Trigger and Data Acquisition
at colliders

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Overview

- Introduction
  - *History*
  - *A basic T/DAQ system*
- Front end electronics
  - *Amplifier, shaper, pipeline,…*
- Digital electronics
  - *The basics (ADC, TDC), digital processing*
- Trigger & DAQ architecture
- Event builder & networking
- Introduction to the lab session on FPGA

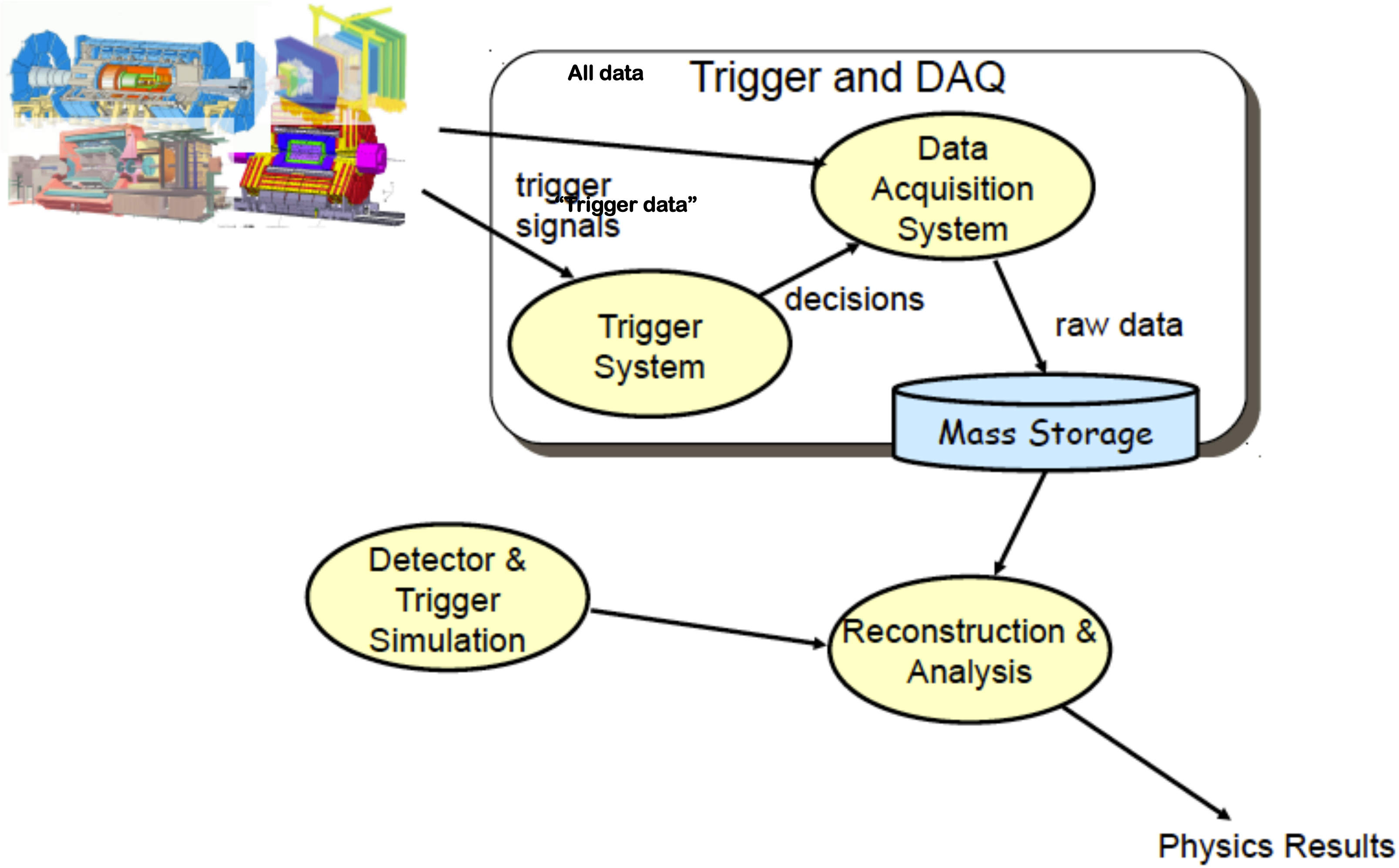
Introduction

- This lecture covers two topics strongly interlaced:

  Trigger and Data Acquisition (DAQ)

- What are they ?
  - *The DAQ is responsible to acquire the data, from the detector up to the recording of this data on a material support allowing offline analysis*
  - *The Trigger system is responsible to trigger the data acquisition*
- This looks trivial but in reality it is very complex because of many constraints from the physics and from the technology
- The goal of these lectures is to give you an overview of Trigger and DAQ systems by following step by step the data path from the detector up to the final storage for offline analysis

Trigger and DAQ in HEP

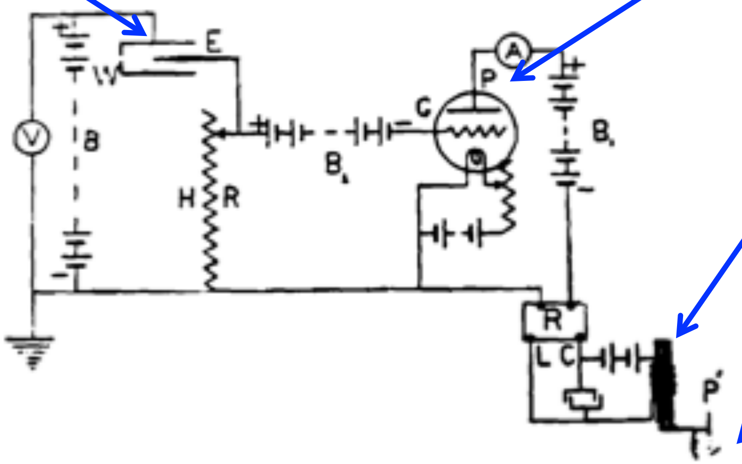


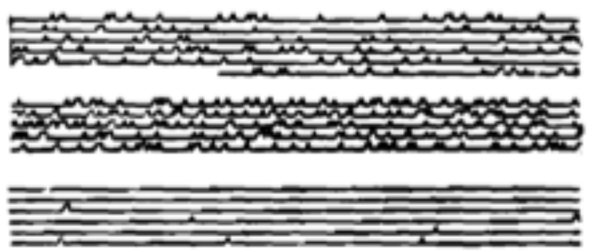
Some history

- Before electronic detectors:
  - *Detection system : the eyes (which was also the trigger) looking at flashes on a phosphorescent screen*
  - *Data acquisition : manual recording in a logbook*
- It worked BUT
  - *Can't make long runs (unless you have a lot of students)*
  - *« manually recording the passage of particles […] was hard on the experimenter because of the random rate at which the information came in »*
- First one-channel electronic recording device in 1919:
  - *« On the Automatic Registration of Alpha Particles, Beta Particles, and Gamma Ray Pulses." A. F. Kovarik*

First « automatic DAQ »

ON THE AUTOMATIC REGISTRATION OF α-PARTICLES, β-PARTICLES AND γ-RAY AND X-RAY PULSES

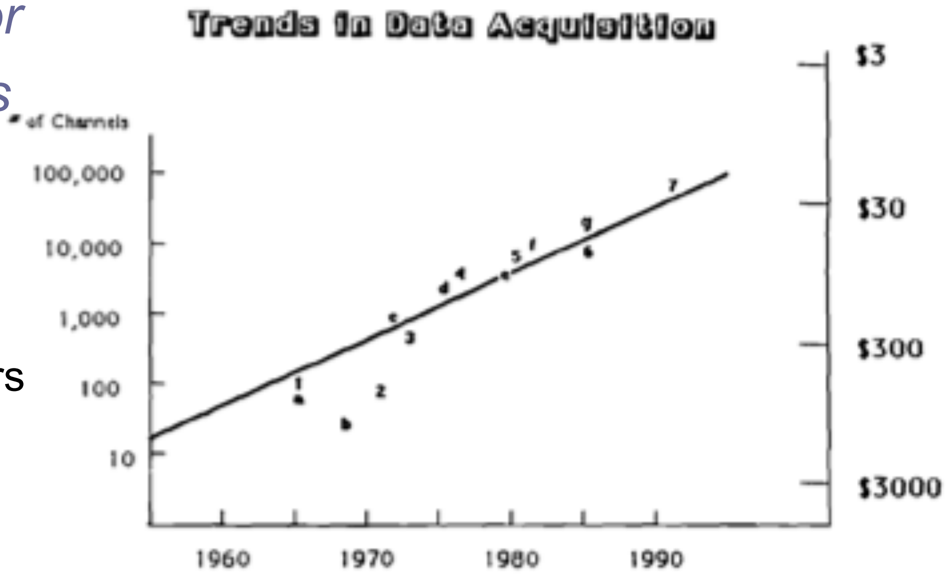




Alois F. Kovarik
Sheffield Scientific School
Yale University
New Haven, Conn.
January 25, 1919

First electronic detectors

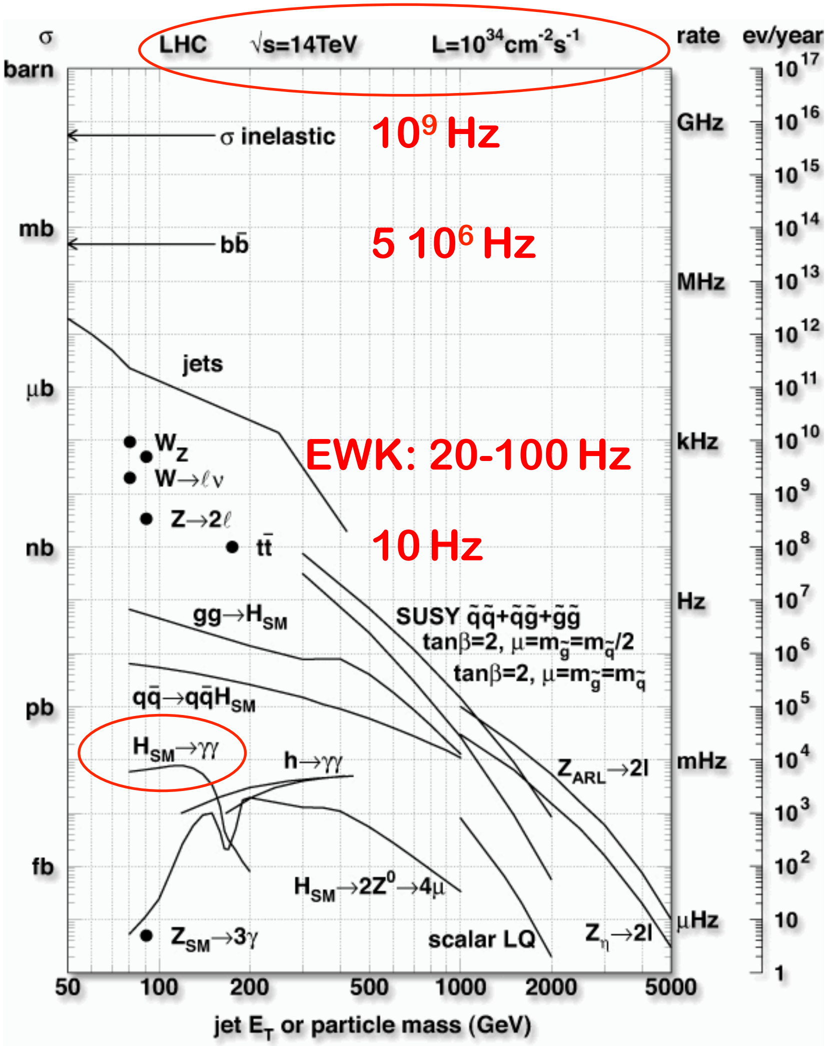
- With the introduction of electronic readout systems the DAQ and trigger history could really take-off:
  - *1947 : introduction of the transistor*
  - *60's : < 100 channels experiments*
  - *68: MWPC (Charpak)*
    - Before tracking detectors were almost all optical:
      - – emulsions, cloud/bubble chambers
  - *Today:*
    - LHC experiments
      - – O(10^7) channels
      - – 40 MHz ($10^{34} cm^{-2} s^{-1}$)
  - *Not so long ago*
    - LEP experiments
      - – O(10^5) channels
      - – 40 kHz



Number of Channels/Instrument/Experiment vs. Time
and
Cost/Channel of ADC or TDC vs. Time

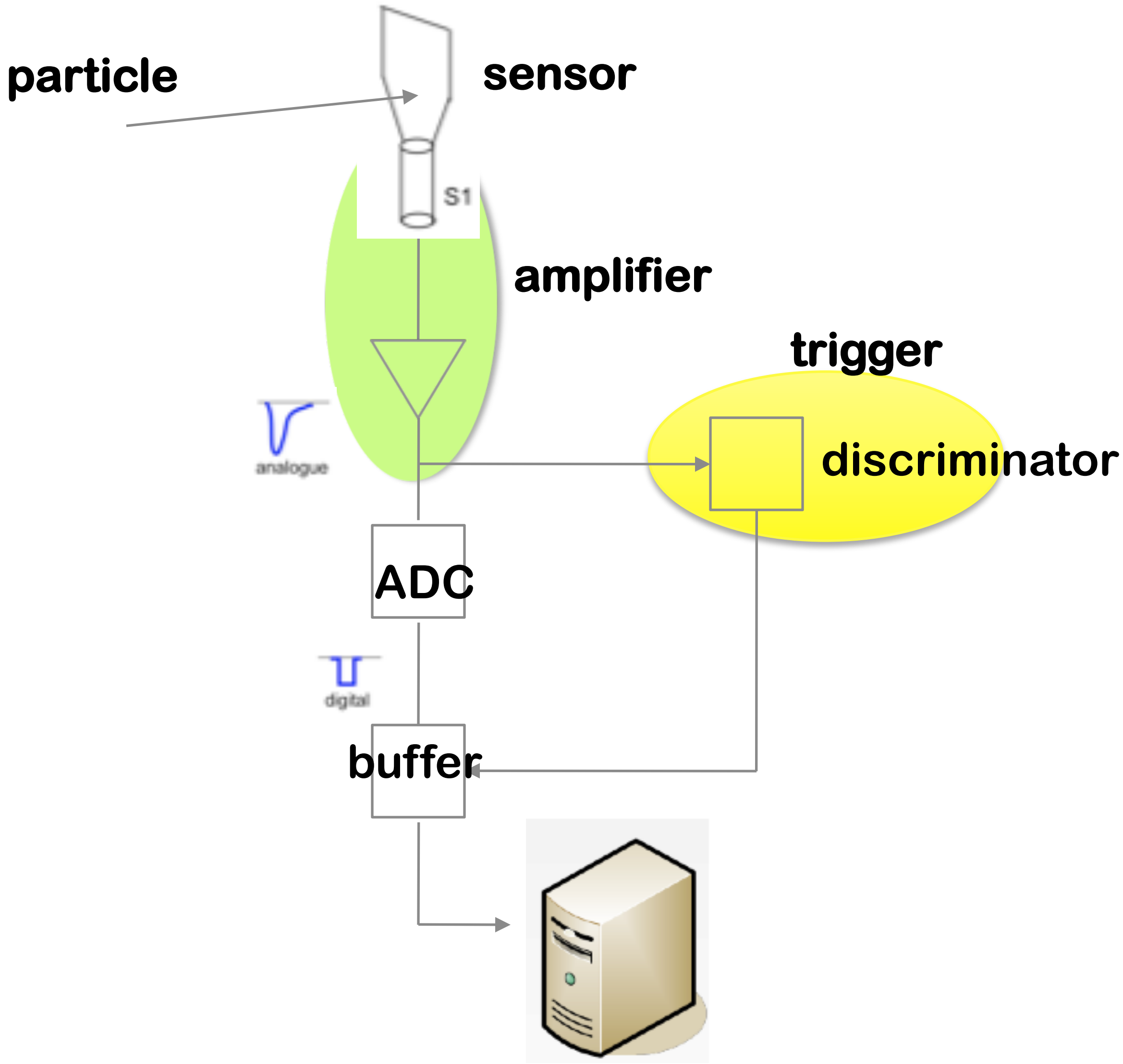
Should we read everything ?

- There is not only the « technical » issues to record so many events in a such a small time, there is also the issue of the event selection:
  - *We are now looking to very rare new phenomena:*
    - For instance at LHC (14 TeV, L = $10^{34} cm^{-2} s^{-1}$), SM Higgs rate < 0.1 Hz!
  - *→ the millions other collisions are "uninteresting" !!*
    - These have to be rejected while still recording the Higgs…

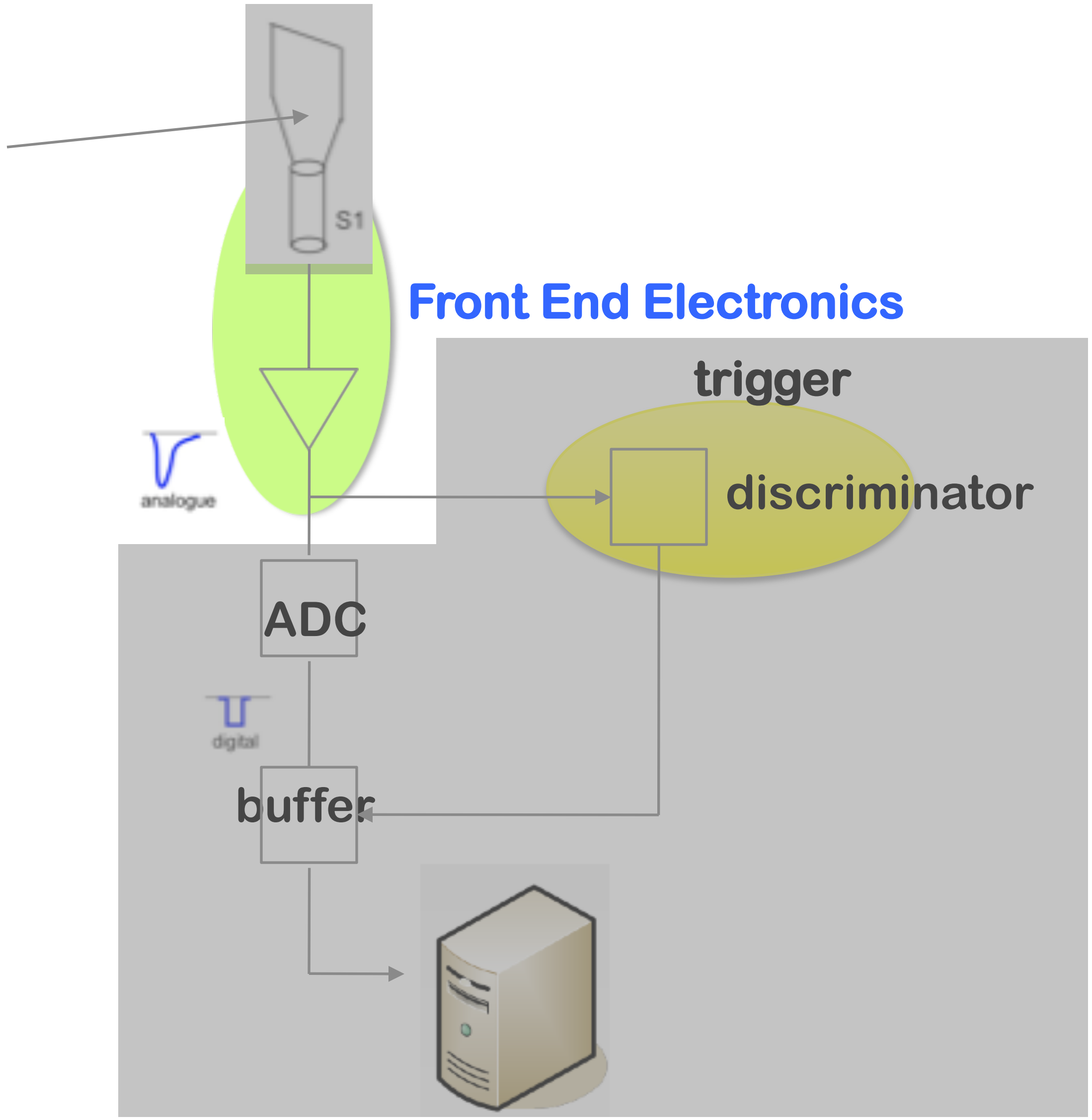


The basics

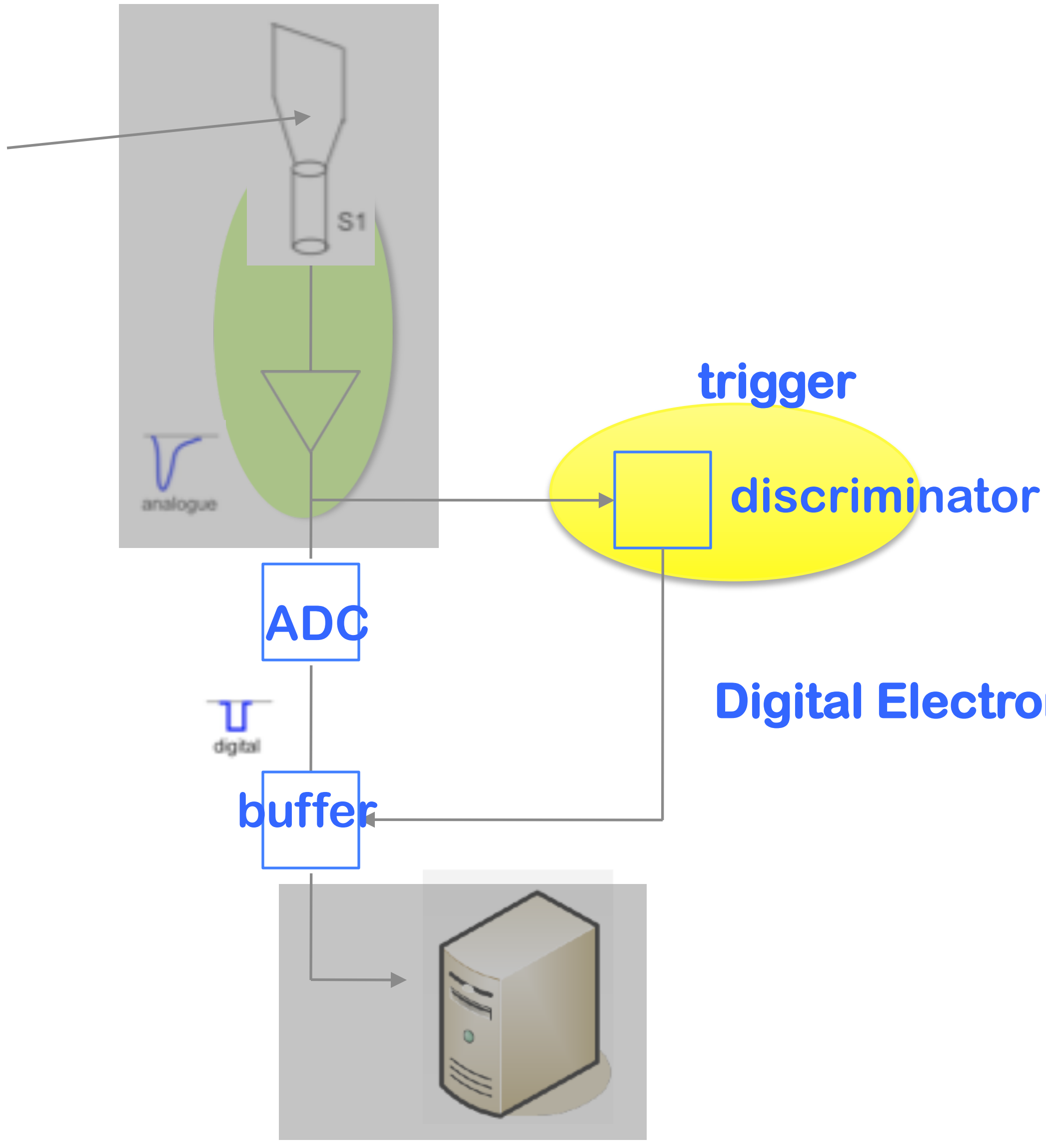
- Our basic picture of a DAQ/Trigger system:



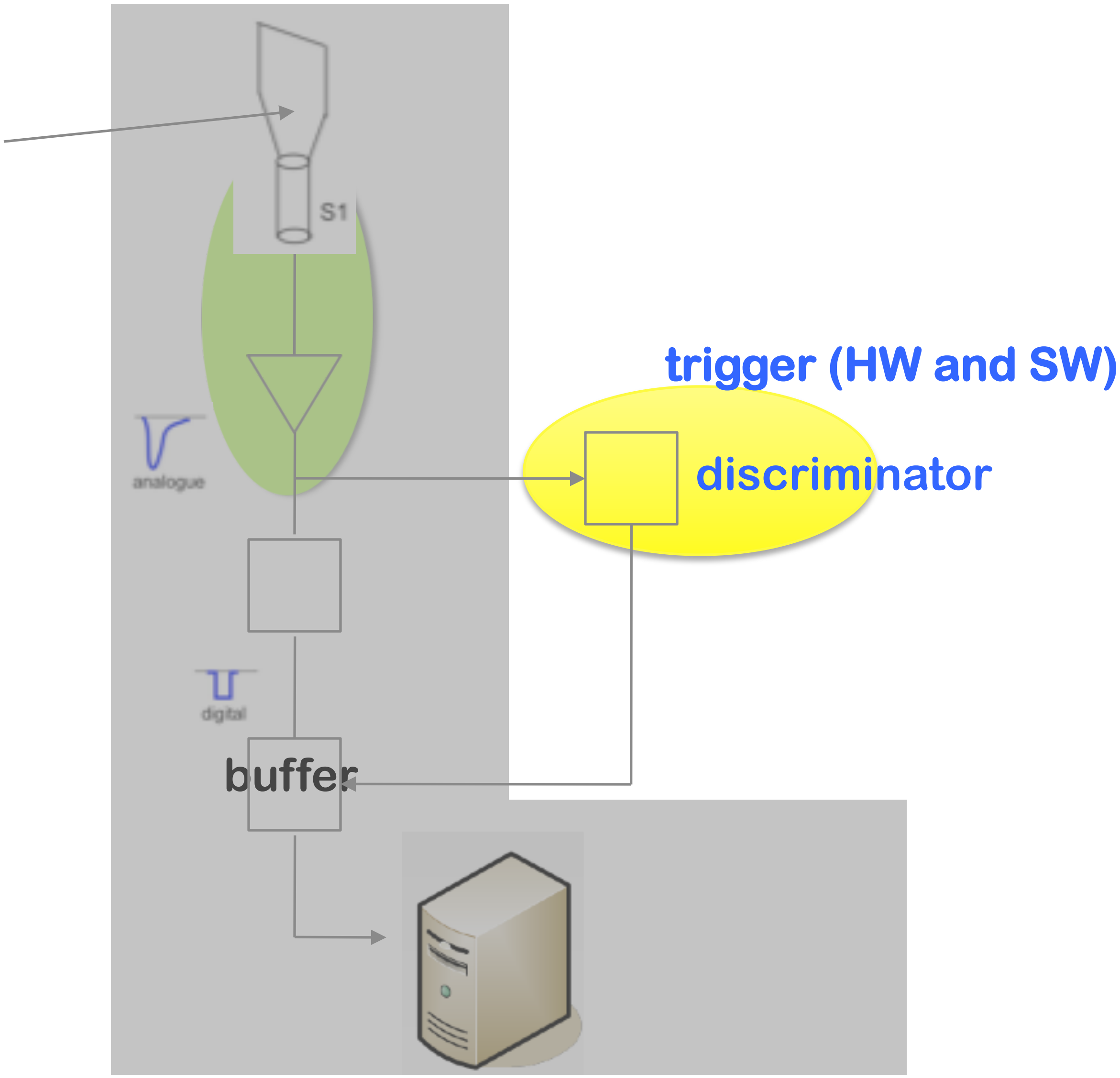
Part I: Front End Electronics



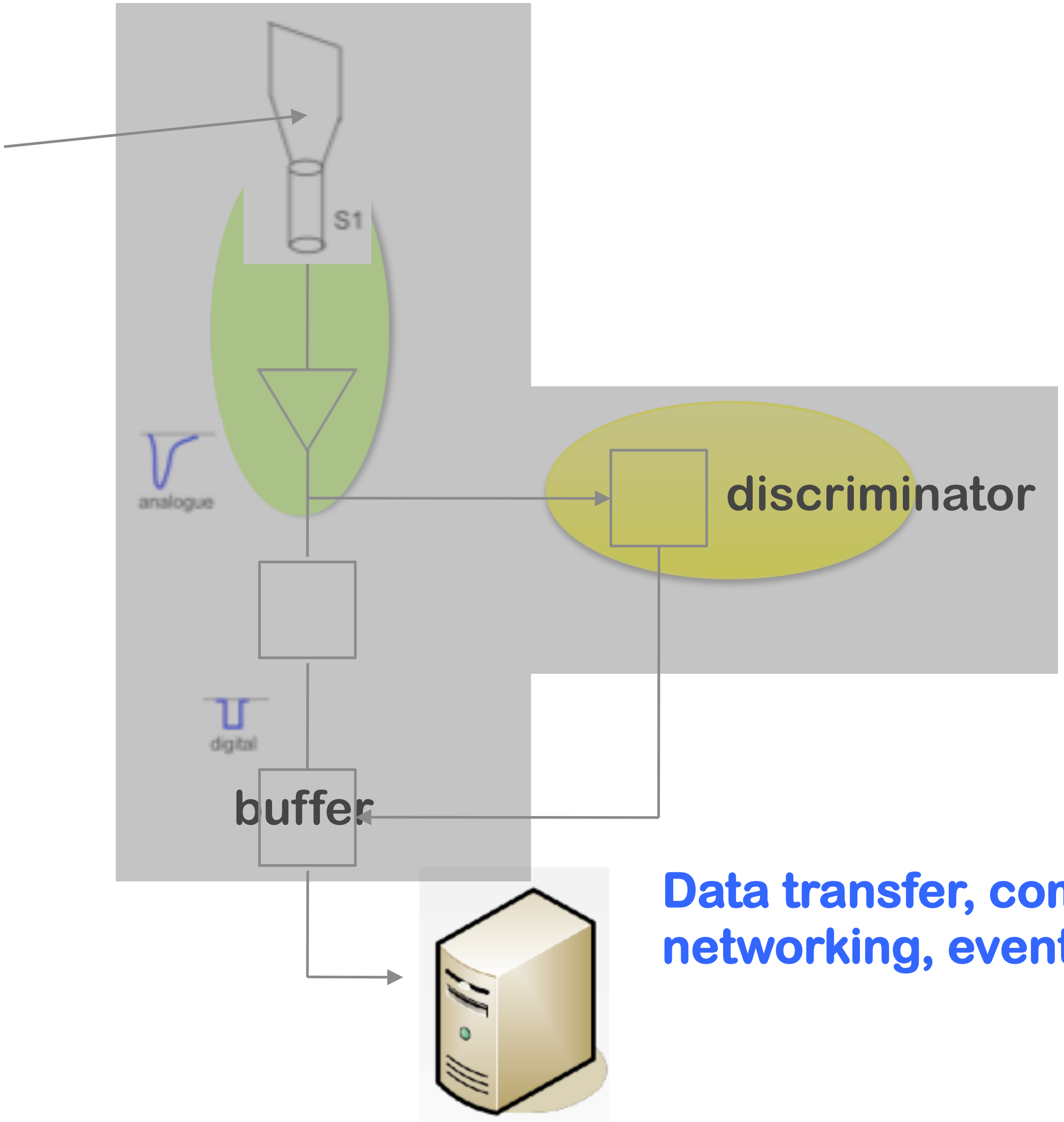
Part II: Digital Electronics



Part III: Trigger

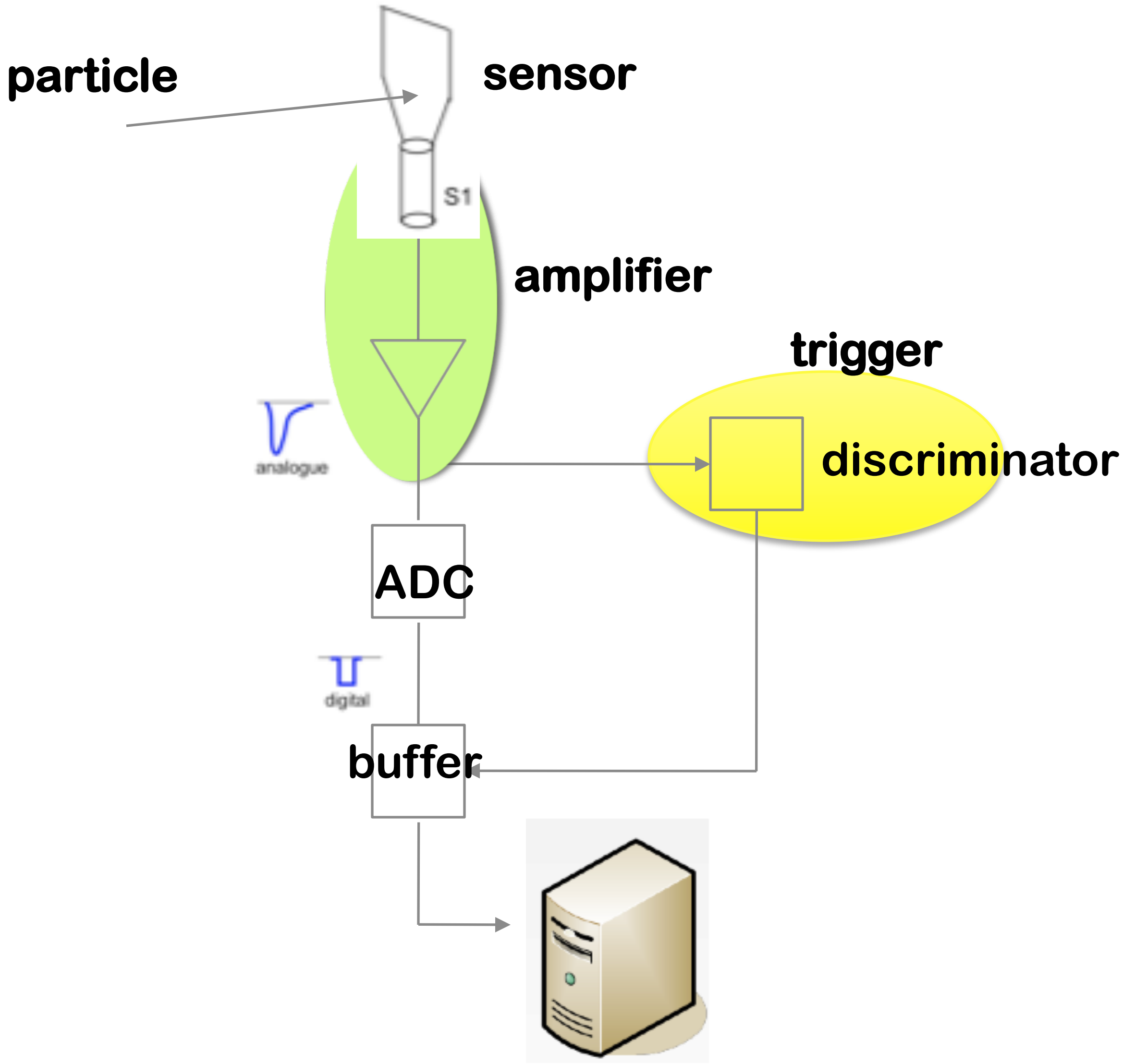


Part IV: All the rest…



Data transfer, computing, networking, event building,…

From here...


particle
sensor
S1
amplifier
trigger
discriminator
analogue
ADC
digital
buffer

… to there

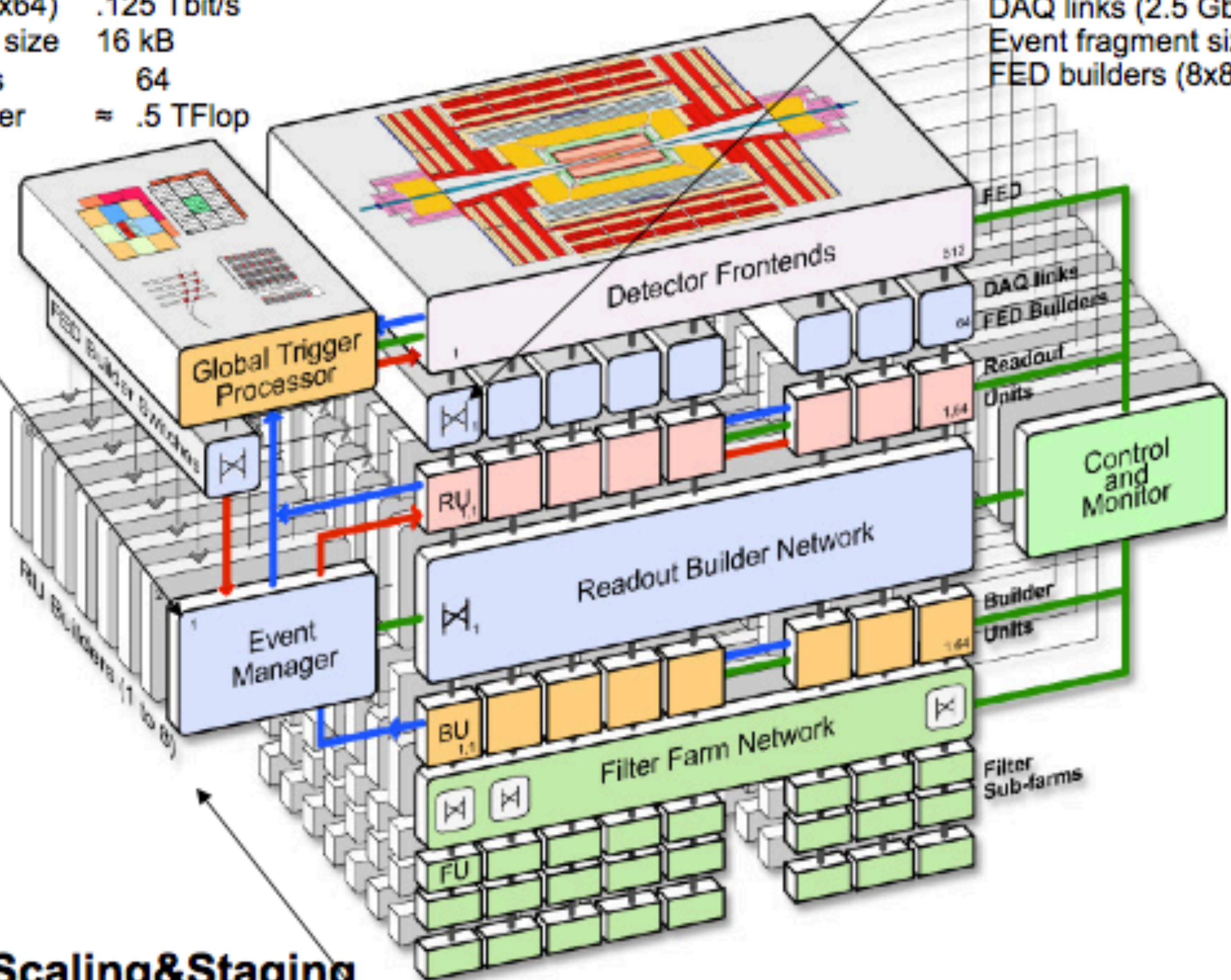
- CMS DAQ

DAQ unit (1/8th full system):

Lv-1 max. trigger rate	12.5 kHz
RU Builder (64x64)	.125 Tbit/s
Event fragment size	16 kB
RU/BU systems	64
Event filter power	≈ .5 TFlop

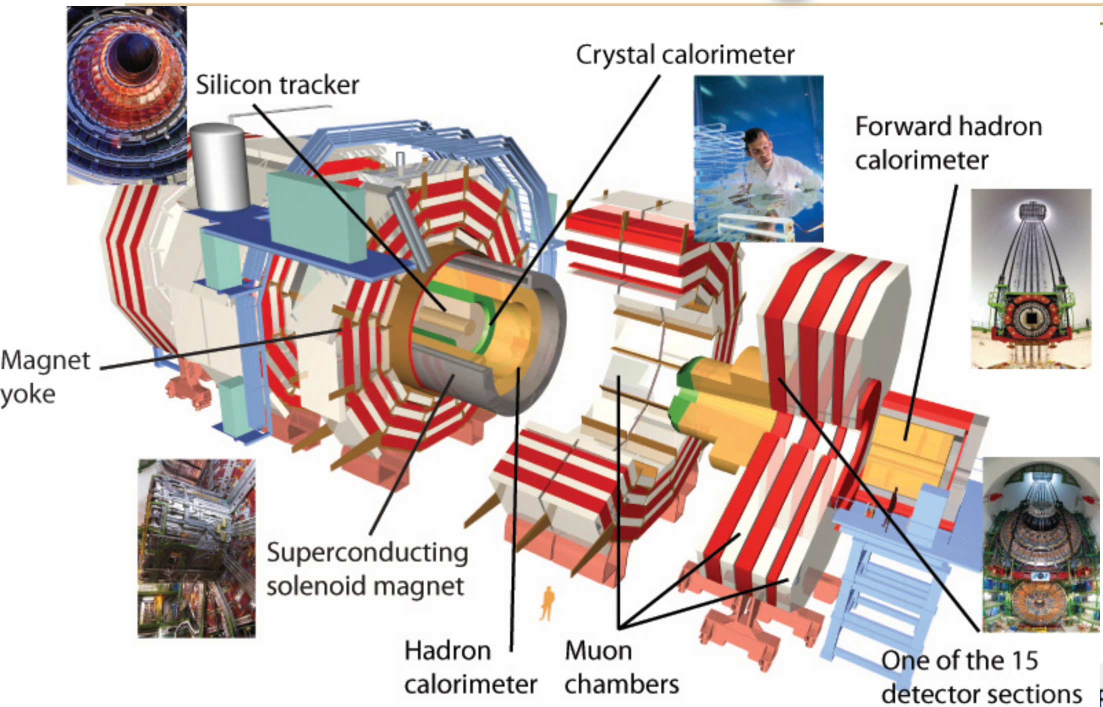
DATA to surface

Average event size		1 Mbyte
No. FED s-link64 ports	>	512
DAQ links (2.5 Gb/s)		512+512
Event fragment size		2 kB
FED builders (8x8)	≈	64+64



DAQ Scaling&Staging

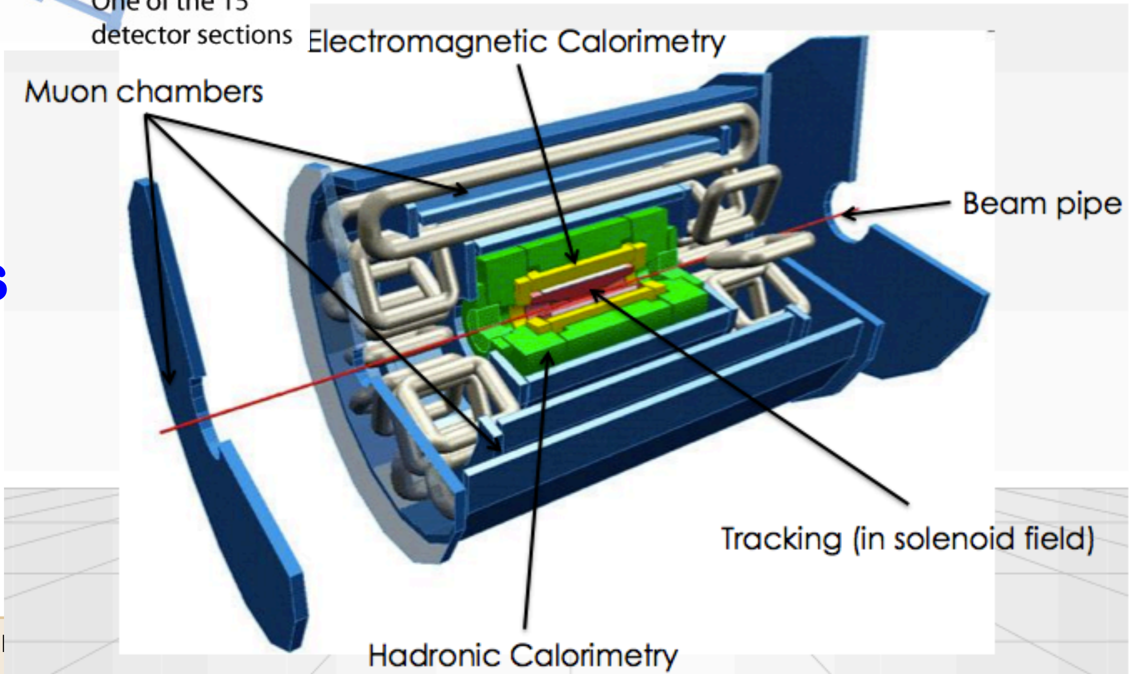
Before starting: a word on detectors



Most of the talk take CMS and ATLAS as examples

CMS

ATLAS



Detector signals

- The signal is usually a small current pulse varying in duration
  - *from ~ 100 ps for a Si sensor to O(10) μs for inorganic scintillators*
- There are many sources of signals.
  - *Magnitude of signal depends on deposited energy and excitation energy*

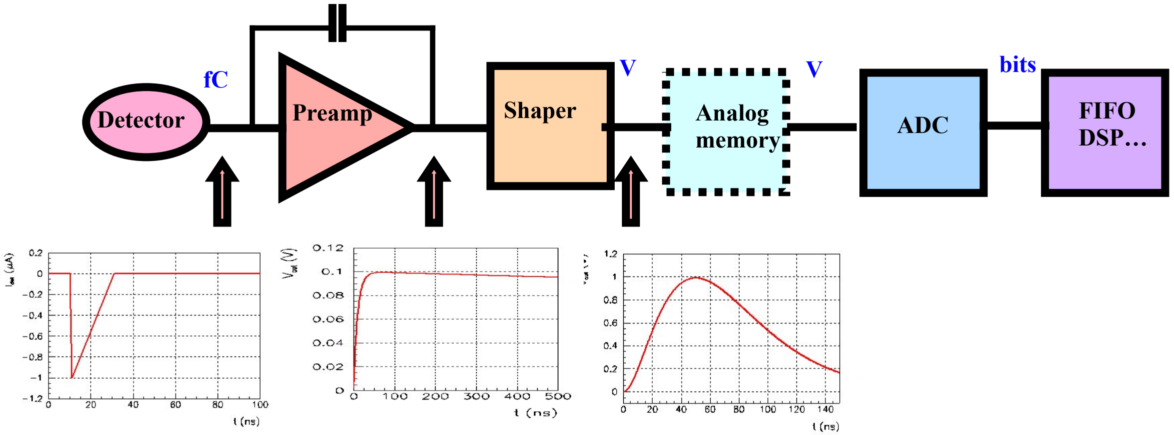
Signal	Physical effect	Excitation energy
Electrical pulse (direct)	Ionization	30 eV for gases 1- 10 eV for semiconductors
Scintillation light	Excitation of optical states	20 – 500 eV

- Signals must be amplified, digitized to allow storage and processing

PART I: FRONT END ELECTRONICS

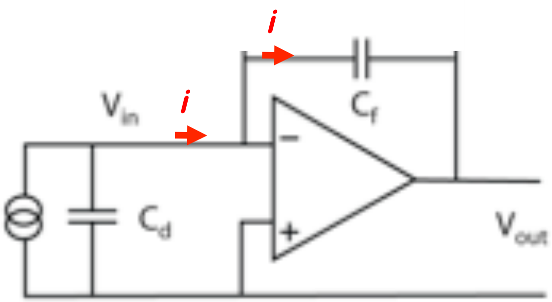
Signal from the detectors

- The Front End Electronics (FEE) is the electronics which is “on” the detector, that is directly connected to the detector.
- The FEE is detector dependent but the basics are the same:
  - *Detectors generate signals (charge) from ionization in a medium (gas, liquid, semiconductor), sometimes with a detector gain (gas, PM)*
  - *These signals are generally small*
    - ~22k electrons (4fC) in a 300 μm thick Si sensor
  - *These signals need to be adapted:*
    - Amplified
    - Shaped, to optimize signal to noise ratio, event rate, energy/time measur.
    - Digitized (not always at FEE stage)
    - Stored for further treatment (for instance waiting for the trigger decision)



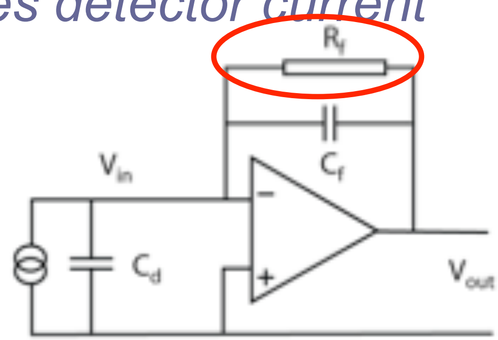
Pre-amplifier

- From electronic point of view, detectors behaves like a current source with a capacitance (C_d) and an internal resistor
- Charge sensitive preamp (90% of HEP pre-amp):
  - *Integrates the charge carried by the incoming pulse on the feedback capacitance C_f*
    - $$i = C_f \frac{d}{dt}(v_{in} - v_{out}) \approx -C_f \frac{dv_{out}}{dt}$$
      $$v_{out} = -\frac{1}{C_f}\int i dt = -\frac{Q}{C_f}$$
    - No dependence on detector capacitance:



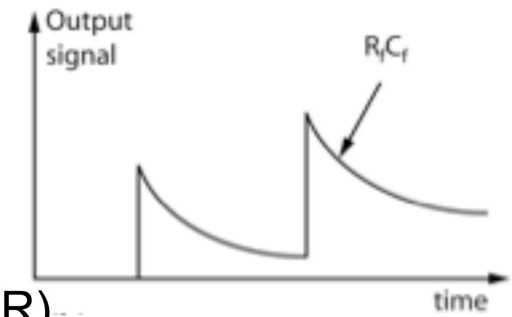
  - *The needed gain determines C_f*
  - *Gain only depends on charge integration capacitor C_f and not on detector capacitance*
    - Gain is independent of detector and parasitic capacitance variations
    - However detector capacitance has direct effect on noise
  - *Problem: output voltage continues to integrates detector current*
    - need to reset the capacitor

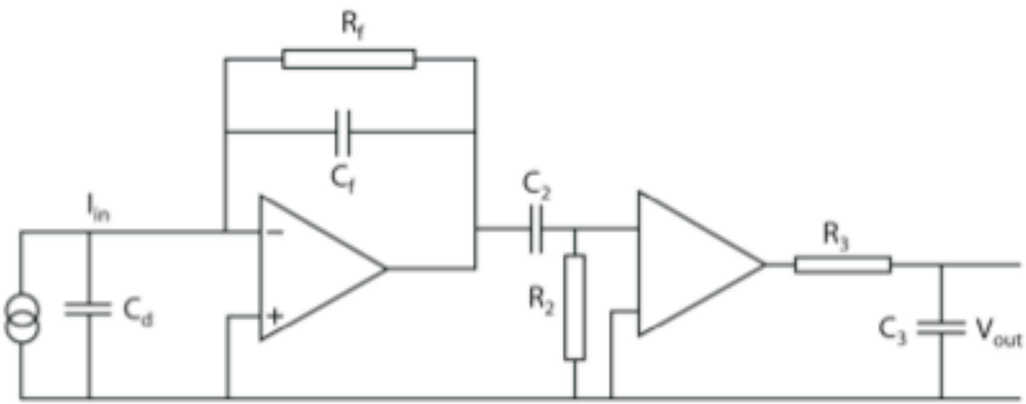
    → continuous discharge by resistor R_f:

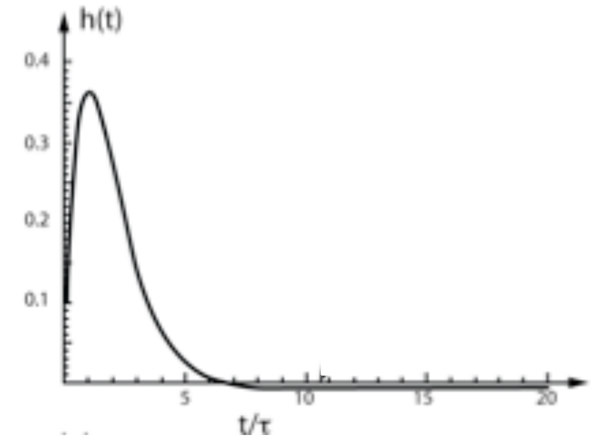


Shaping

- The response of a charge integrating amplifier to a current pulse will be a sharp rising edge at the moment the pulse arrives, followed by an exponential decay with a time constant $R_f C_f$, of the order of (typical.) 40-50 µsec.
  - *This severely limits the counting rate*
  - *Need a way to make output pulses shorter*
    - → Shaping
    - Typically CR-RC stages: Pulse is filtered at low (CR) and high (RC) frequencies.
    - Usually $C_2 R_2 = R_3 C_3 << R_f C_f$

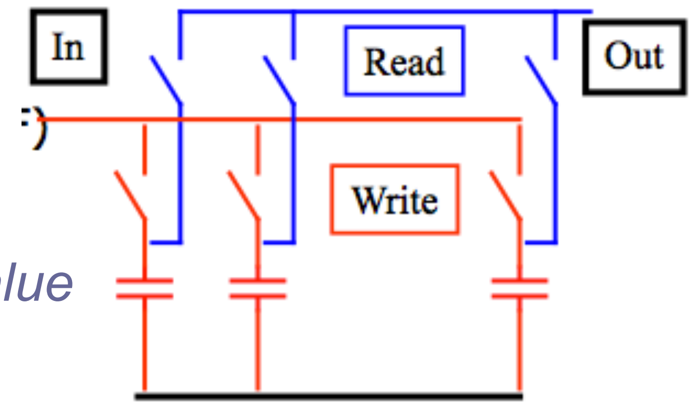






Analogue memories

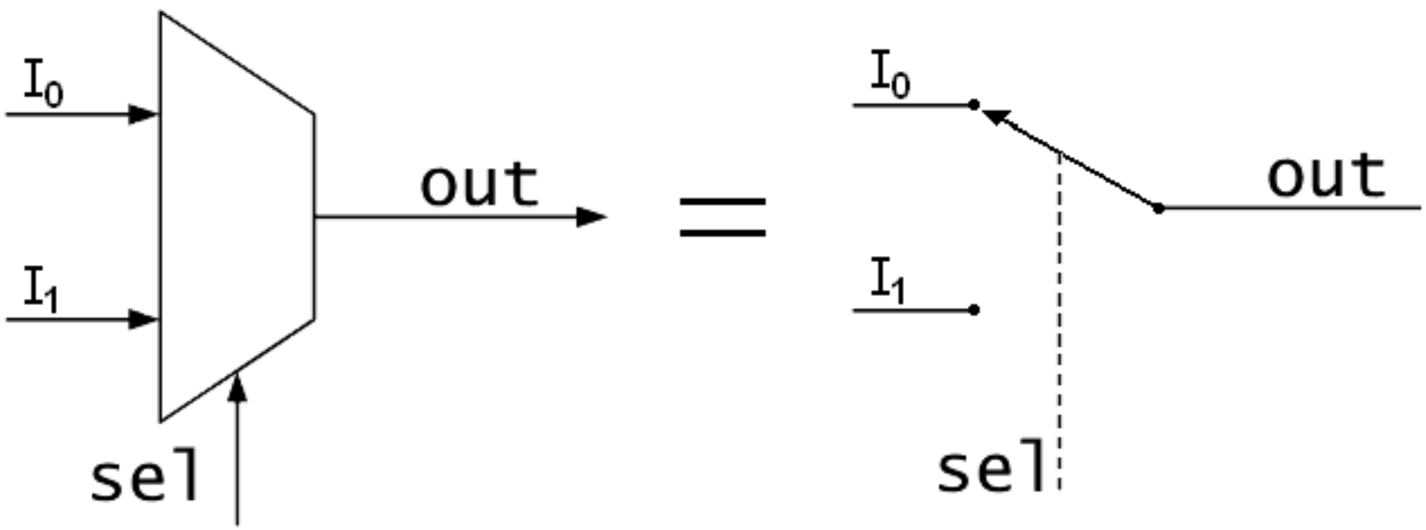
- It is often convenient to store analog signals while the trigger makes its decision.
- → use of Switching Capacitor Array (SCA), often called pipeline
  - *The signal is sampled and stored on capacitors (pF)*
  - *Fast write (~GHz)*
  - *# of cells 100 – 1000*
  - *The capacitor cells can be written to or read from in a sequential or random manner*
  - *No dependence on the absolute capacitor value*
  - *Low power consumption*
  - *BUT possible loss in signal integrity (signal drop, leakage current)*



- Example CMS Tracker APV chip:
  - *192 cell pipeline / ch, at 40 MHz sampling => 4.8 μs*

Mux

- In electronics a mux (abbreviation of multiplexer) is a device which perform multiplexing that is it selects one out of many analogue or digital input signals and forward the selected input into a single line.
- Multiplexers are used as one method of reducing the number of integrated circuit packages required by a particular circuit design. This in turn reduces the cost of the system.
- Typical representation:



Let put all these components together:

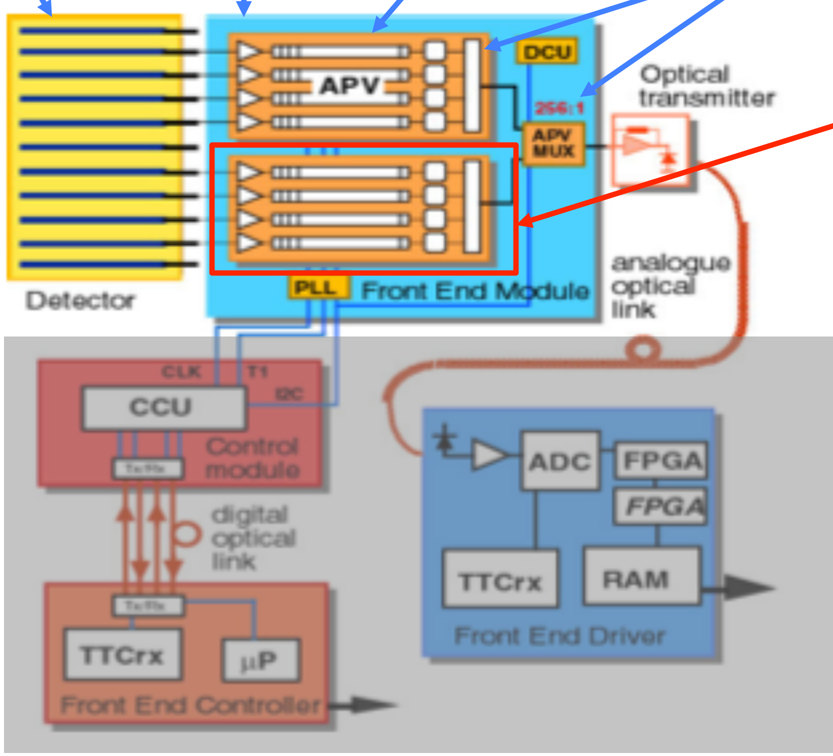
- Example : the CMS Tracker FEE (APV):

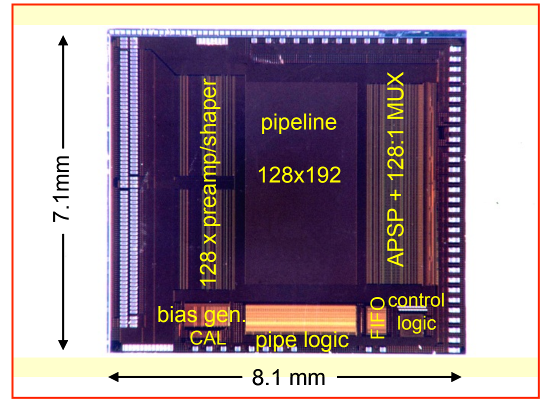
Silicon sensor

Preamplifier, shaper

Analog pipeline

Mux





128 channels APV chip

(BTW: this is what we call an ASIC Application-Specific Integrated Circuit)

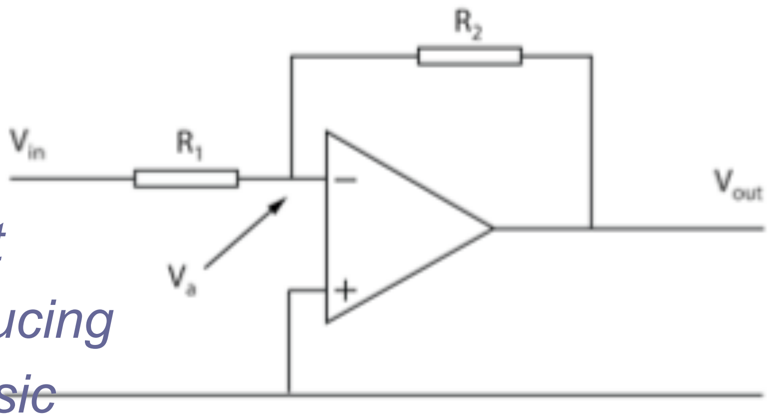
Next steps

- At this stage in the CMS Si strip tracker the data are sent out of the detector towards crates in the underground area
- In the case of the CMS Si strip tracker, analogue data are sent through optical fibres towards modules were further processing will be performed (like conversion to digital signals, etc.)
- Other detector electronics go from analogue to digital at a earlier stage (see ALICE TPC readout later)
- So let’s move to the digital world

BACK-UP

FEE basics: the signal amplification

- From electronic point of view, detectors behaves like a current source with a capacitance (C_d) and an internal resistor
- There are 3 types of amplifier:
  - *Current sensitive (works w/. very low impedance devices → not for HEP)*
  - *Voltage sensitive*
  - *Charge sensitive*
- Voltage sensitive amplifier:
  - *Amplifies any voltage appearing at input*
  - *Since detectors are mainly charge producing devices, voltage appears through the intrinsic capacitance of the detector + any stray capacitance at the input*



- *$V = Q/C_{tot}$, where $C_{tot} = C_d + C_{other}$*
- *detector capacitance must be very stable*
- *Not advisable for semiconductor devices*

Another reason why this amplifier is not optimal is the presence of a resistor connected at the input (see noise section)

Pole-zero cancellation and baseline restoration

- The long negative tail after the main pulse (called undershoot) is due to the differentiation (CR) of finite length pulses. Theoretically no undershoot would occur if these tail pulses were infinitely long.
- Without entering into details there are several ways to cancel the undershoot. These are called ‘pole zero cancellation’. One way is illustrated in the picture:
- This circuit gives the following output pulse:

Electronic noise

- Would need a 4 hours lecture for itself
- As a staring point, remember that:
  - *Any piece of matter is made up of electrons and nuclei. These charges are constantly in motion due to thermal agitation. It is obvious that these motions will induce small voltage and current fluctuations in any piece of material, and in particular in any resistor. This noise is called thermal noise or Johnson noise.*
  - *In order to minimise this noise at the pre-amp stage. it is essential that the feedback resistance is as large as possible. On the other hand, the feedback capacitance cannot be made arbitrarily small. It should always be sufficiently large compared to any stray capacitance that are unavoidably present in the system. In practice it is difficult to have this capacitance less than about 1pF. The result is that $R_f C_f$ must be large if we want to have low noise.*