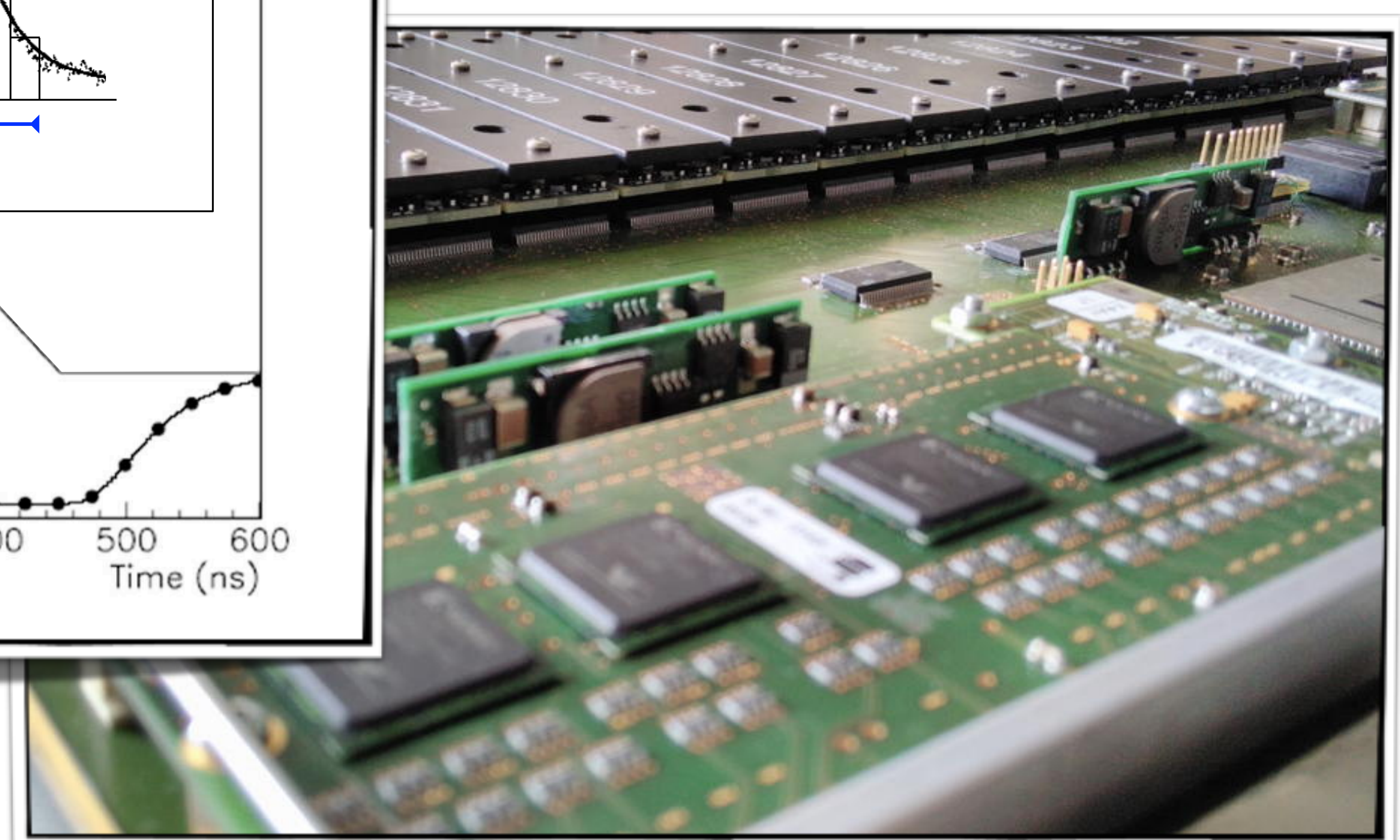
With ns-precision!

Signal Synchronization



Timing
precision guarantee
correct energy determination …

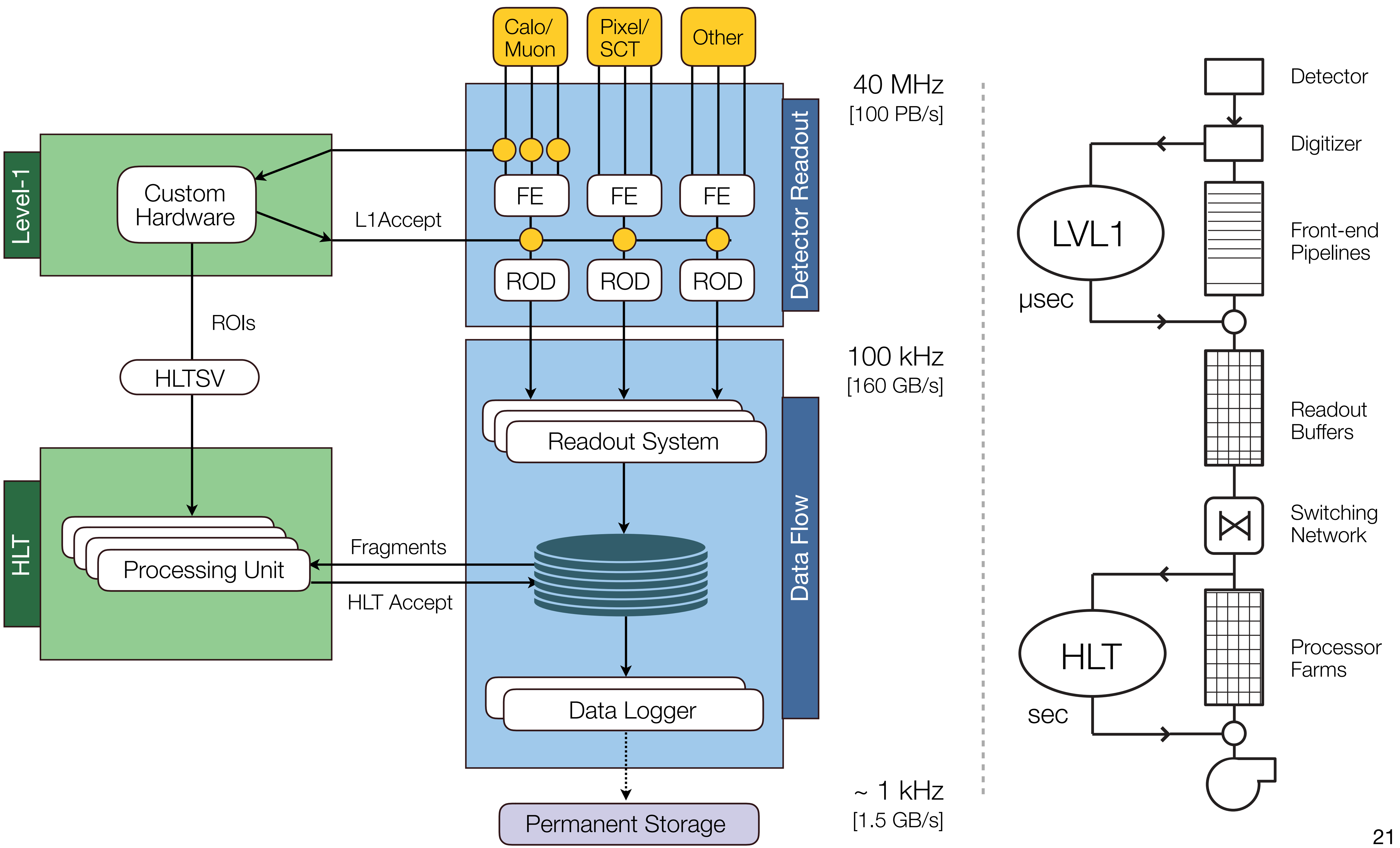
[e.g. ATLAS L1Calo Trigger]



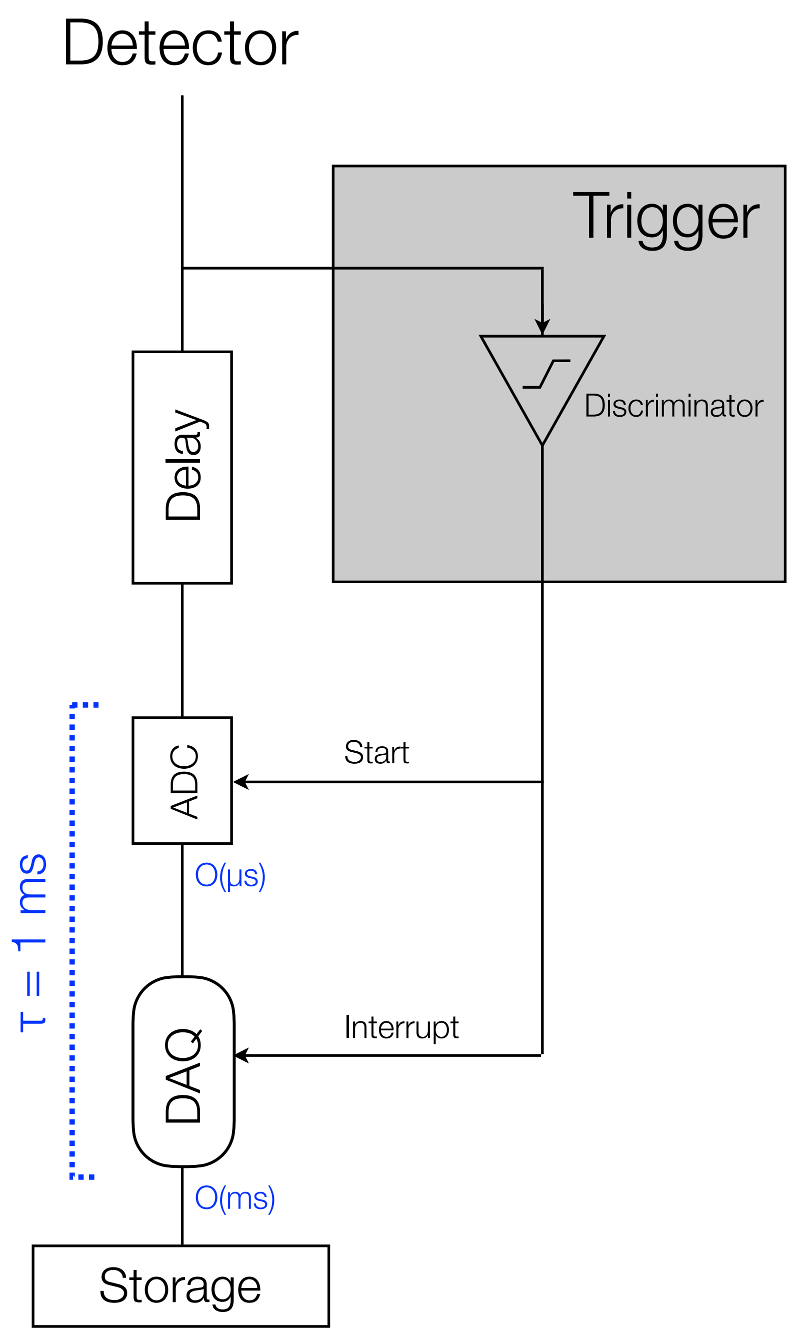
Part 2

"Concepts, Dead Time & Buffering"

Typical DAQ Example – ATLAS @ Run-2



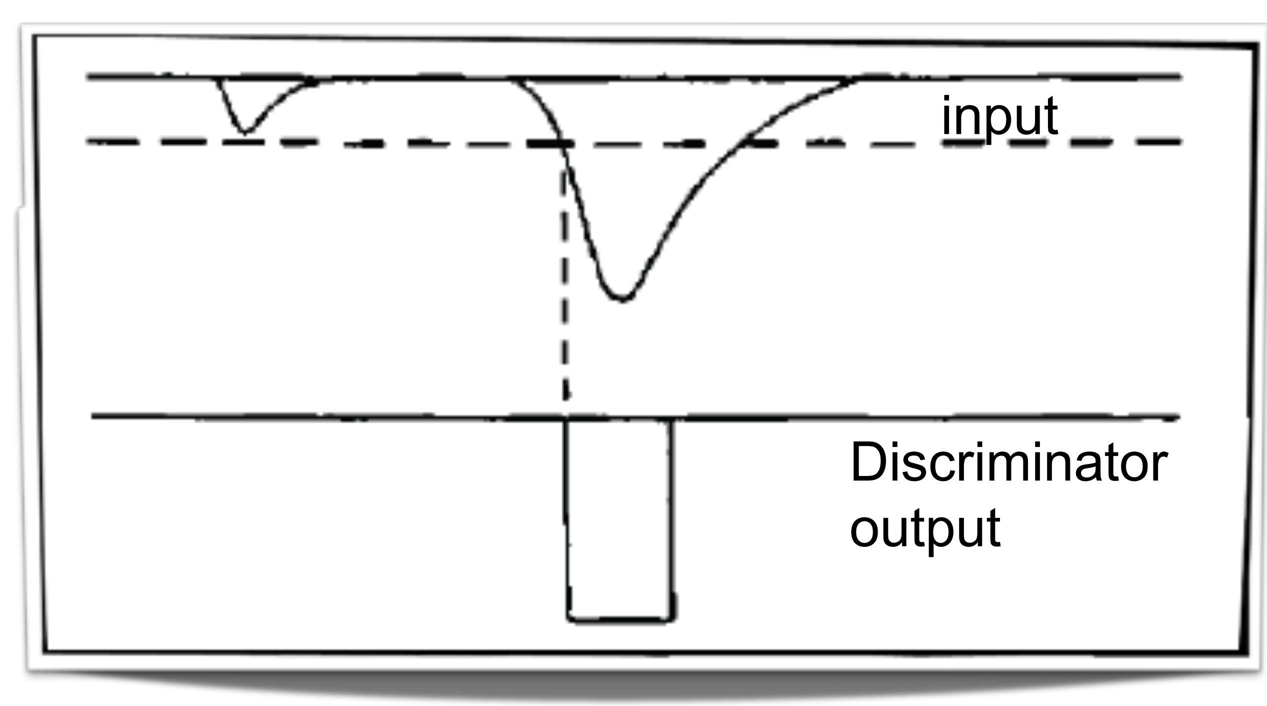
Simple Trigger & DAQ System



Simple
Trigger & DAQ system

Detection
Signal digitization
Signal processing & storage

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



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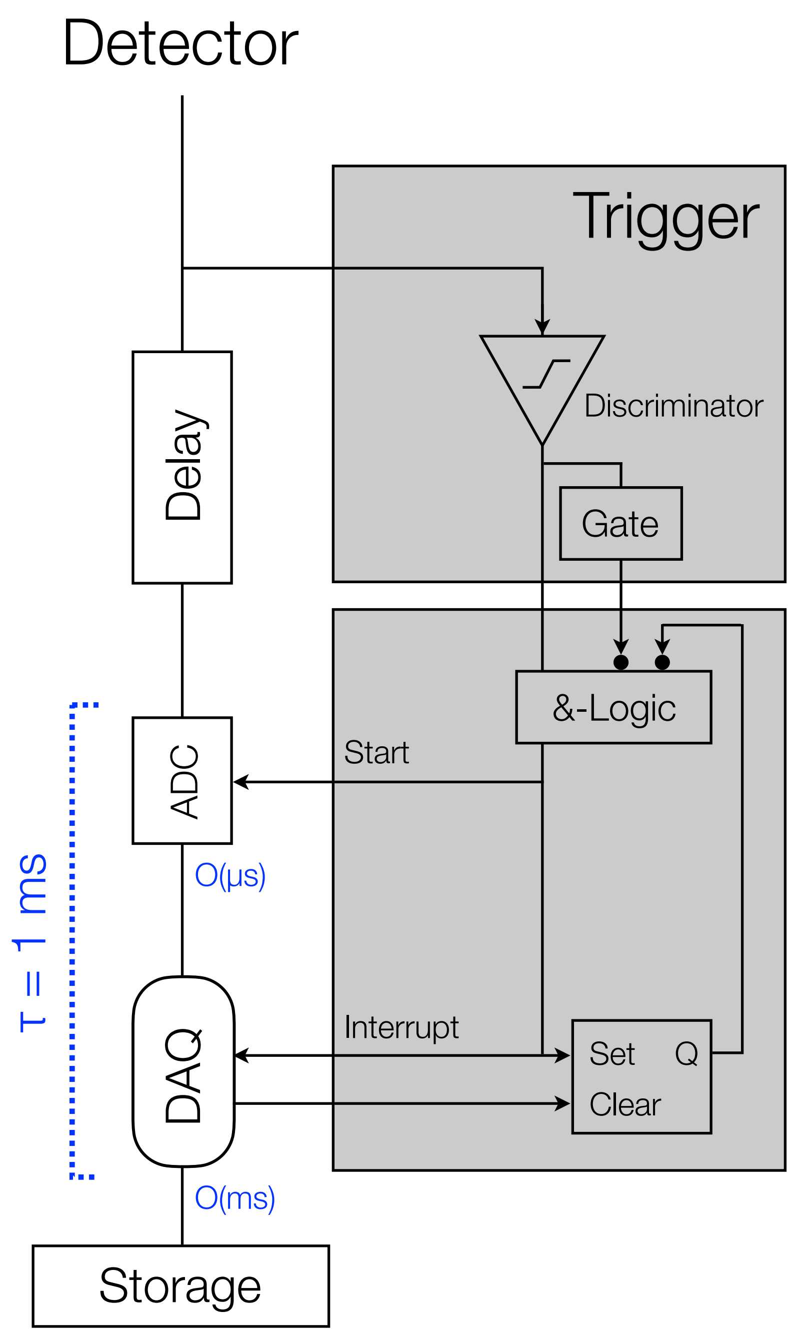


Simple
Trigger & DAQ system

Detection
Signal digitization
Signal processing & storage

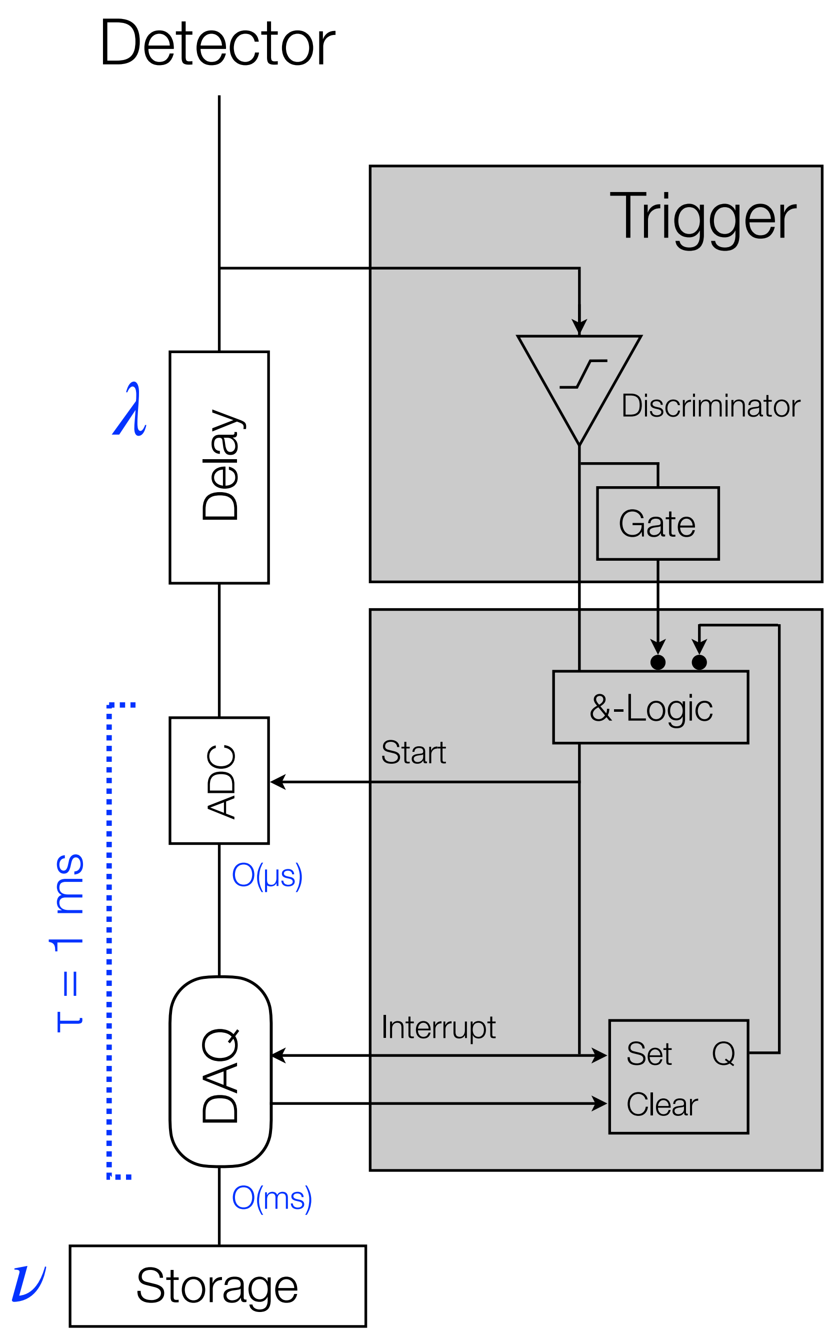
Started by fast trigger signal
[e.g. Discriminator]

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:

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

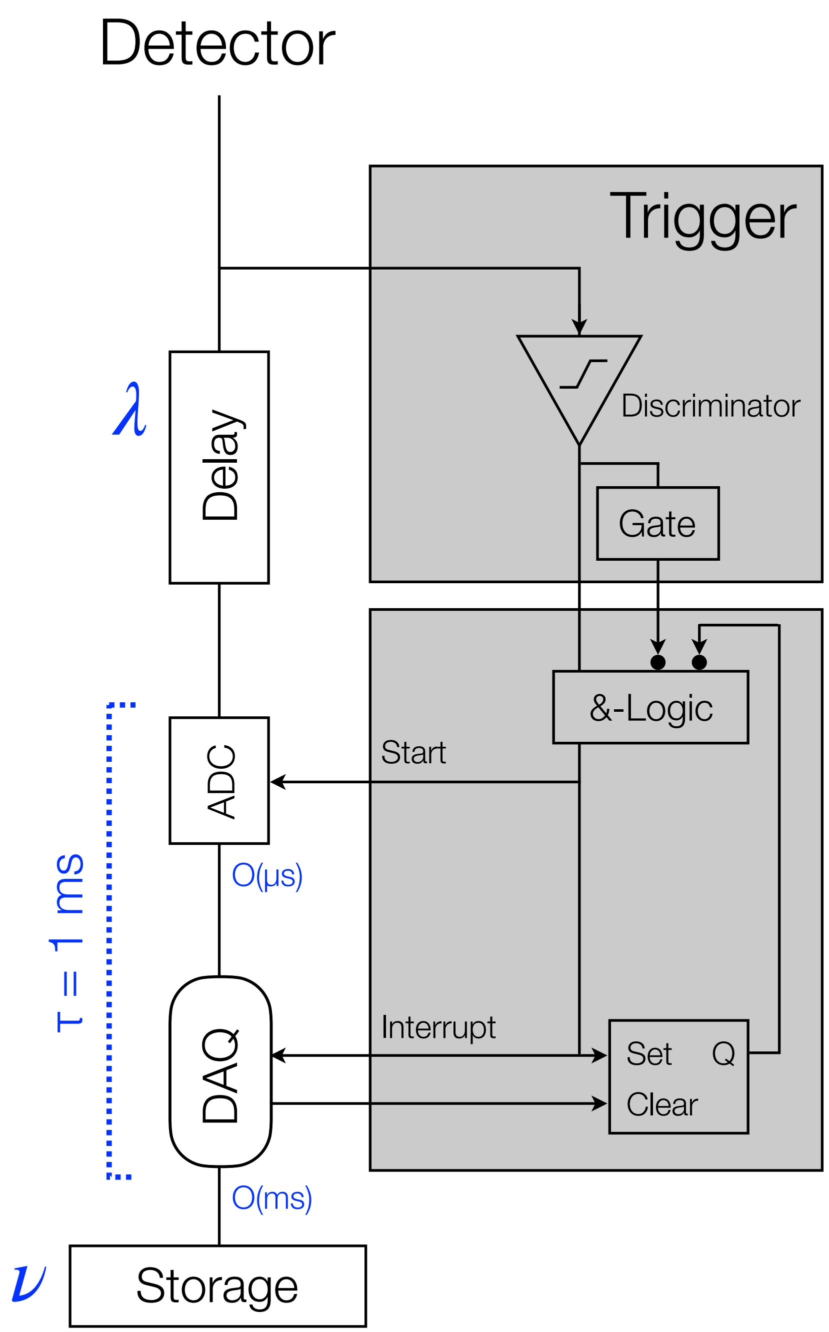
$[\nu < \lambda]$

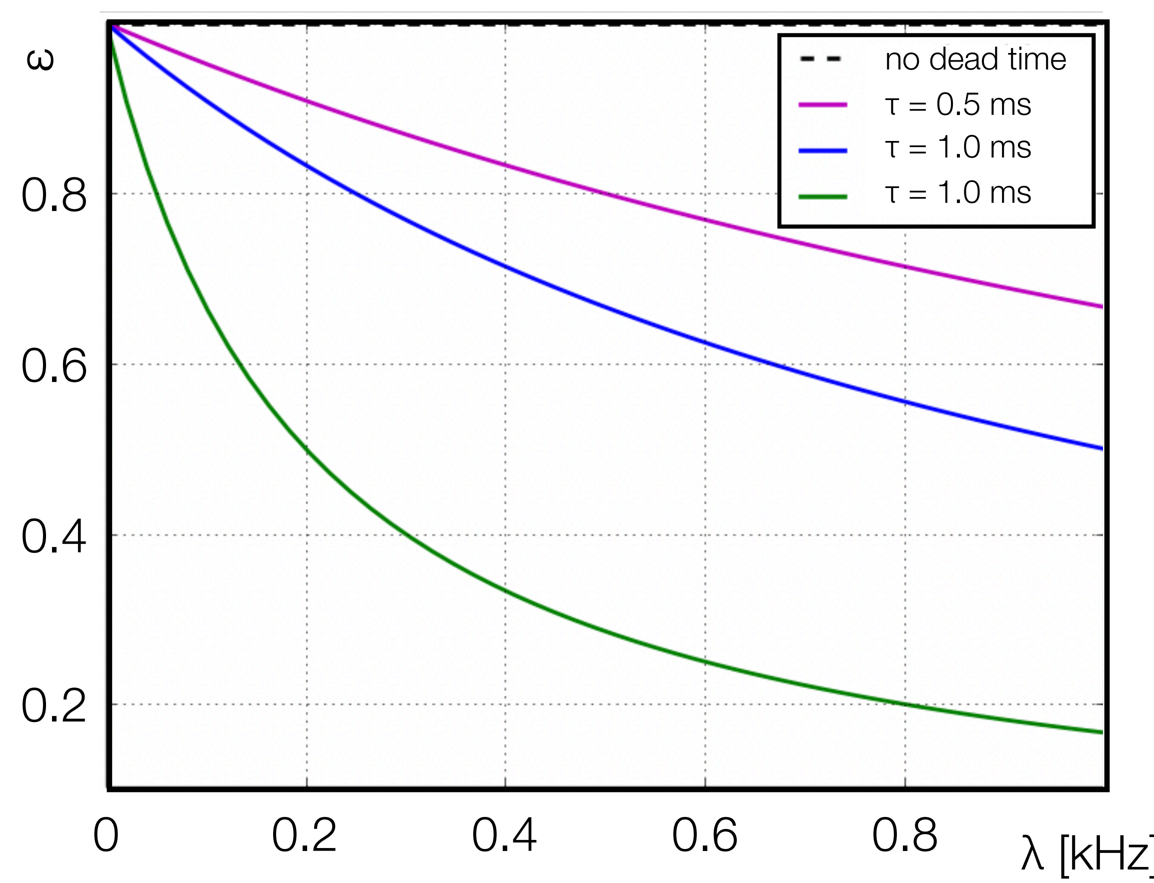
Efficiency : $\epsilon = \nu/\lambda = (1 + \lambda\tau)^{-1}$

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

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

DAQ Efficiency & Dead Time



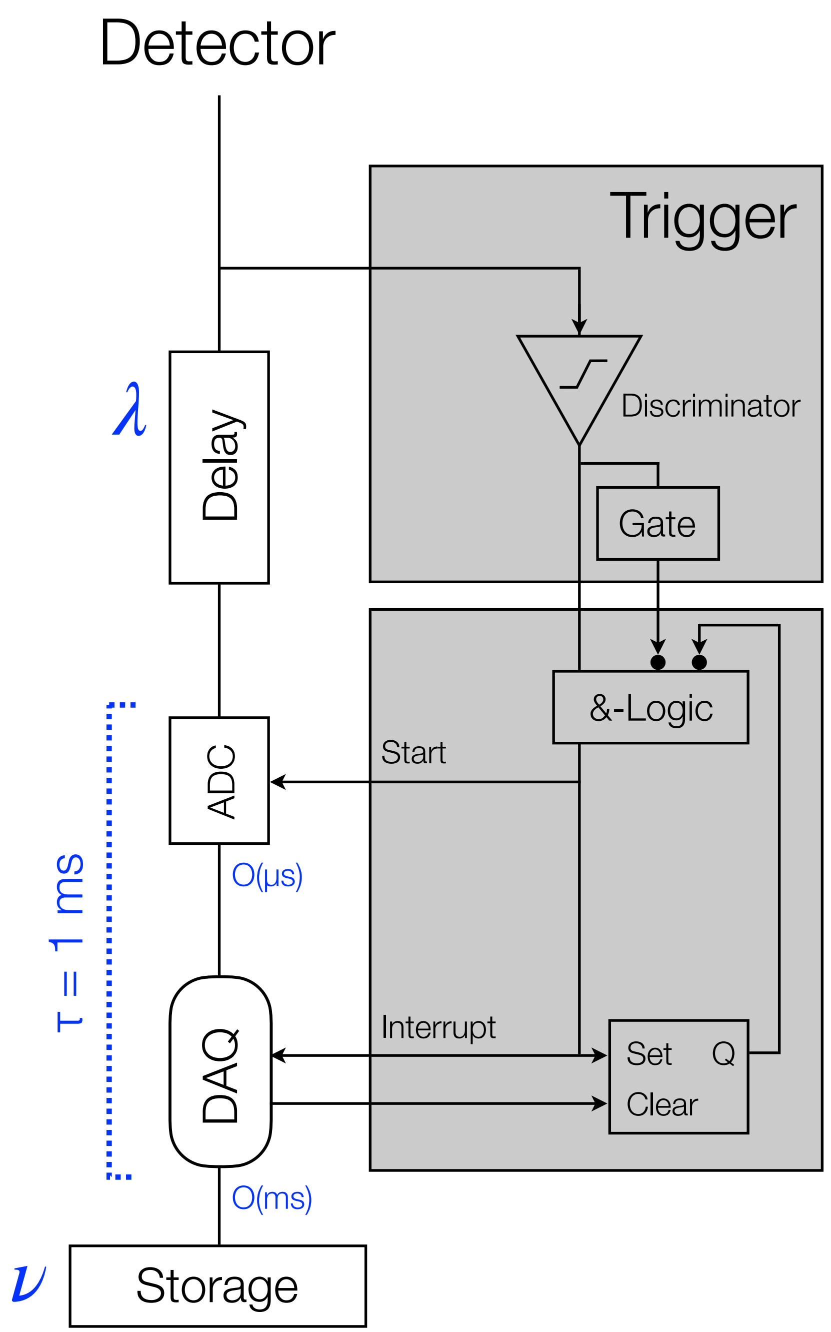


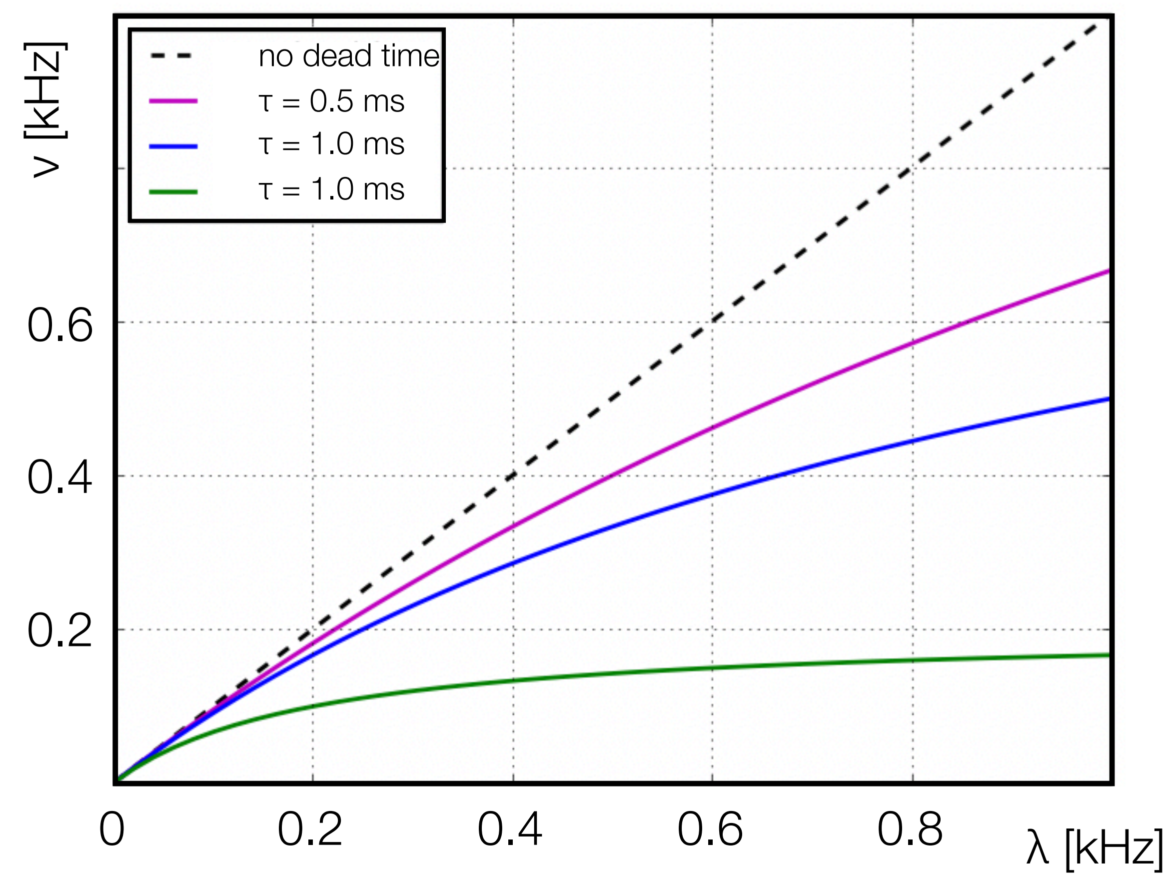
Efficiency : $\epsilon = \nu/\lambda = (1 + \lambda\tau)^{-1}$

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

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

DAQ Efficiency & Dead Time



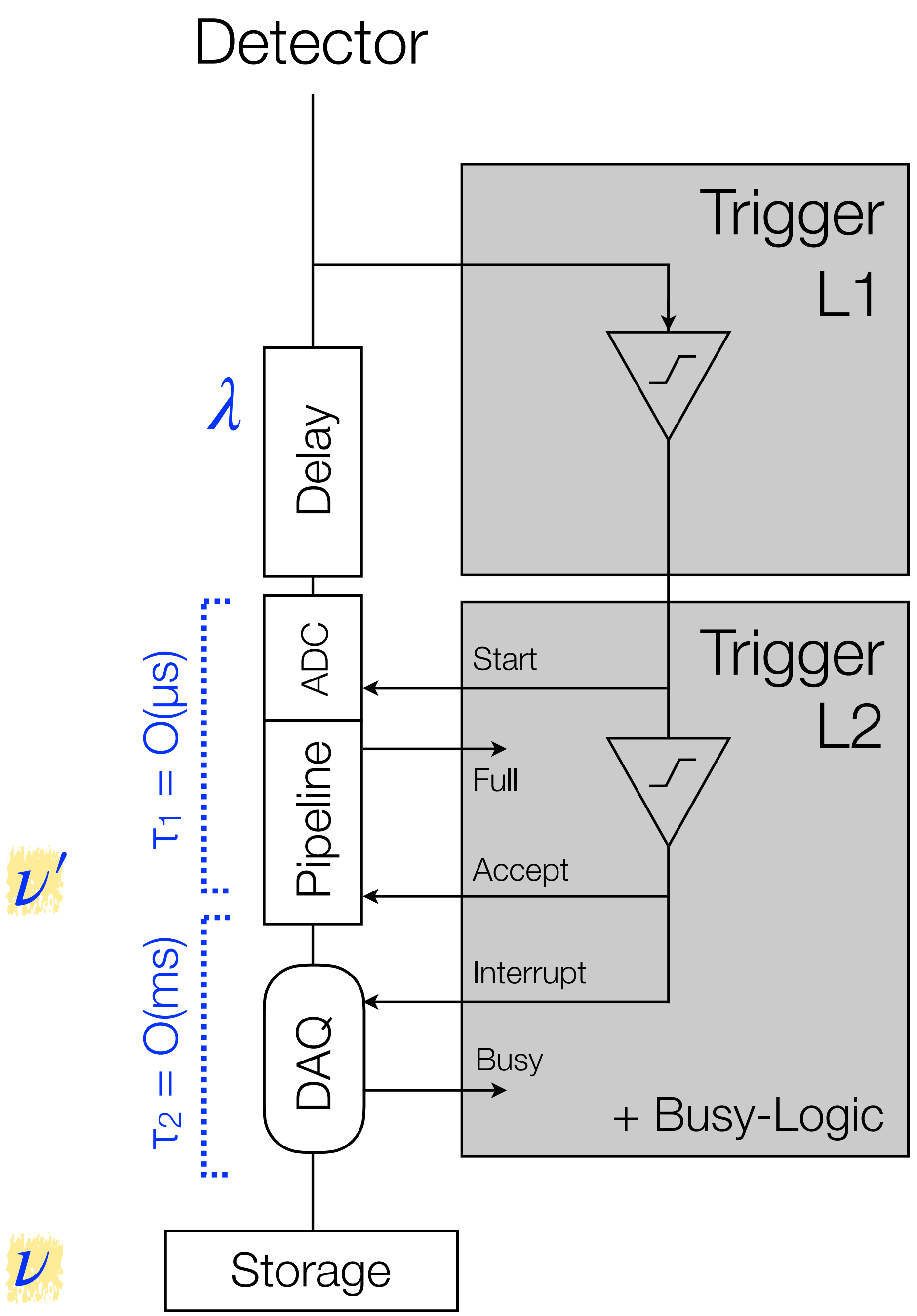


Efficiency : $\epsilon = \nu/\lambda = (1 + \lambda\tau)^{-1}$

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

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

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

→

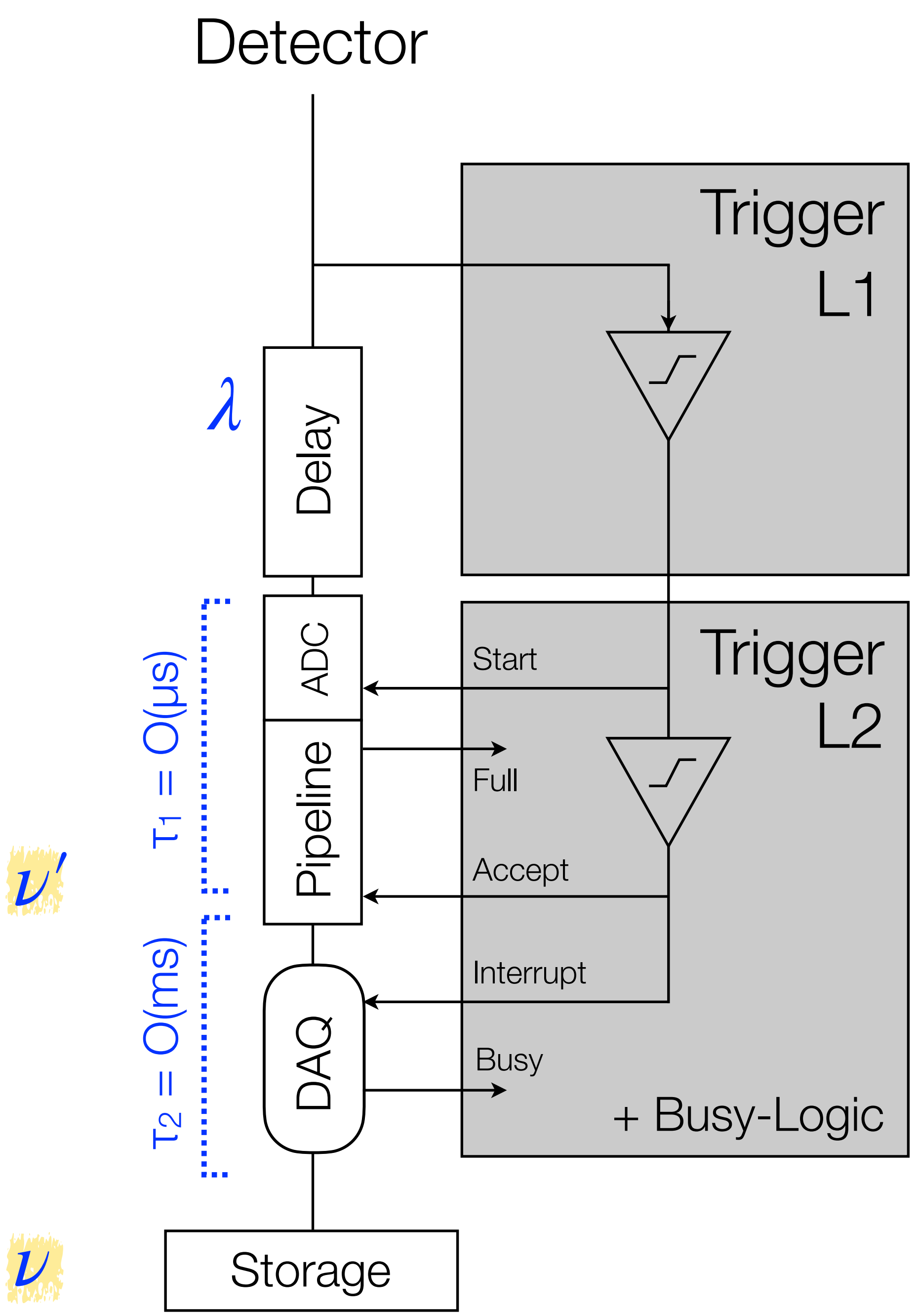
$$\nu' = \lambda\,(1 - \nu\tau - K\nu\tau_1)$$

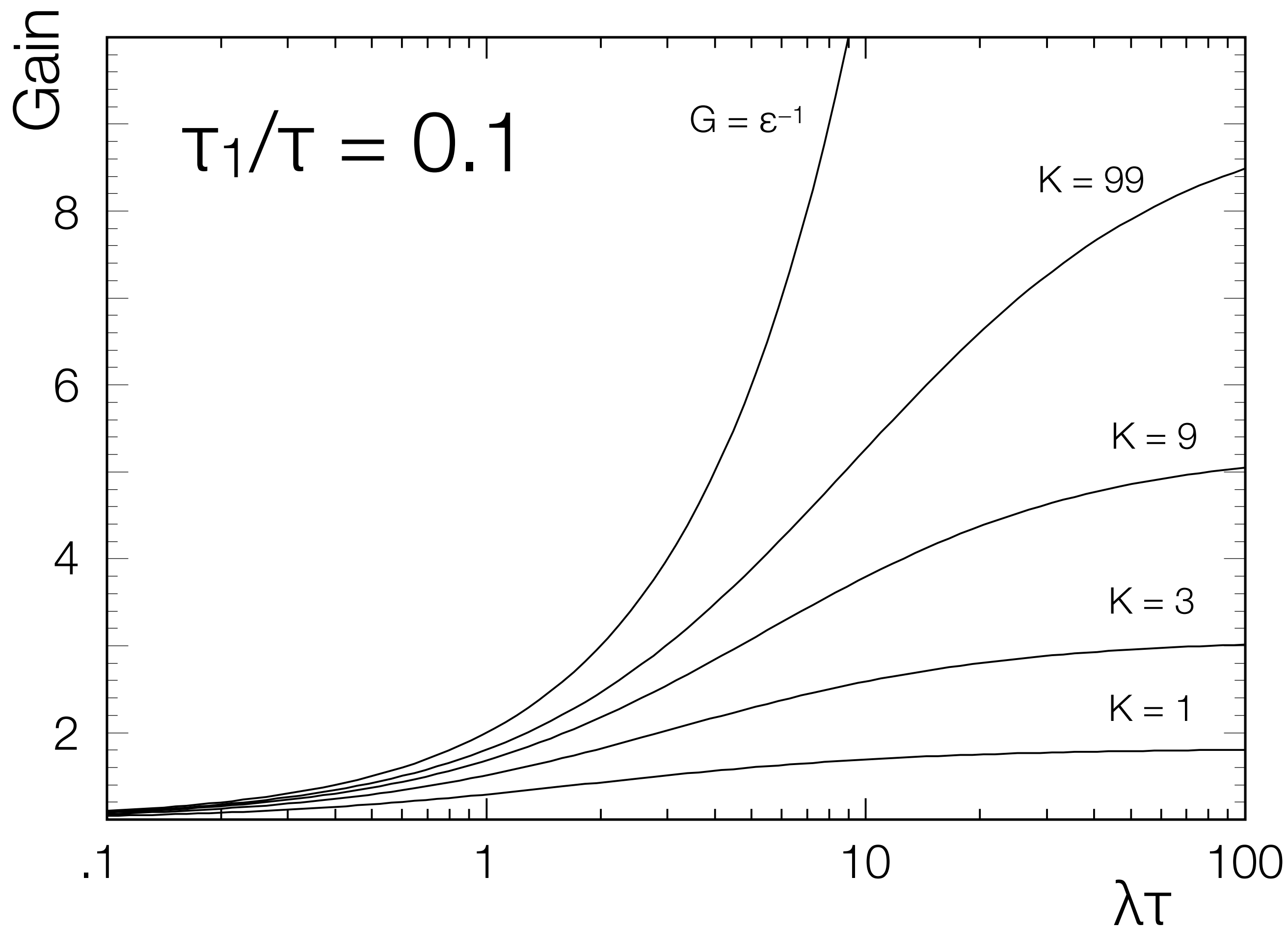
[...]

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

ϵ × Gain (G)

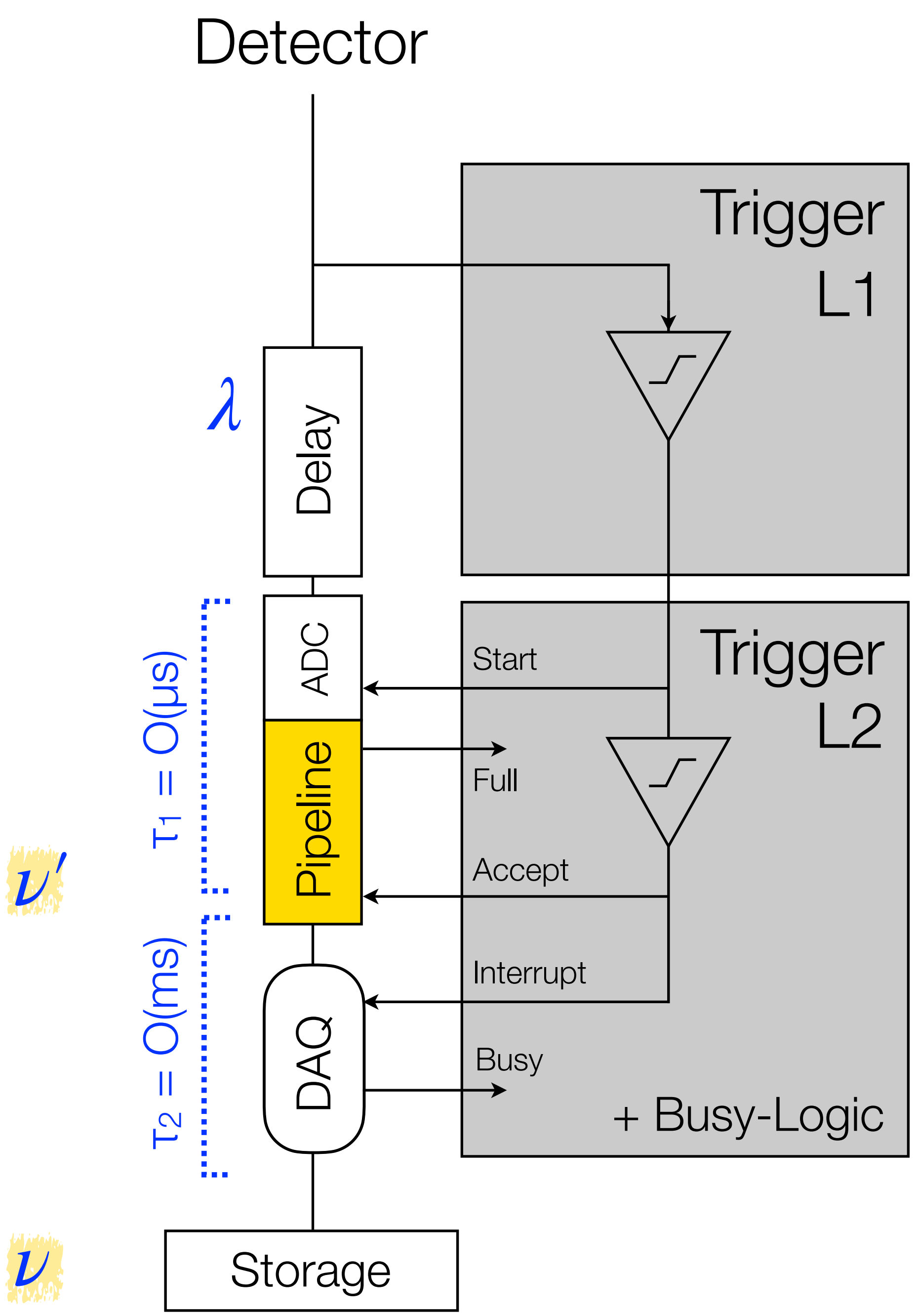
Adding an Extra Trigger Levels

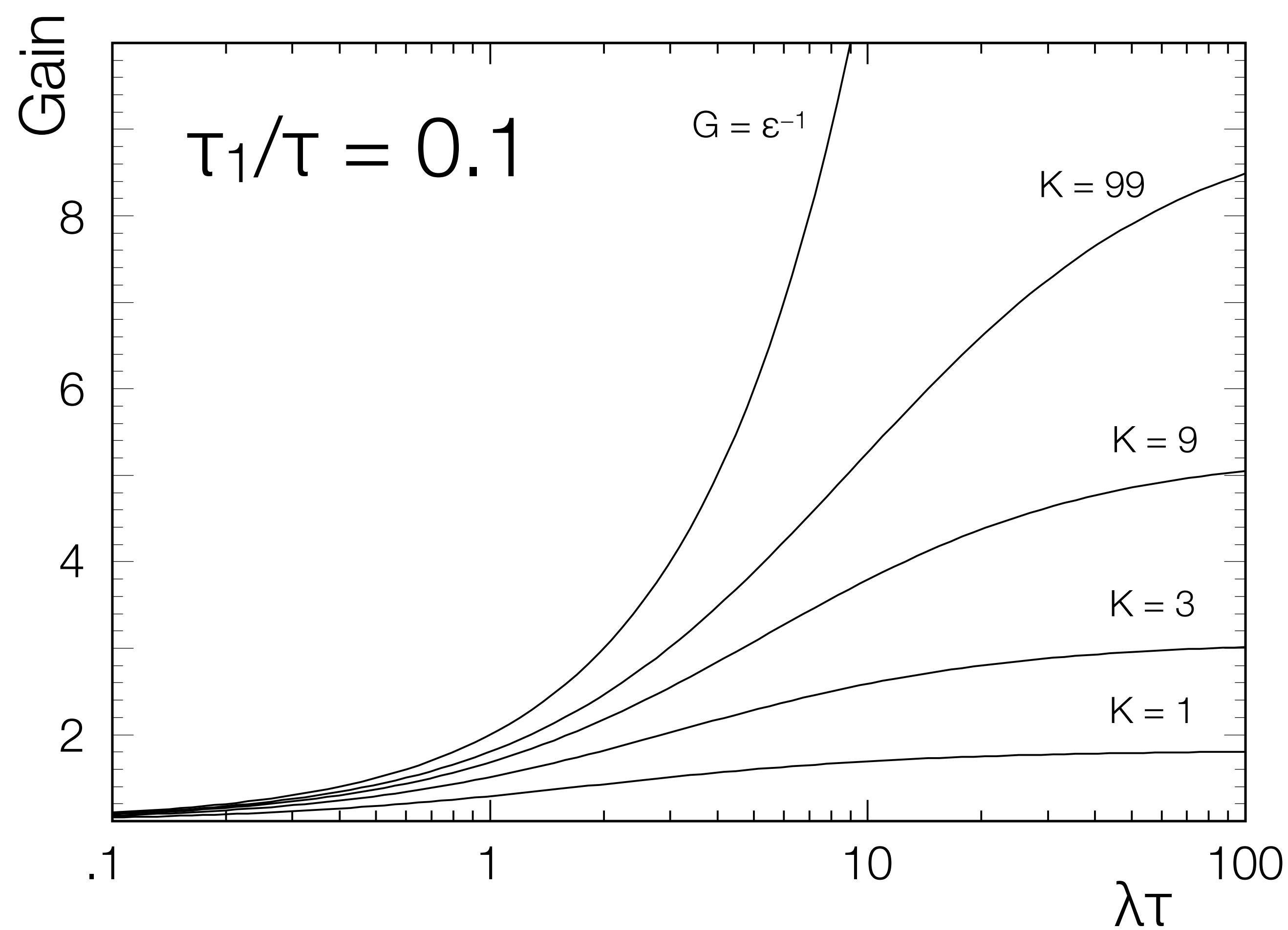




$$\epsilon' = \underbrace{(1+\lambda\tau)^{-1}}_{\epsilon} \times \underbrace{\left(\frac{K+1}{1+K(1+\lambda\tau_1)/(1+\lambda\tau)}\right)}_{\text{Gain (G)}}$$

Adding an Extra Trigger Levels





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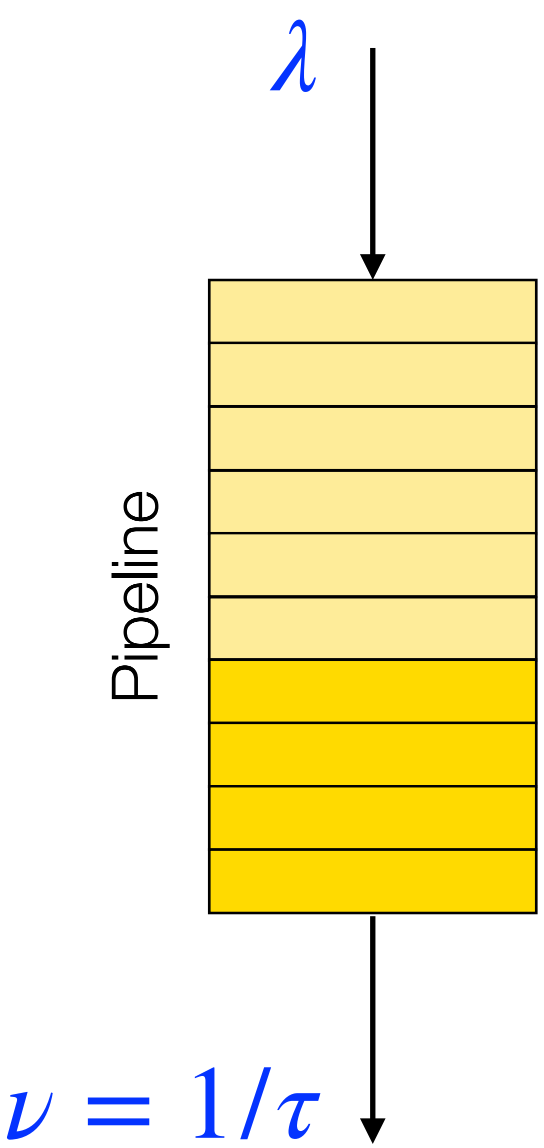
ϵ × Gain (G)

De-Randomizing Using Pipelines



Probability of n filled buffers: P_n

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

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

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

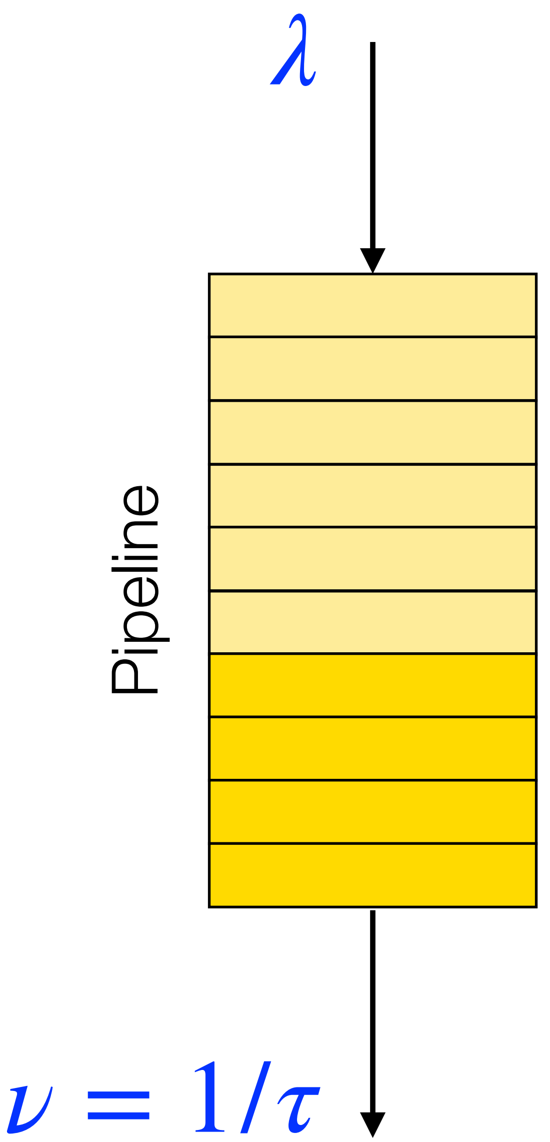
$$P_n = (\lambda/\nu)^n P_0 = (\rho)^n P_0 \quad \text{[with } \rho = \lambda/\nu = \lambda\tau\text{]}$$

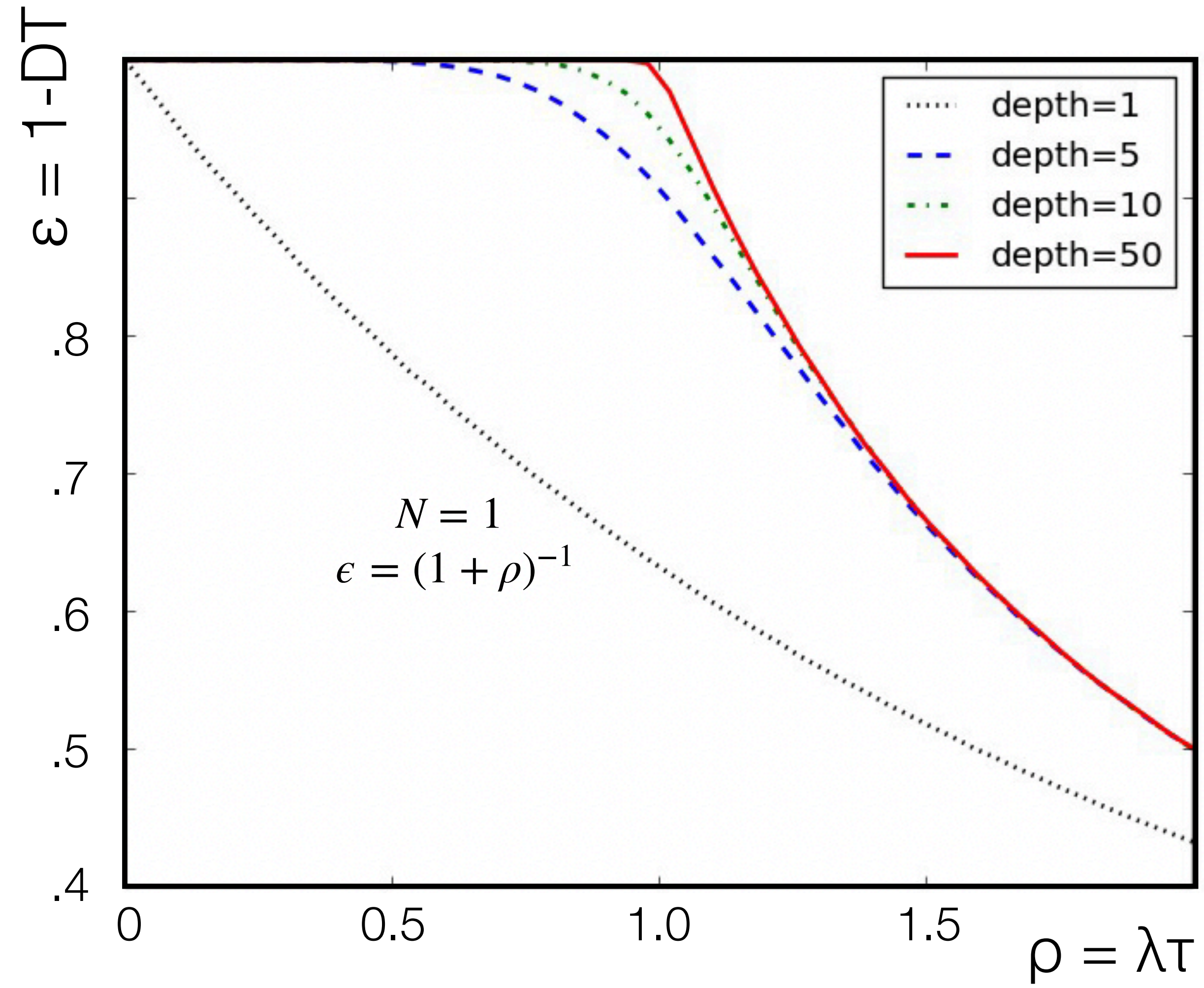
Using $\Sigma P_n = 1$ yields:

$$\mathrm{DT} = P_N = \begin{cases} P_n = \dfrac{(1-\rho)\rho^N}{1-\rho^{N+1}} & \text{for } \rho \neq 1 \\[2ex] P_n = \dfrac{1}{N+1} & \text{for } \rho = 1 \end{cases}$$

$\rho = \lambda\tau$

De-Randomizing Using Pipelines

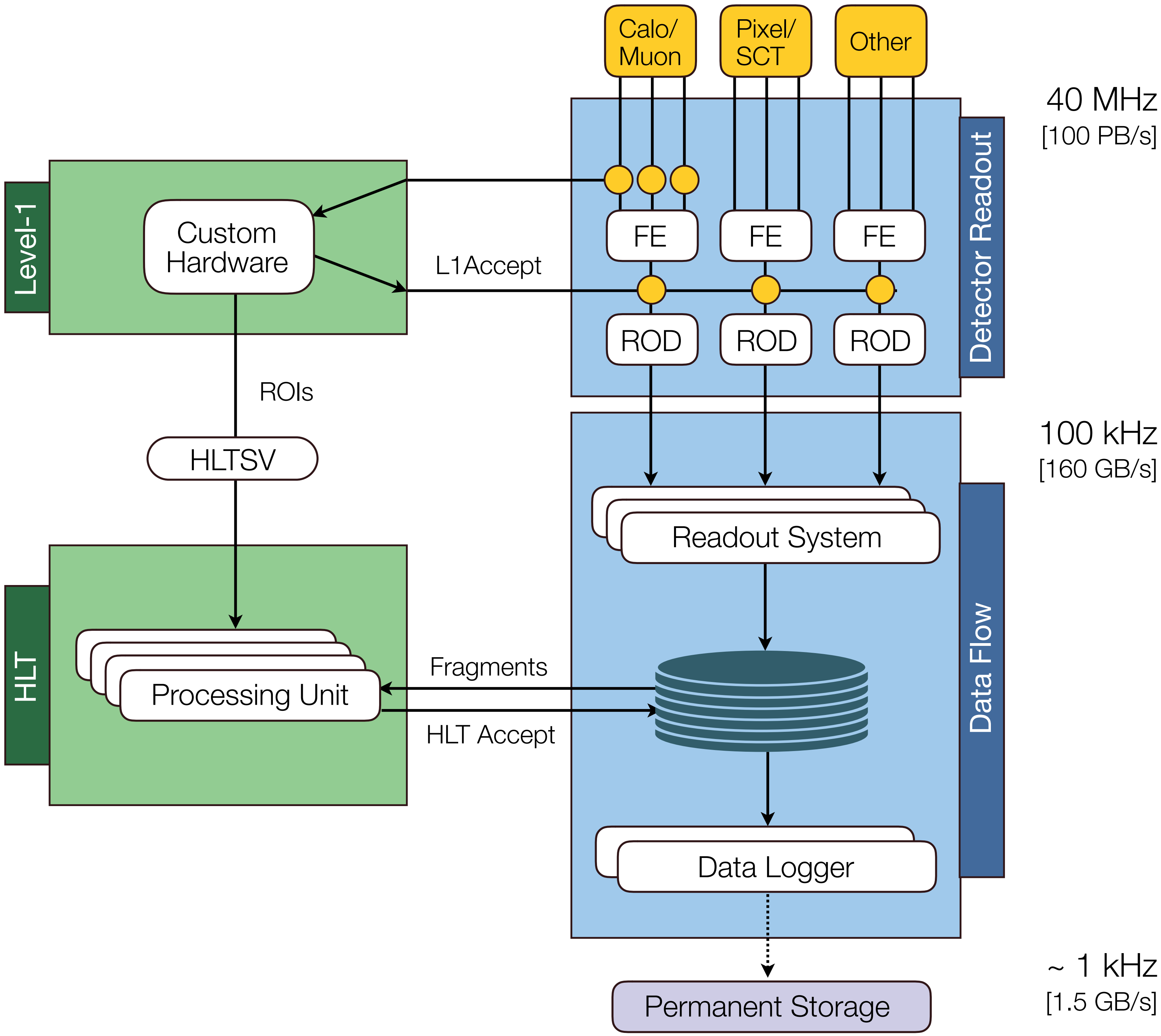


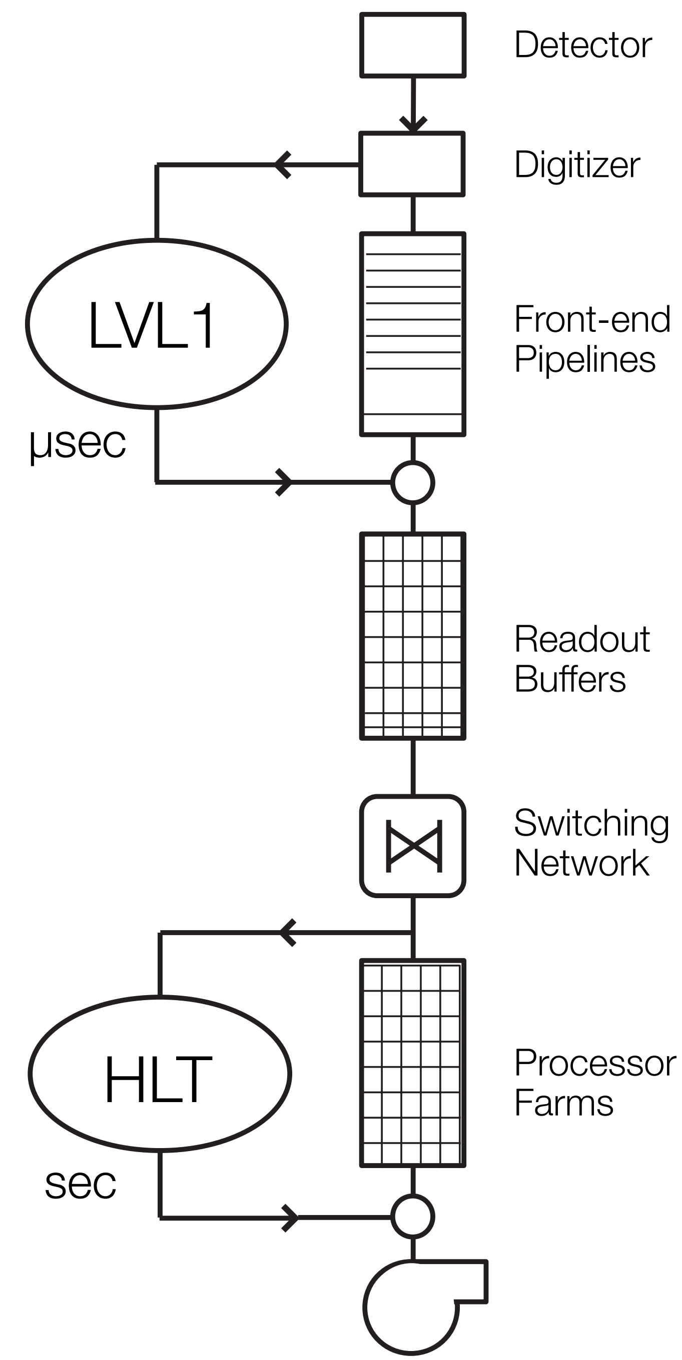


$$\text{DT} = P_N = \begin{cases} P_n = \dfrac{(1-\rho)\rho^N}{1-\rho^{N+1}} & \text{for } \rho \neq 1 \\ P_n = \dfrac{1}{N+1} & \text{for } \rho = 1 \end{cases}$$

$\rho = \lambda\tau$

Typical DAQ Example – ATLAS @ Run-2





Some Rates, Latencies & Dead Times

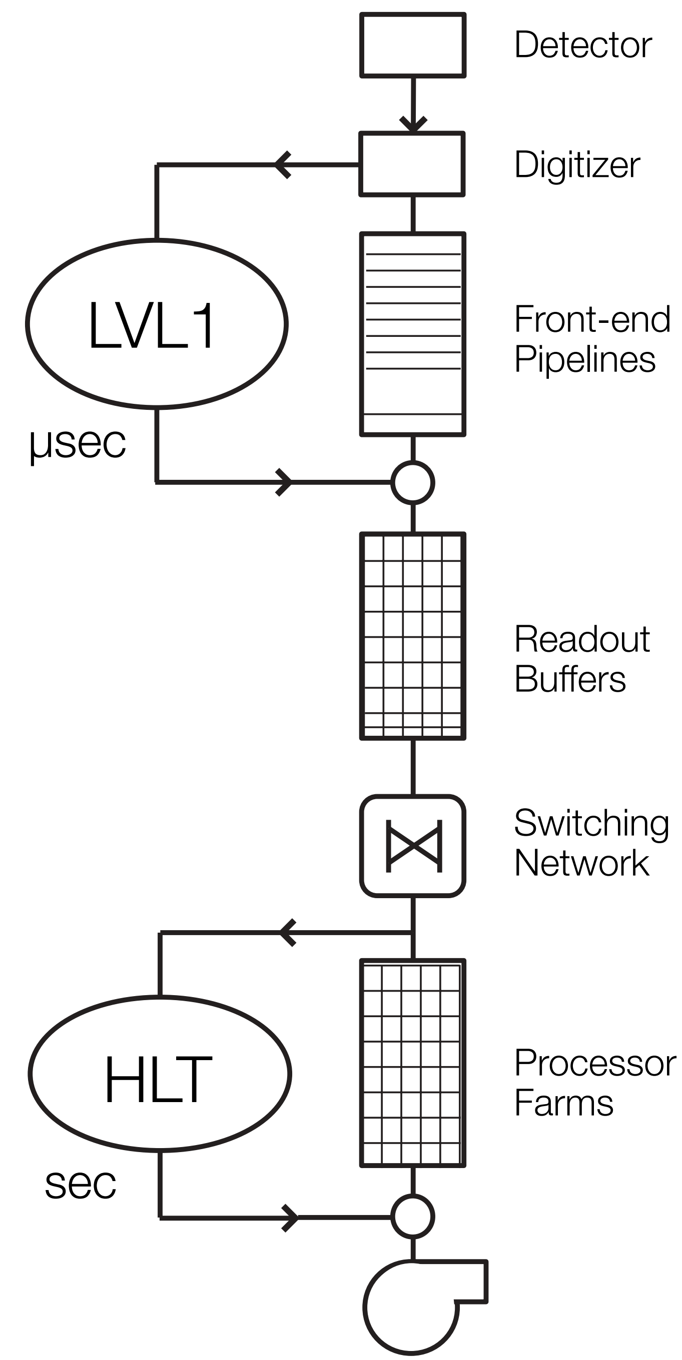
LVL1 dead time:

DT = r/o Rate × busy after L1A

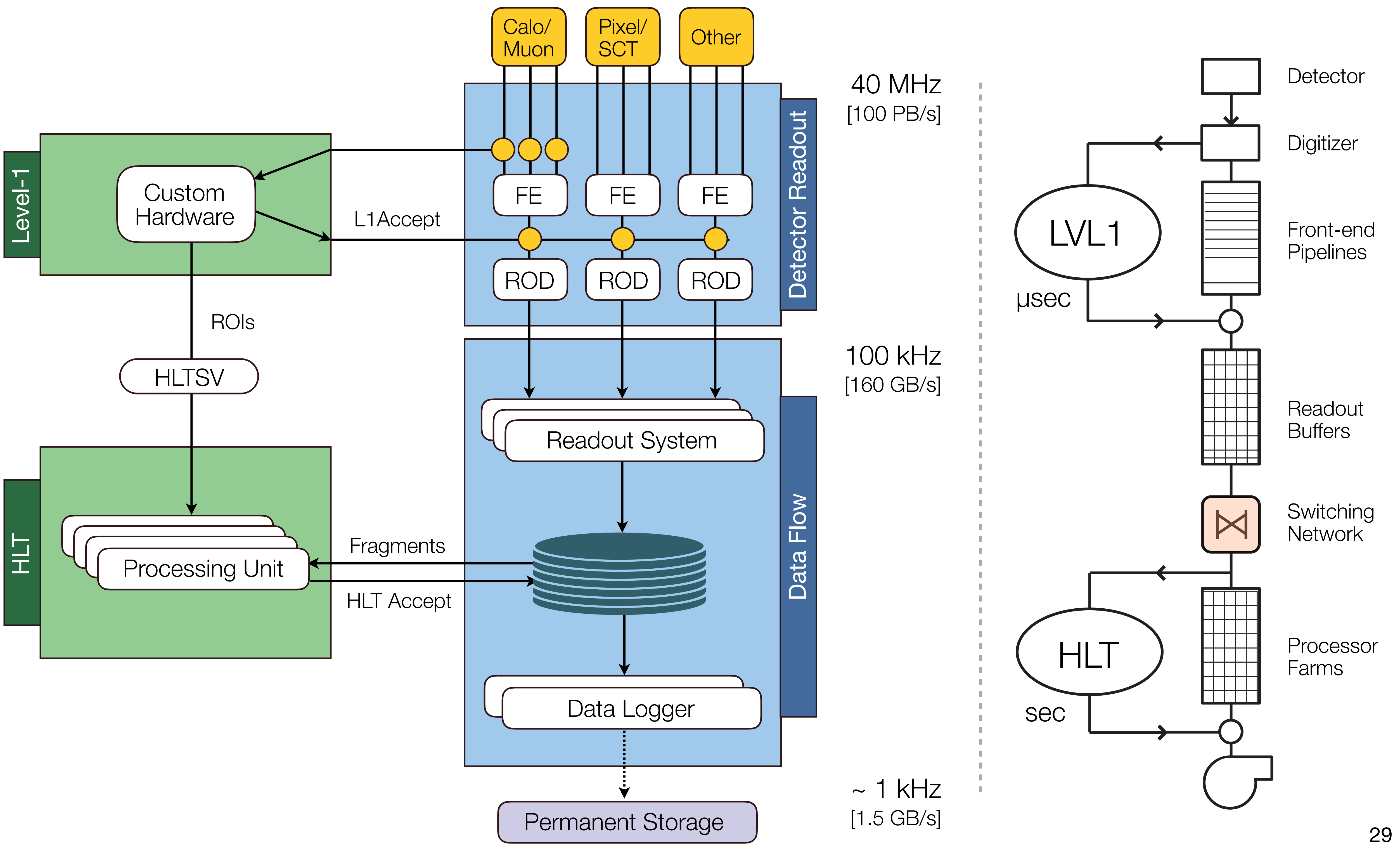
e.g. H1: 50 Hz × 2 ms (L1)
ATLAS: 100 kHz × 125 ns (L1)

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 %

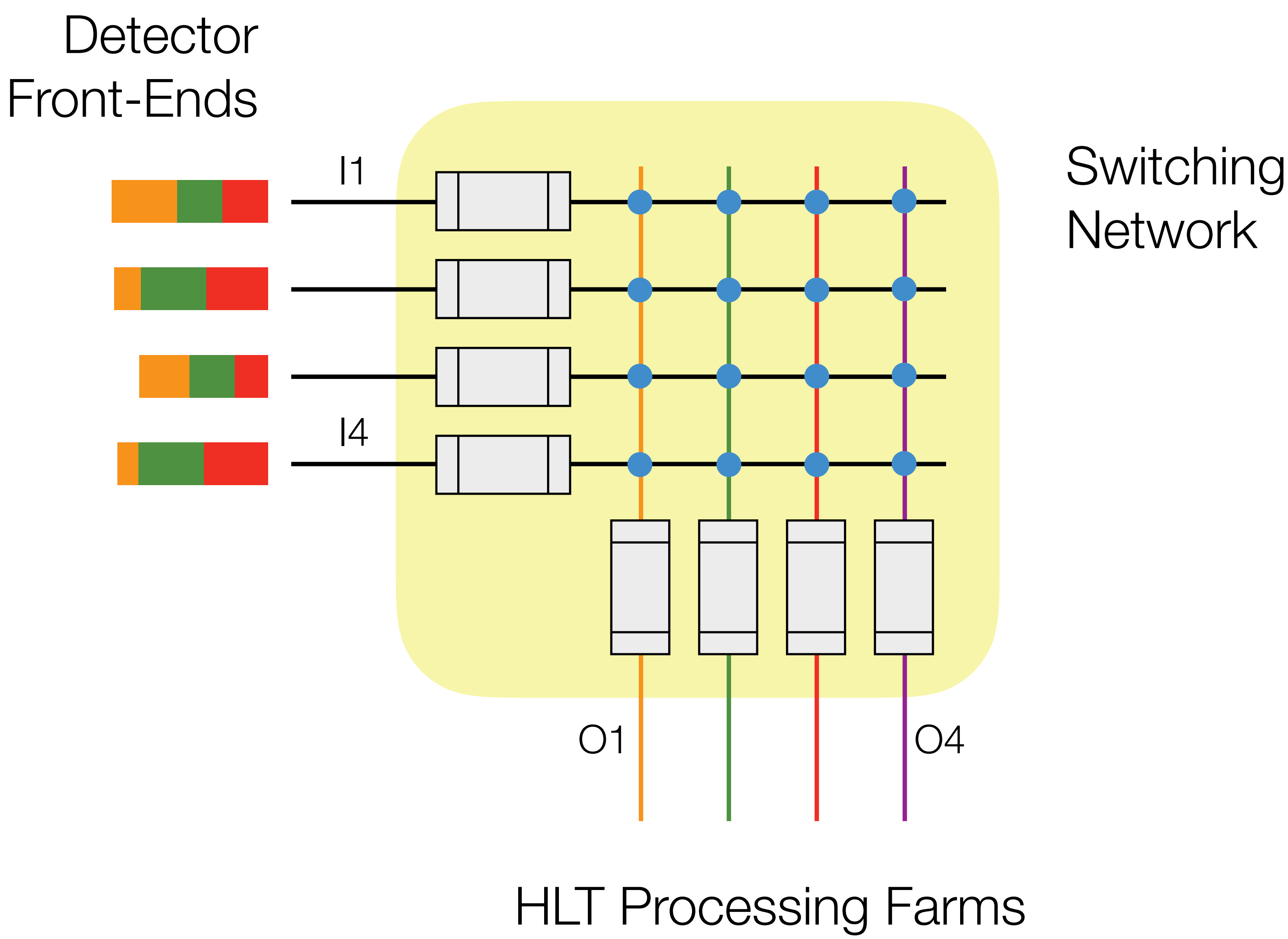
† Trigger-less readout in gab between bunch trains

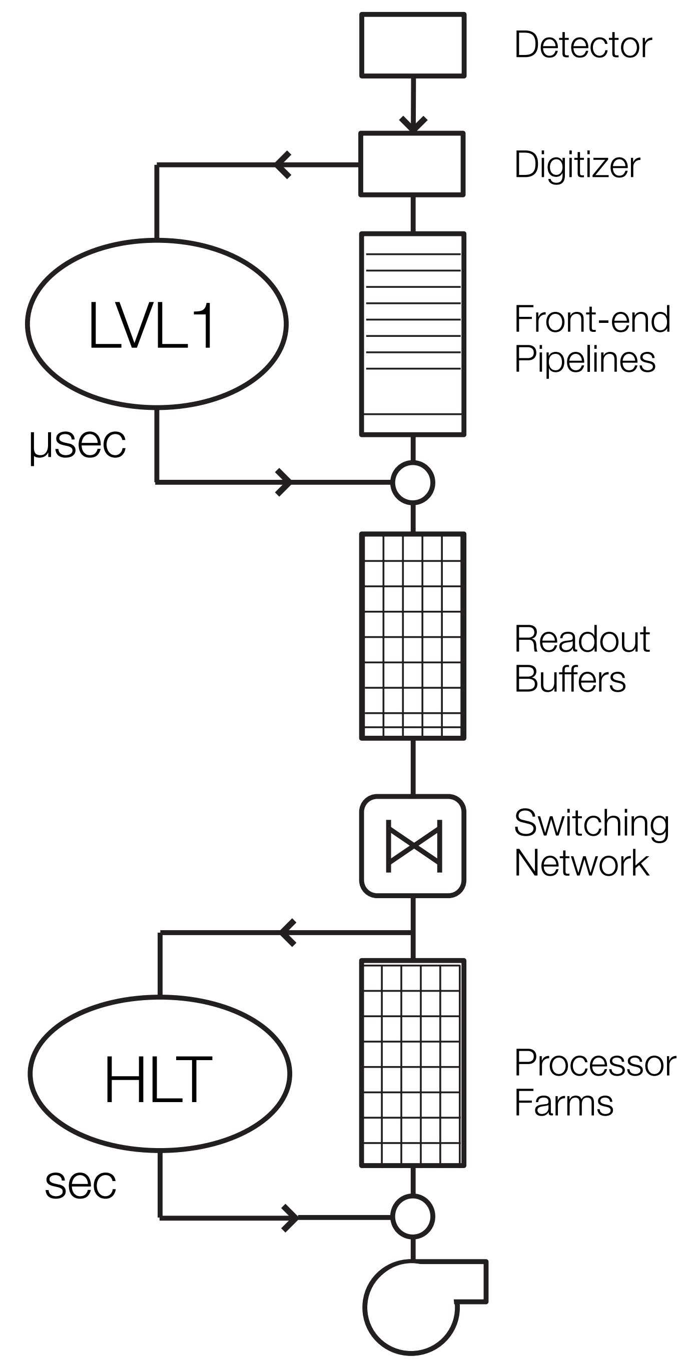


Typical DAQ Example – ATLAS @ Run-2

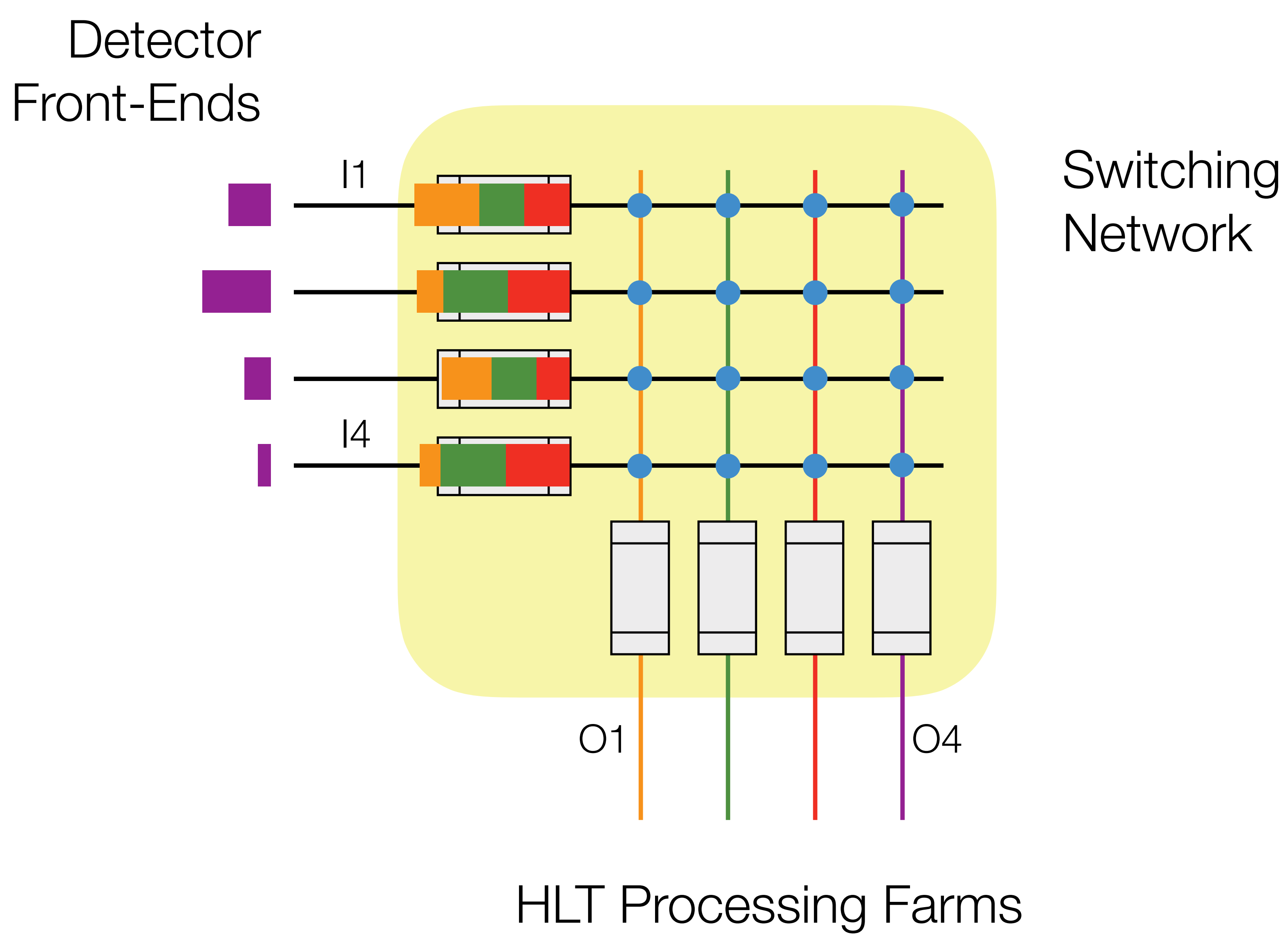


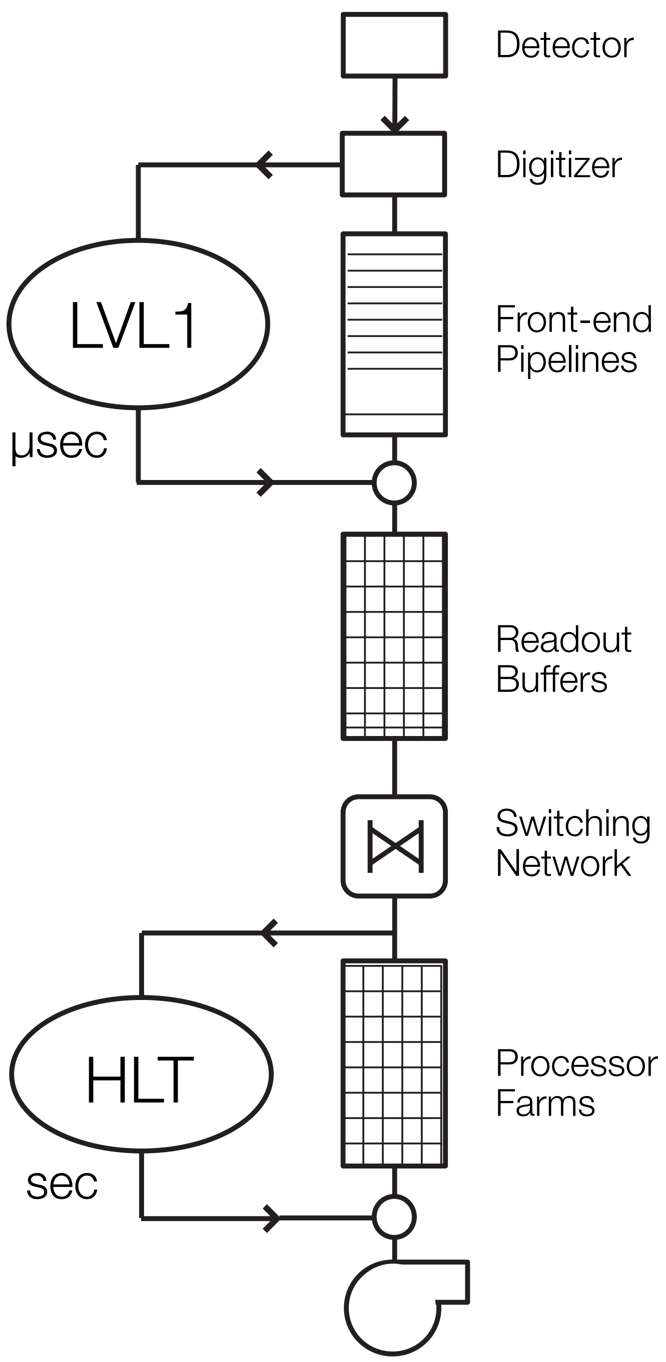
DAQ Switching Network



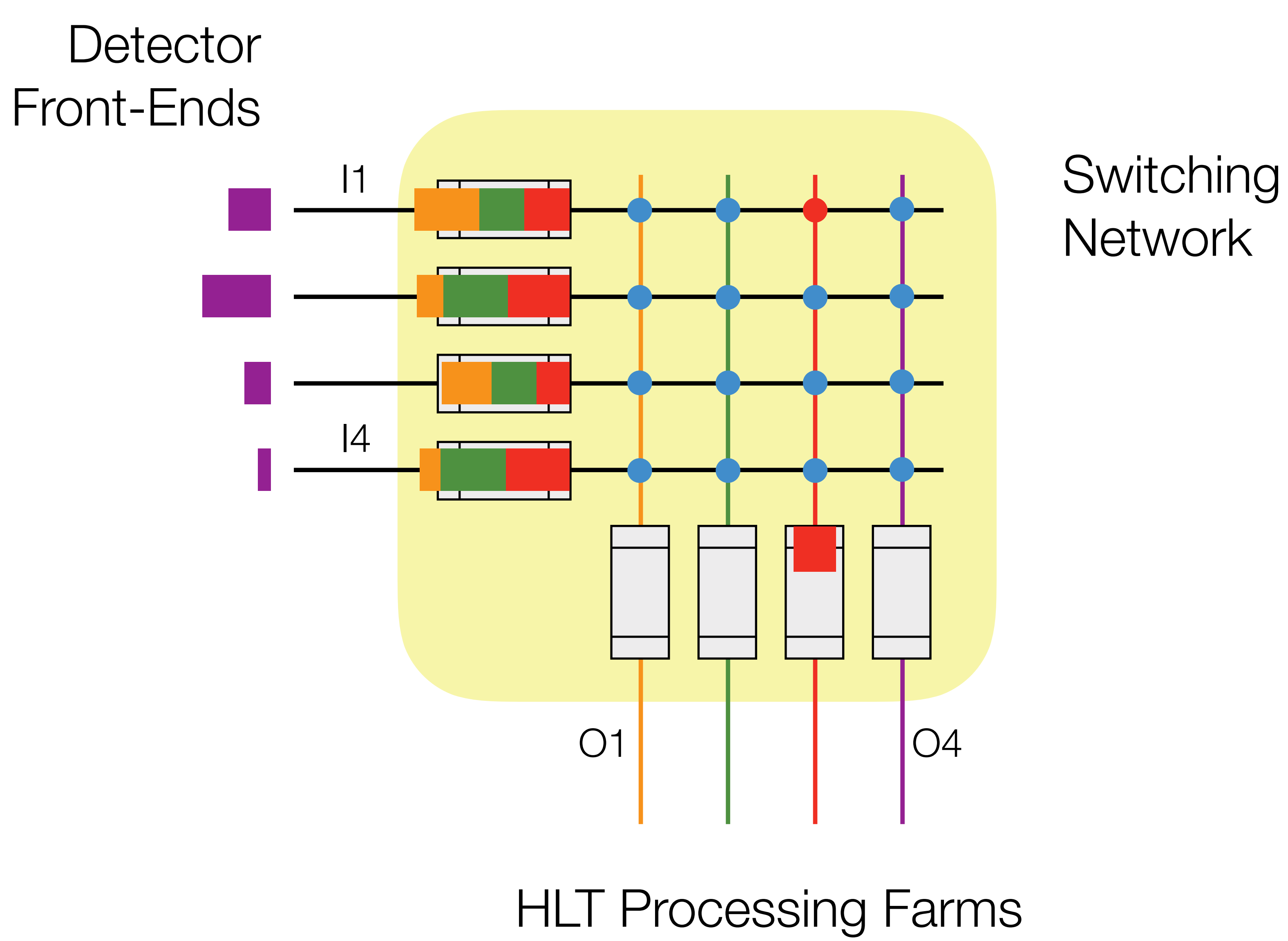


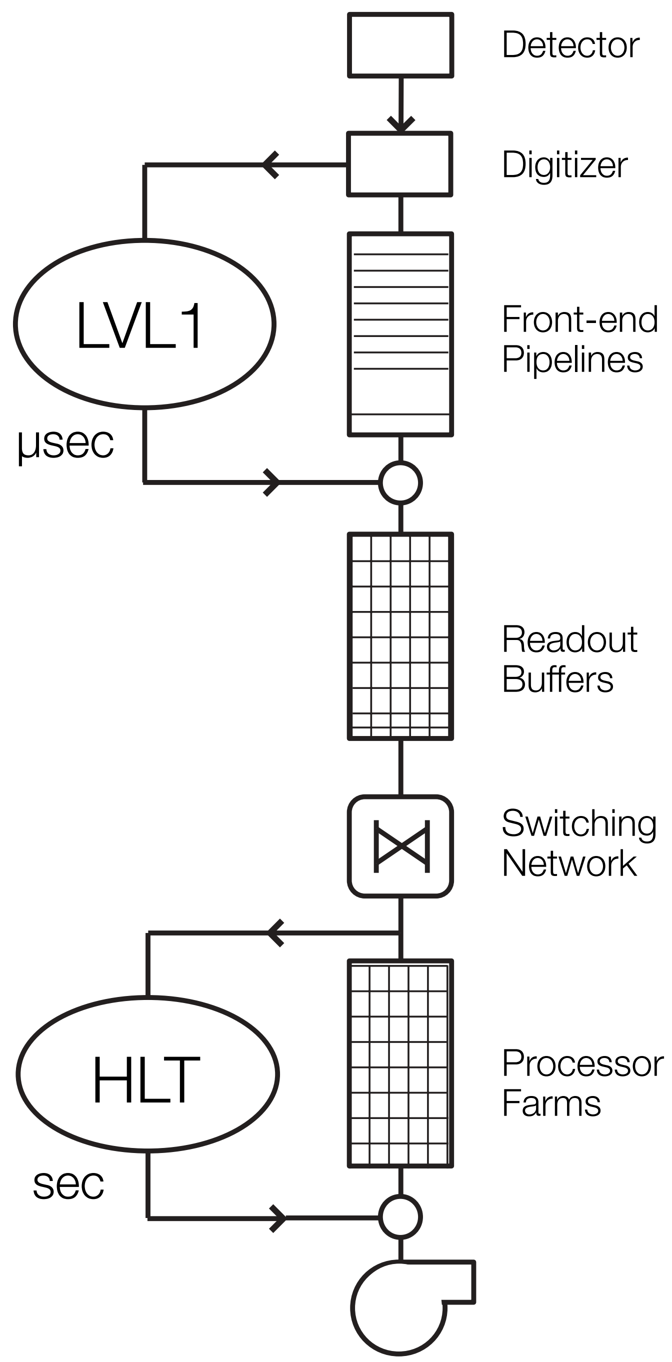
DAQ Switching Network



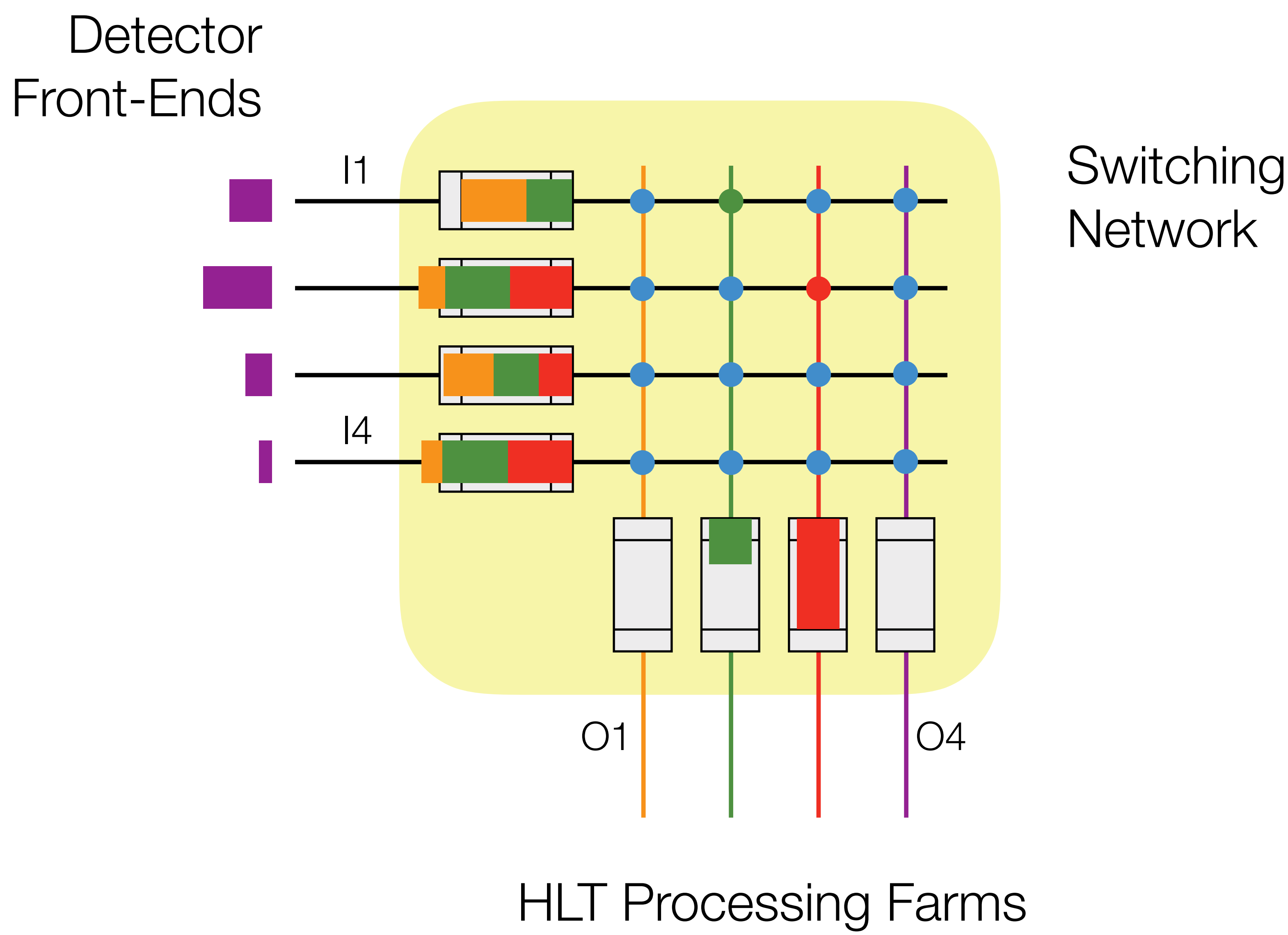


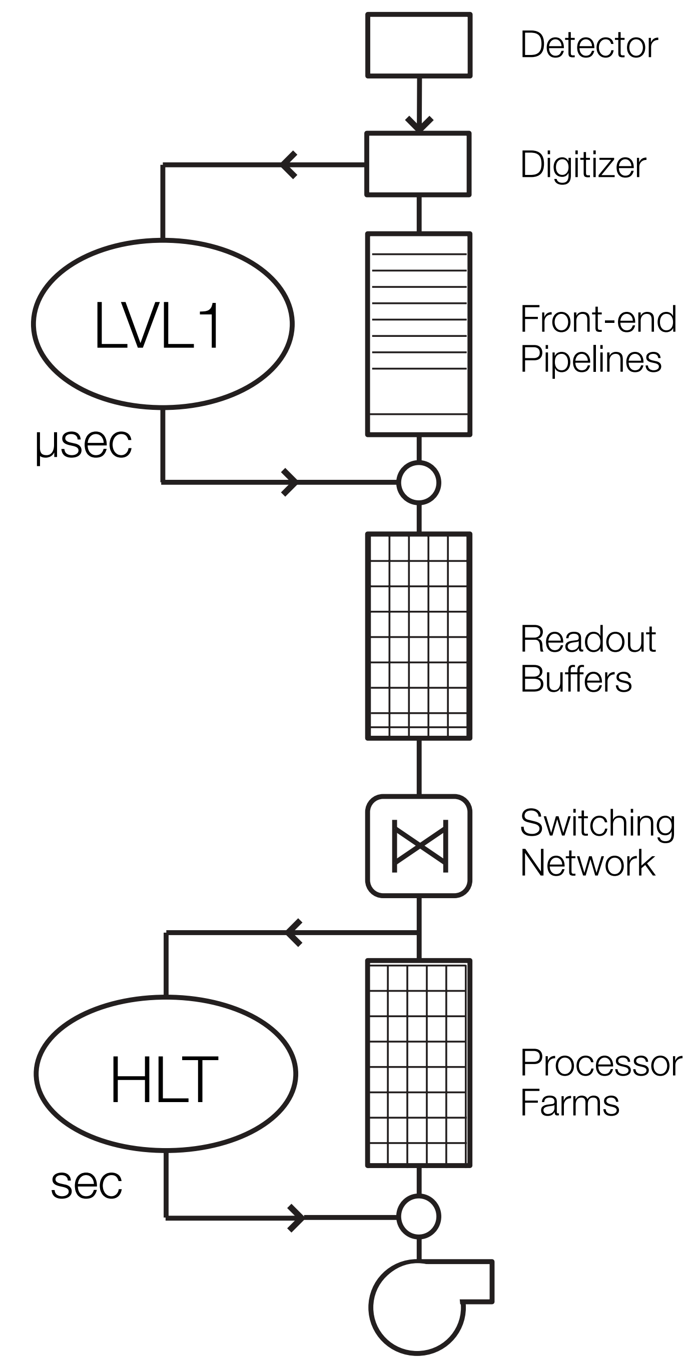
DAQ Switching Network



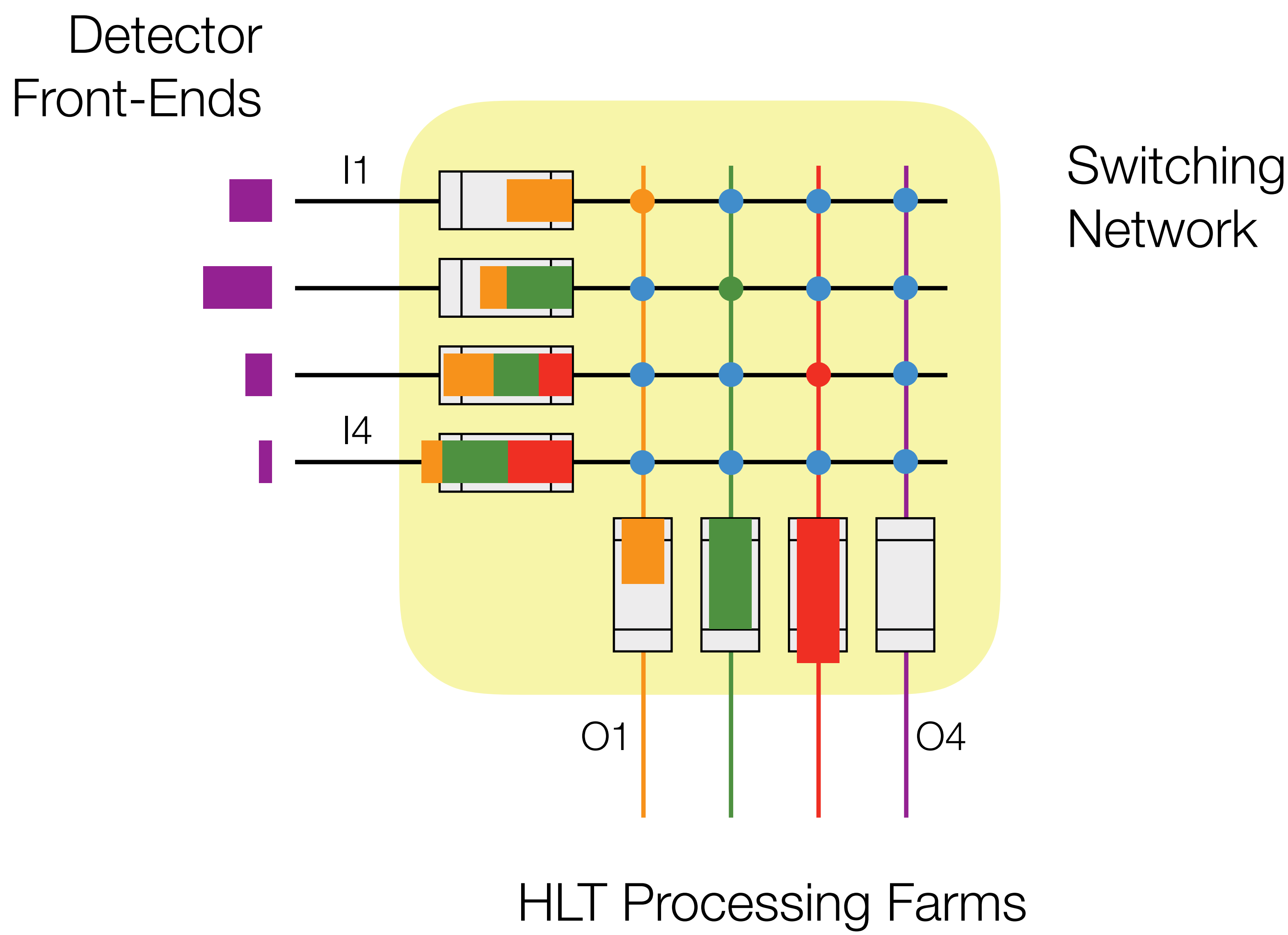


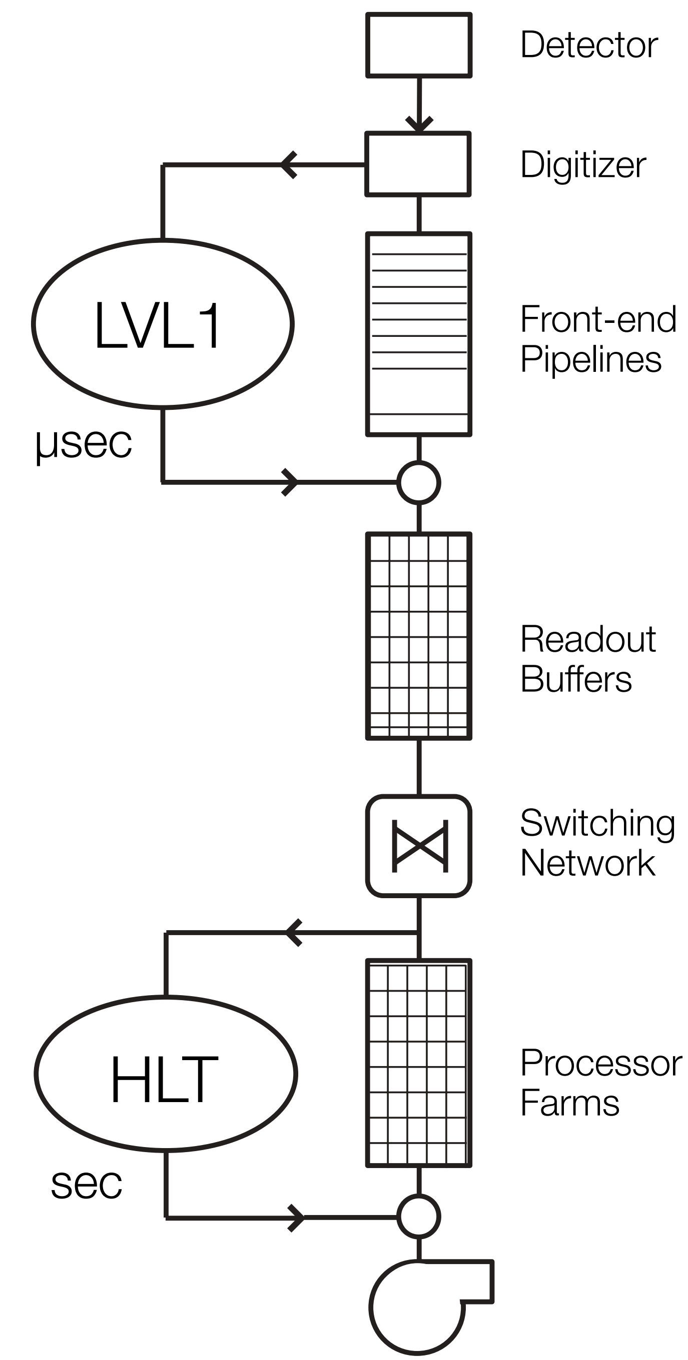
DAQ Switching Network



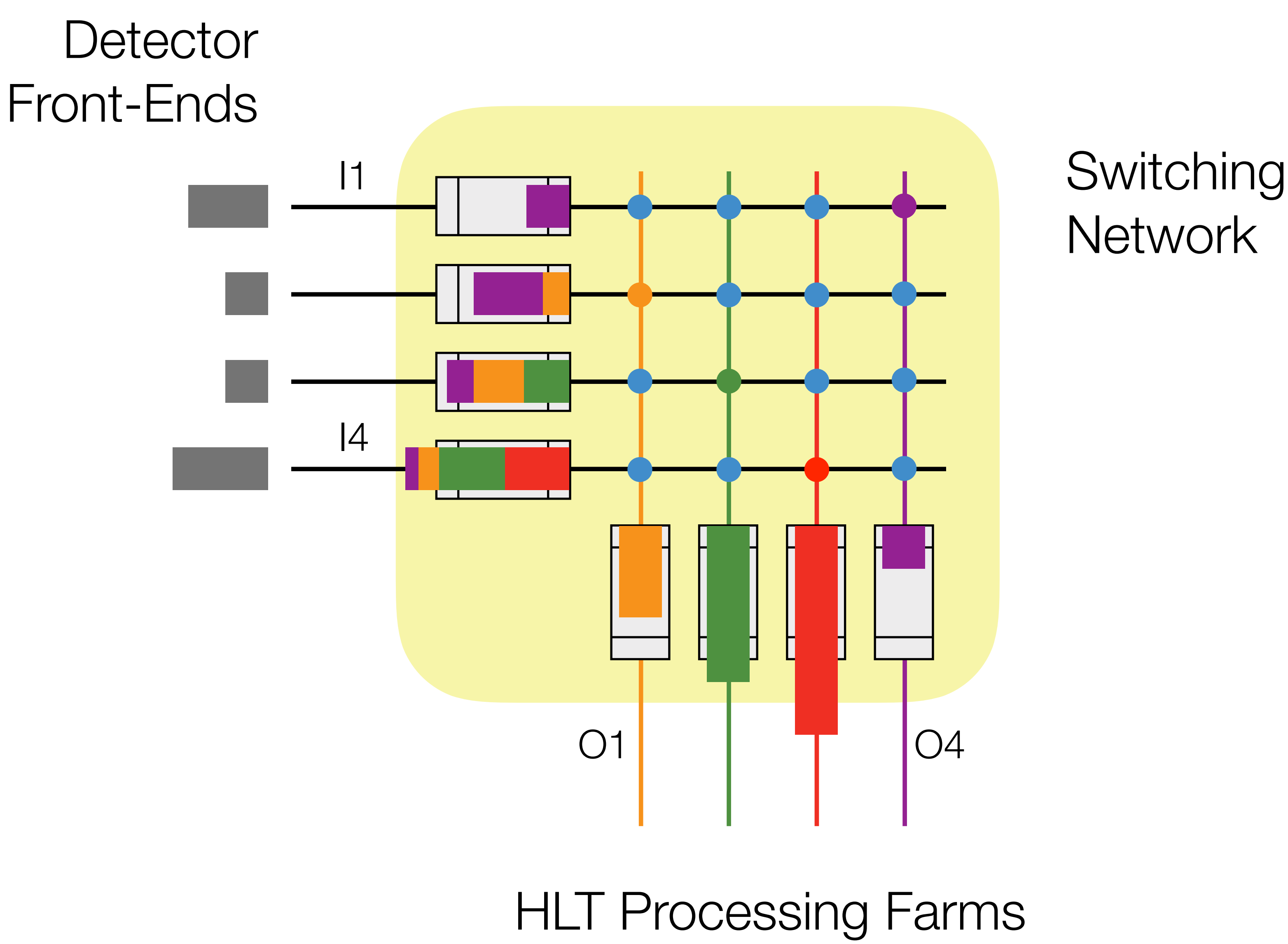


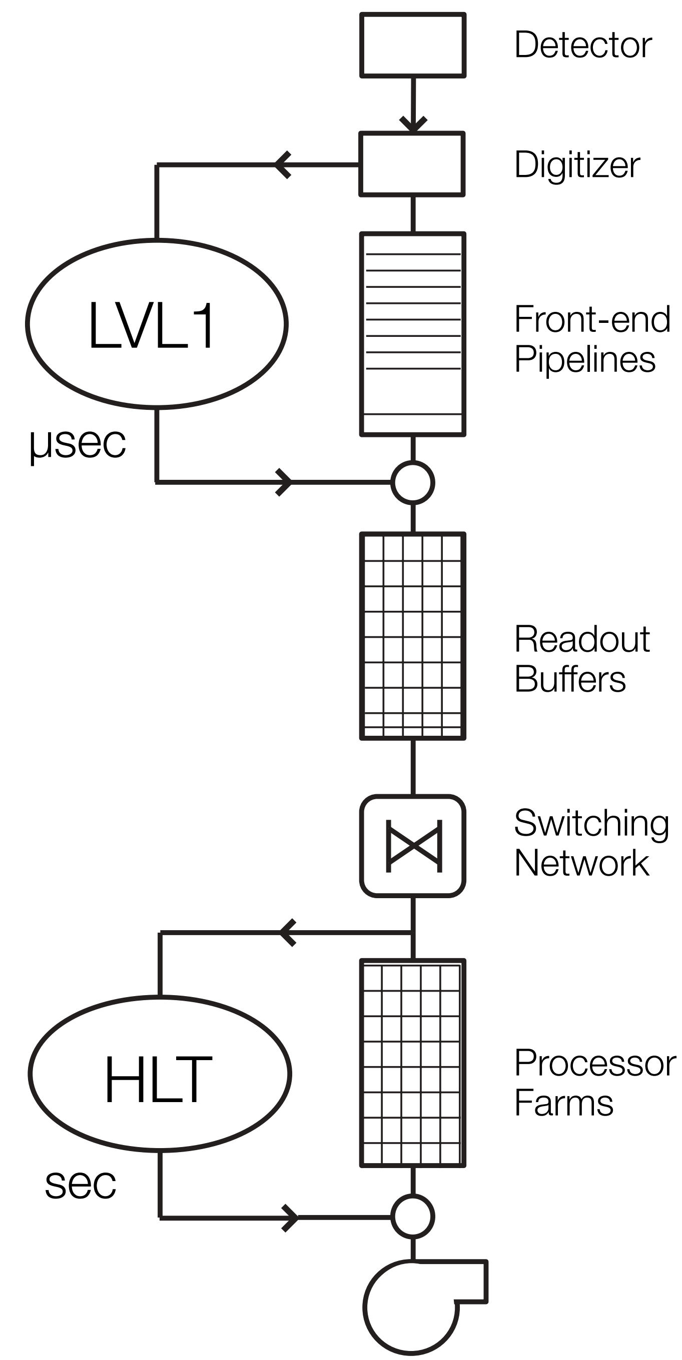
DAQ Switching Network



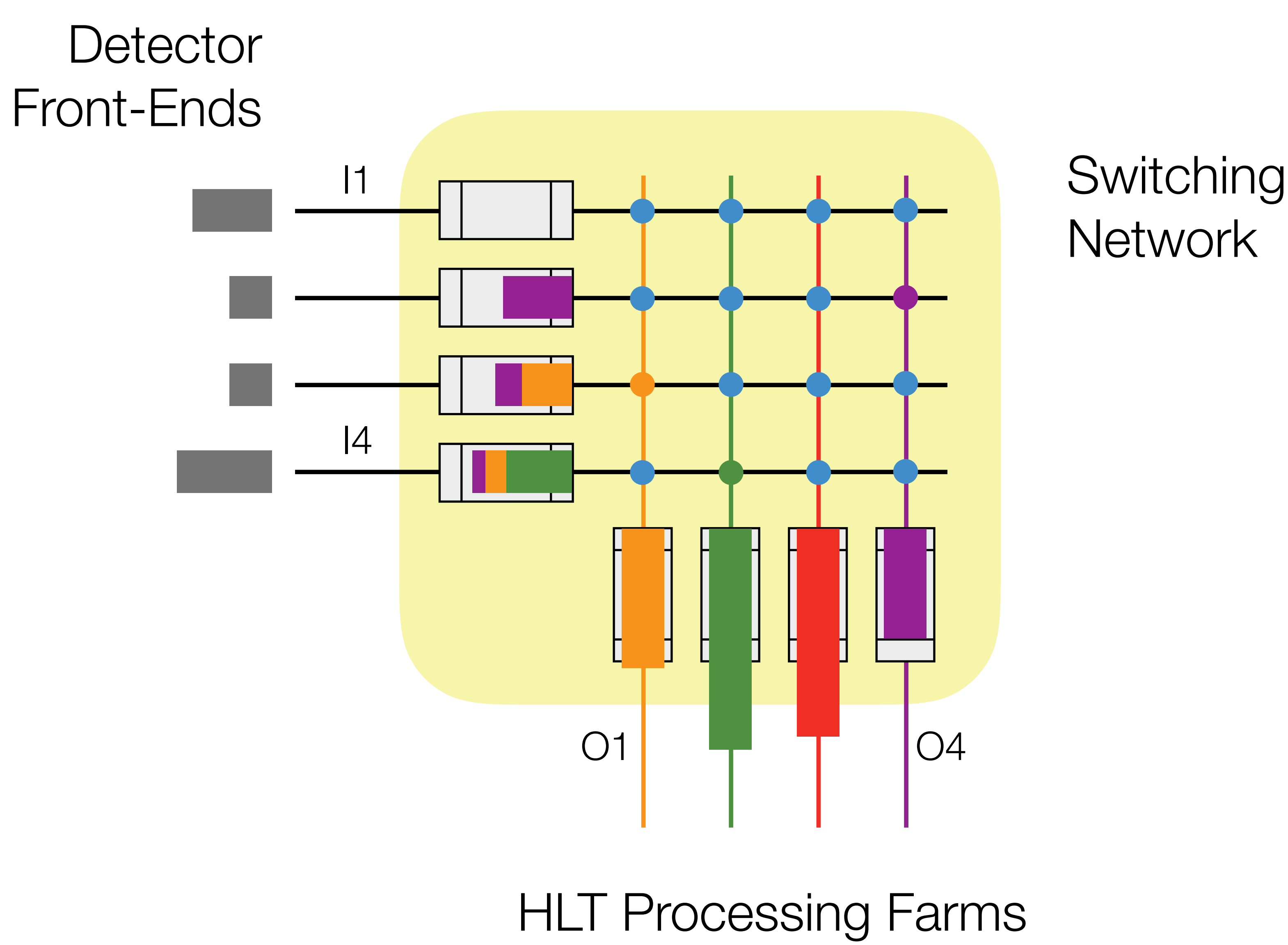


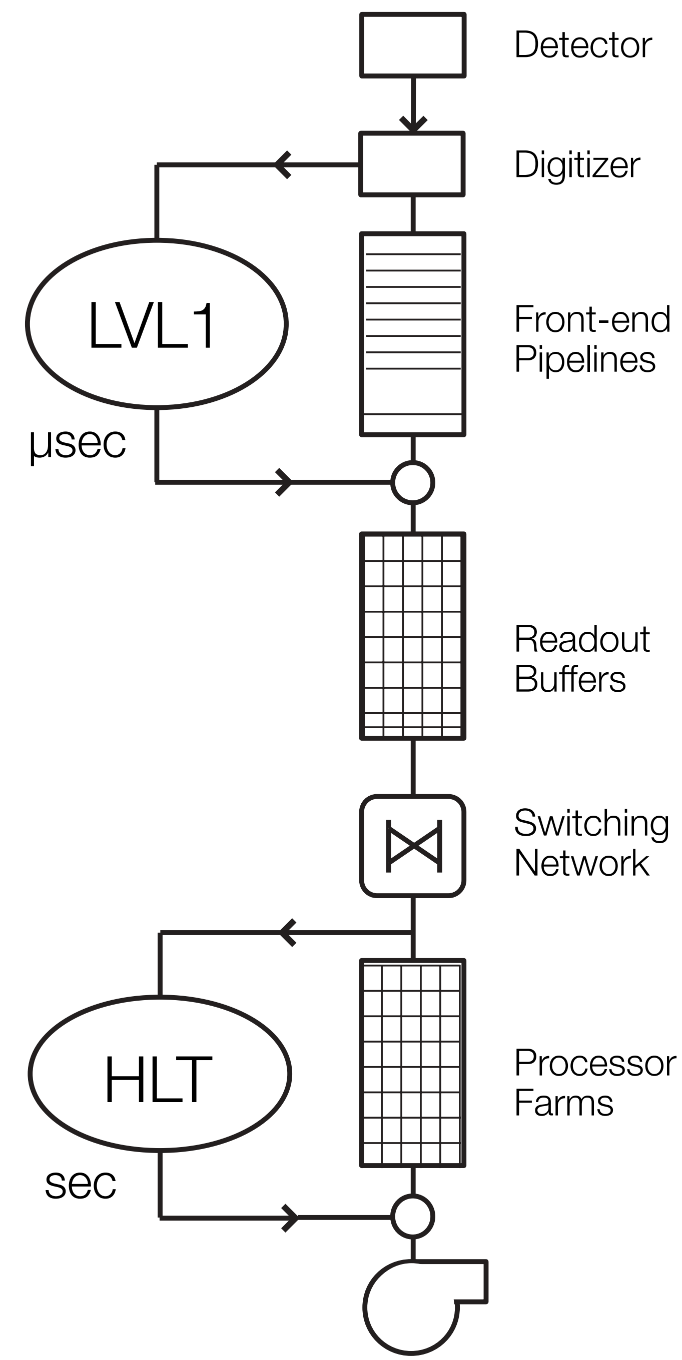
DAQ Switching Network



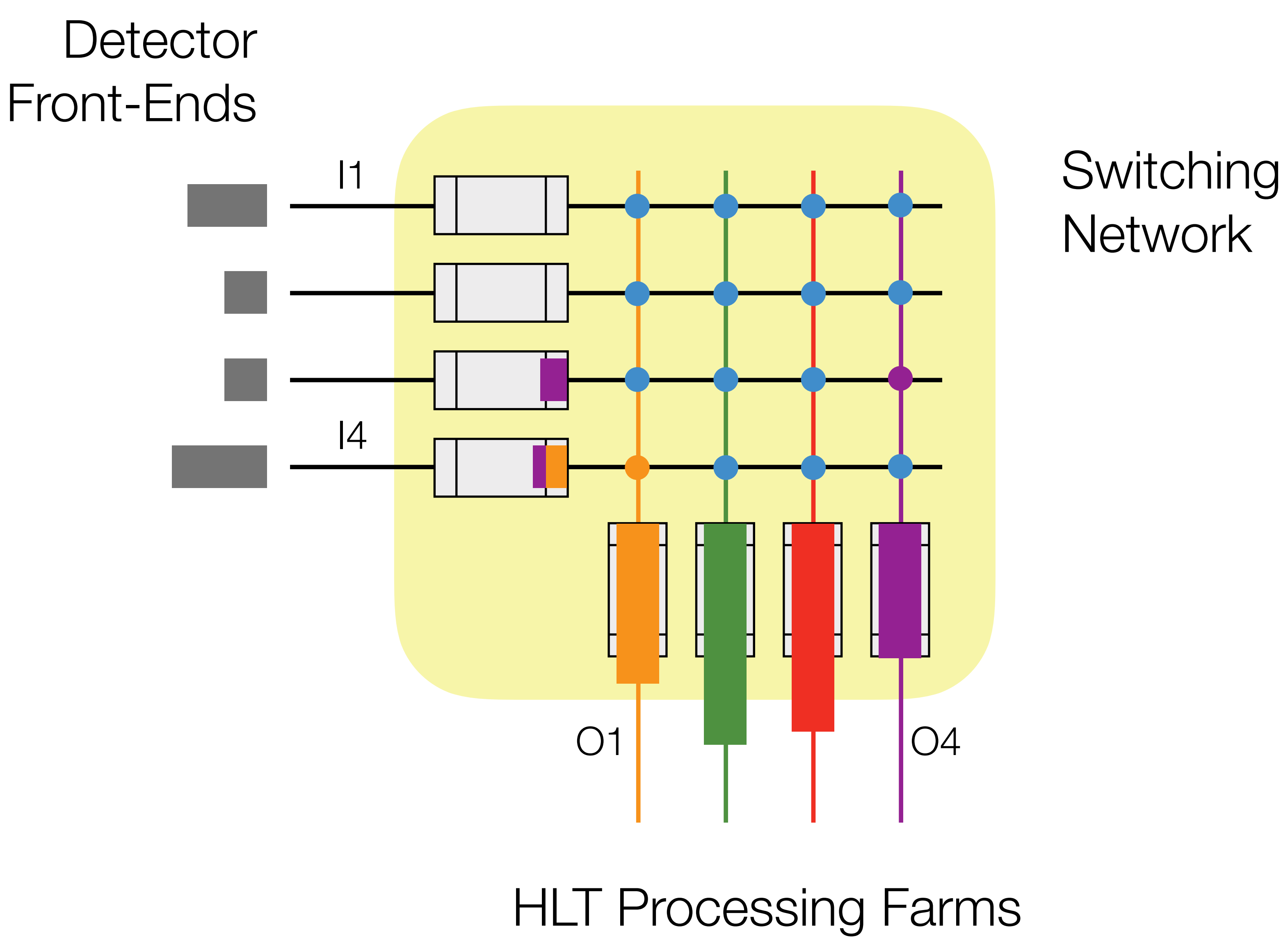


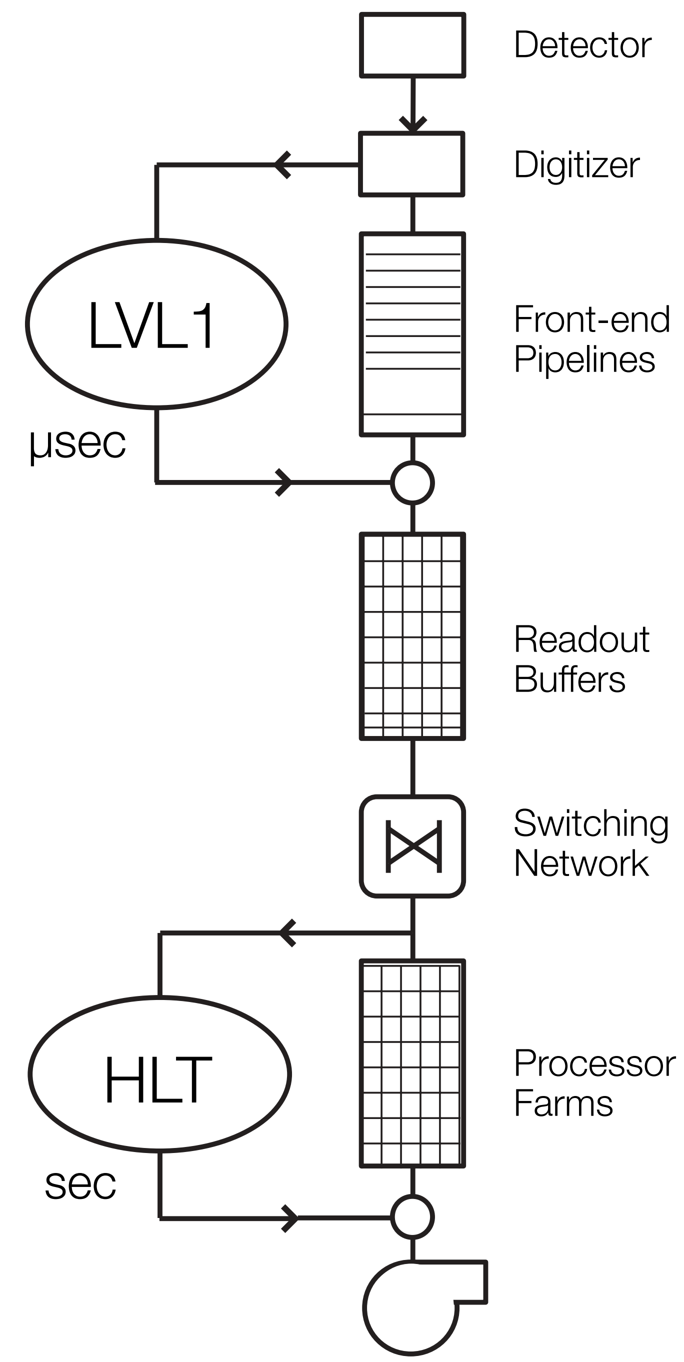
DAQ Switching Network



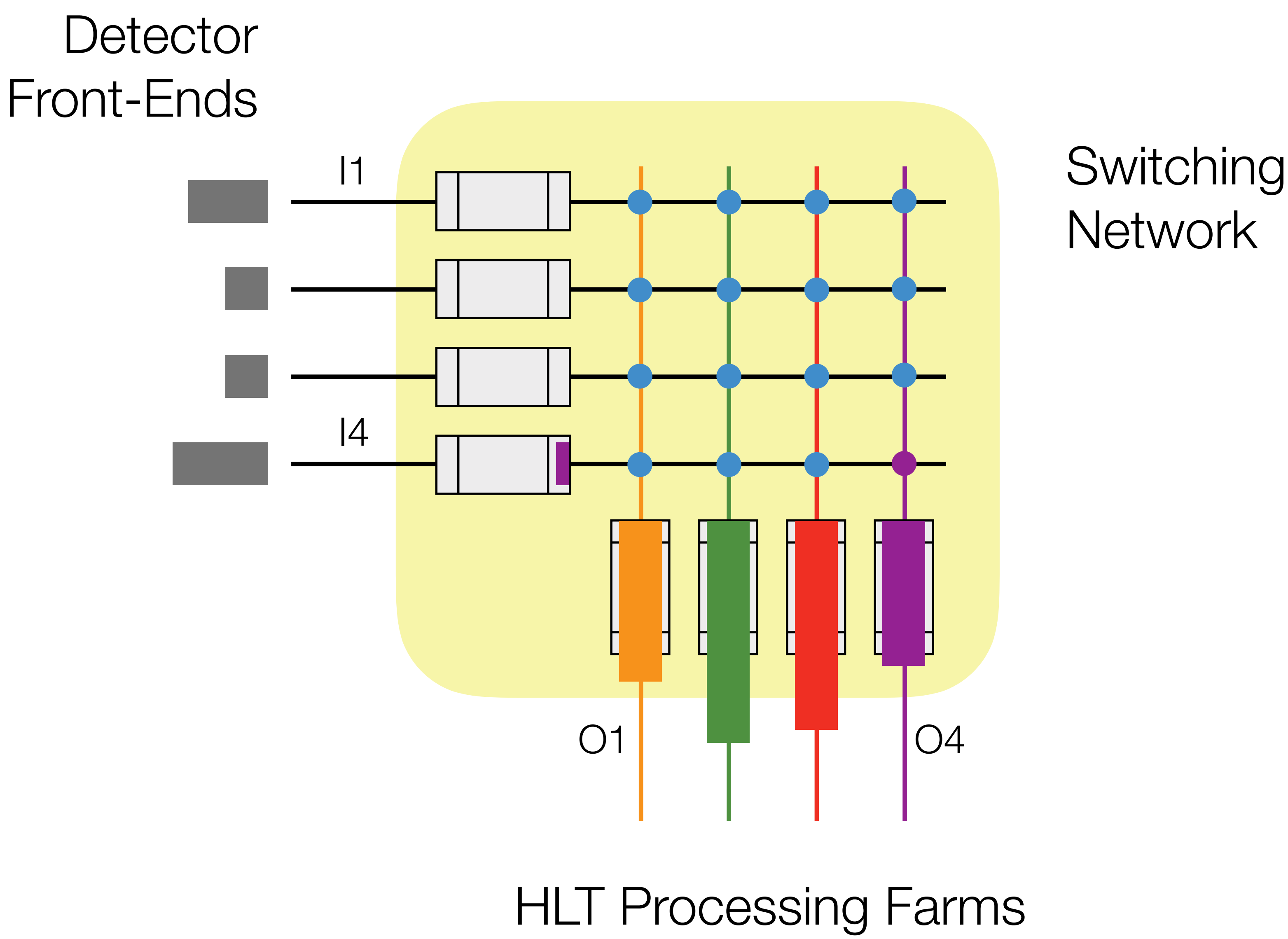


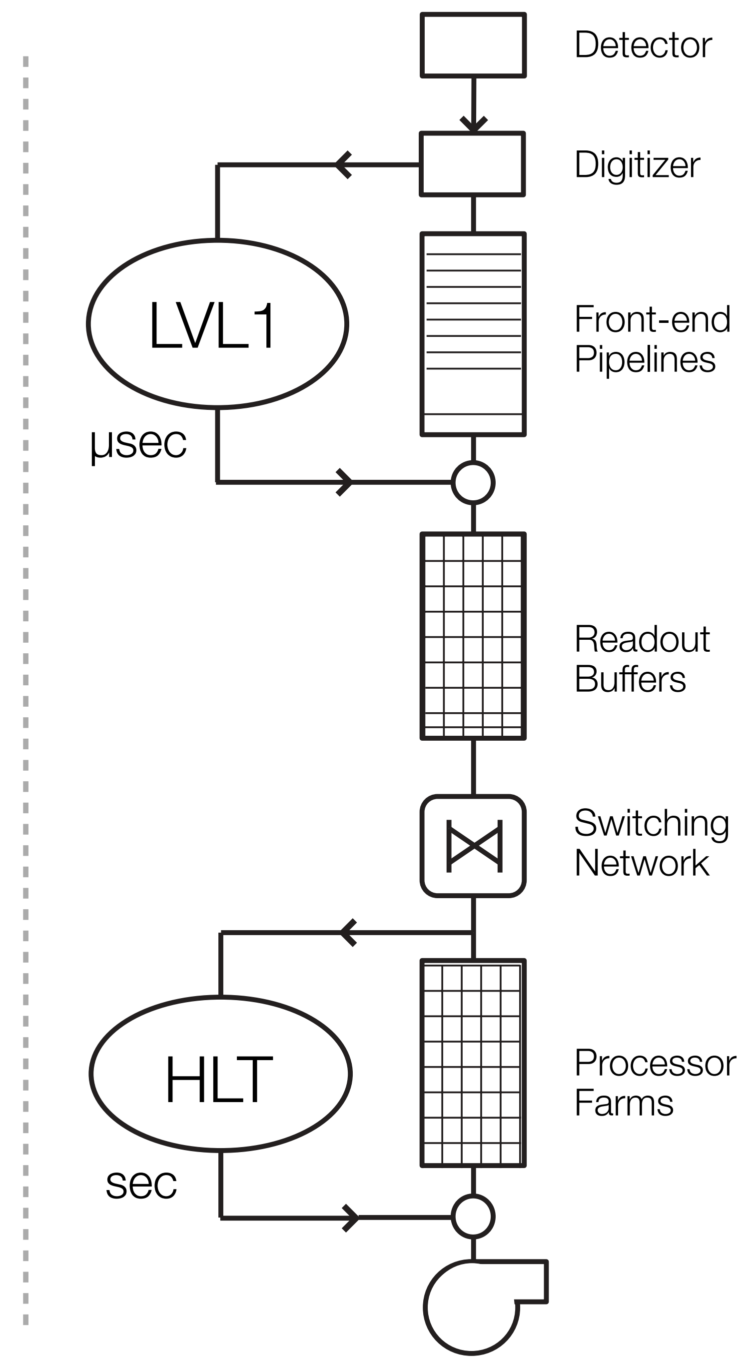
DAQ Switching Network



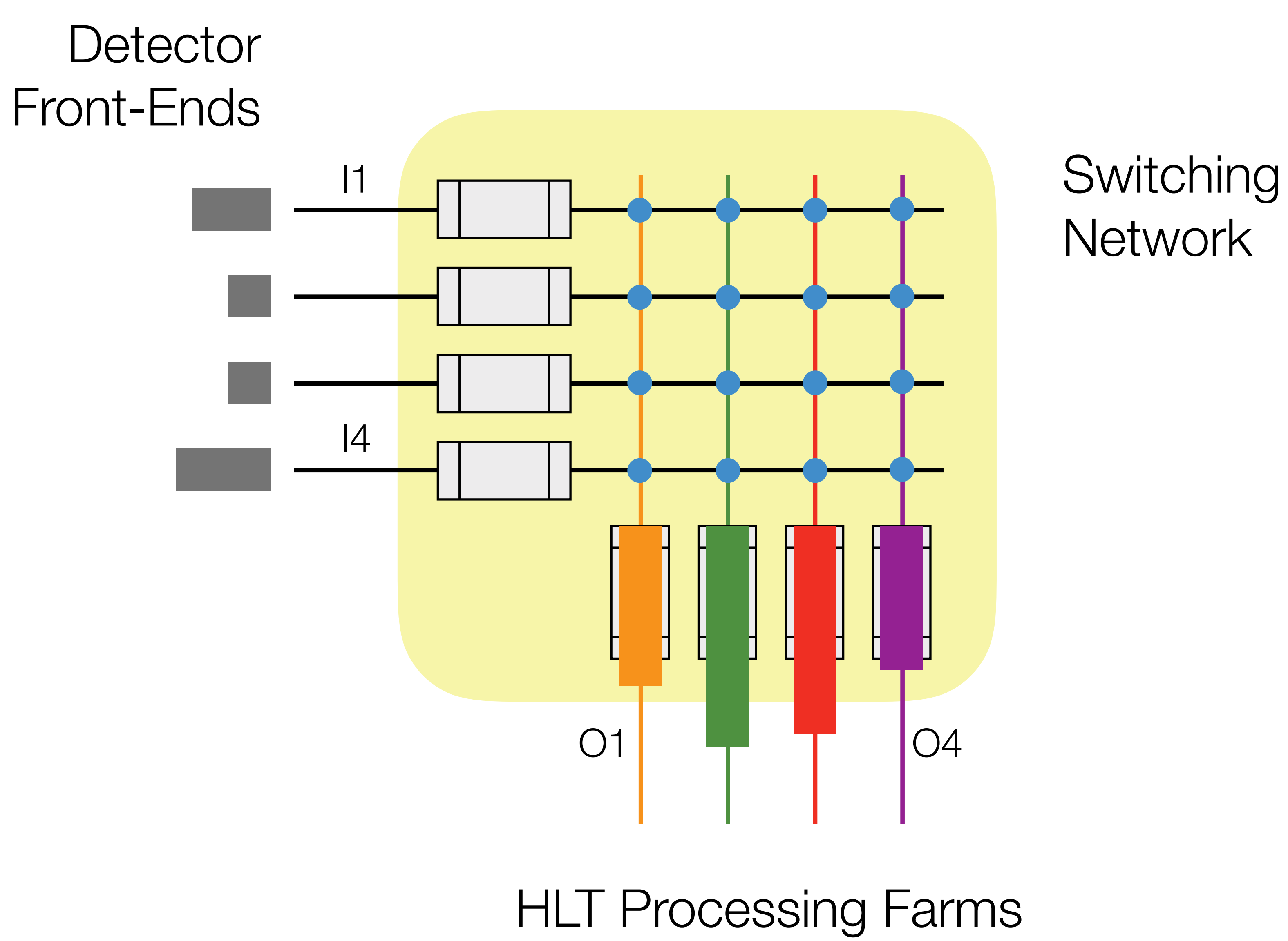


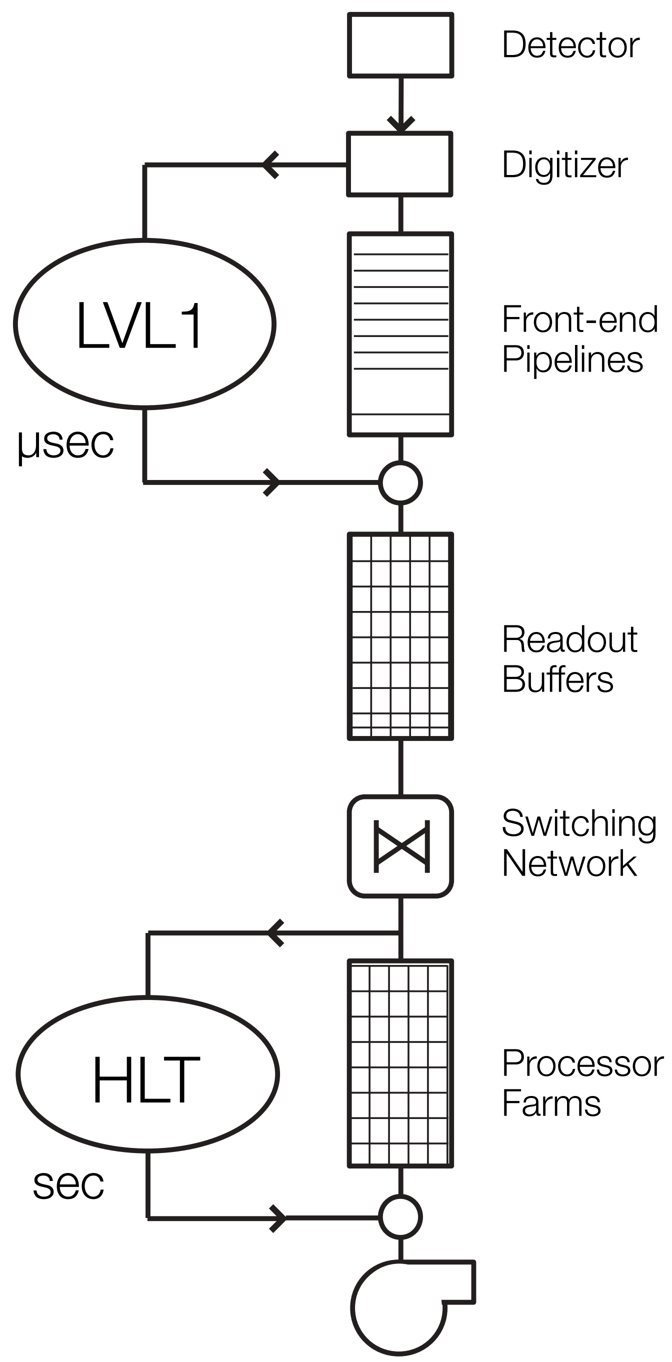
DAQ Switching Network





DAQ Switching Network

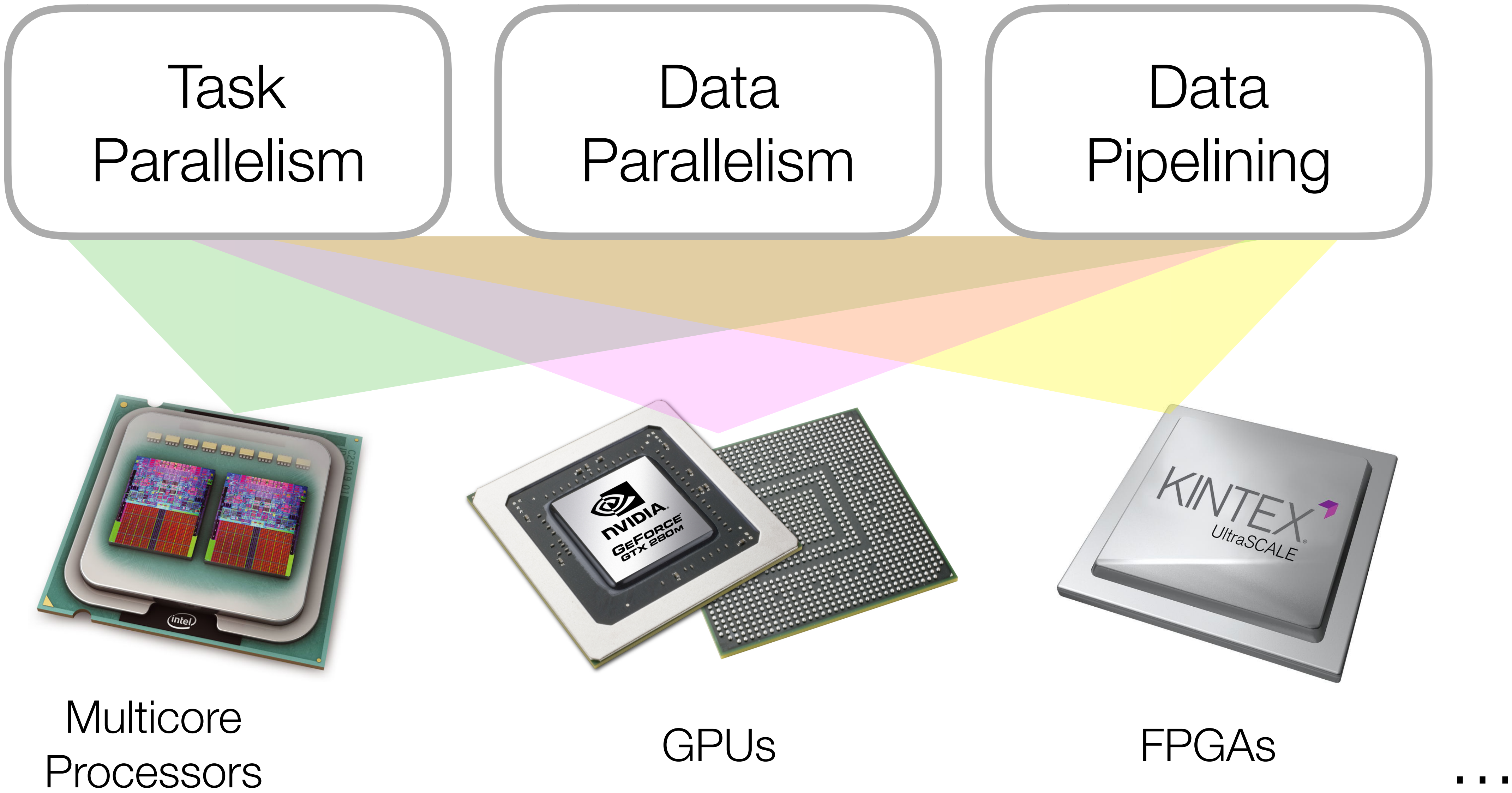




Part 3

"Realizing Trigger Systems"

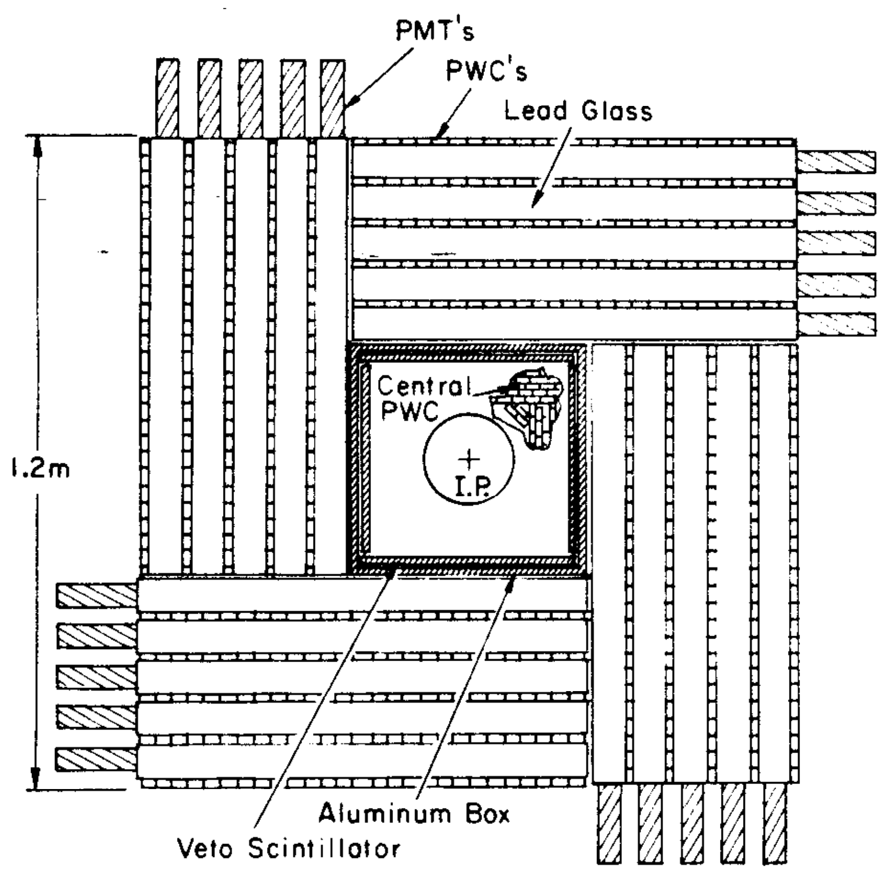
Fast & Parallel Processing



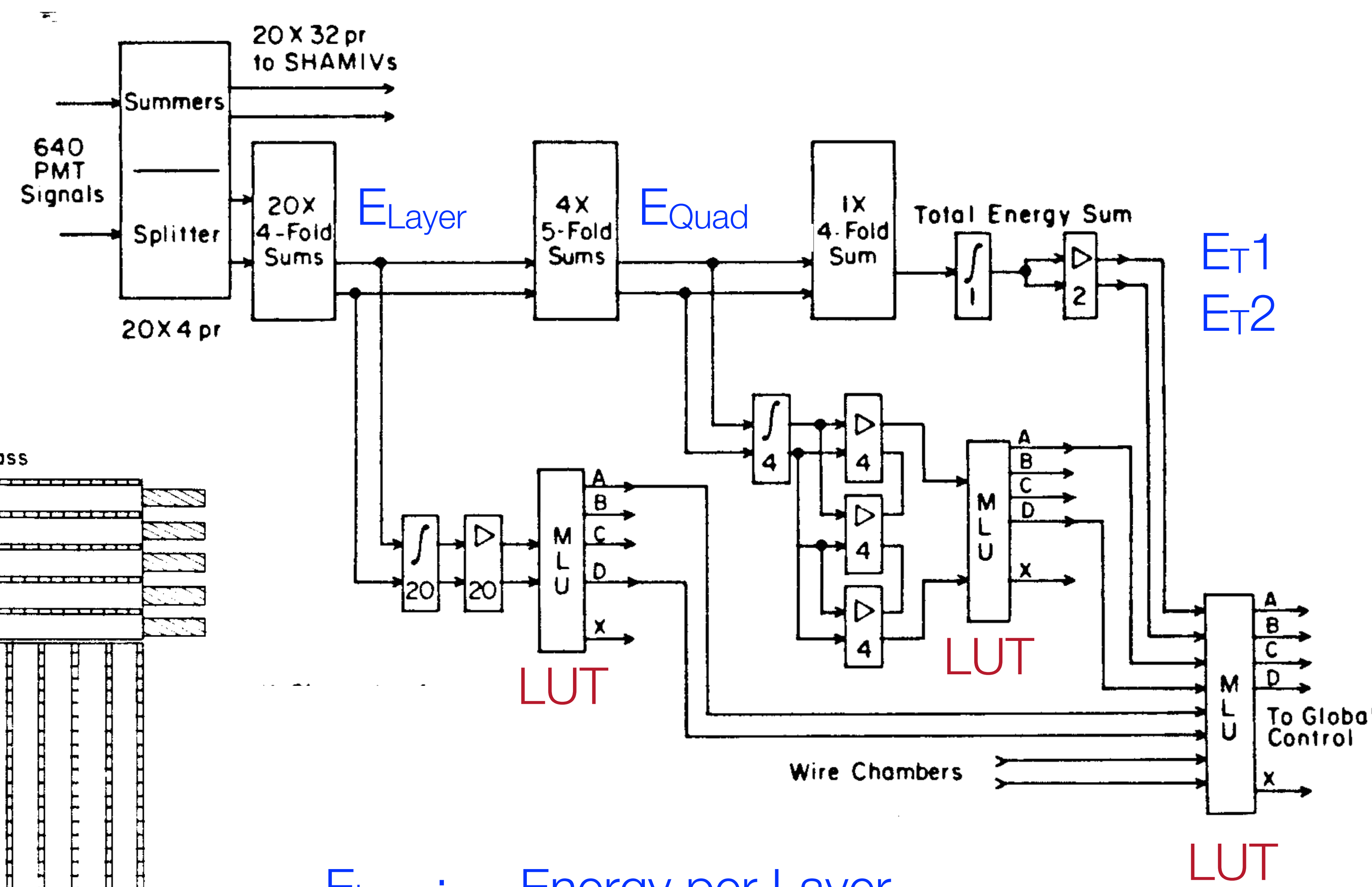
Different technologies to do in-situ signal analysis

[Choice depends on requirements]

Calorimeter Trigger – ASP Detector



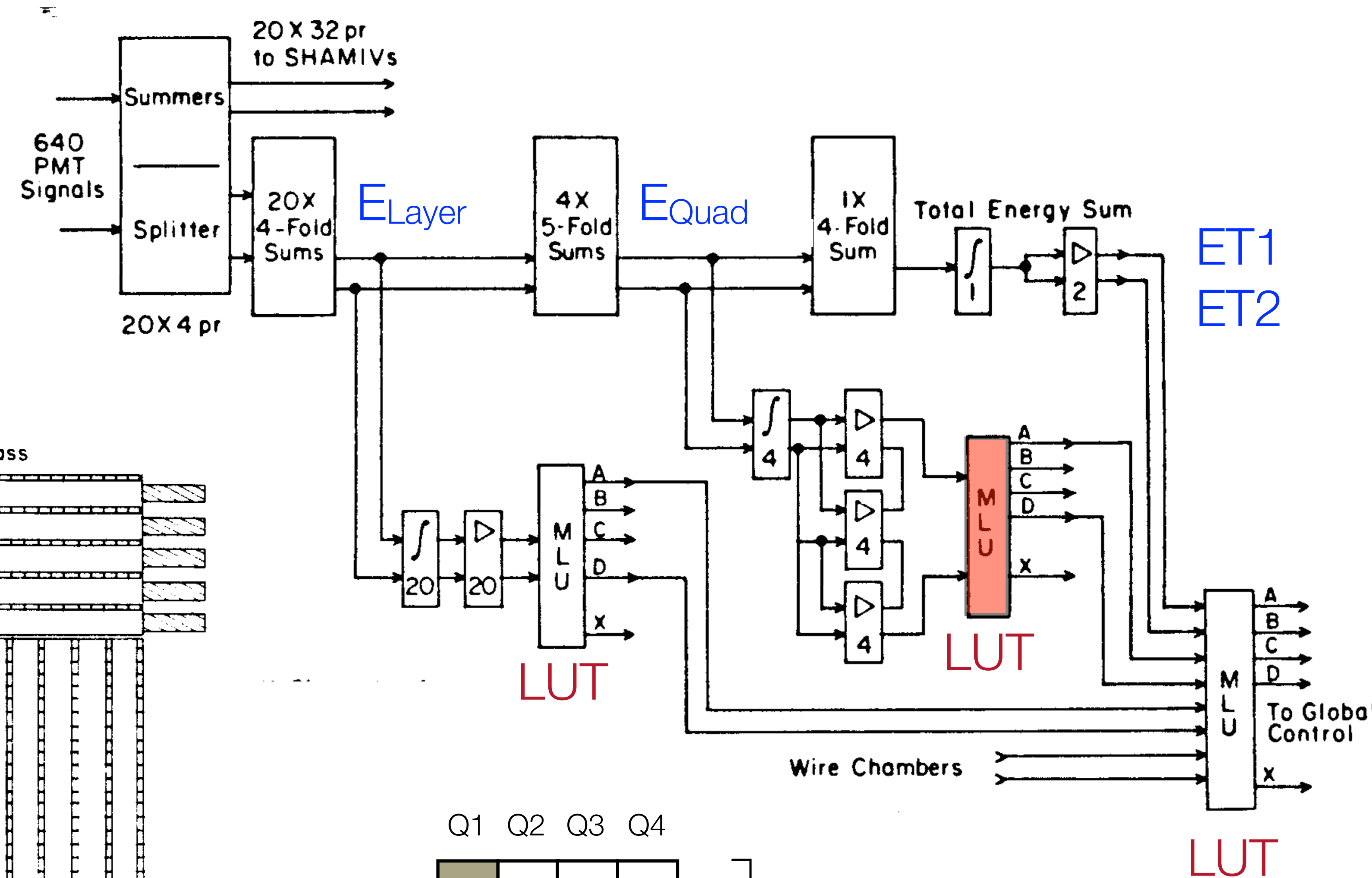
ASP Calorimeter
[Anomalous Single Photon Search]

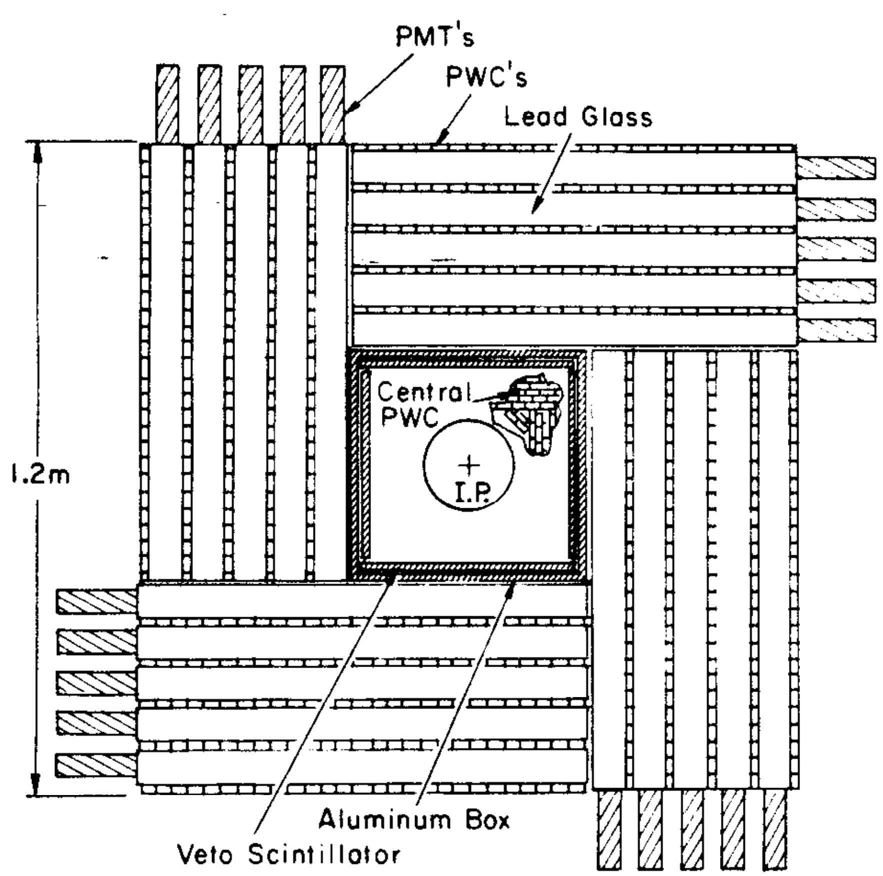


E_{Layer}: Energy per Layer
E_{Quad}: Energy per Quadrant
E_T: Total energy

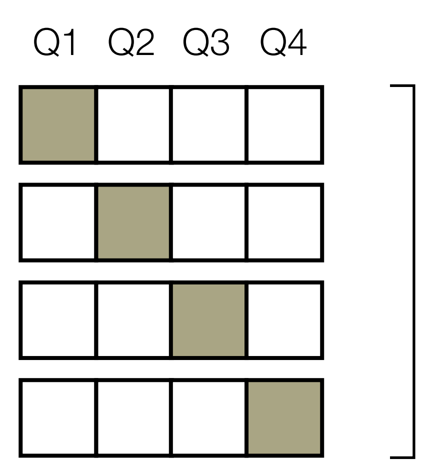
LUT: Look Up Table

Calorimeter Trigger – ASP Detector



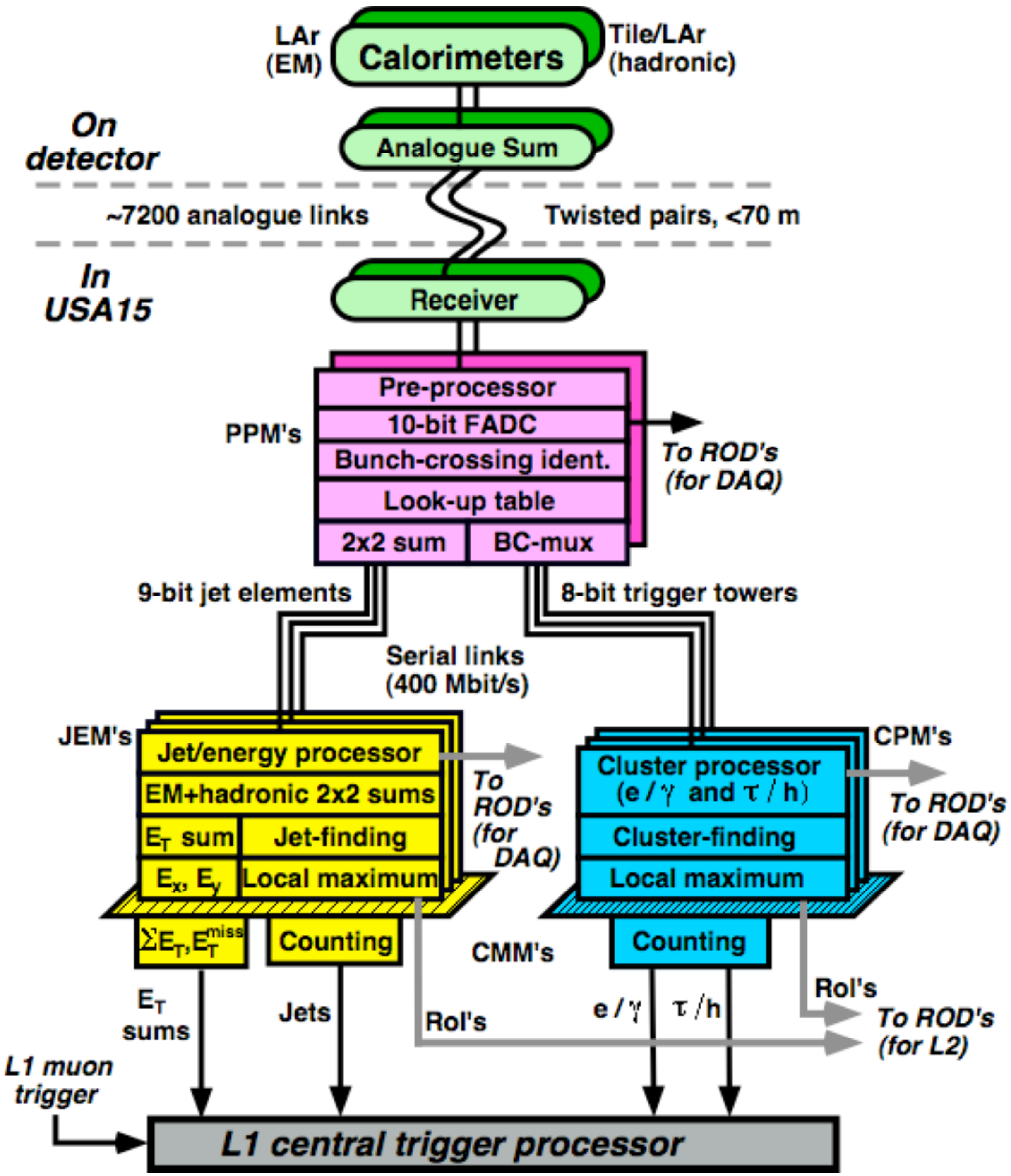


ASP Calorimeter
[Anomalous Single Photon Search]

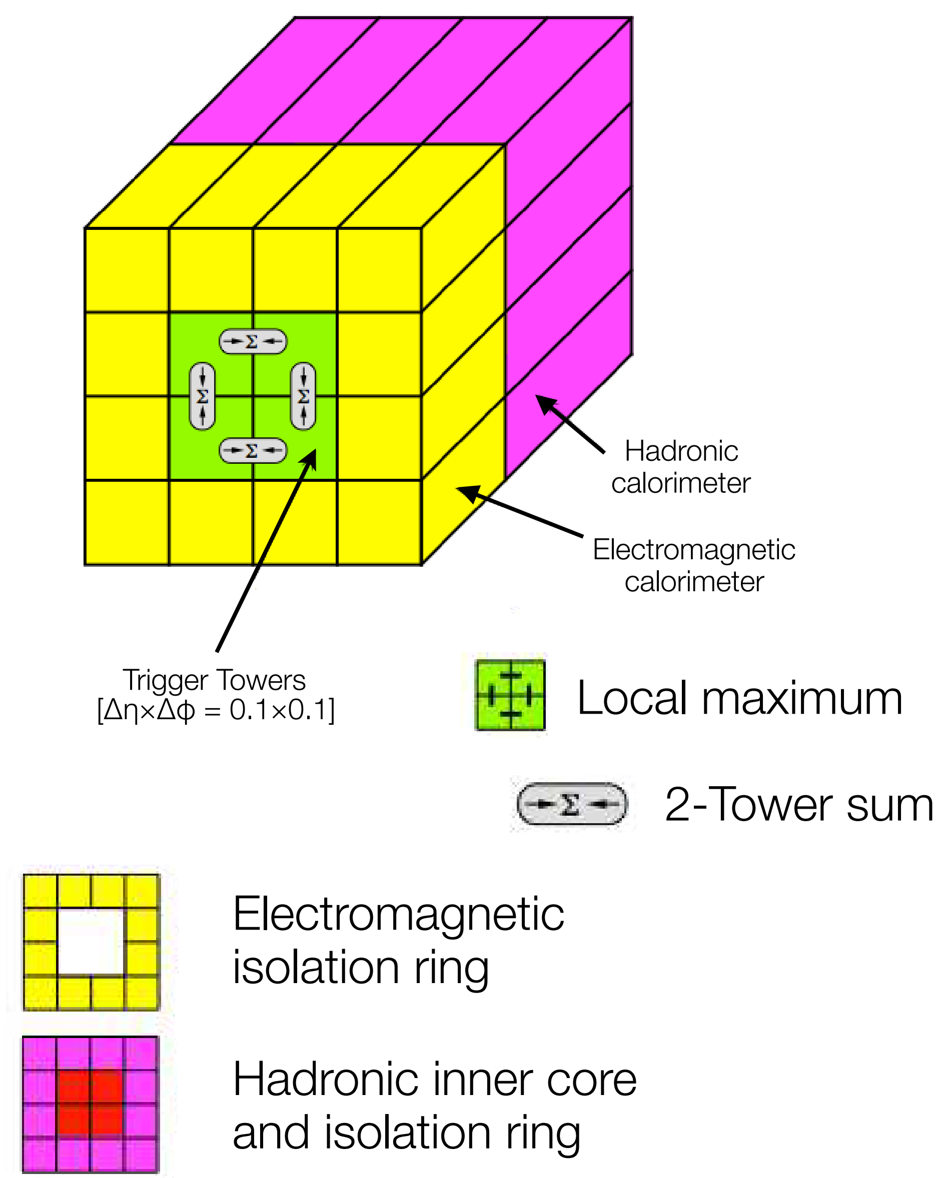


LUT addresses
generating trigger

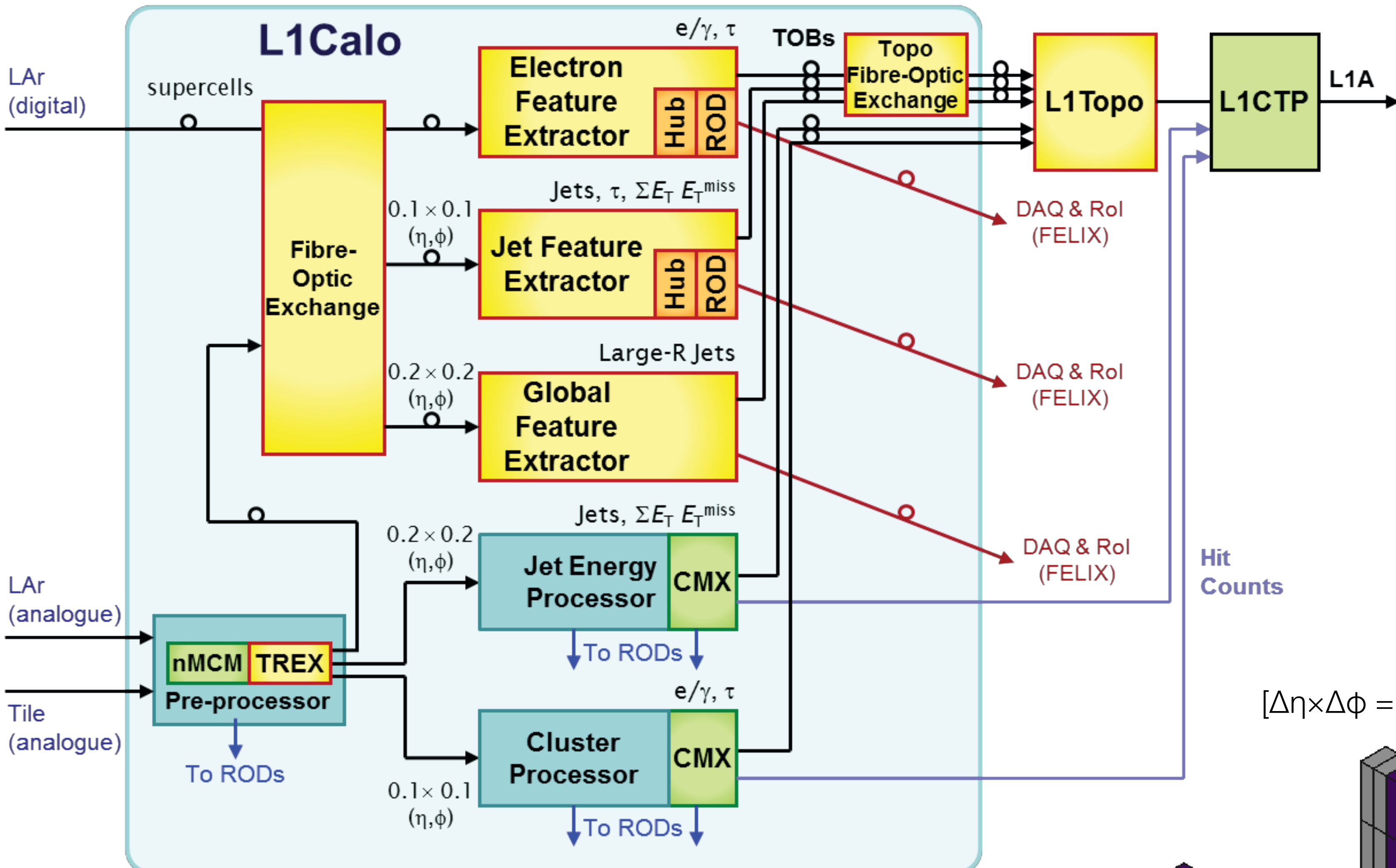
Calorimeter Trigger – ATLAS Run-1 & Run-2

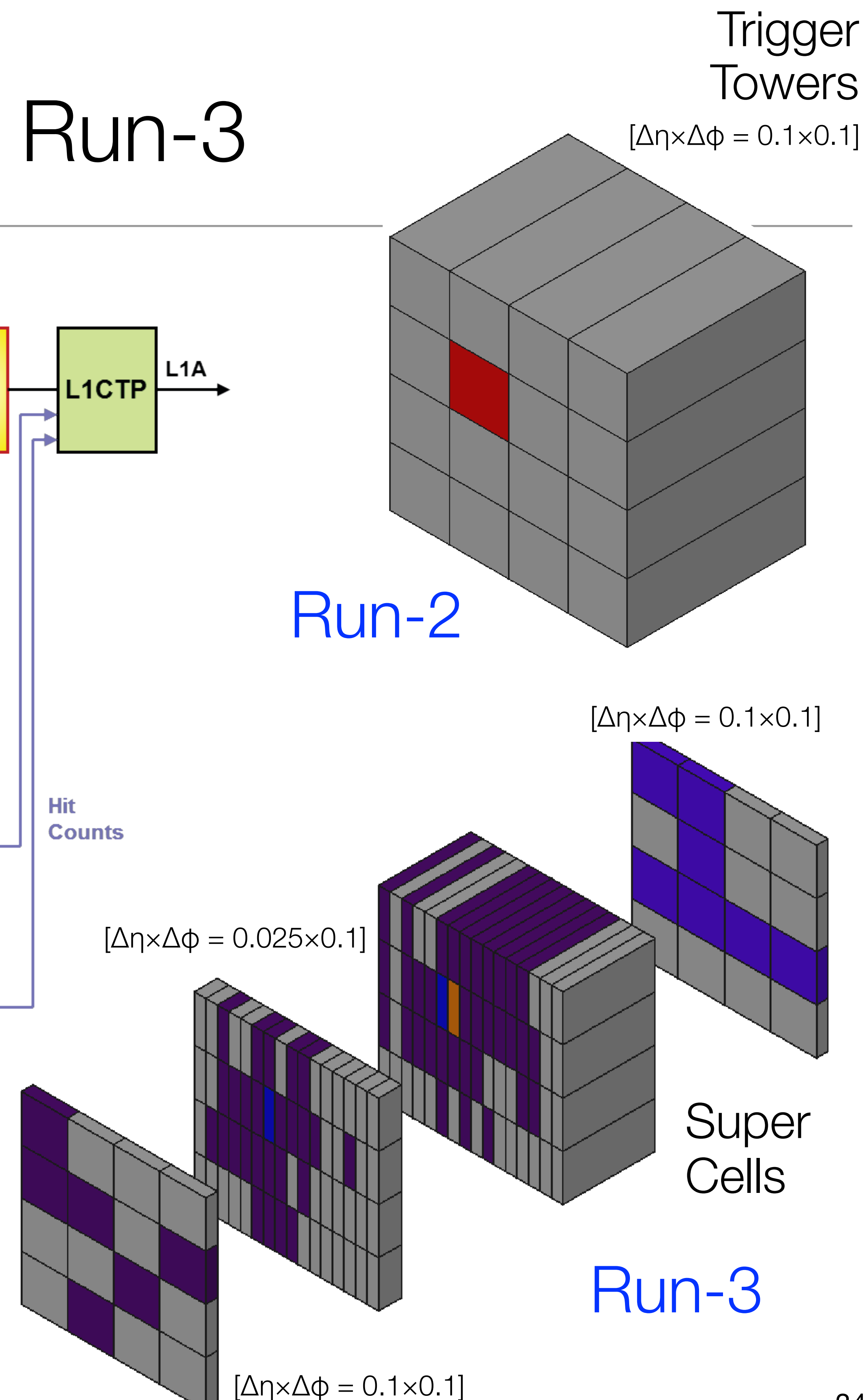


e/γ Identification



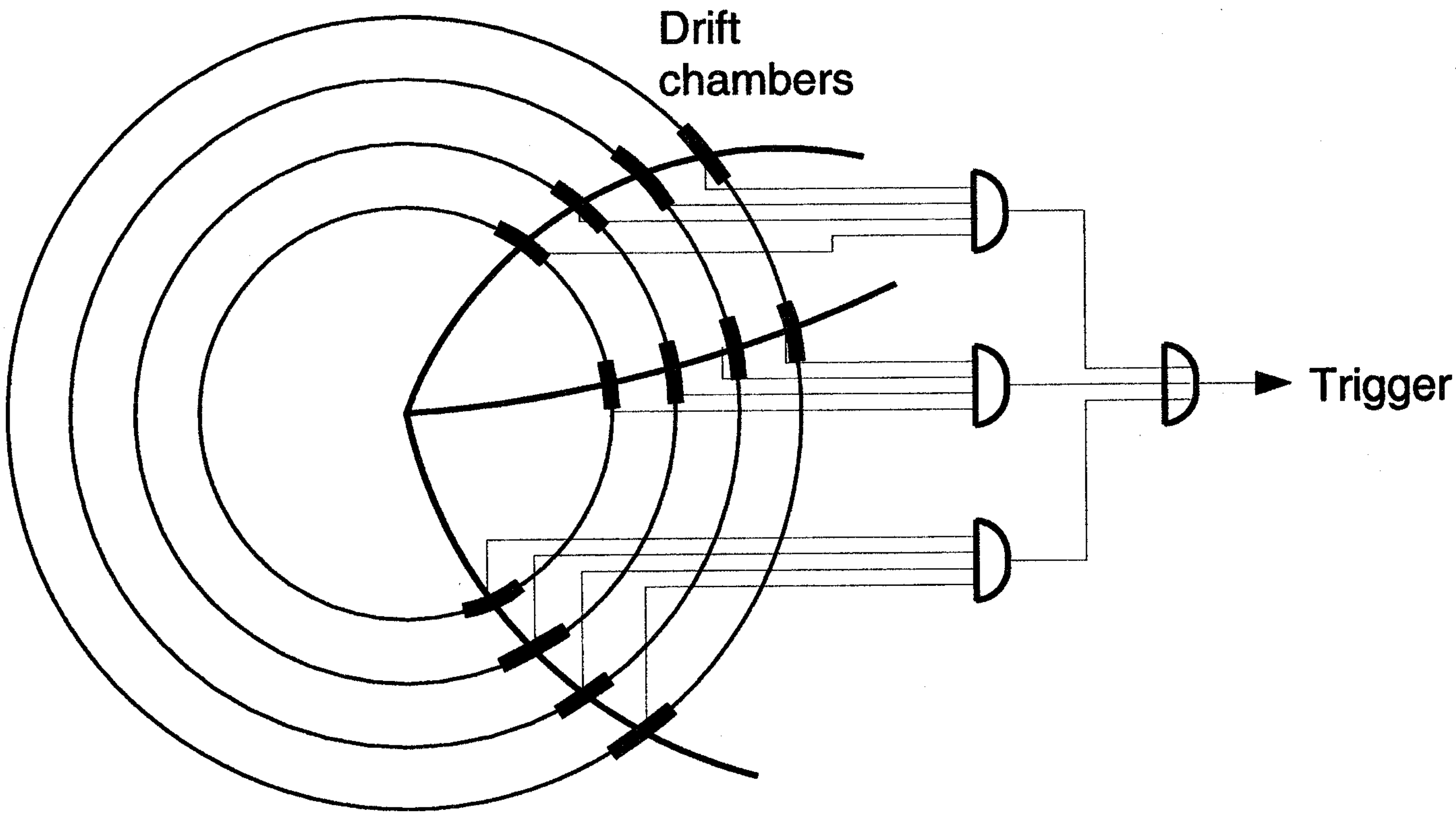
Calorimeter Trigger – ATLAS Run-3



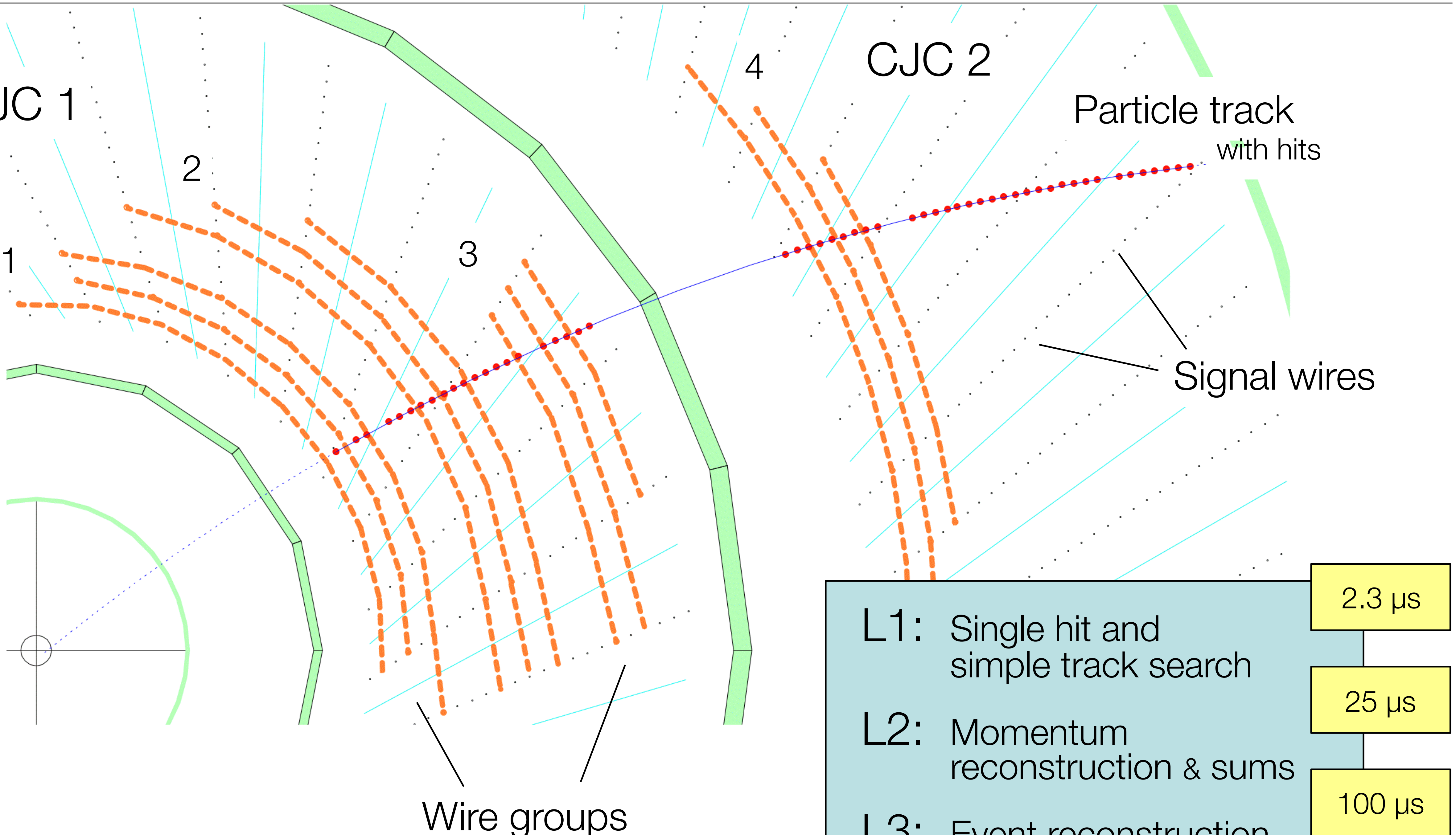


Toward higher granularity …

Tracking Triggers



Tracking Triggers – FTT @ H1



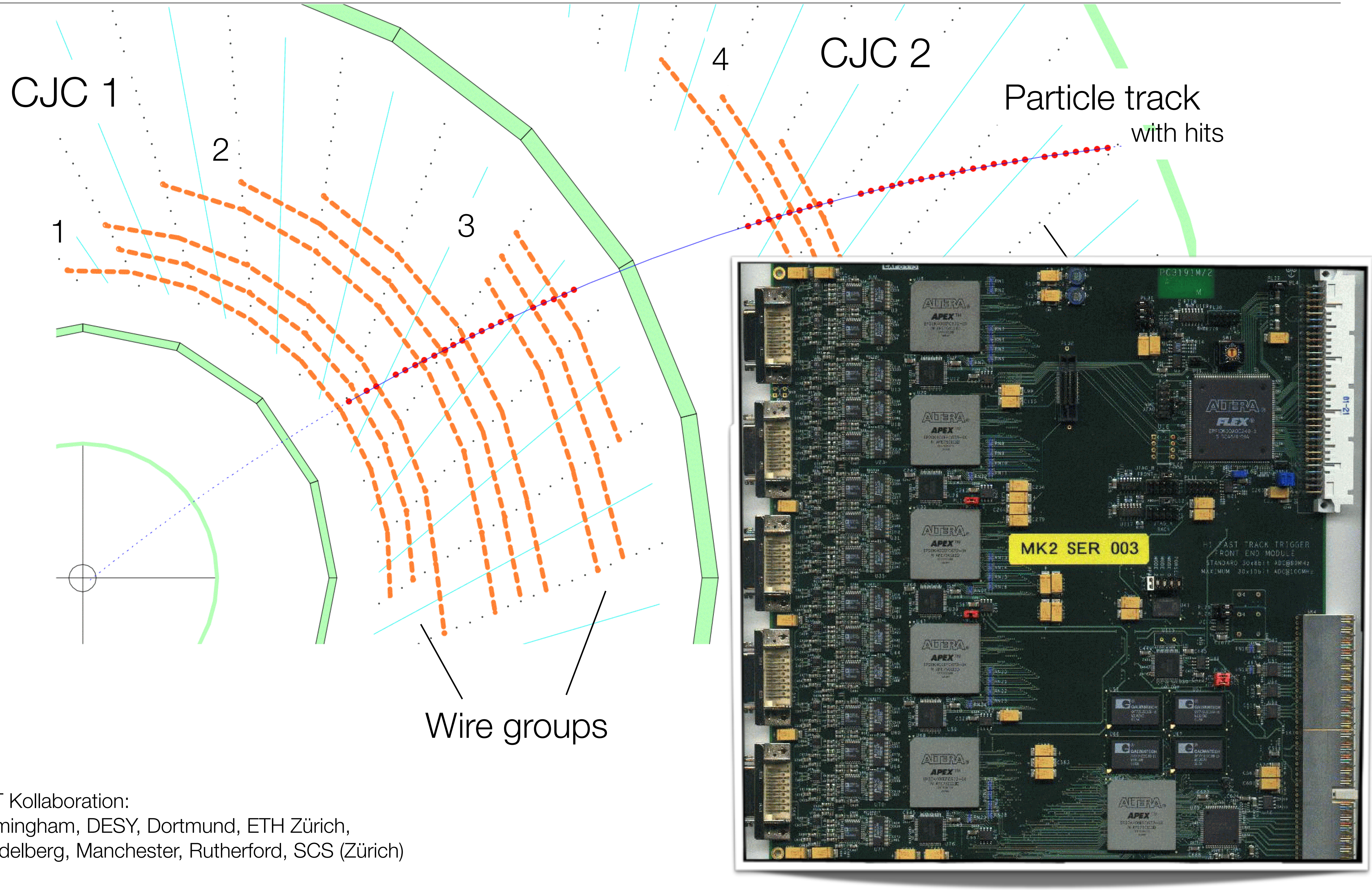
L1: Single hit and simple track search — 2.3 μs

L2: Momentum reconstruction & sums — 25 μs

L3: Event reconstruction Track-based topologies Invariant Masses — 100 μs

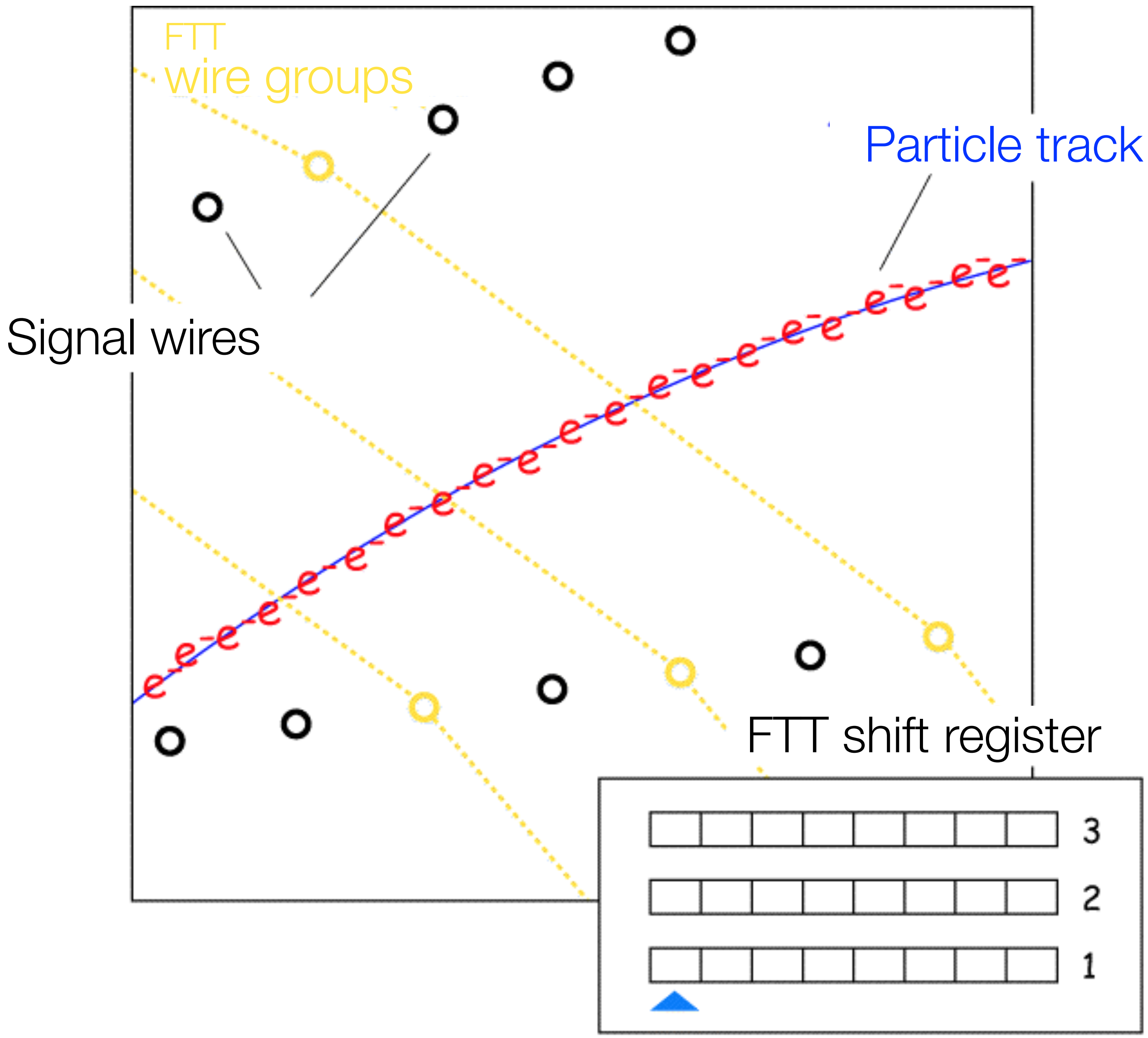
FTT Kollaboration:
Birmingham, DESY, Dortmund, ETH Zürich,
Heidelberg, Manchester, Rutherford, SCS (Zürich)

Tracking Triggers – FTT @ H1

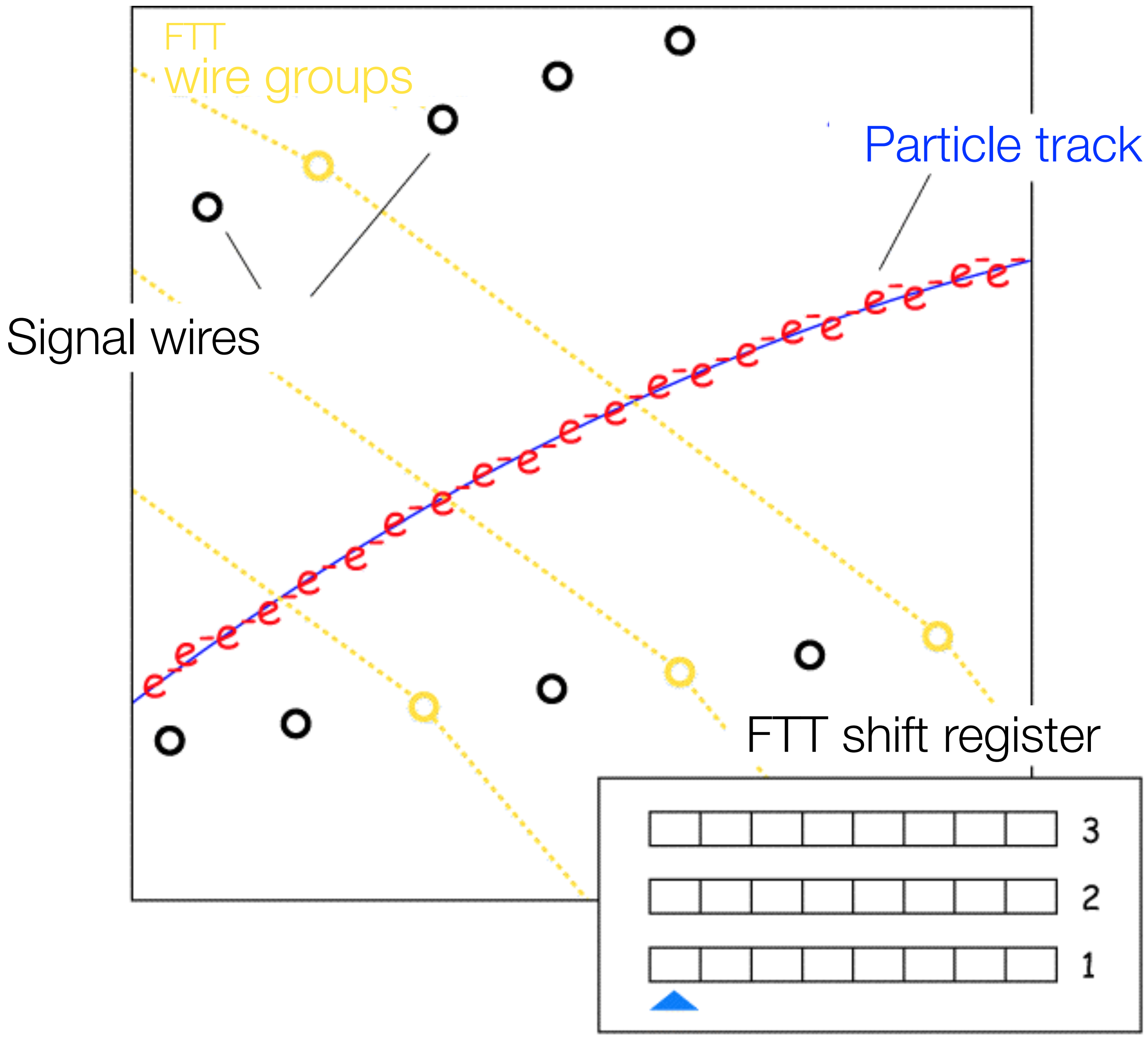


FTT Kollaboration:
Birmingham, DESY, Dortmund, ETH Zürich,
Heidelberg, Manchester, Rutherford, SCS (Zürich)

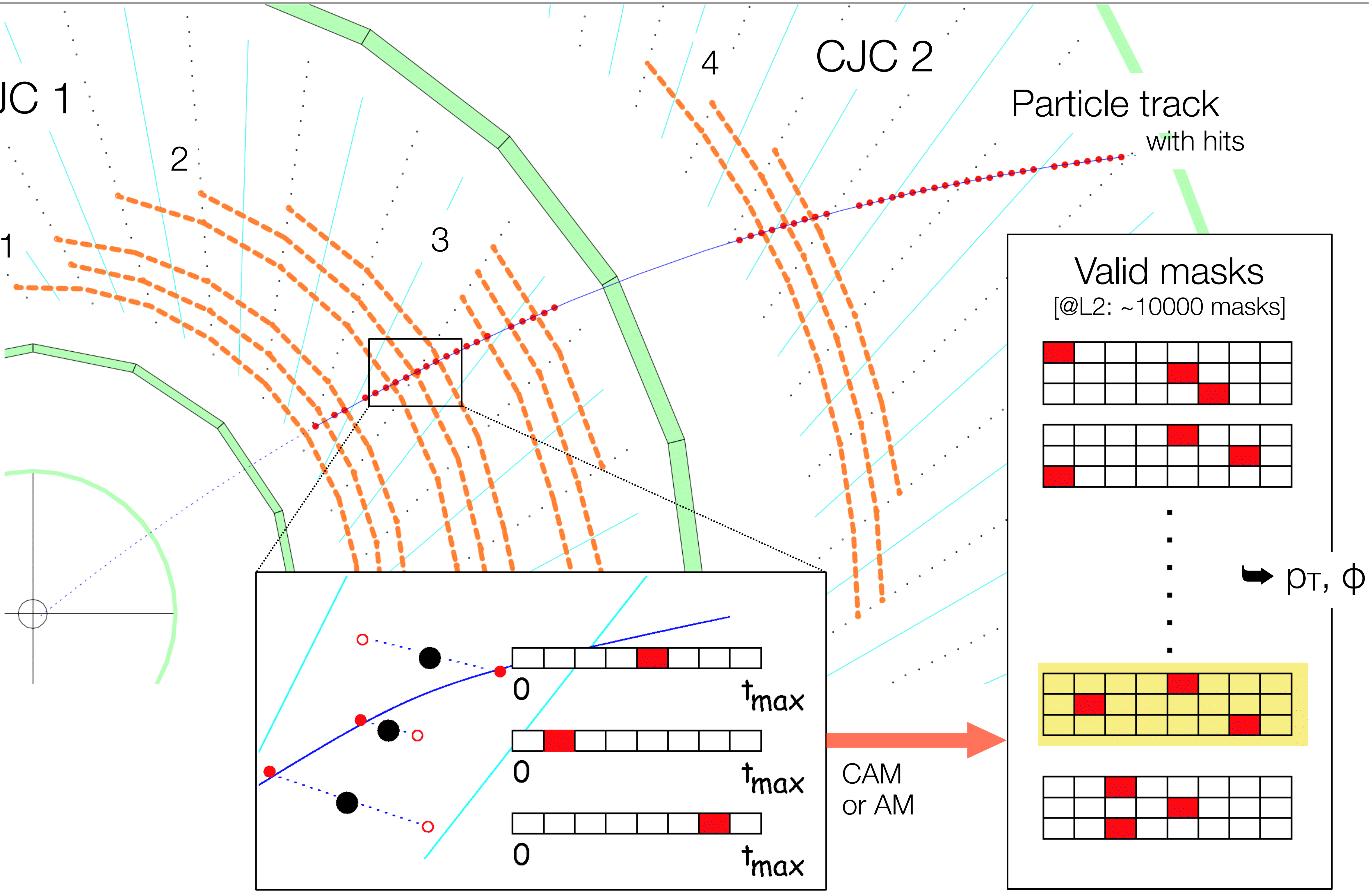
Tracking Triggers – FTT @ H1



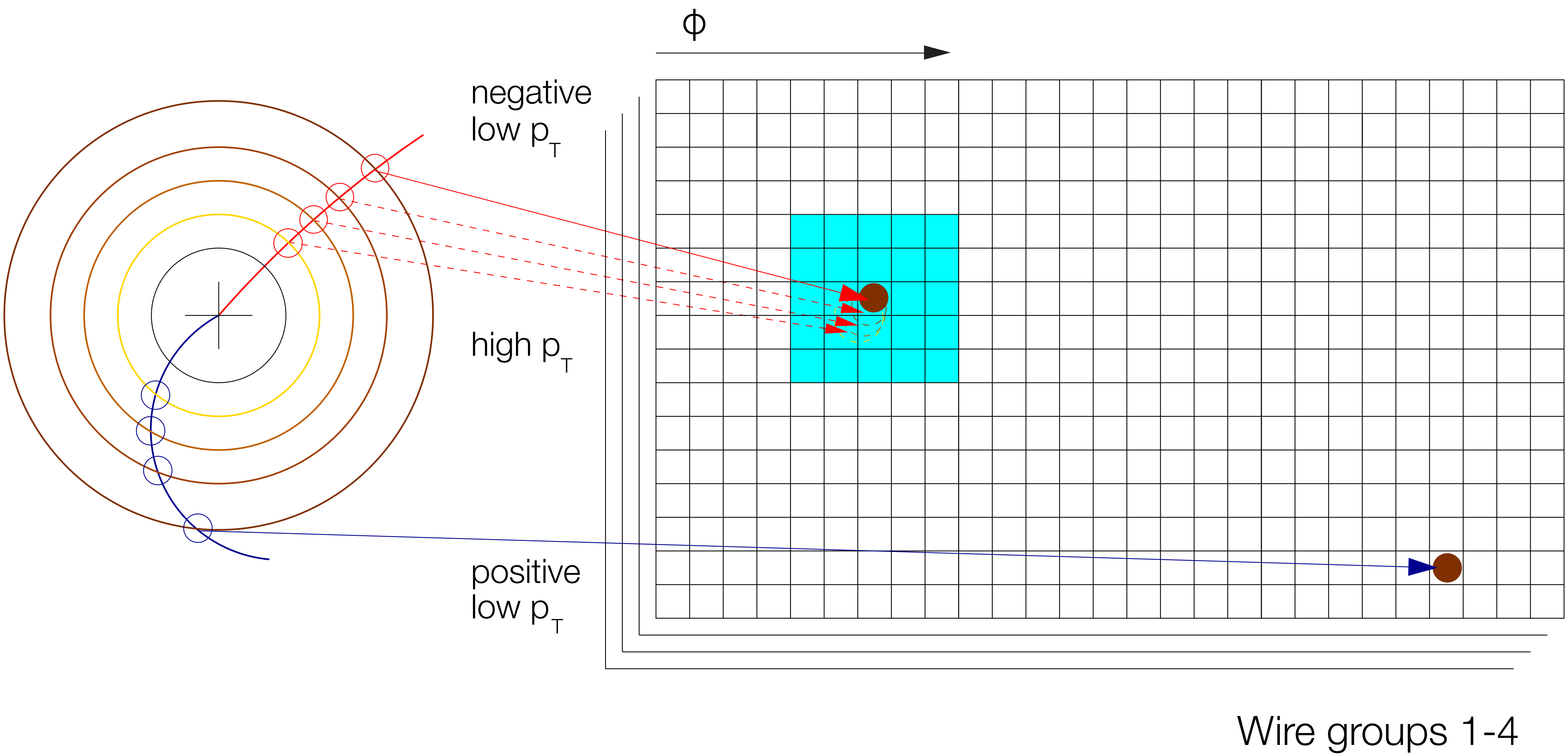
Tracking Triggers – FTT @ H1



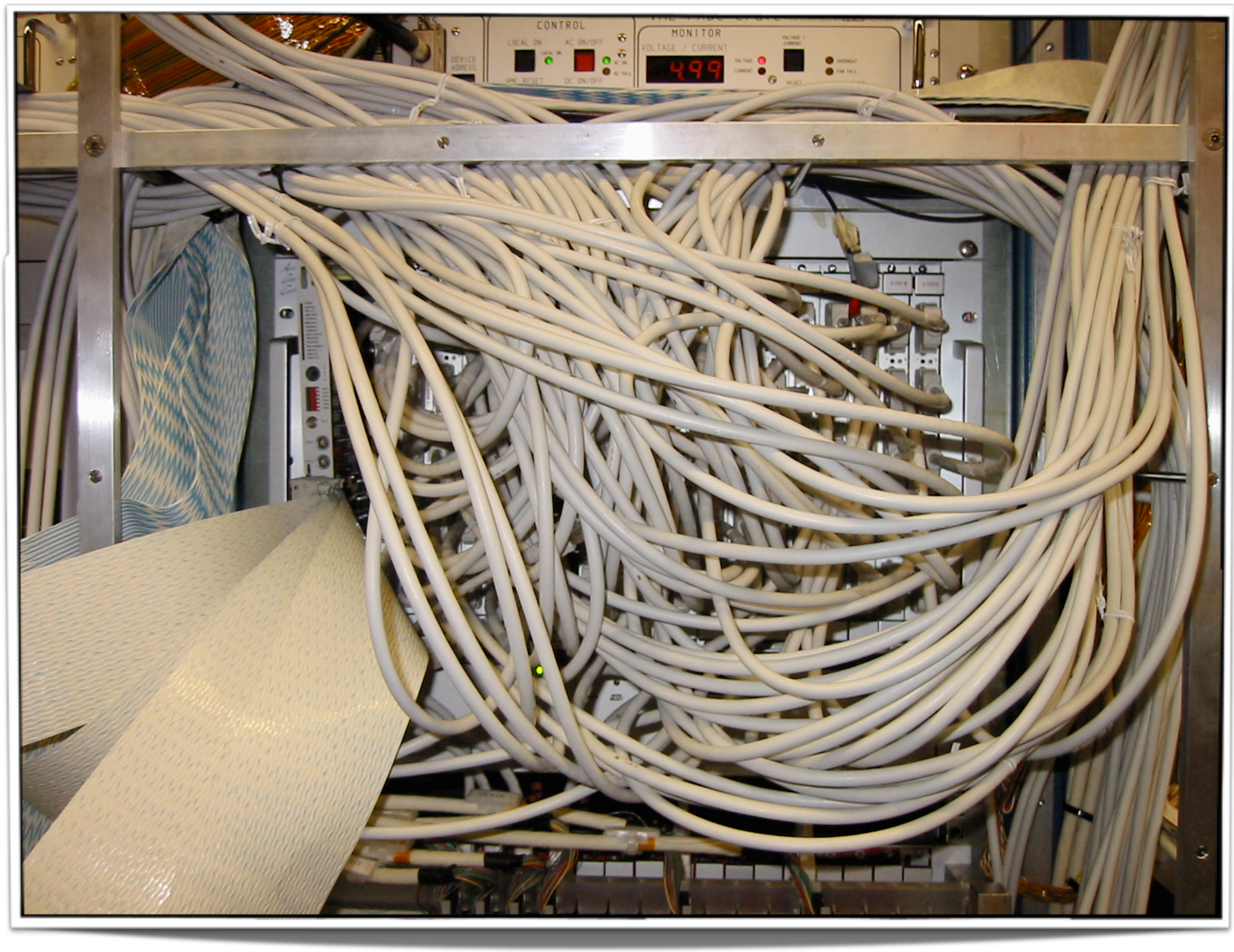
Tracking Triggers – FTT @ H1



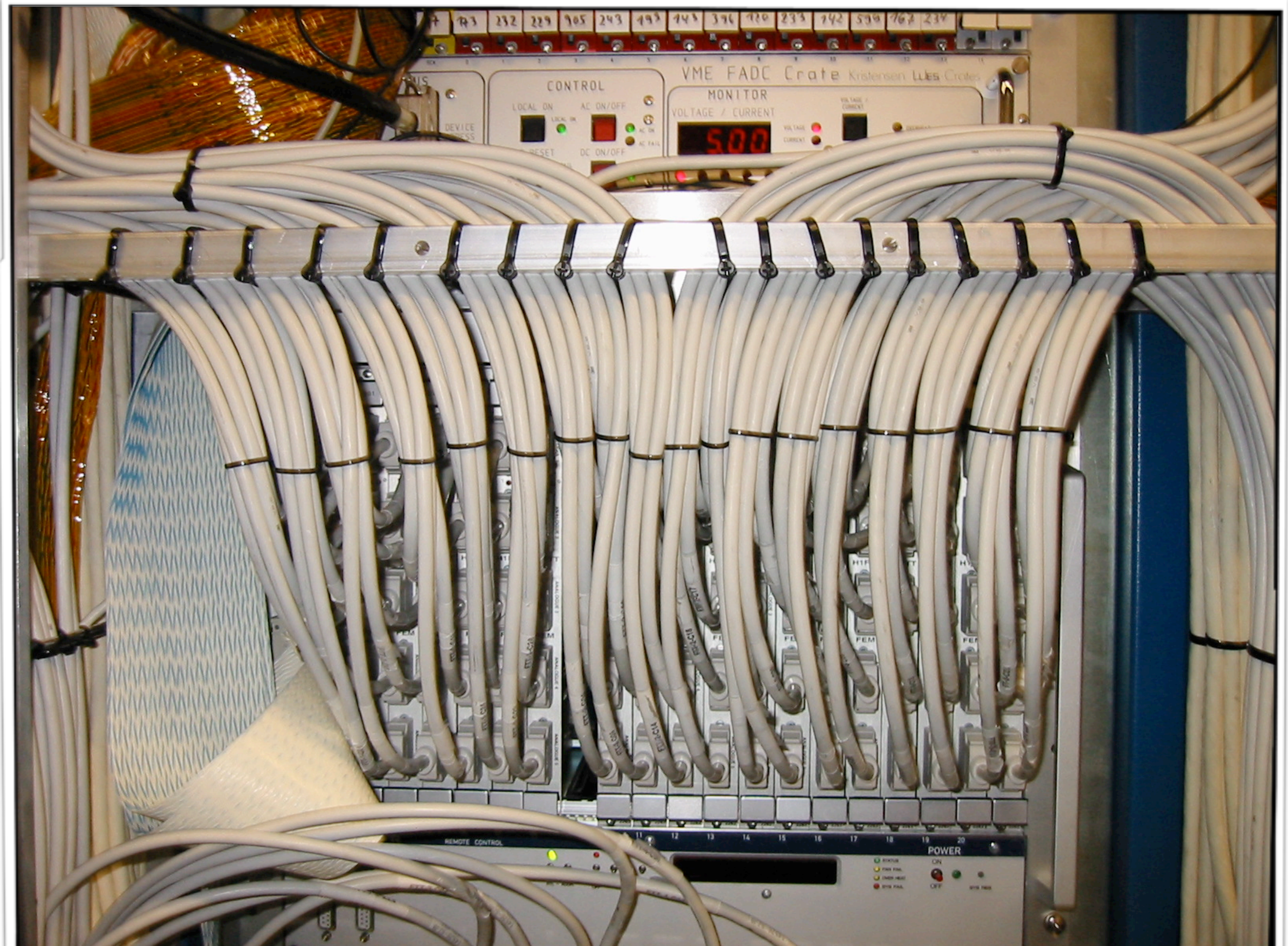
Finding tracks from segments …



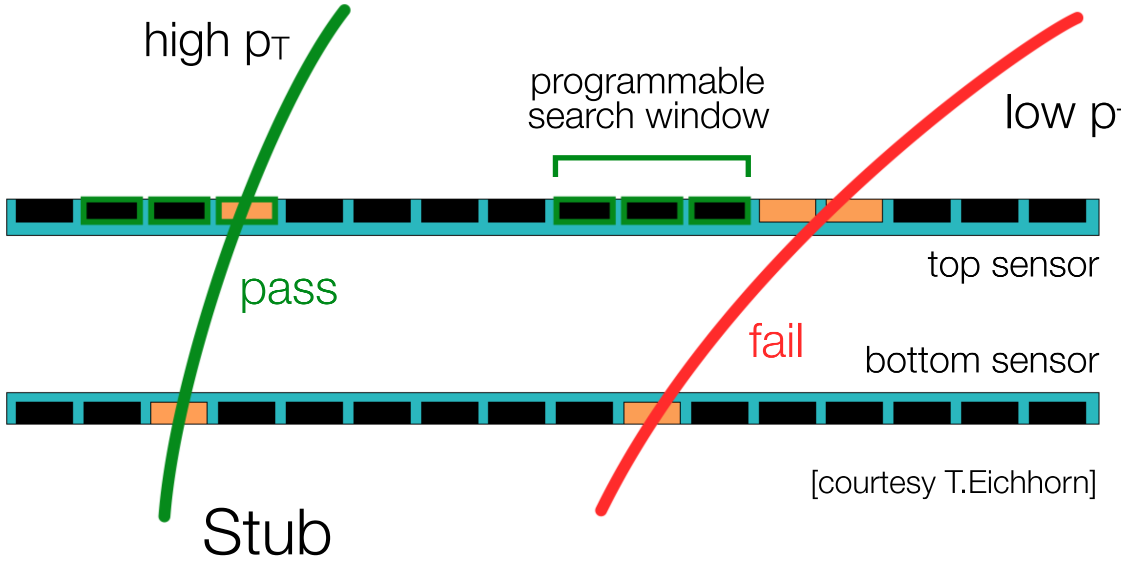
Tracking Triggers – FTT @ H1



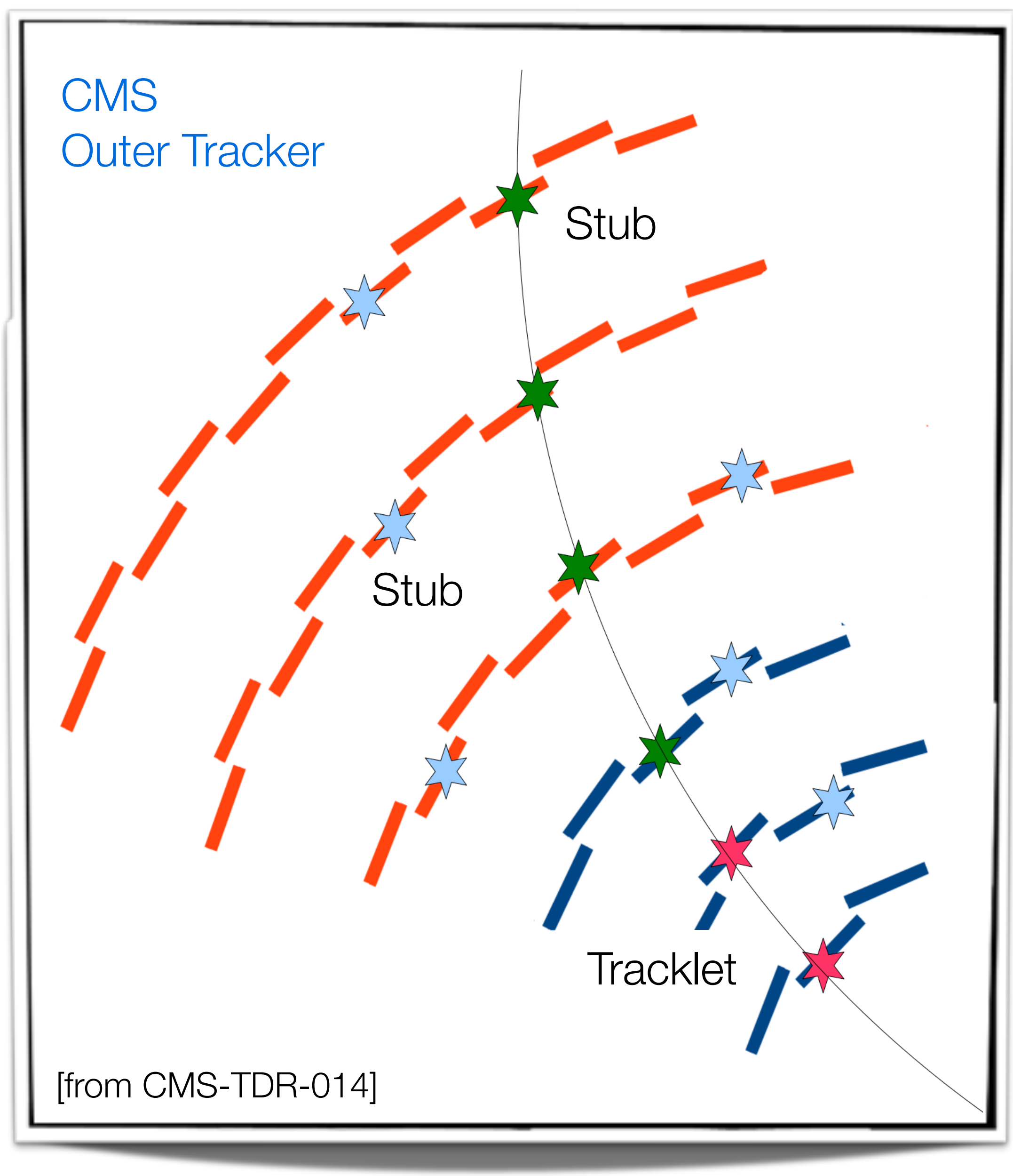
Tracking Triggers – FTT @ H1

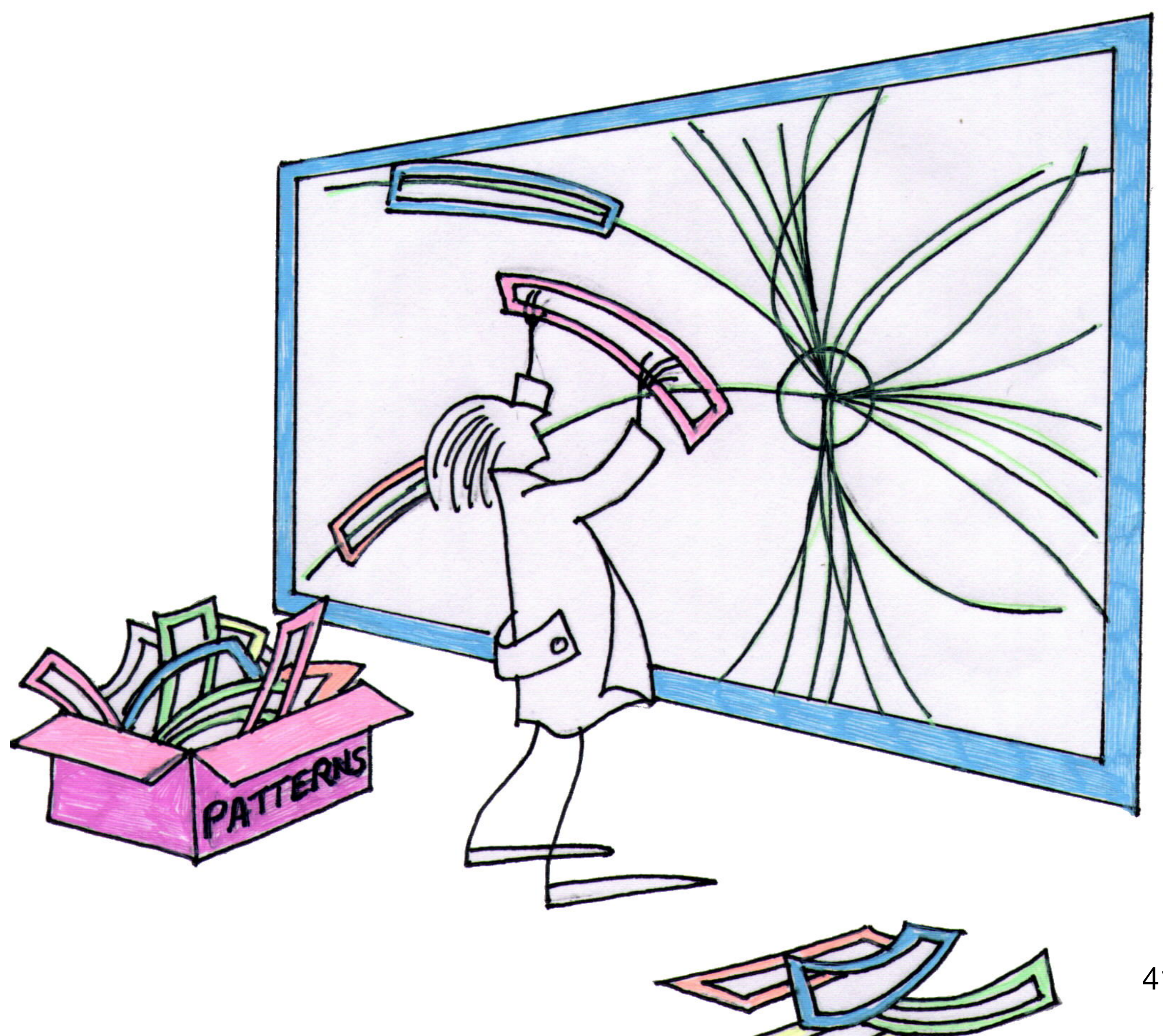


CMS Tracking @ Level-1

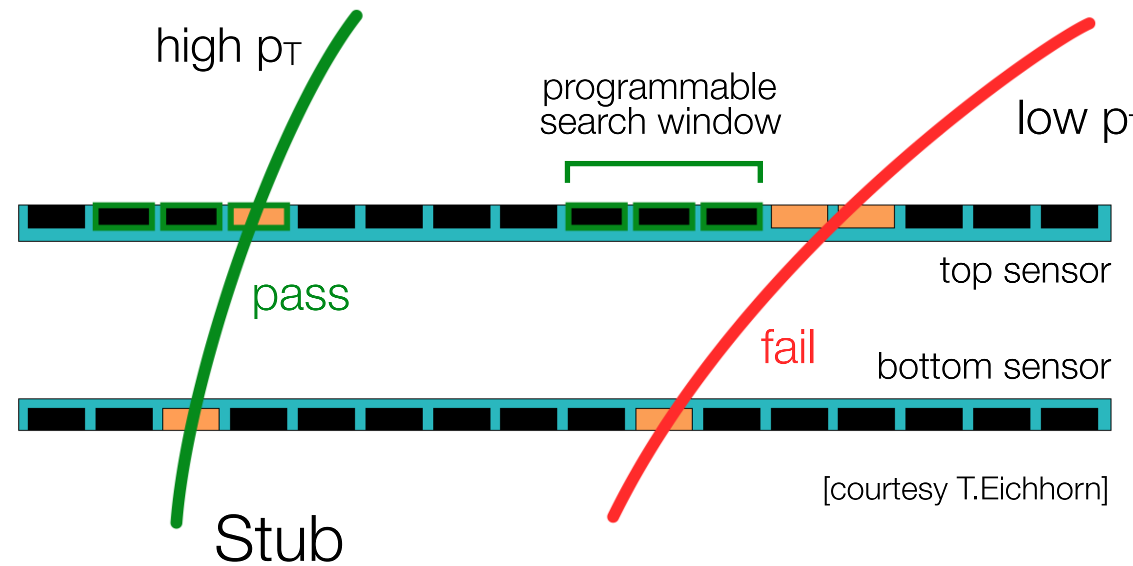


Tracking based on correlated hit pairs (‘stubs’) & tracklets (stub pairs)

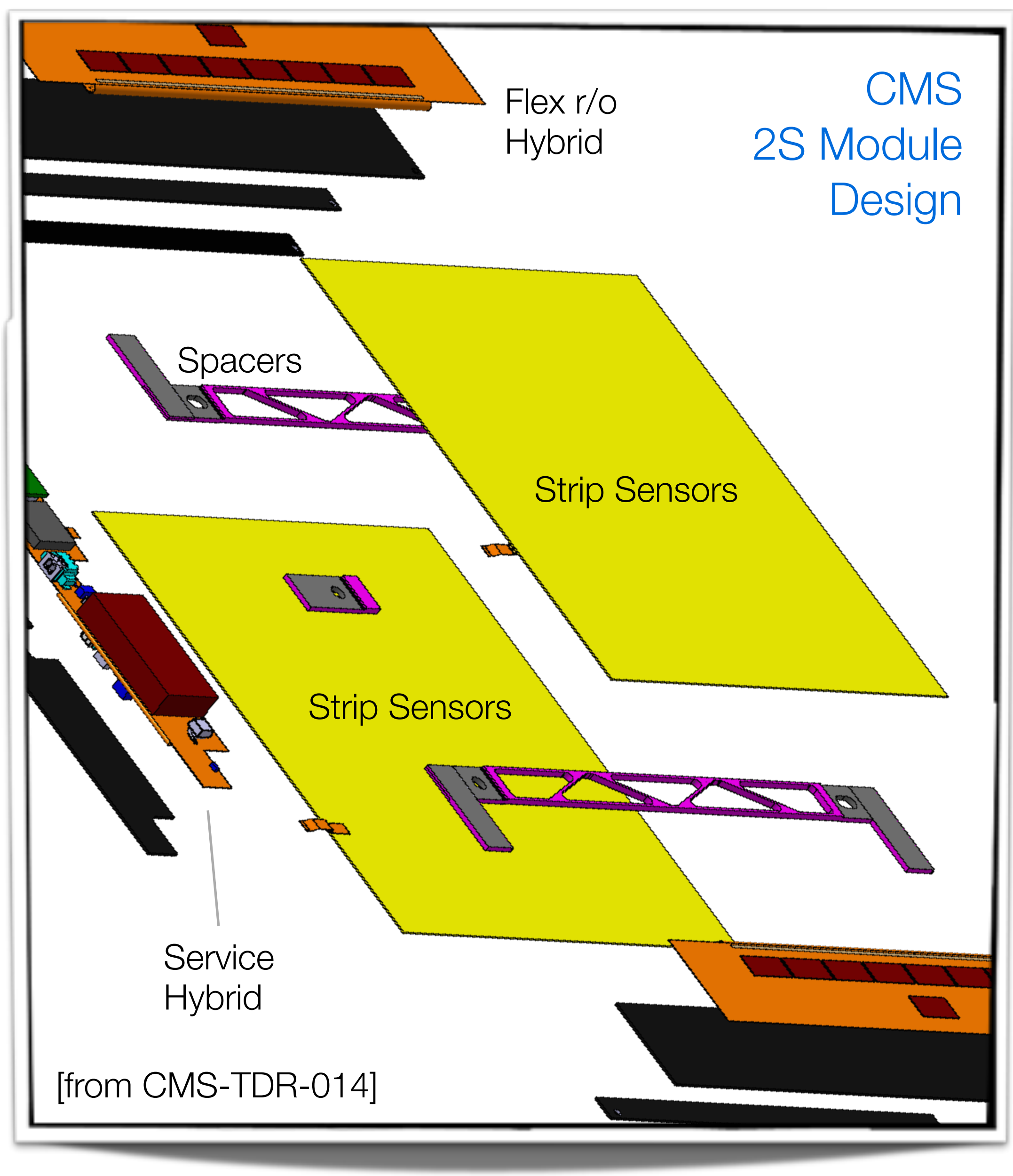


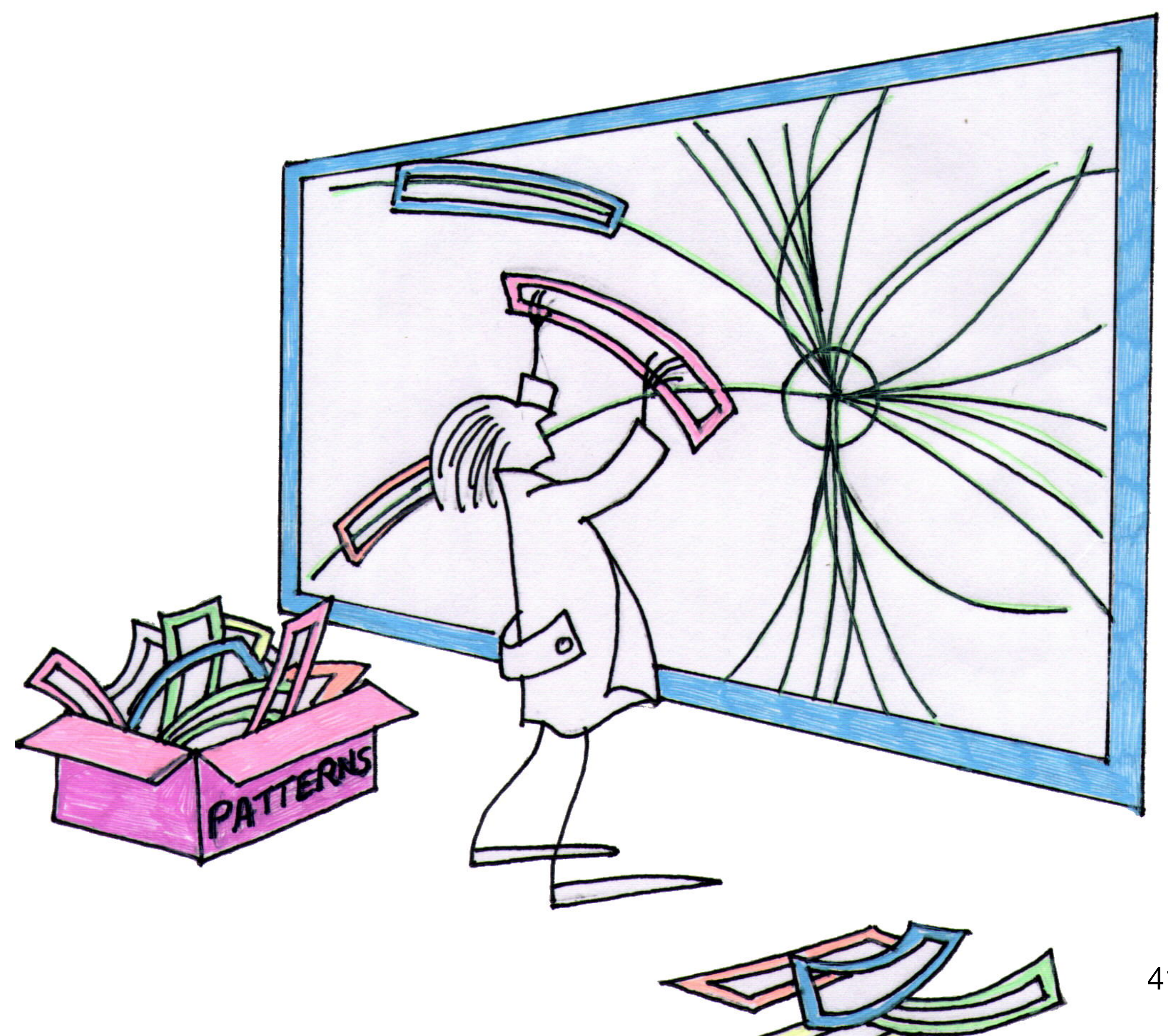


CMS Tracking @ Level-1



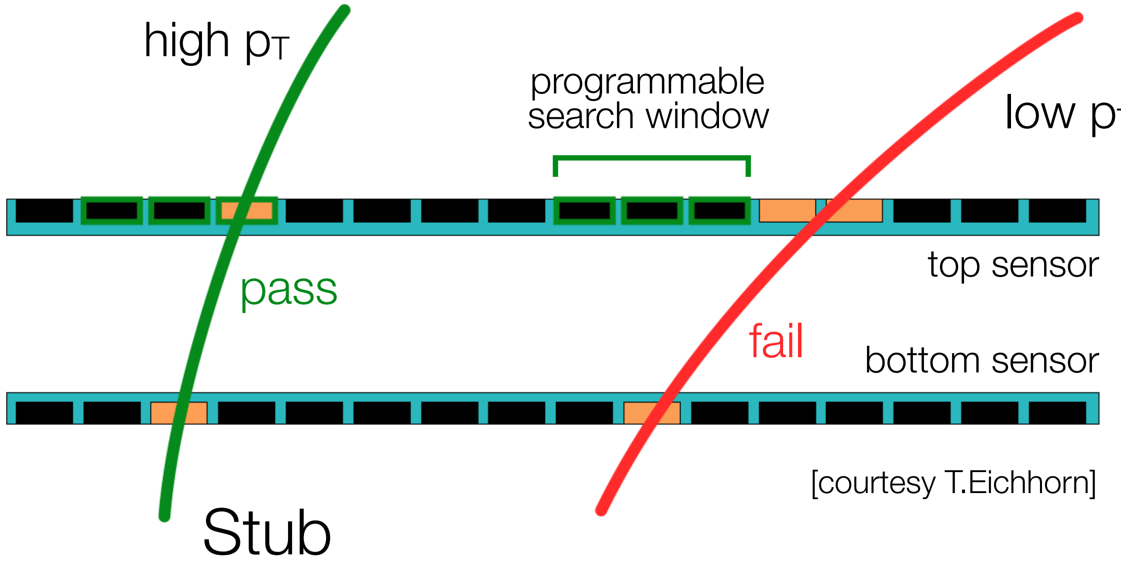
Requires double-sided
silicon pixel/strip modules …

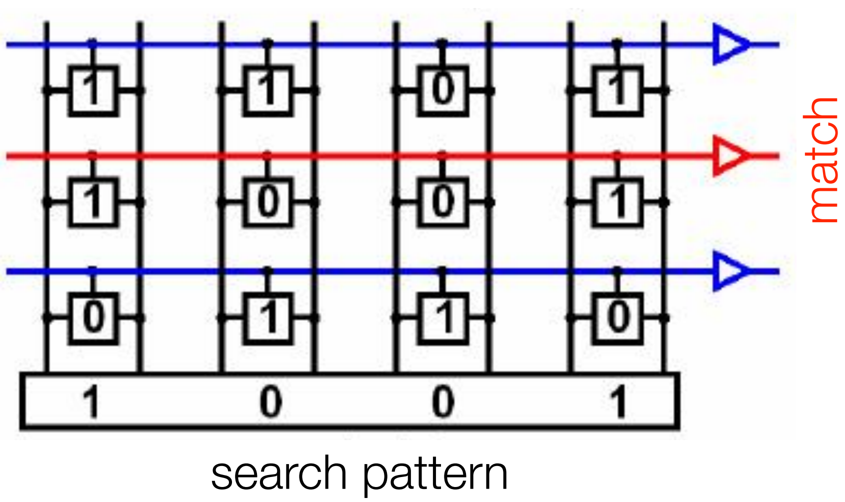


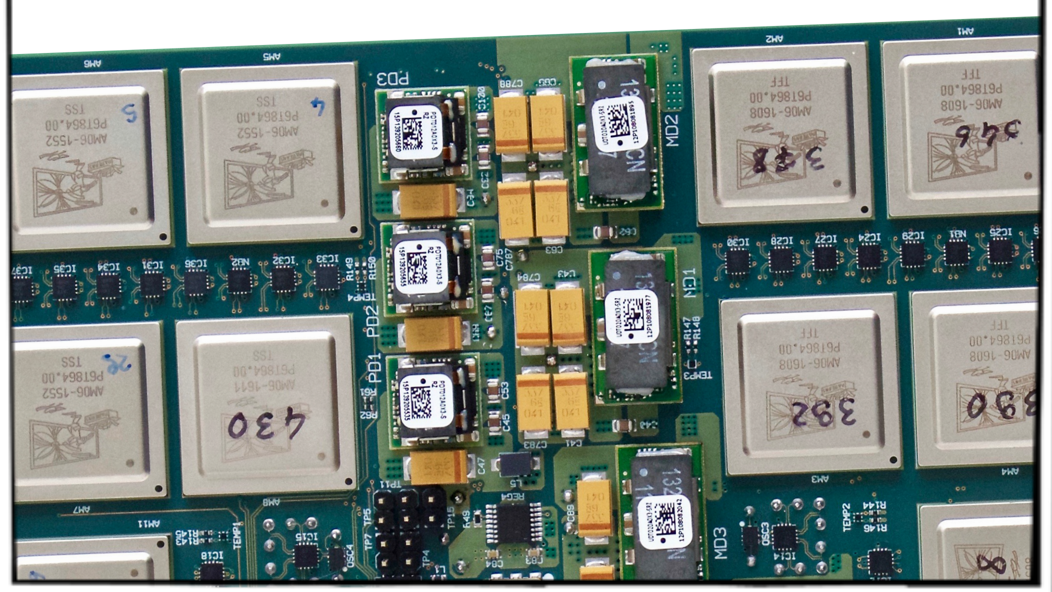


CMS Tracking @ Level-1

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

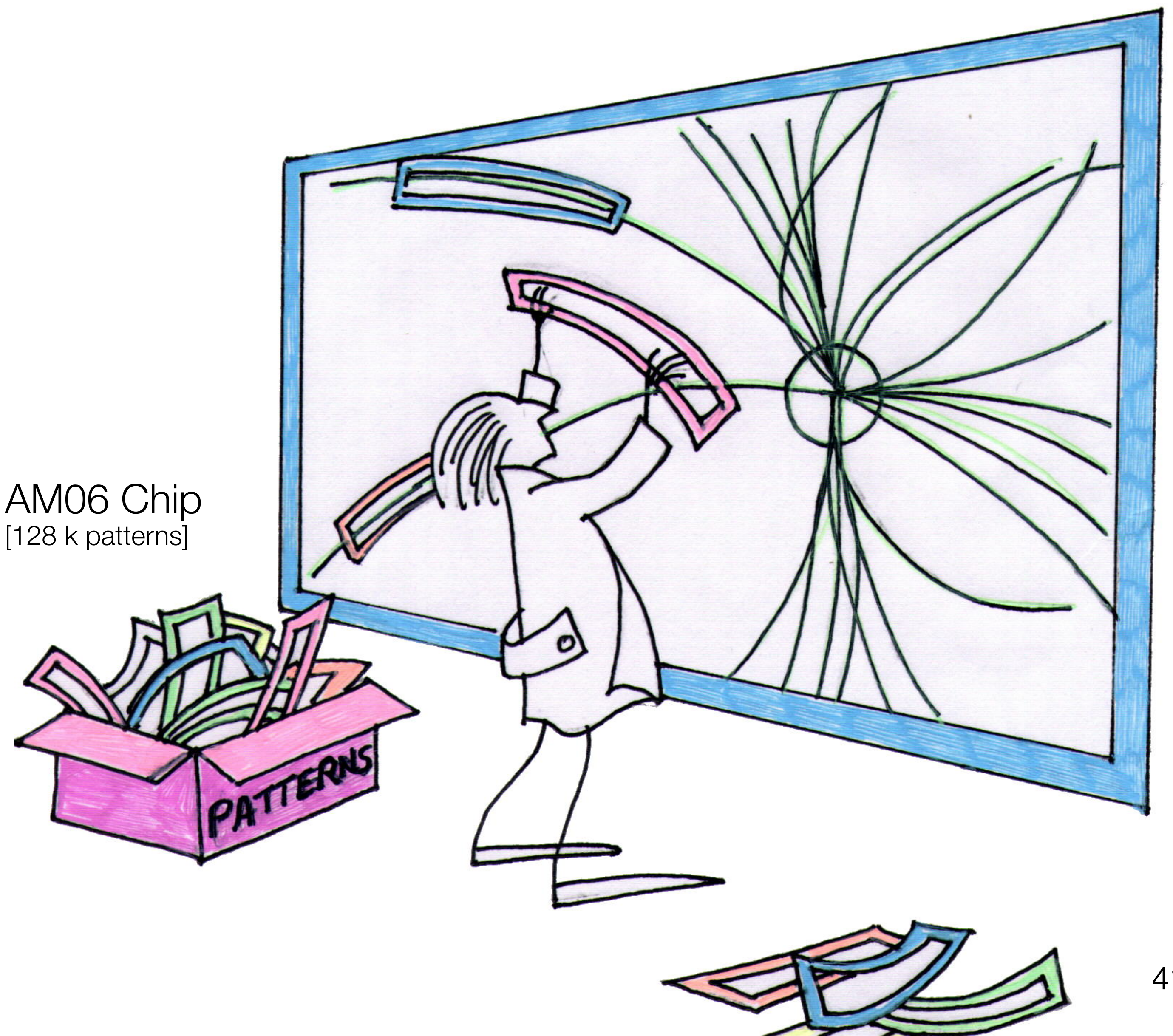






PRM Prototype

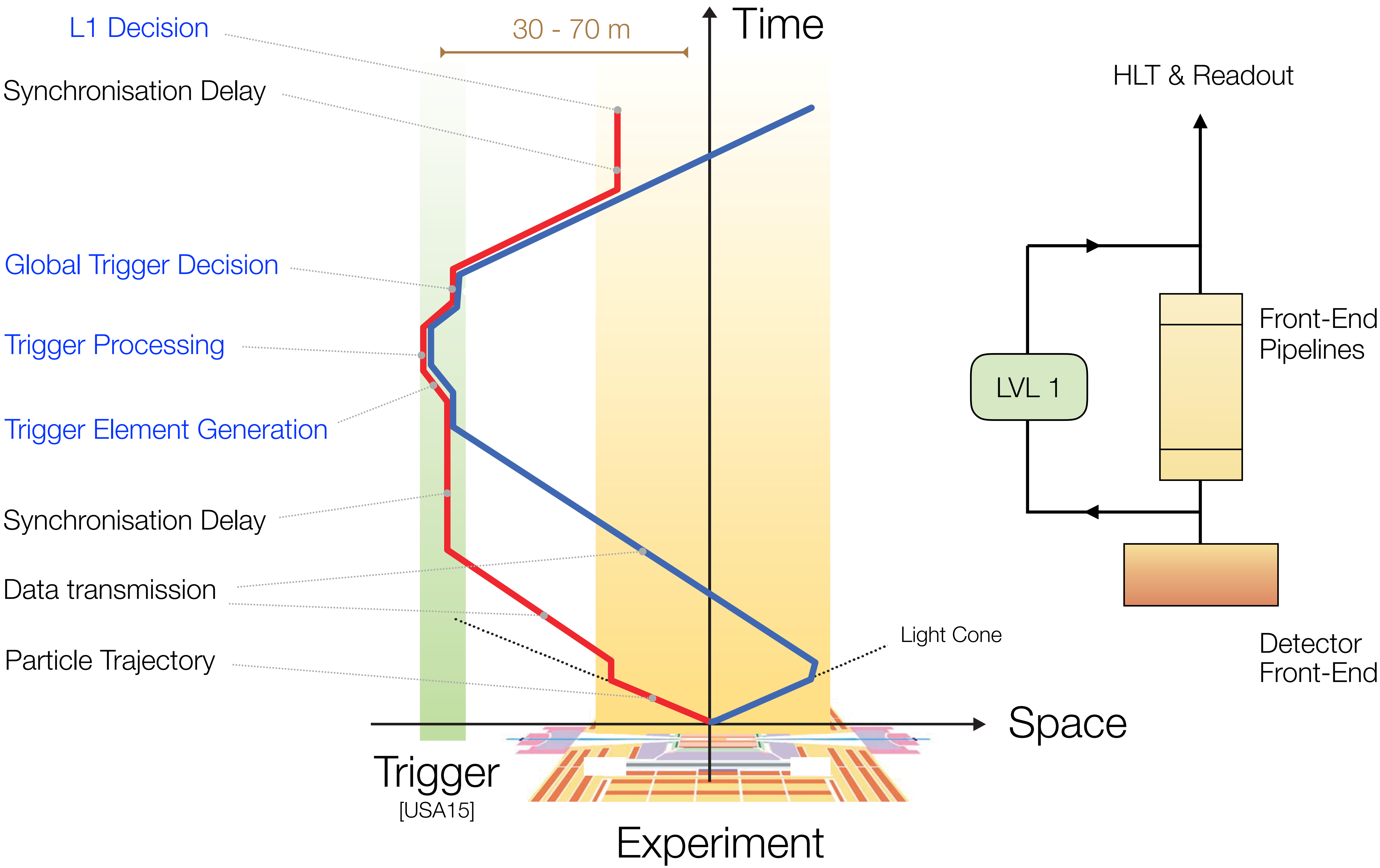
AM06 Chip
[128 k patterns]



Epilogue

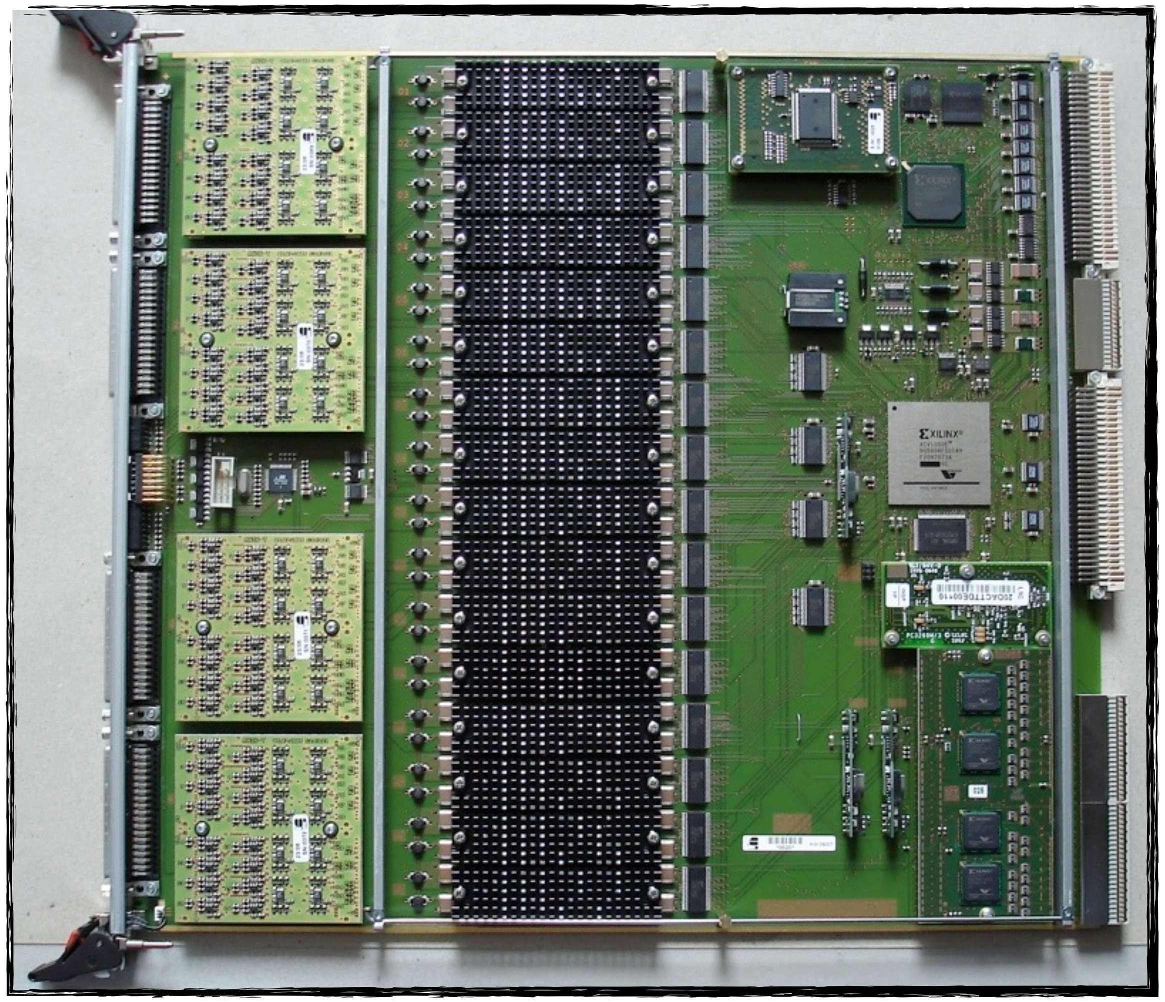
“Synchronization Challenge by Example”

Trigger Real-Time Path [Level-1]



Example: ATLAS L1 Calorimeter Trigger

The L1Calo Pre-Processor System



PreProcessor

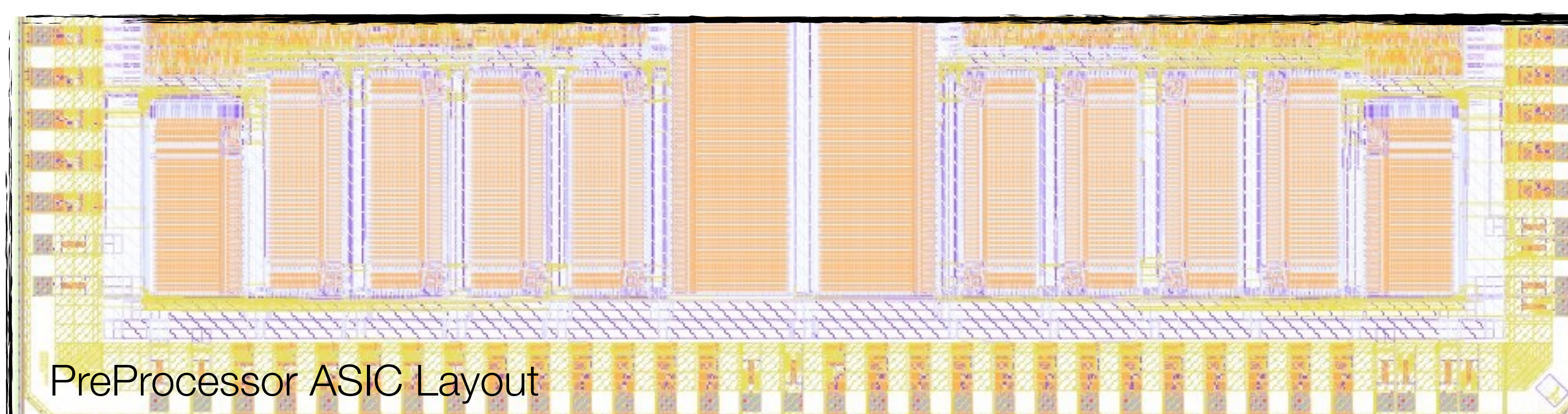
PPr Latency: 0.4 μs
Modules: 124

Input:

About 7000 analogue calorimeter signals

Output:

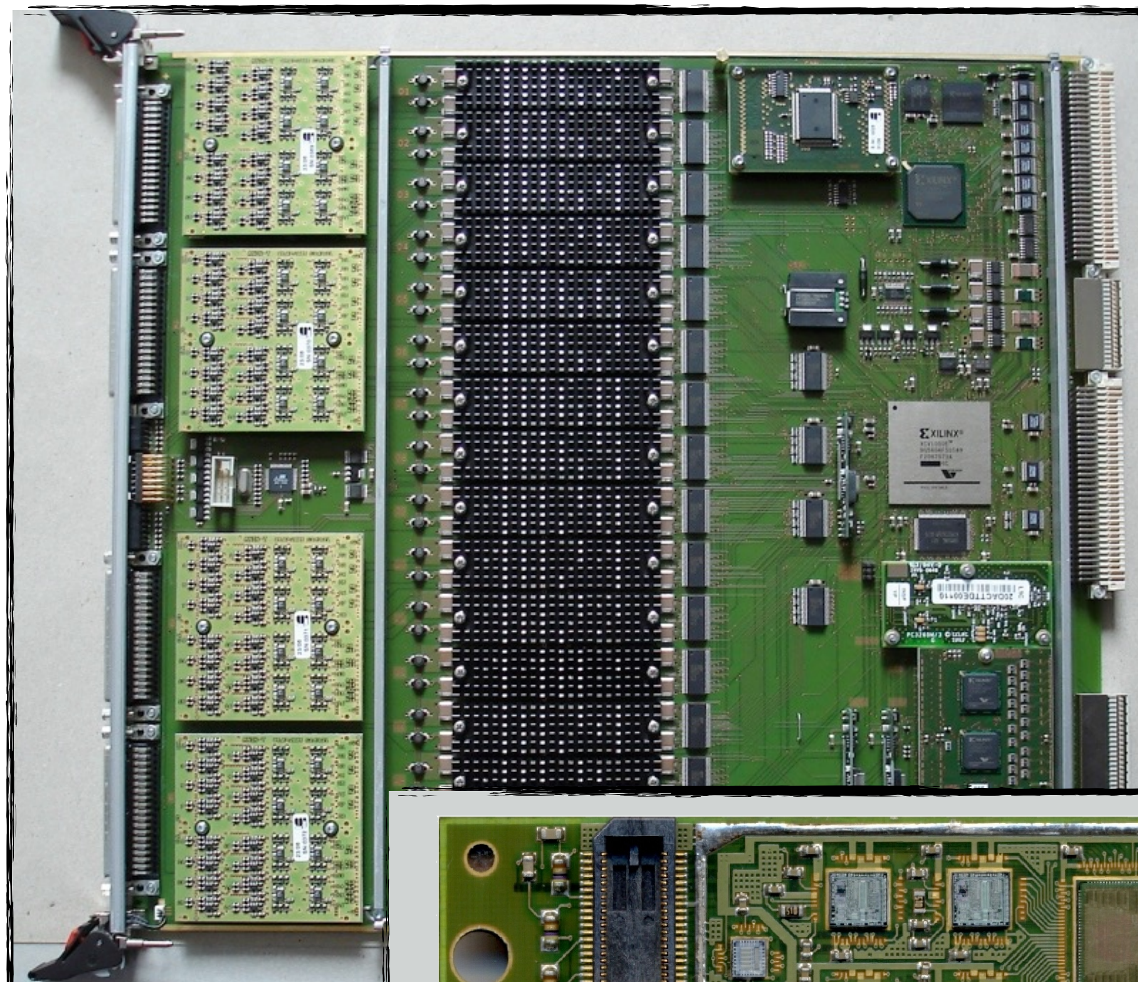
Digital energy measurement and time stamp



Example: ATLAS L1 Calorimeter Trigger

The L1Calo Pre-Processor System

ATLAS
L1Calo Trigger



PreProcessor

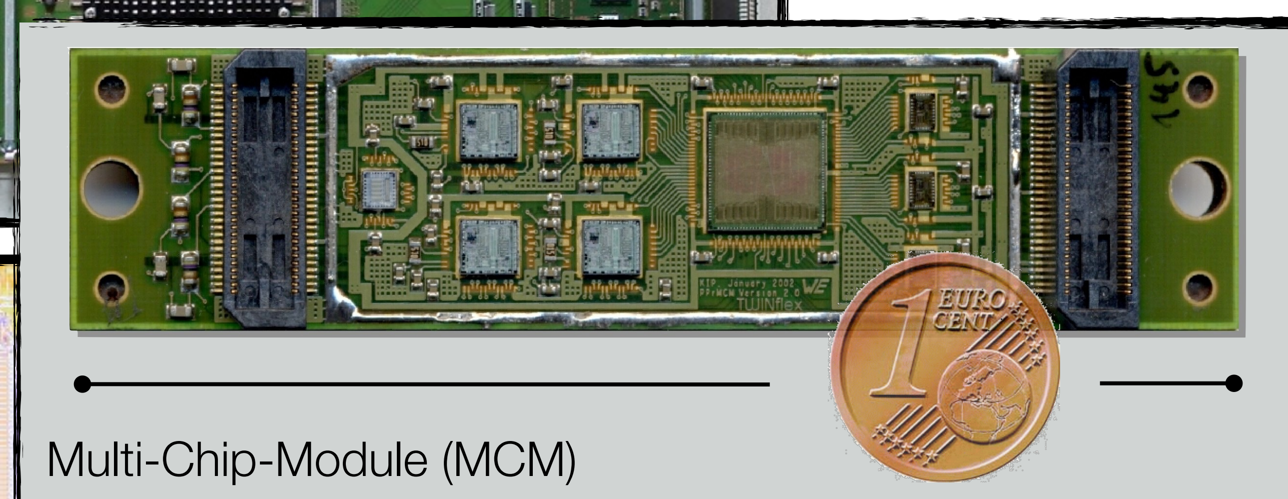
PPr Latency: 0.4 μs
Modules: 124

Input:

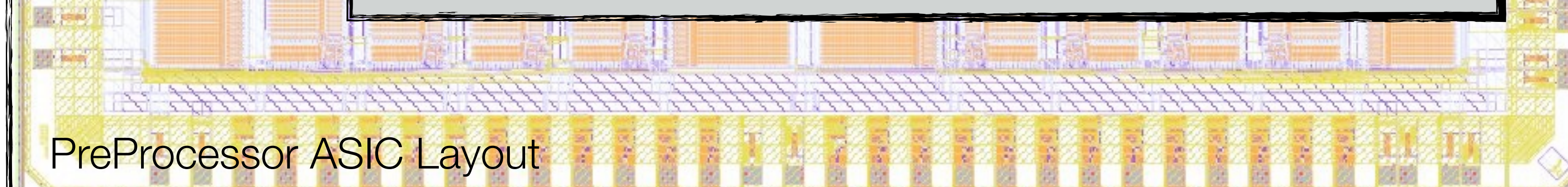
About 7000 analogue calorimeter signals

Output:

Digital energy measurement and time stamp



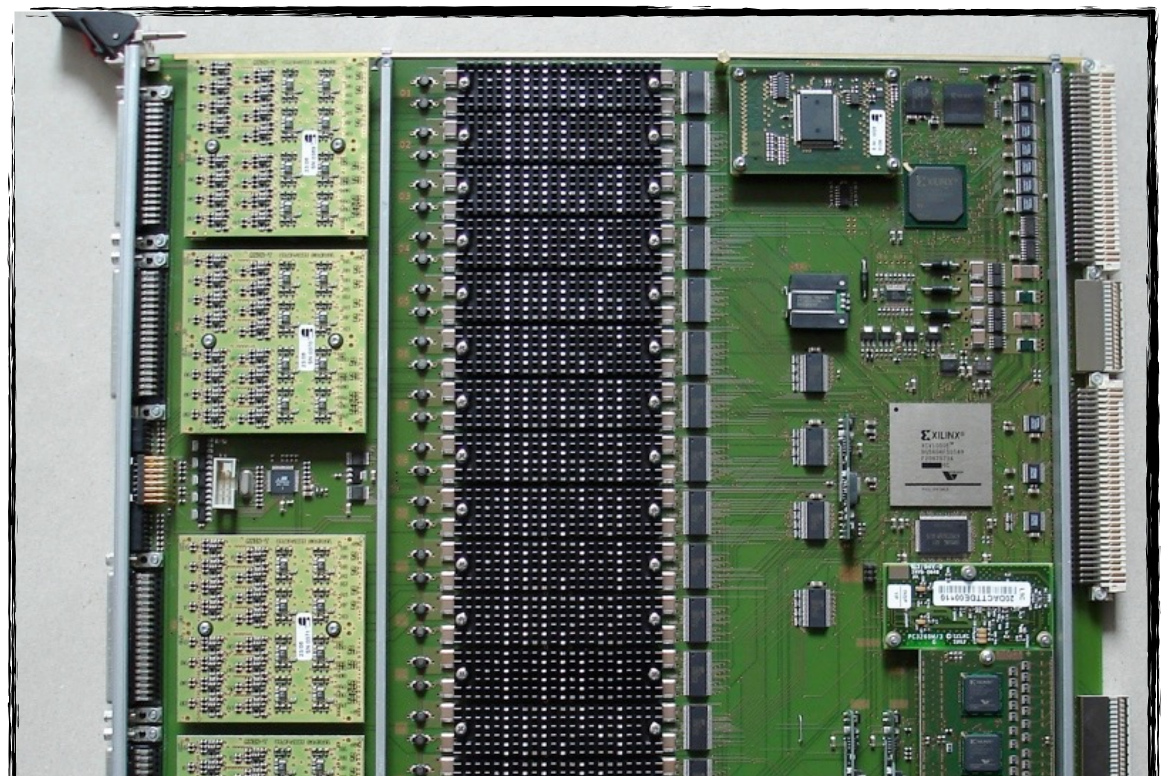
Multi-Chip-Module (MCM)



PreProcessor ASIC Layout

Example: ATLAS L1 Calorimeter Trigger

The L1Calo Pre-Processor System



PreProcessor

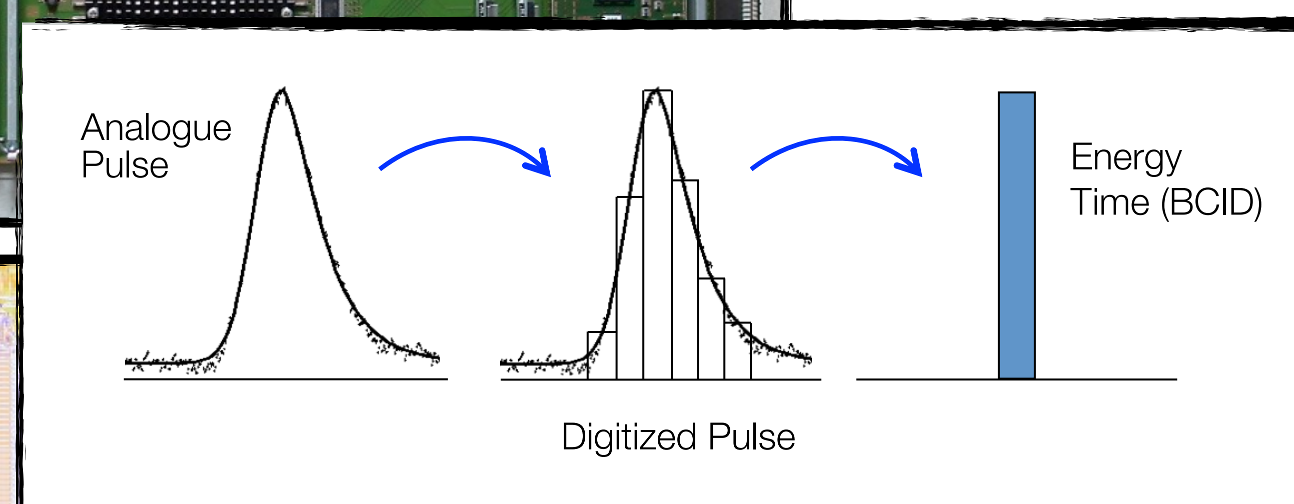
PPr Latency: 0.4 μs
Modules: 124

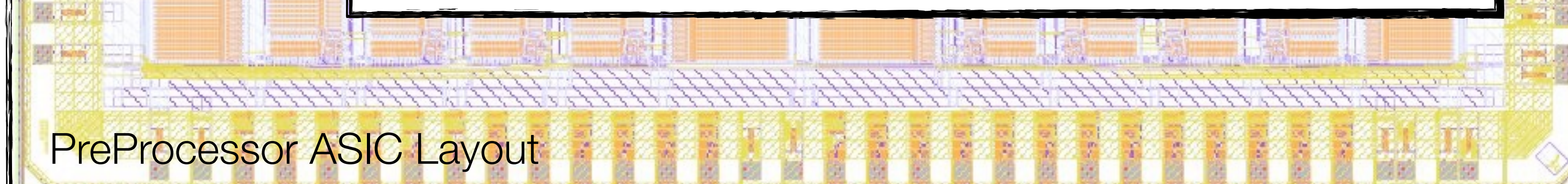
Input:

About 7000 analogue calorimeter signals

Output:

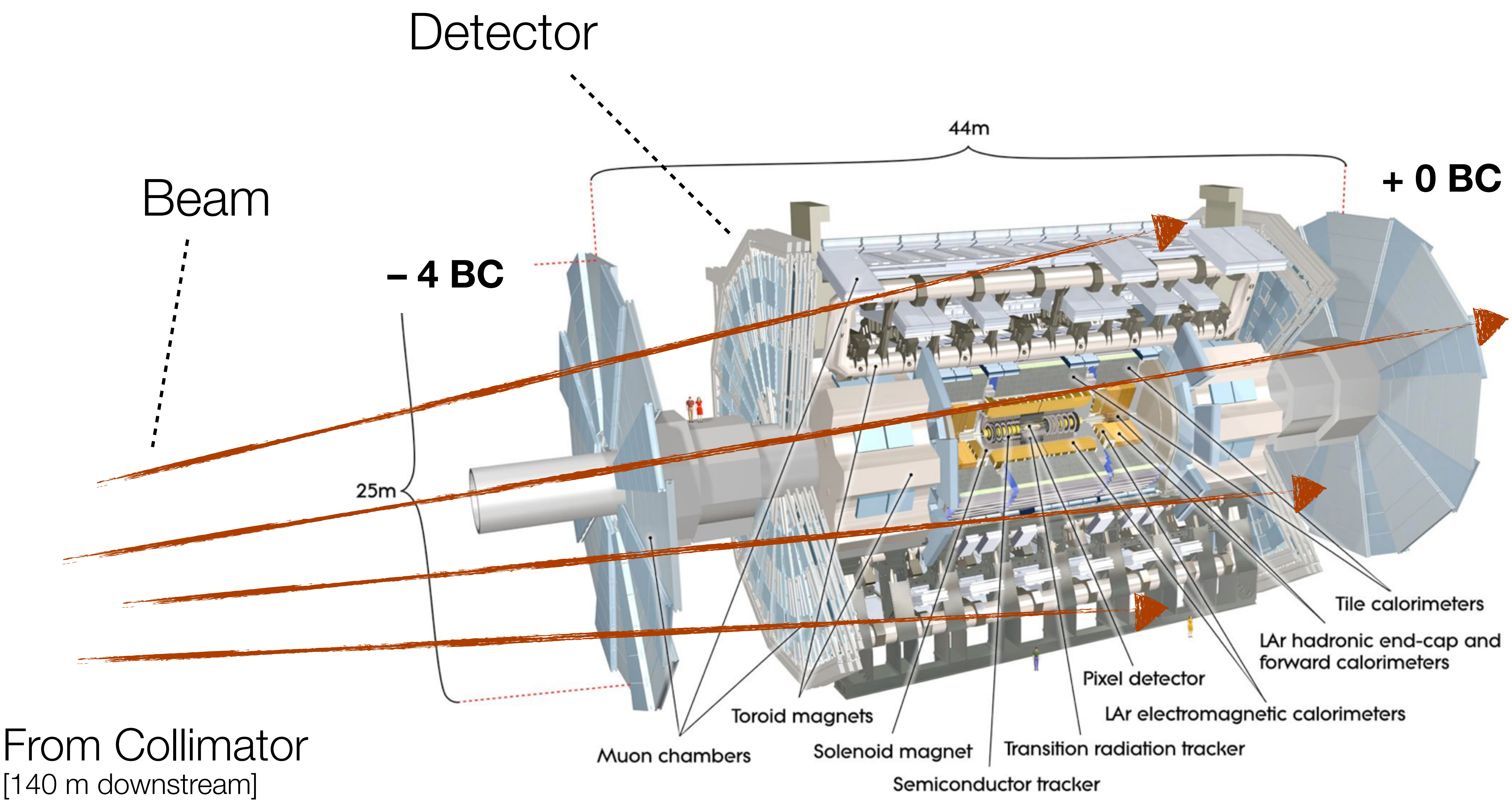
Digital energy measurement and time stamp





Example: ATLAS L1 Calorimeter Trigger

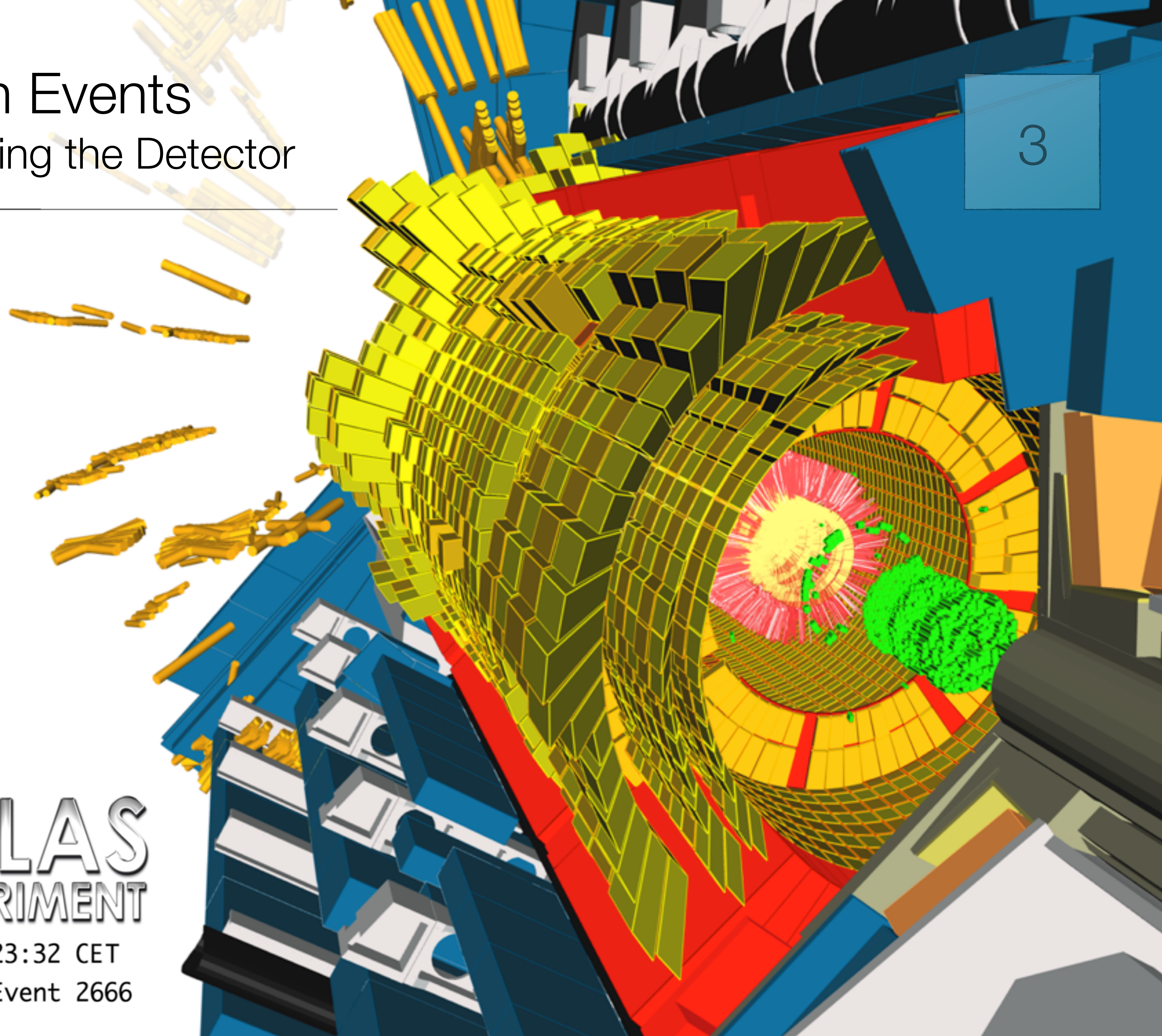
First Synchronisation in 2010



Splash Events

Illuminating the Detector

3



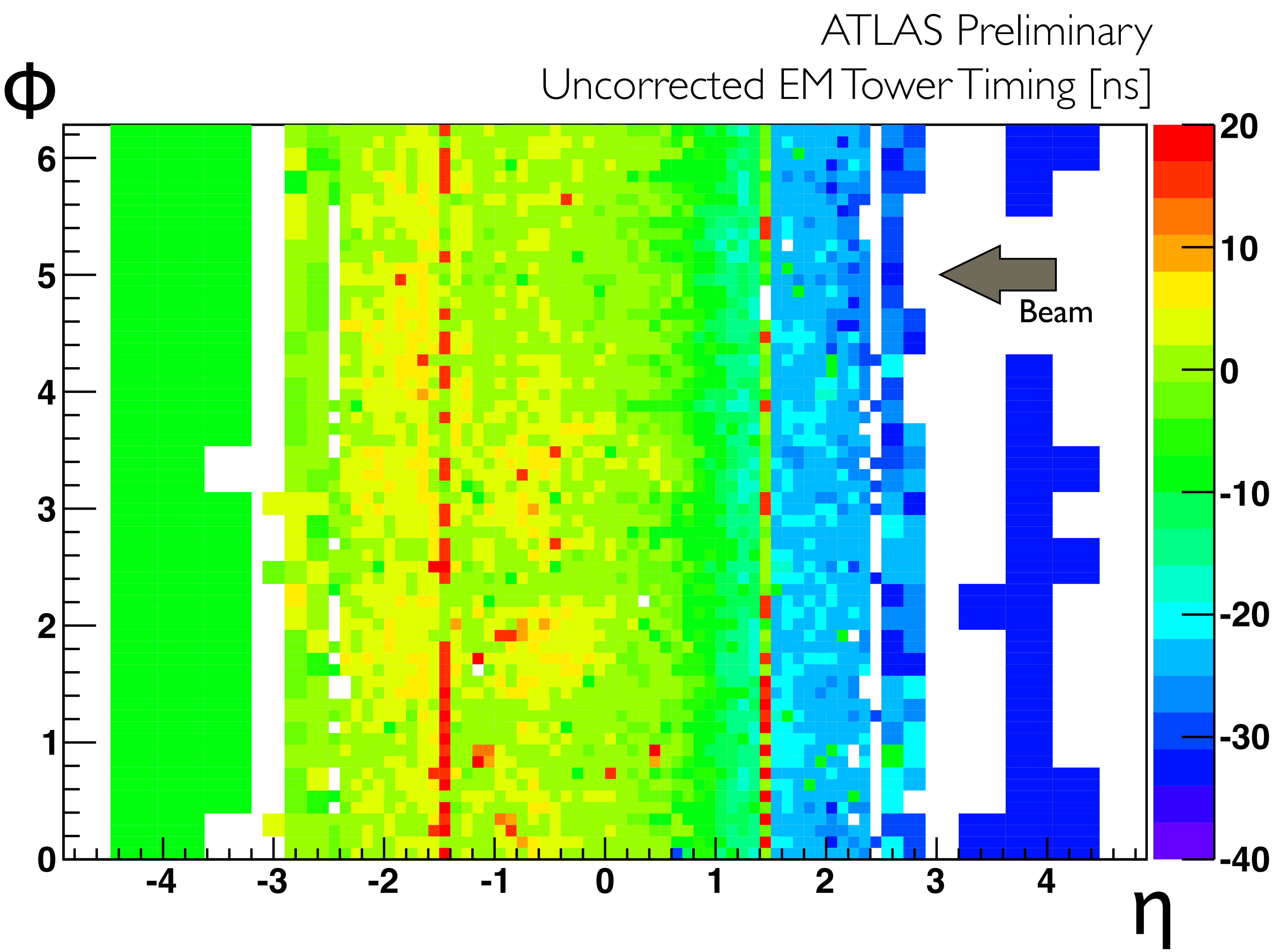
ATLAS EXPERIMENT

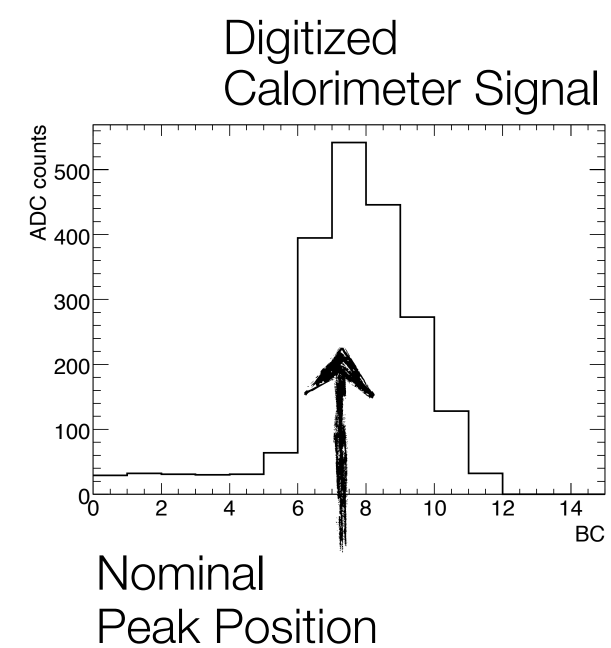
2009-11-20, 23:32 CET

Run 140370, Event 2666

Example: ATLAS L1 Calorimeter Trigger

First Synchronisation in 2010



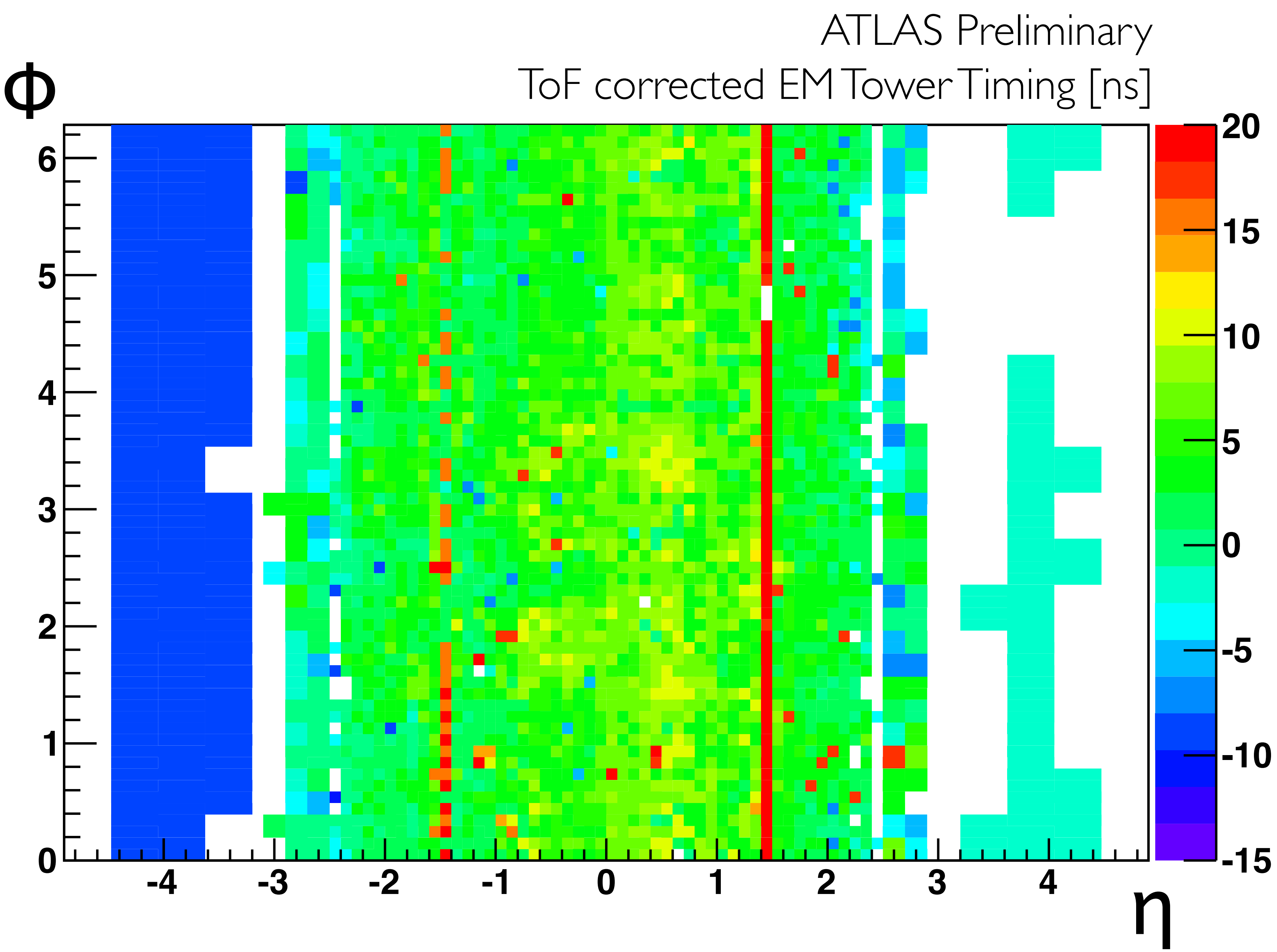


Fine-Timing
via fit to ADC spectra

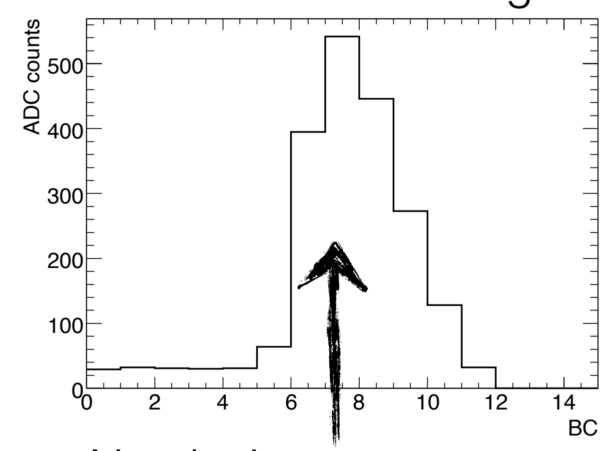
Timing Asymmetry due to Time-of-Flight ...

Example: ATLAS L1 Calorimeter Trigger

First Synchronisation in 2010



Digitized Calorimeter Signal



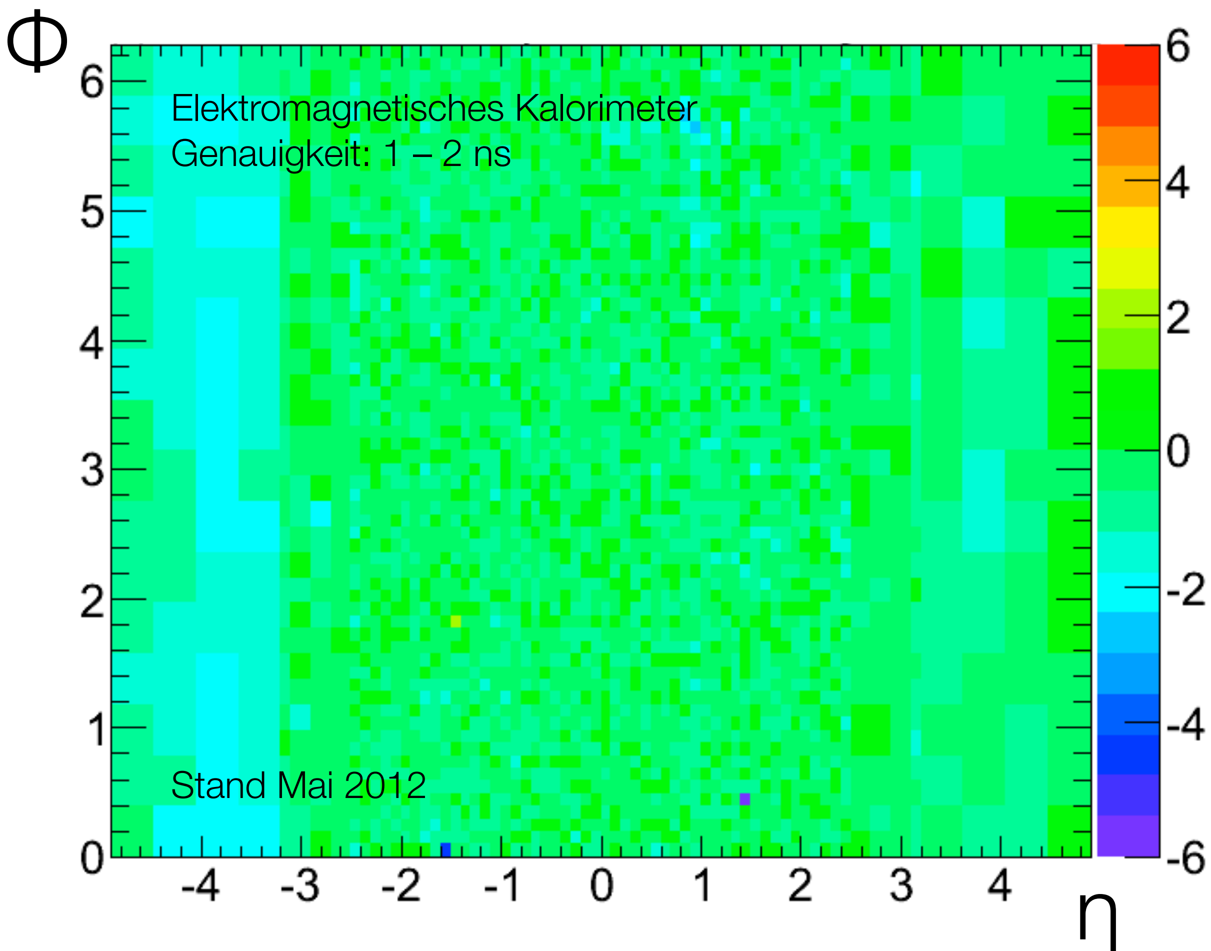
Nominal Peak Position

Fine-Timing via fit to ADC spectra

Relative Trigger Timing at ± 10 ns @ Startup !

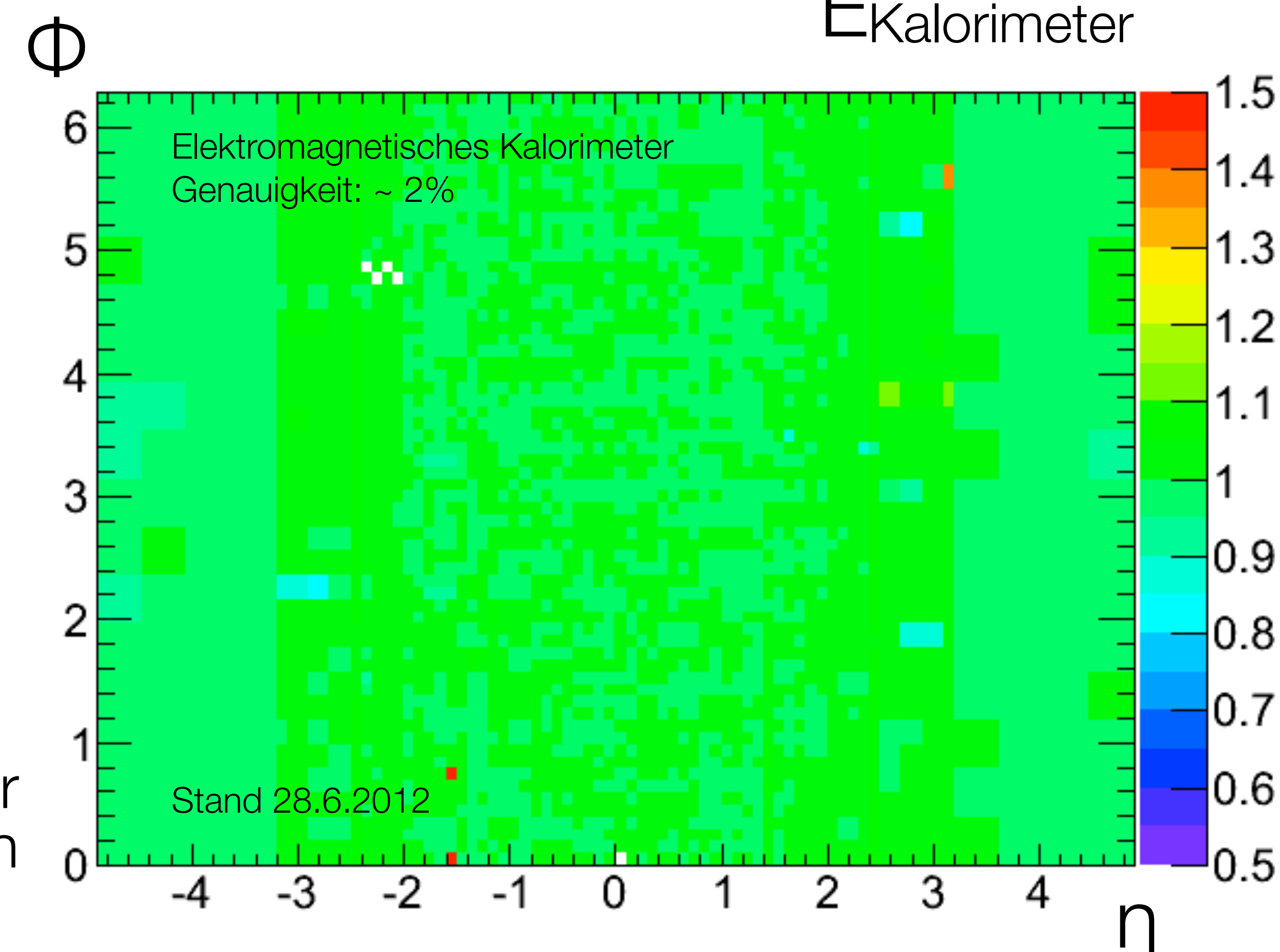
Example: ATLAS L1 Calorimeter Trigger

Timing & Energy Calibration after Synchronisation



t_{set} - $t_{meas.}$ [ns]

Qualität der Zeitsynchronisation



Qualität der Energiekalibration

Thanks

Extras