CMS
CMS Experiment at LHC, CERN
Data recorded: Tue Jul 26 07:58:48 2016 CEST
Run/Event: 277427 / 669414
Lumi section: 9

LHC machine and Top quark properties

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5th School on LHC Physics
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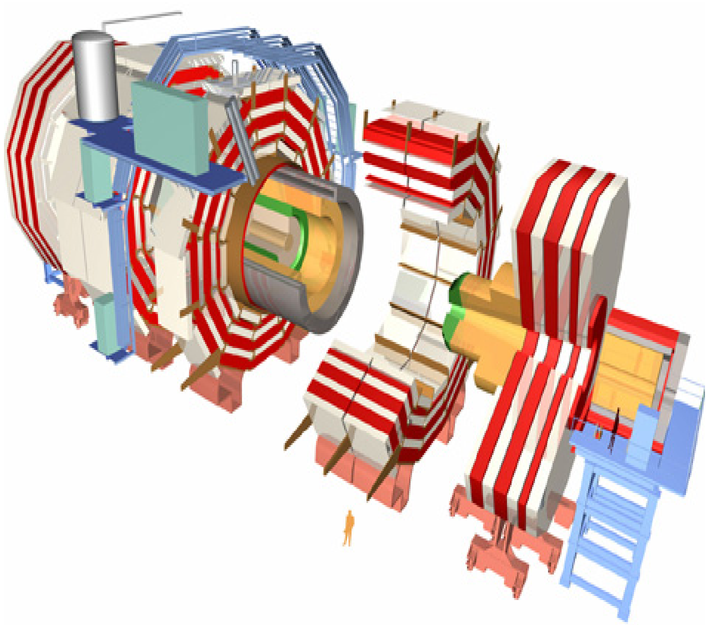
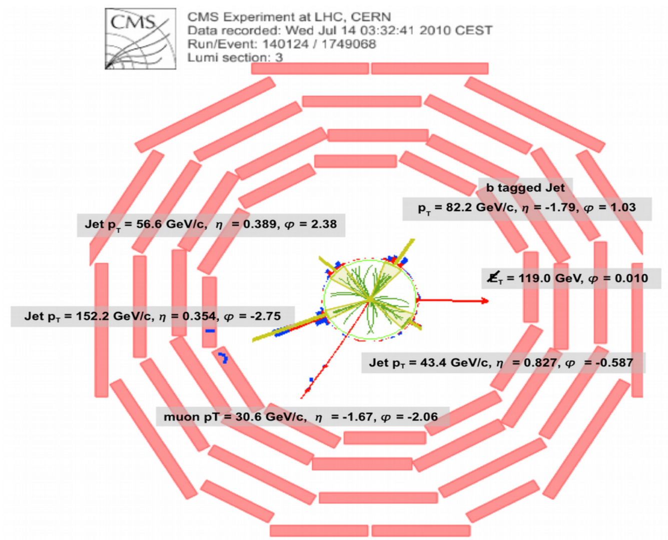
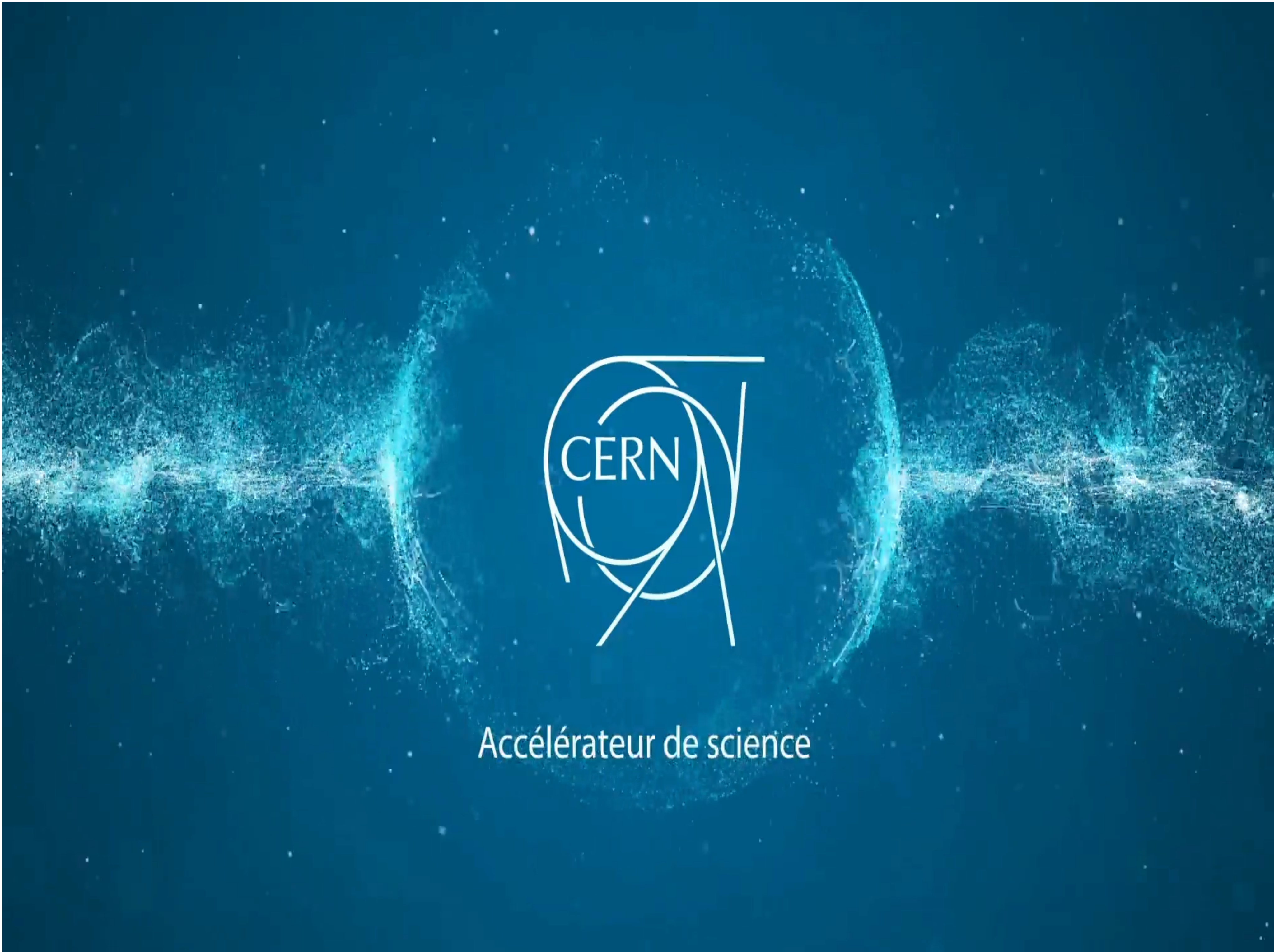
Outline

- LHC Machine
- Experimental tools, TDAQ and triggering
  - Constraints and architectures
  - Why using a trigger
  - Physics requirements
- Analysis strategies
- Top quark physics
- Helicity measurement
- Cross section measurements at 13TeV





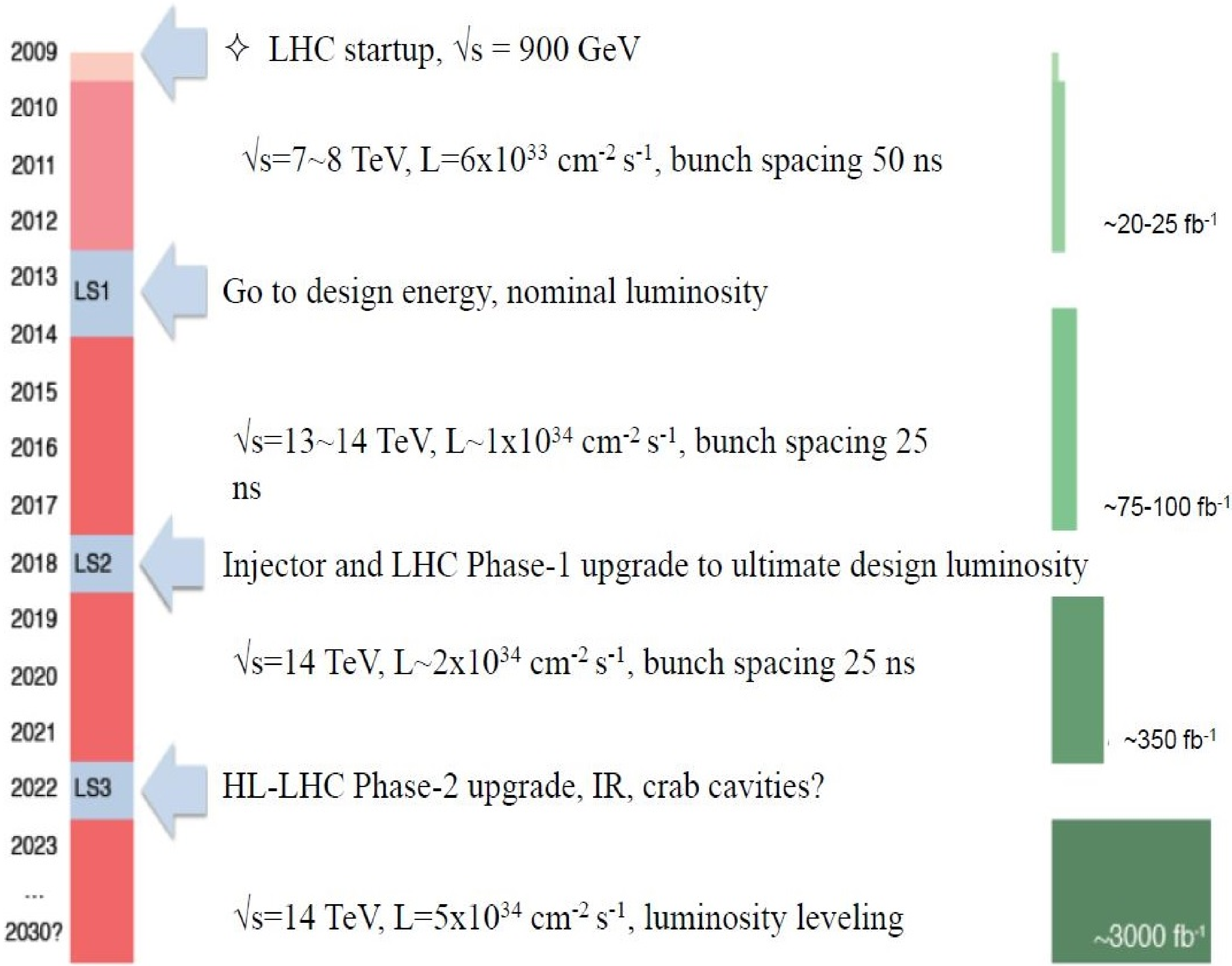
LHC machine


CERN
Accélérateur de science

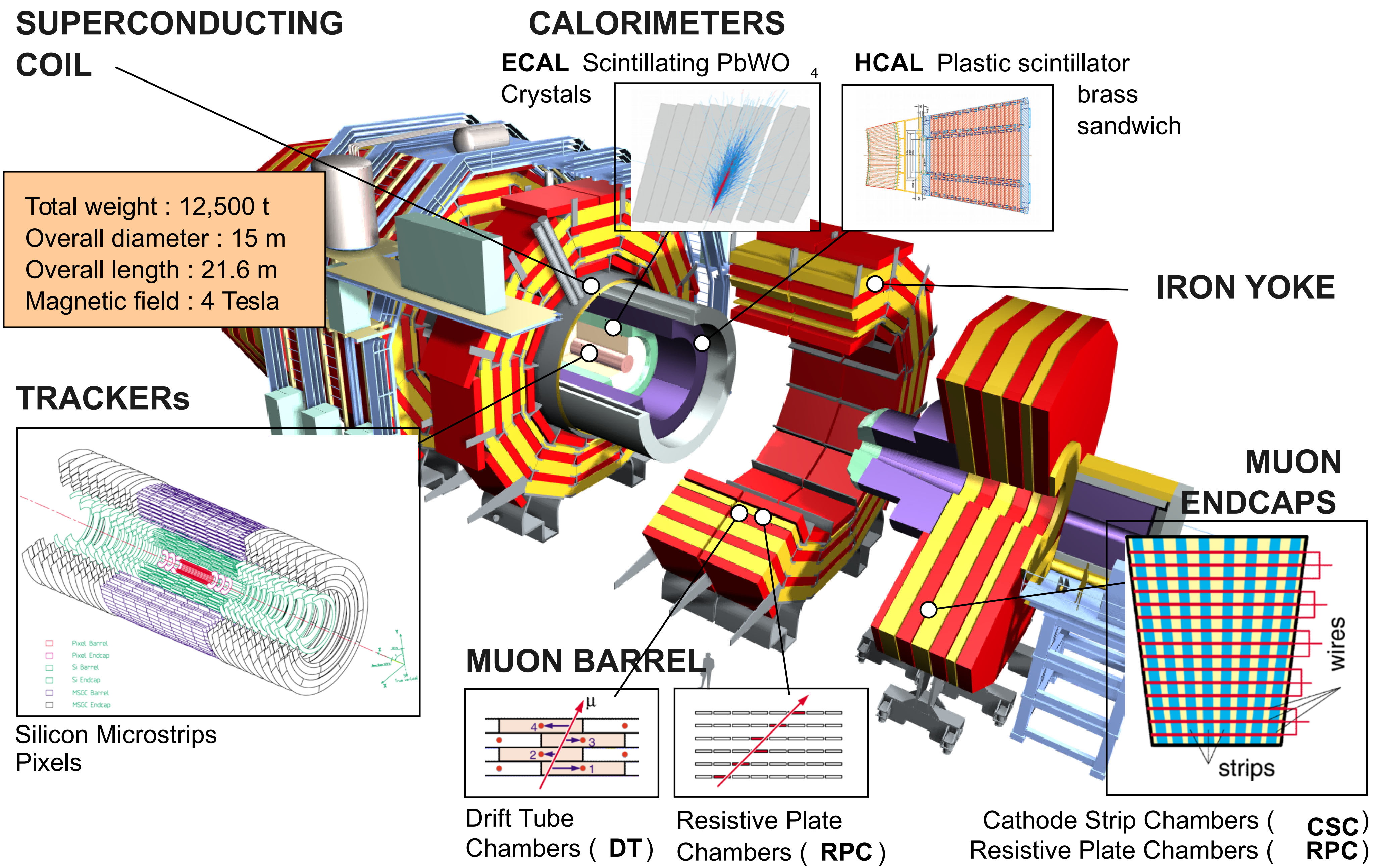
LHC Facts:

- Protons arrived in the LHC, traveled at **0.999997828** times the speed of light.
- Between each consecutive bunch there are **7.5 m**
  - time between bunches = $7.5/3*10^8$
  - Bunch spacing = $\mathbf{2.5*10^{-8}\ s}$
- The effective number of bunches is **2808**
- **11245 * 2808 ~ 32 millions crosses/s** , the "average crossing rate"
  - **20 * 32 millions crosses/s** ~ 600 millions collision/s
- Probability $\approx (d_{proton})^2/(\sigma 2) \Rightarrow$ Probability $\approx \mathbf{(10^{-15})^2/(16*10^{-6})^2 \approx 4*10^{-21}}$
  - $\mathbf{(4*10^{-21})*(1.15*10^{11})^2} \Rightarrow$ ~ **50 interactions** every crossing

LHC Road map


2009
2010
2011
2012
2013
2014
2015
2016
2017
2018
2019
2020
2021
2022
2023
...
2030?
LS1
LS2
LS3
✧ LHC startup, √s = 900 GeV
√s=7~8 TeV, L=6x10^33 cm^-2 s^-1, bunch spacing 50 ns
~20-25 fb^-1
Go to design energy, nominal luminosity
√s=13~14 TeV, L~1x10^34 cm^-2 s^-1, bunch spacing 25 ns
~75-100 fb^-1
Injector and LHC Phase-1 upgrade to ultimate design luminosity
√s=14 TeV, L~2x10^34 cm^-2 s^-1, bunch spacing 25 ns
~350 fb^-1
HL-LHC Phase-2 upgrade, IR, crab cavities?
√s=14 TeV, L=5x10^34 cm^-2 s^-1, luminosity leveling
~3000 fb^-1

CMS


SUPERCONDUCTING COIL
CALORIMETERS
ECAL Scintillating PbWO4 Crystals
HCAL Plastic scintillator brass sandwich
Total weight : 12,500 t
Overall diameter : 15 m
Overall length : 21.6 m
Magnetic field : 4 Tesla
IRON YOKE
TRACKERs
Pixel Barrel
Pixel Endcap
Si Barrel
Si Endcap
MSGC Barrel
MSGC Endcap
Silicon Microstrips
Pixels
MUON BARREL
μ
Drift Tube Chambers (DT)
Resistive Plate Chambers (RPC)
MUON ENDCAPS
wires
strips
Cathode Strip Chambers (CSC)
Resistive Plate Chambers (RPC)

Should we read everything?

- A typical collision is “boring”
- The final rate dominated by not interesting physics

$$R = \sigma_{in} \times L$$

LHC: the trigger challenge!

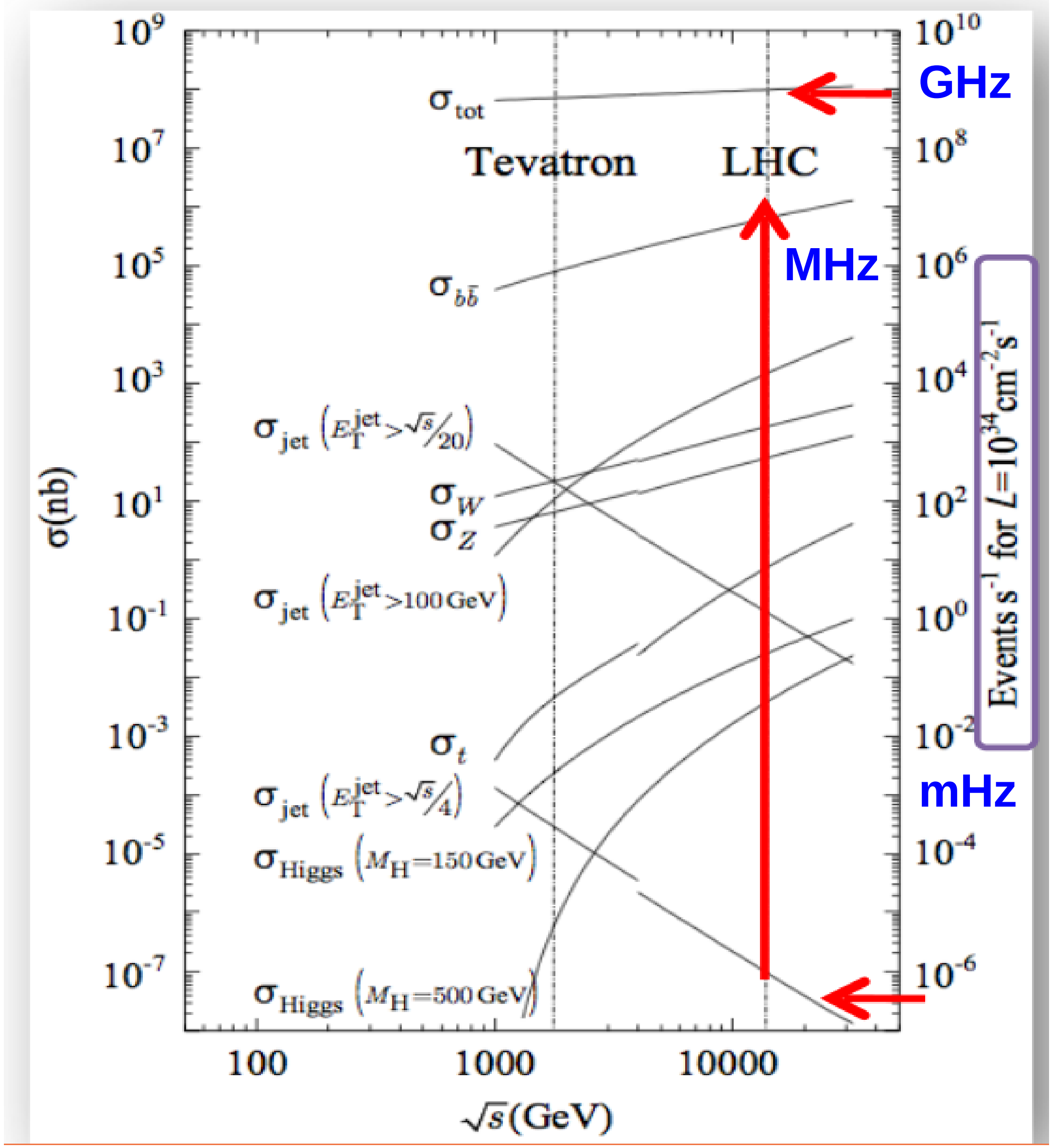
Total non-diffractive p-p cross section is **70 mb**

Total trigger rate is ~ GHz!!!

Huge range of cross-sections and production rates at design:

Beauty (0.7 mb)	– 1000 Hz
W/Z (200/60 nb)	– 100 Hz
Top (0.8 nb)	– 10 Hz
Higgs - 125 GeV (30 pb)	– 0.1 Hz

$$\frac{\sigma_{tot}}{\sigma_{H(500\,\mathrm{GeV})}} \approx \frac{100\,mb}{1\,pb} \approx 10^{11}$$

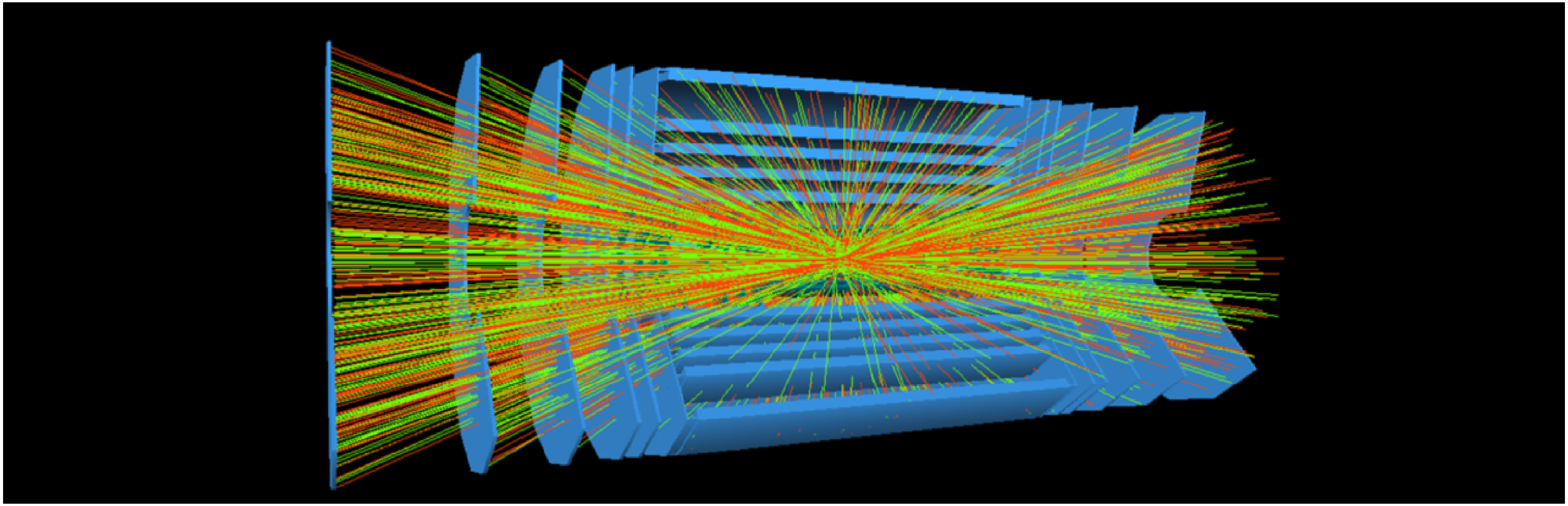


- Efficiently identify the rare processes from the overwhelming background <u>before</u> reading out & storing the whole event
- **Note: this is just the production rate, actual detection is more rare!**

TDAQ Systems at the LHC

A story about how they were designed originally and how they are evolving…

The data deluge



In many systems and experiments, storing all possibly the relevant data provided by sensors are unrealistic.

Three approaches are possible:

-reduce amount of data ⟶ **trigger**

-Faster data transmission and processing

-both

What do we need to read out a detector (successfully)?

- A selection mechanism **("trigger")**
- Electronic readout of the sensors of the detectors **("front-end electronics")**
- A system to keep all those things in sync **("clock")**
- A system to collect the selected data **("DAQ")**
- A **Control System** to configure, control and monitor the entire DAQ
- **Time, money, students** (lots of them)

What is a trigger?

Wikipedia:

“A trigger is a system that uses simple criteria to rapidly decide which events in a particle detector to keep when only a small fraction of the total can be recorded. “

- Simple
- Fast decision
- Low dead time
- Flexibility

Basic DAQ: “real” trigger

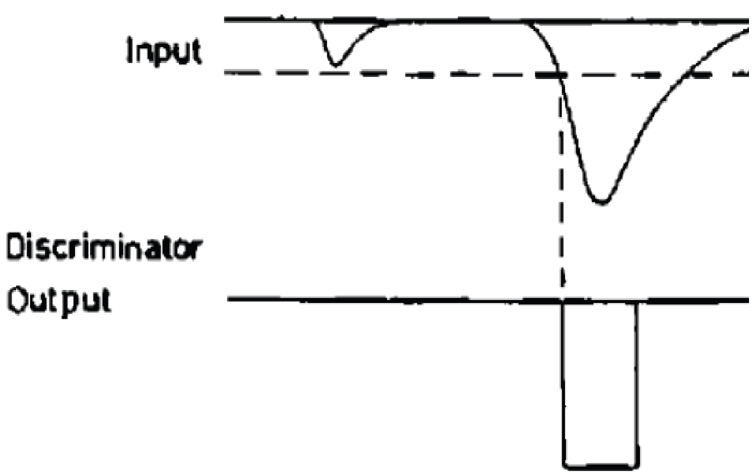
Events asynchronous and unpredictable

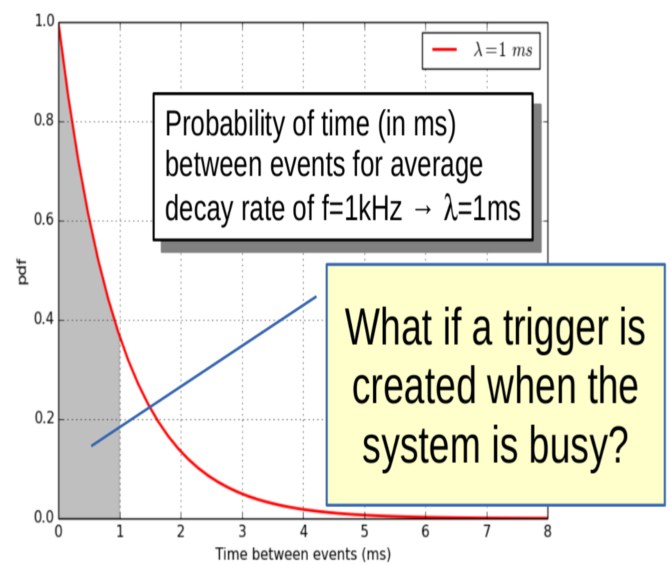
E.g.: beta decay studies

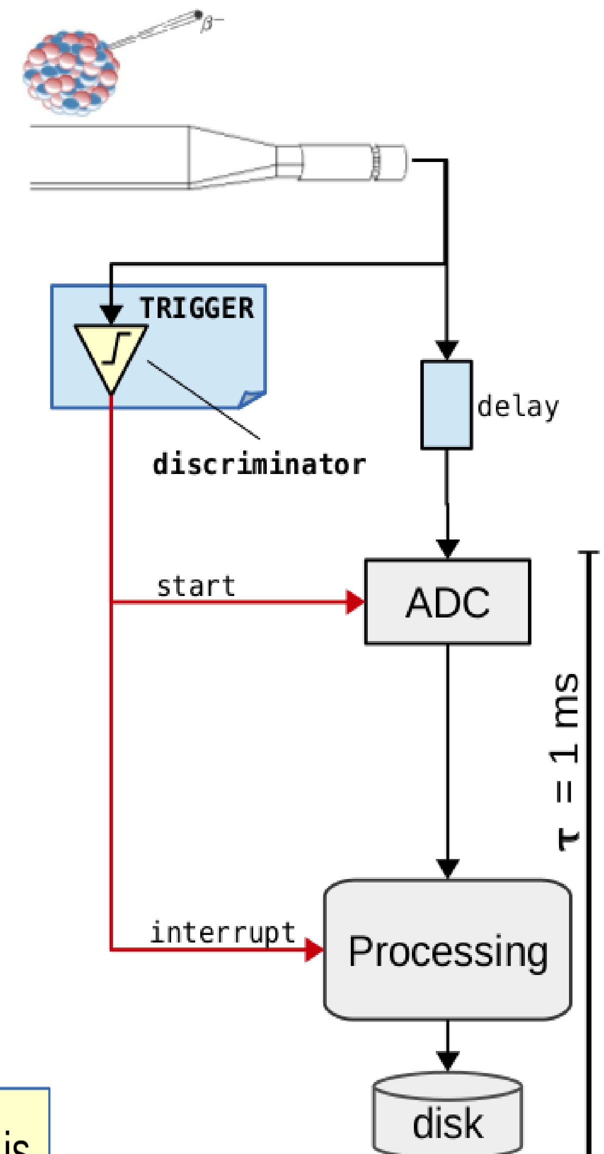
Let's assume for example a process rate f = 1 kHz, i.e. λ= 1 ms and τ = 1 ms

A physics trigger is needed.
delay compensate for trigger latency

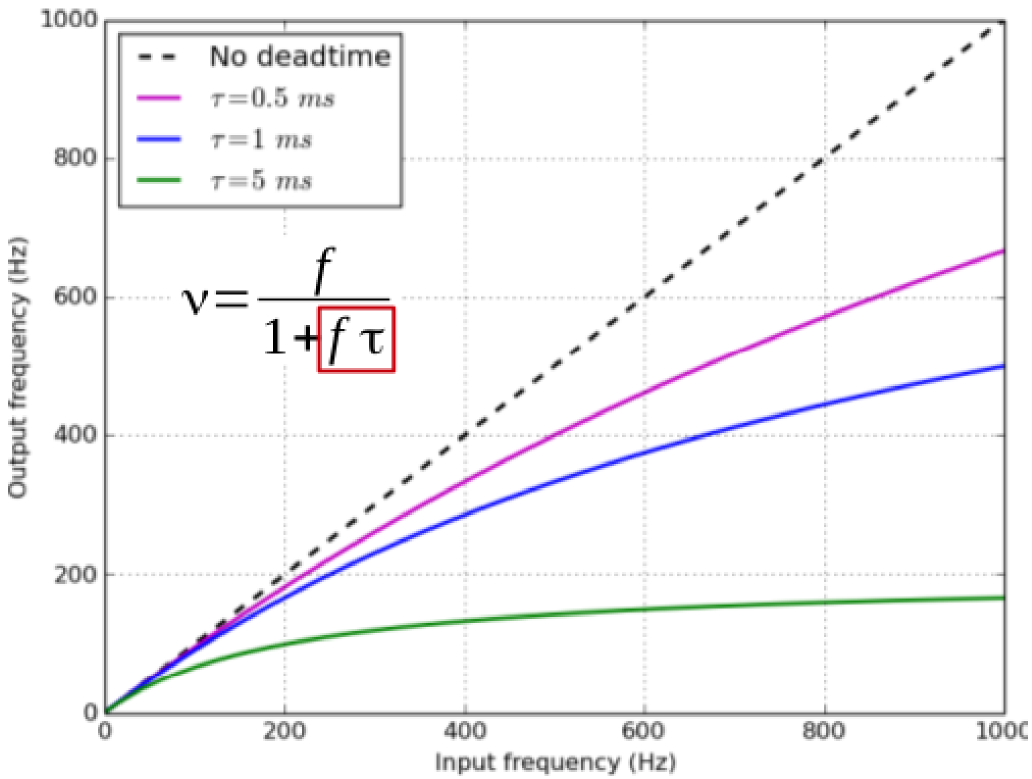
Discriminator: generate an output signal only if amplitude of input pulse is grater than a certain threshold



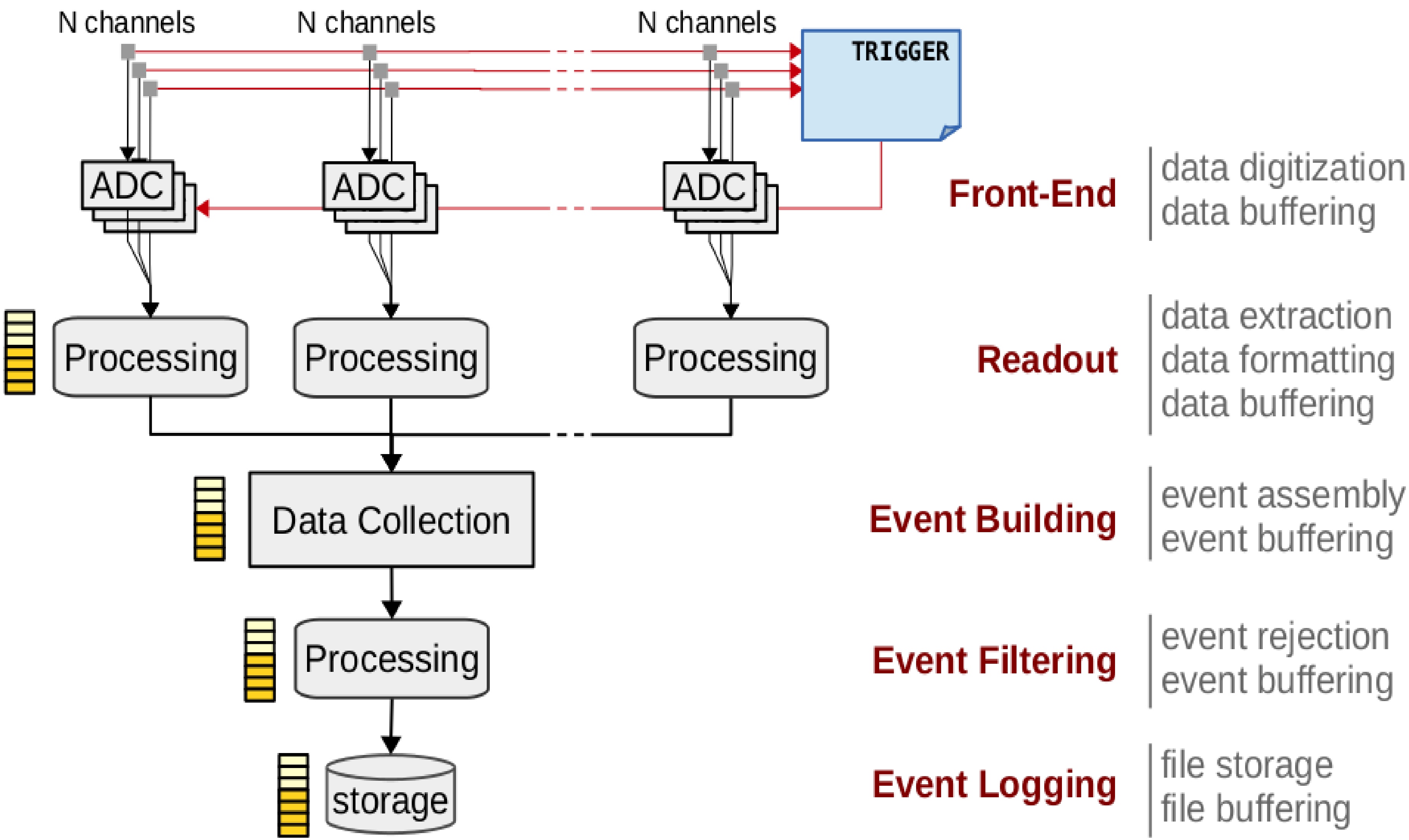




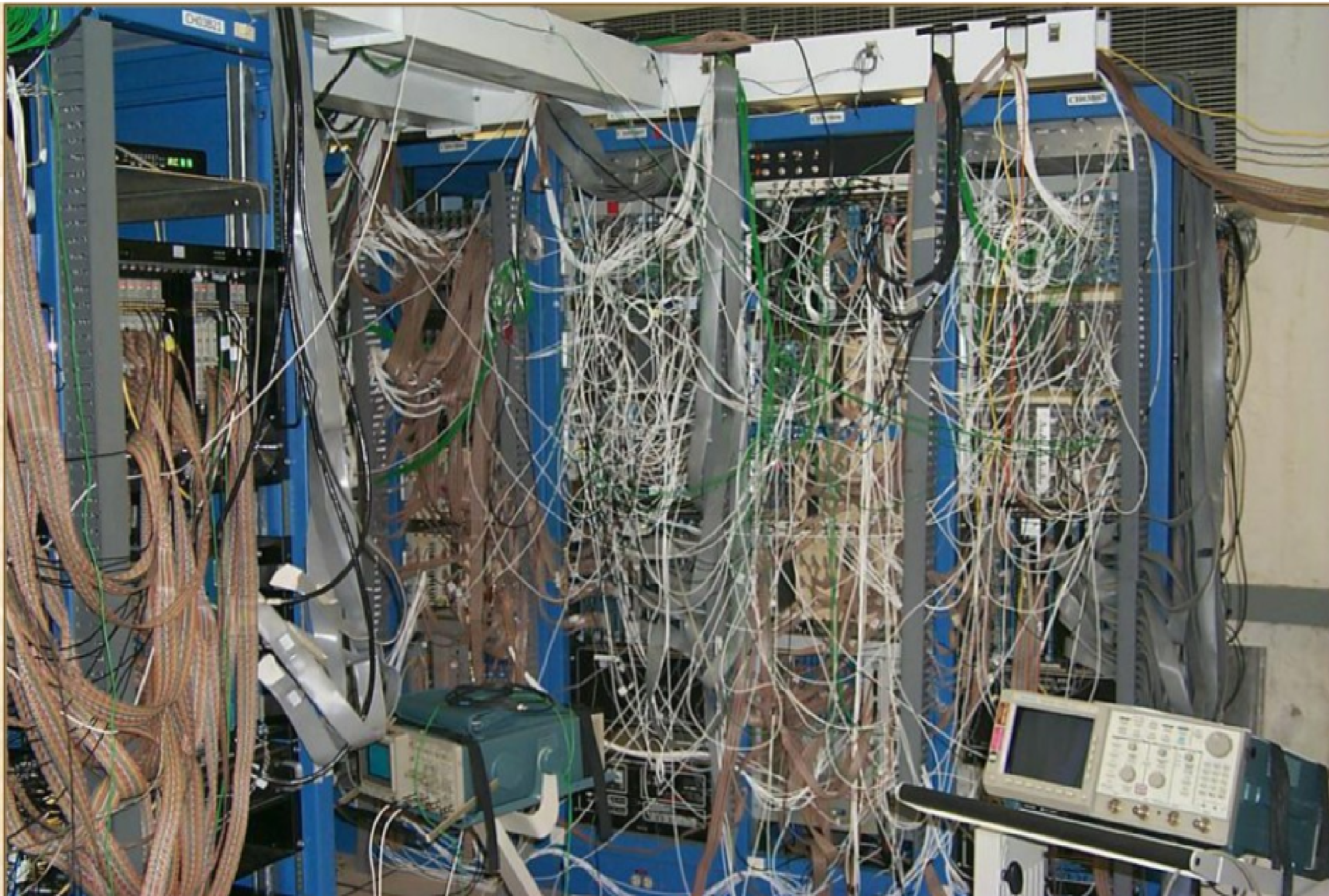
Input frequency v.s. output frequency



- Buffering usually needed at every level



Jungle of experimental tools



In any case:

Multi-level triggers

- Adopted in large experiments
- Successively more complex decisions are made on Successively lower data rates
  - watch out for high transverse momentum electrons, jets or muons
- First level with short latency, working at higher rates
- Higher levels apply further rejection, with longer latency(complexes algorithms)

LHC experiments @ Run1

Exp.	N.of Levels
ATLAS	3
CMS	2
LHCb	3
ALICE	4

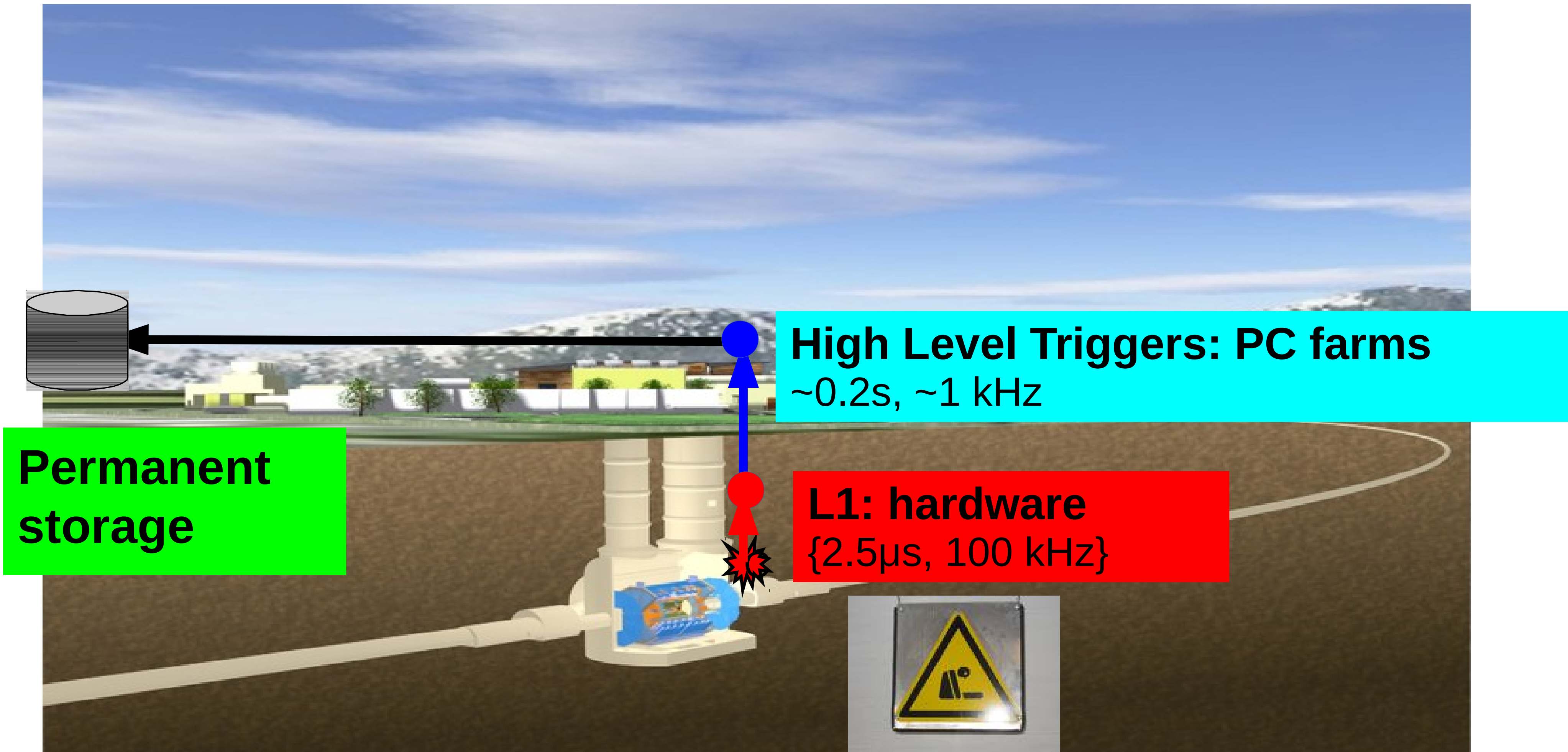
Efficiency for the desired physics must be kept high at all levels, as rejected events are lost for ever

Trigger at 2 stages:

Level1 (L1: fast, no detailed info, Hardwired trigger system, Constant latency buffers in the front-ends)

&

High Level Trigger (HLT: slower, using detailed info)



Trigger & DAQ : Select events and get the data from the detector to the computing center for the first processing.

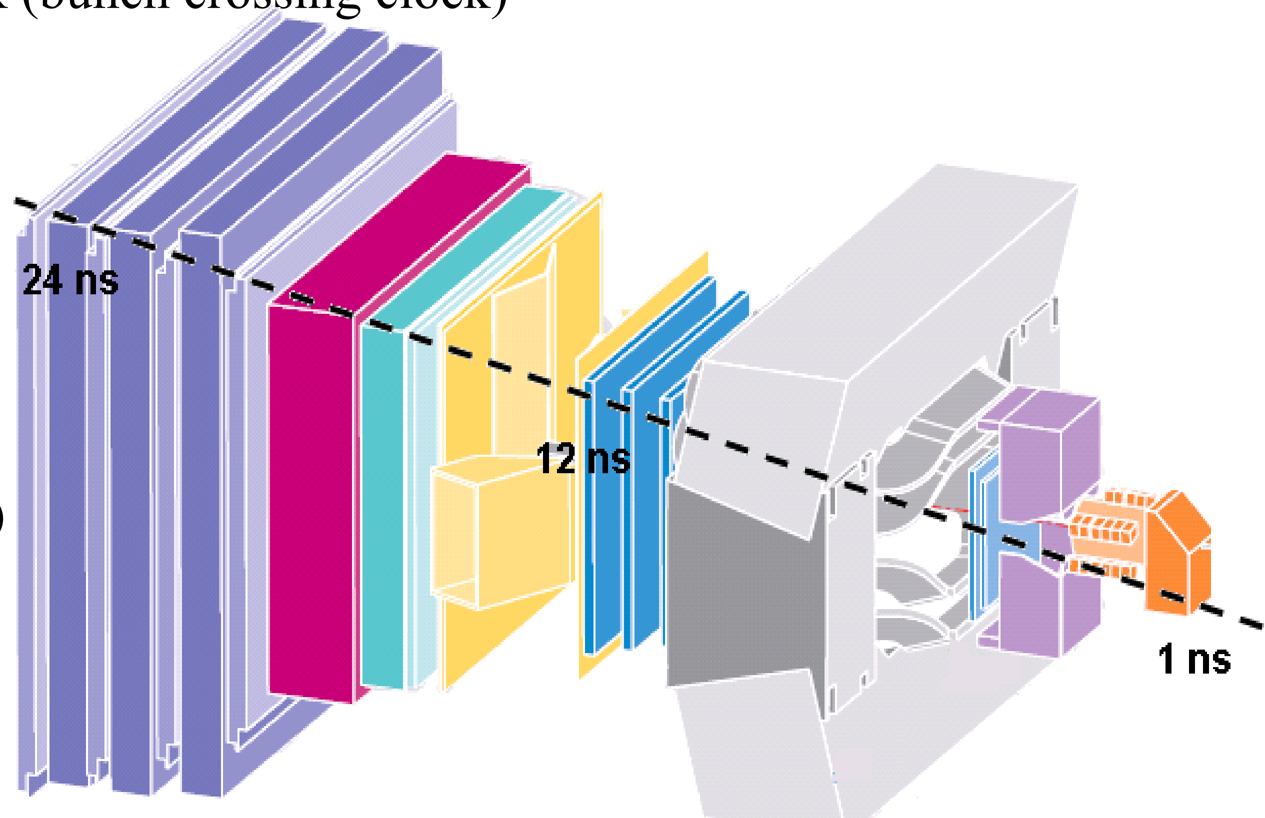
Challenges for the L1 at LHC

- N (channels) ~ O(10^7); ≈20 interactions every 25 ns
  - need huge number of connections
- Detector signal/time of flight can be > 25 ns
  - integrate more than one bunch crossing's worth of information
  - need to identify bunch crossing…
- Need to synchronize detector elements to (better than) 25 ns

  - All channels are doing the same "thing" at the same time

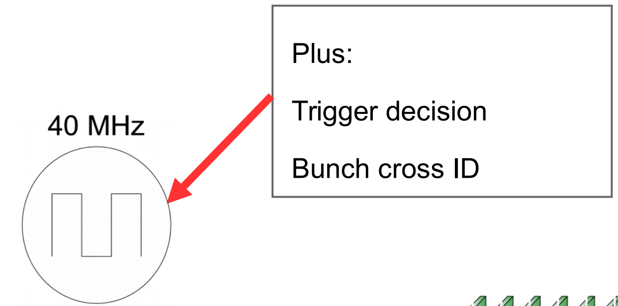
  - Synchronous to a global clock (bunch crossing clock)

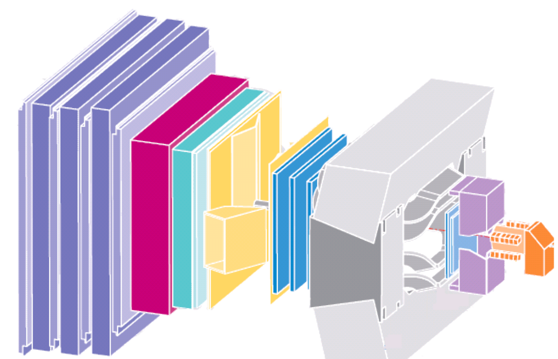
<u>But:</u>
Particle TOF >> 25ns
(25 ns ≈ 7.5m)
Cable delay >> 25ns (vsignal ≈ 1/3 c)
Electronic delays

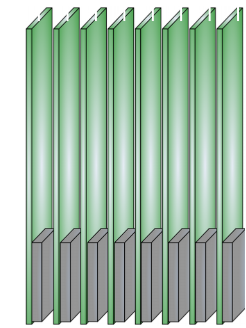


Distributing Synchronous Signals @ the LHC

- **An *event* is a snapshot of the values of all detector front-end electronics elements, which have their value caused by the same collision**
- A common clock signal must be provided to all detector elements
  - Since c is constant, the detectors are large and the electronics are fast, the detector elements must be carefully time-aligned
- Common system for all LHC experiments TTC based on radiation-hard opto-electronics







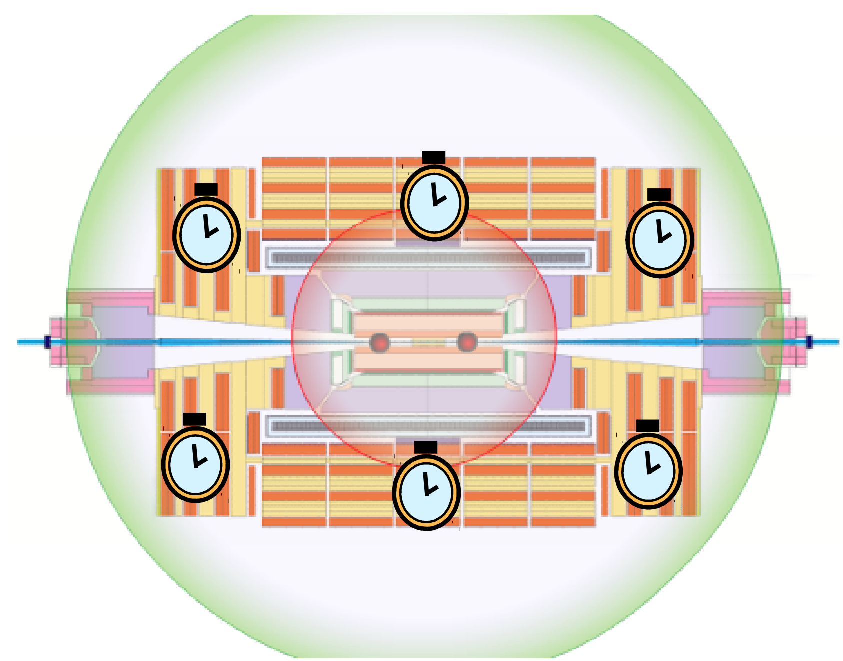
Data corresponding to the same bunch crossing

must be processed together.

<u>Need to:</u>

Synchronize signals with programmable delays.

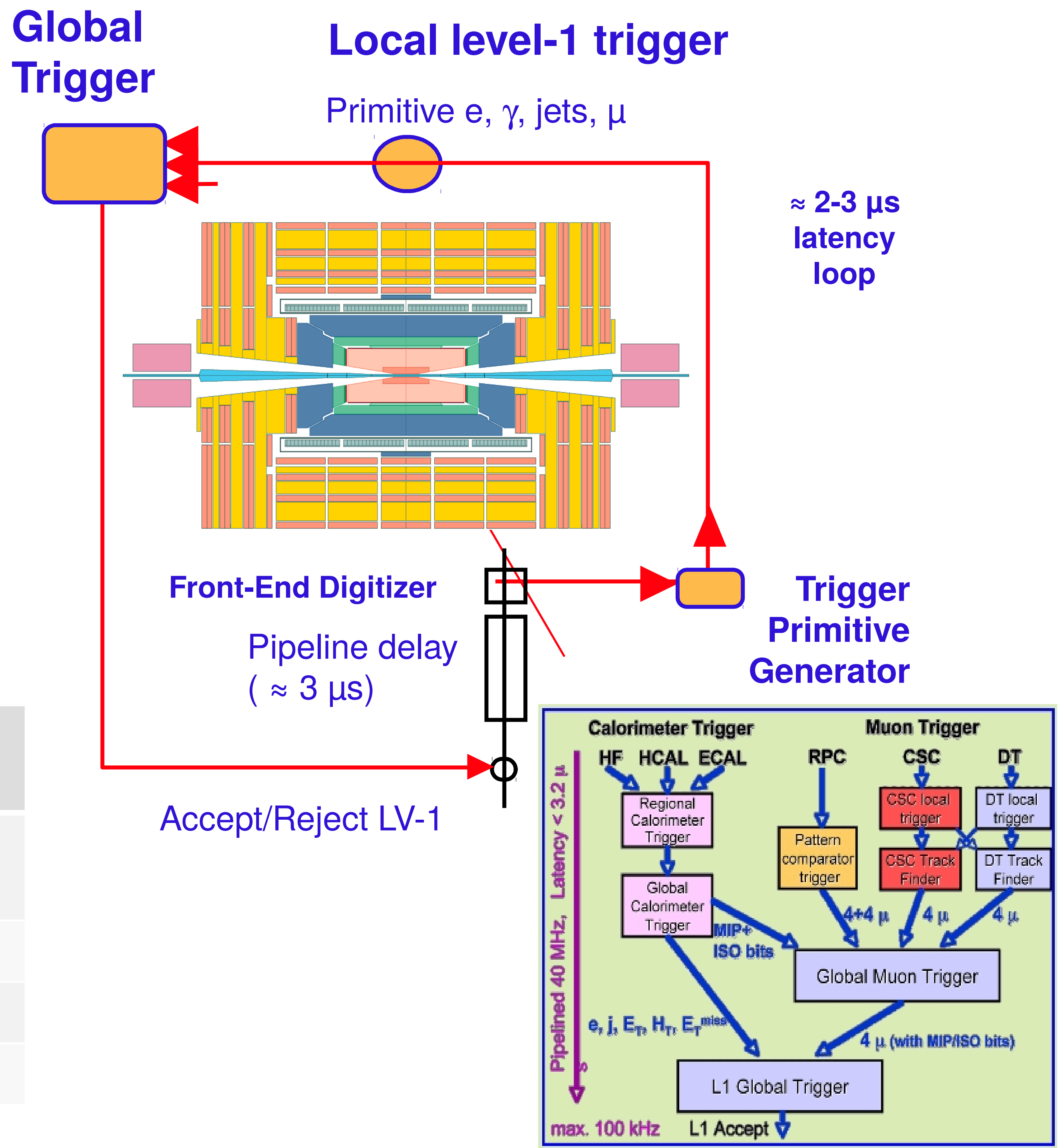
Provide tools to perform synchronization



Distributing the L1 Trigger

- Assuming that a magic box tells for each bunch crossing (clock-tick) **yes or no**
- This decision has to be brought for each crossing to all the detector f**ront-end electronics elements** so that they can send of their data or discard it
- LHC use the same **Timing and Trigger Control** (TTC) system as for the clock distribution

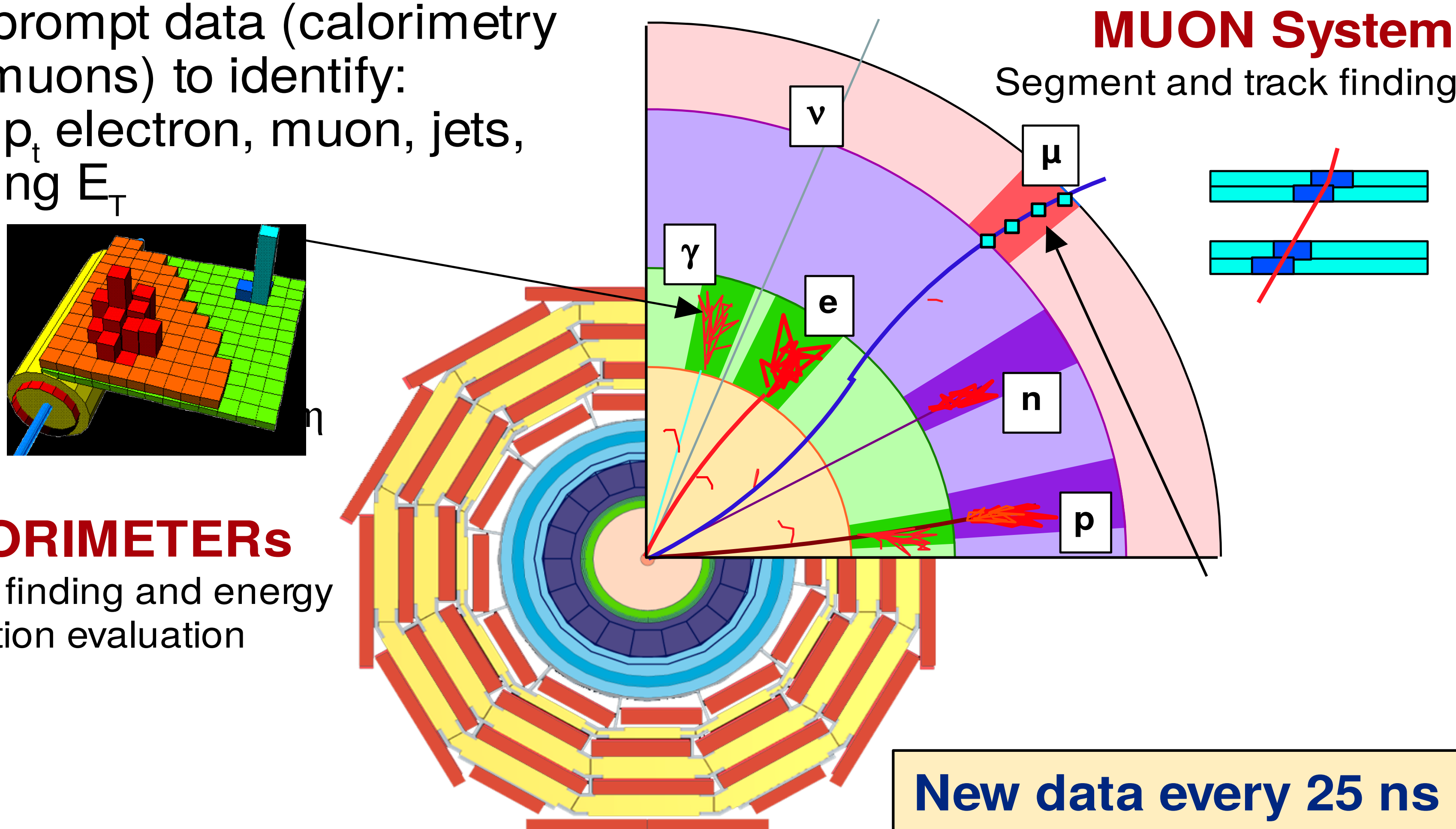
L1 trigger latencies	
ALICE	No pipeline
ATLAS	2.5 us
CMS	3 us
LHCb	4 us



The more you know about the events, the easiest you select the “signal” and reject the “background”

When there is limited time budget (L1 trigger): decide based only on the muon and calorimeter systems

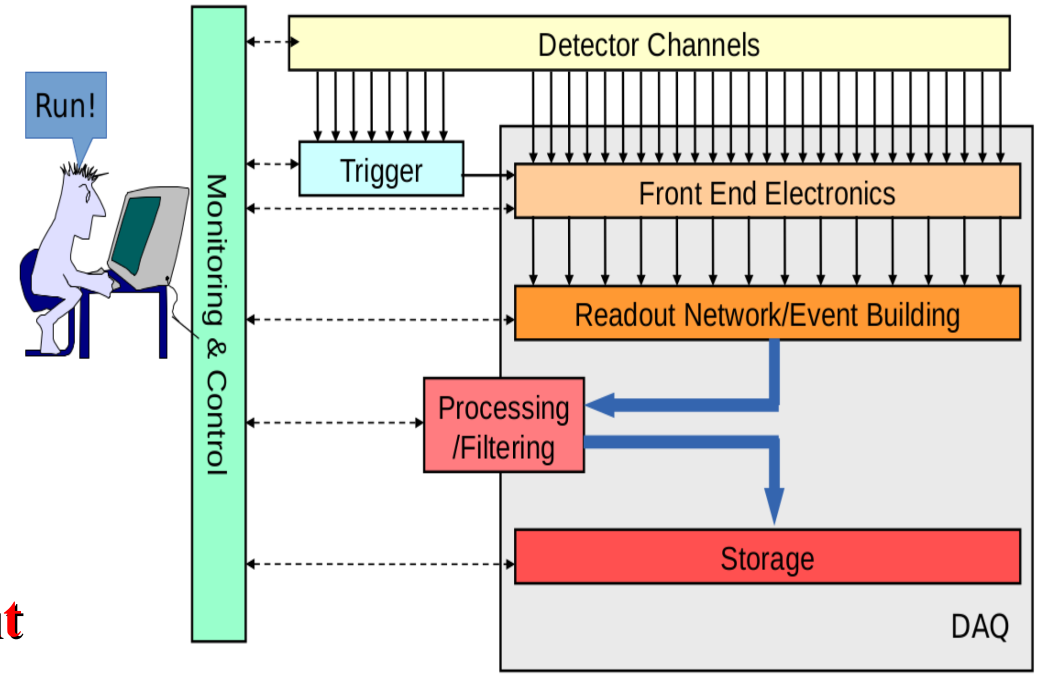
Use prompt data (calorimetry and muons) to identify:
High p_t electron, muon, jets, missing E_T



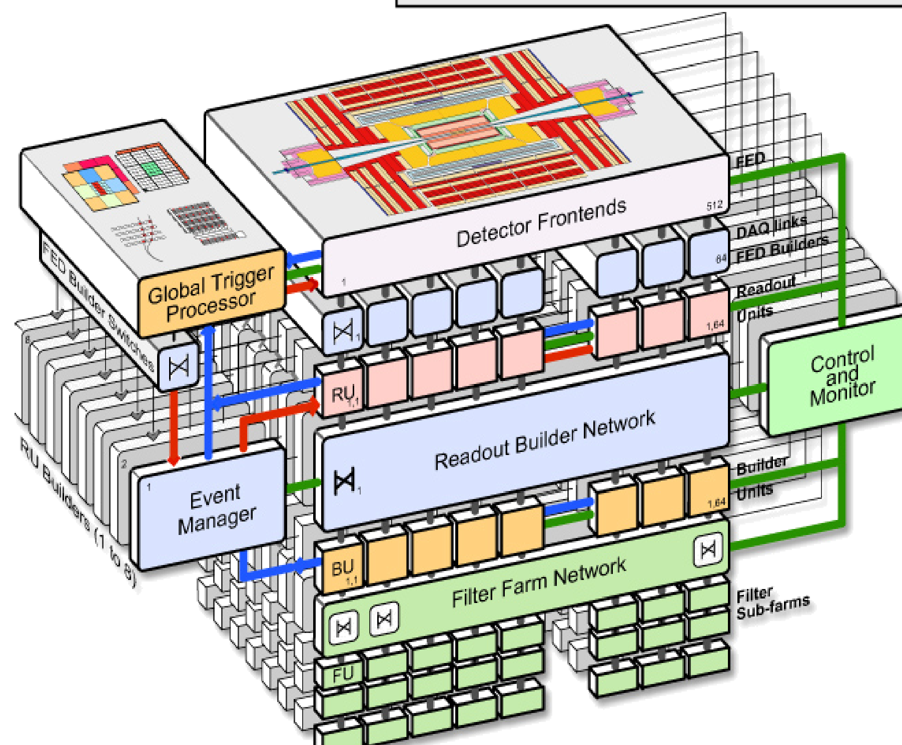
New data every 25 ns
Decision latency ~ µs

Trigger & DAQ

- Trigger
  Either selects interesting events or rejects boring ones, in real time i.e. with minimal controlled latency time it takes to form and distribute its decision



- DAQ
  gathers data produced by detectors: **Readout**
  Possibly feeds several trigger levels: **HLT**
  Forms complete events: **Event Building**
  Stores event data: **Data Logging**
  Provides **Run Control, Configuration and Monitoring**

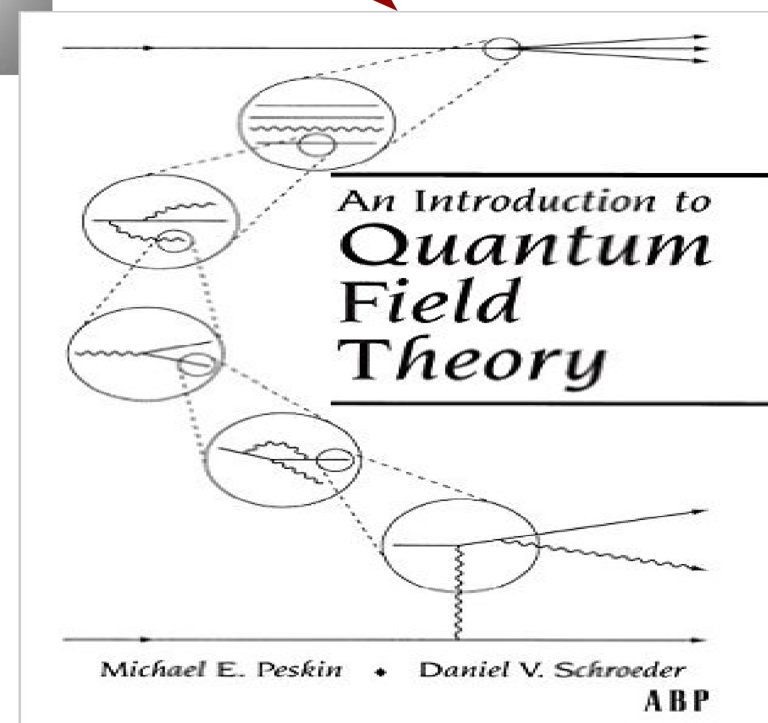


Physics and top quark sector

In which direction an analyzer should be motivated?

Experiment
Soft- or hardware

Phenomenology or theory



Try to get knowledge in both directions as much as possible

Fitting methods

Signal efficiency

uncertainties

Closure tests

Motivation

Real Data

MC simulation

Truth level information

What is signal?

Event reconstruction

What is background?

Bkg estimation

Analysis strategy

Object selection

Control region

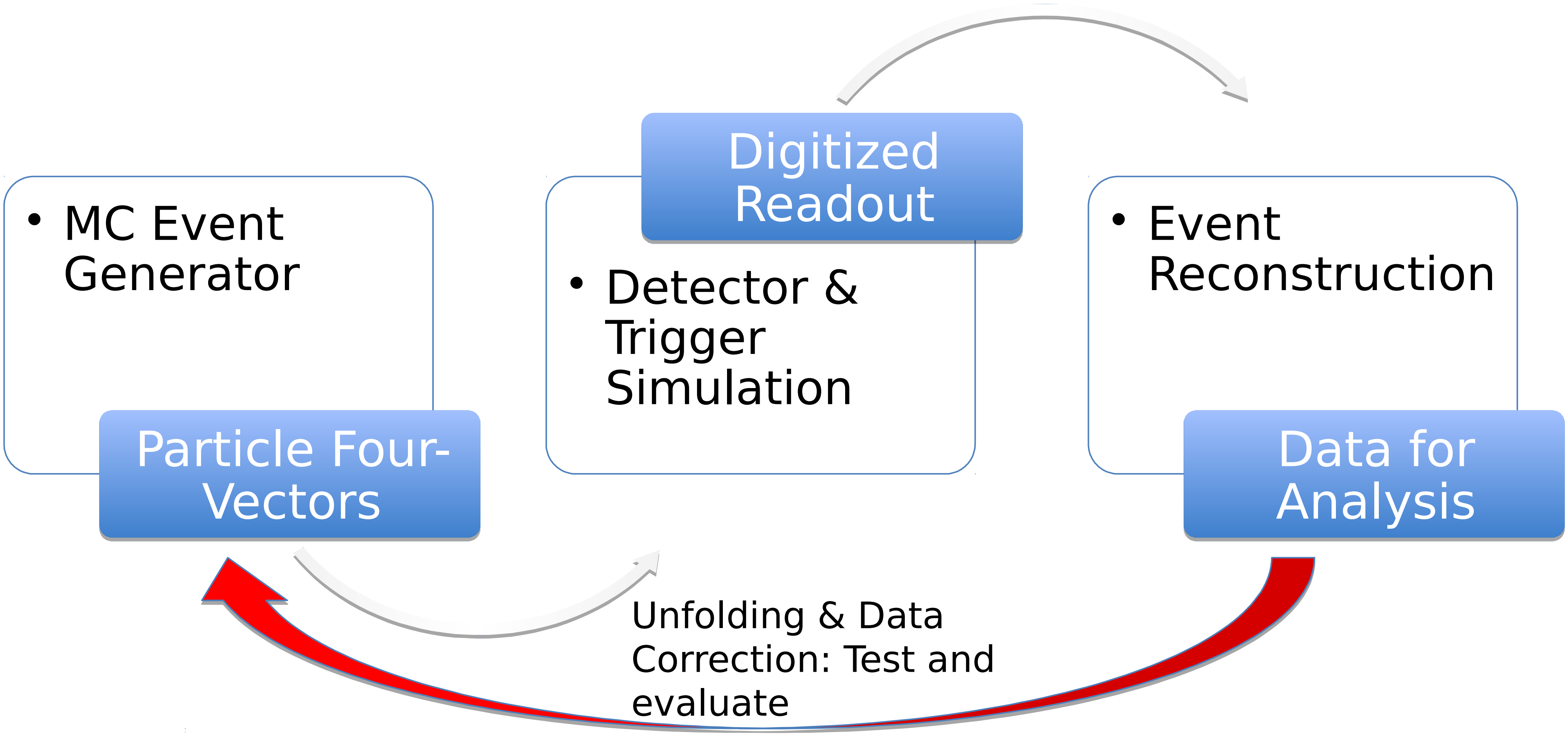
Event selection

Signal region

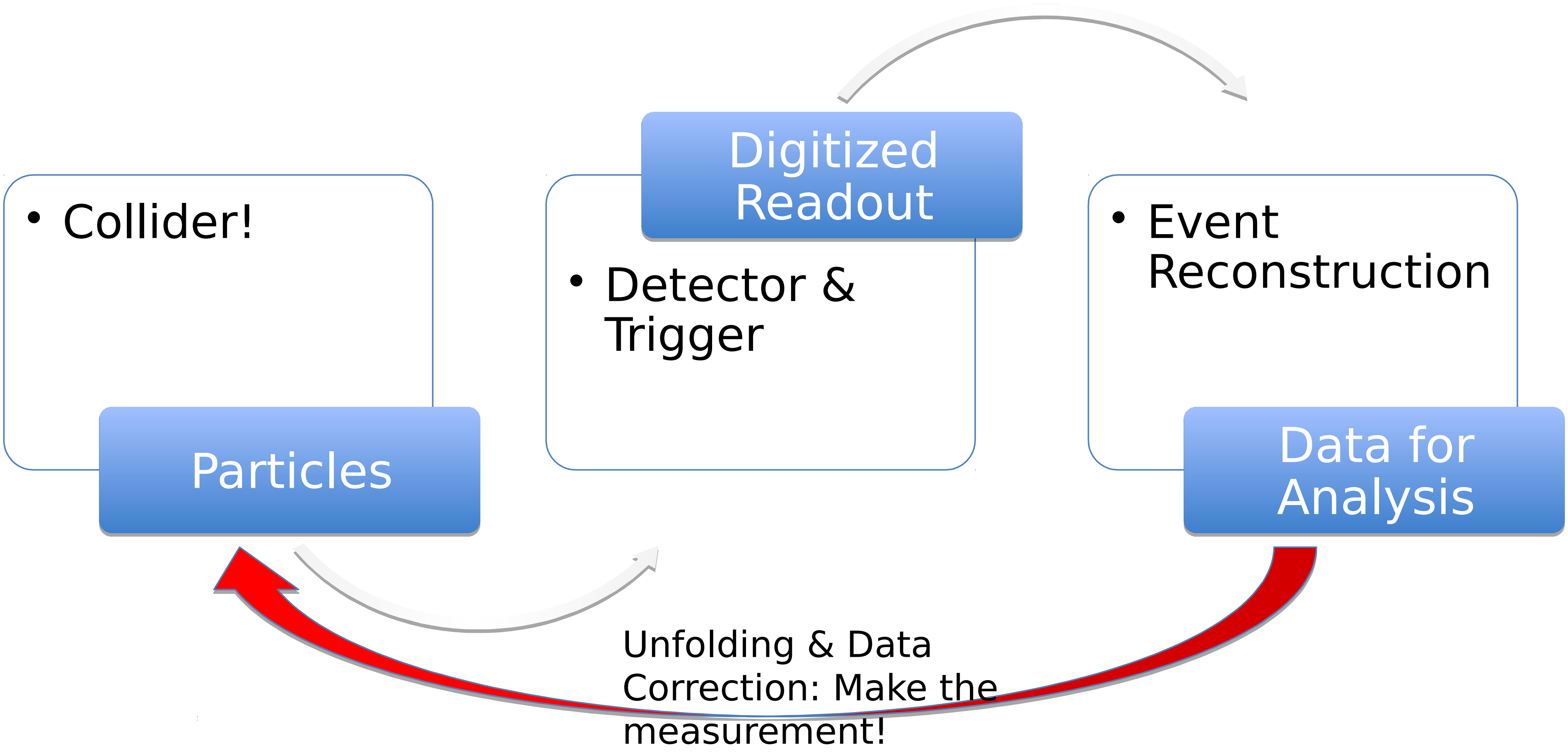
Control plots

What we need to make data based analysis

Simulation and Experiment

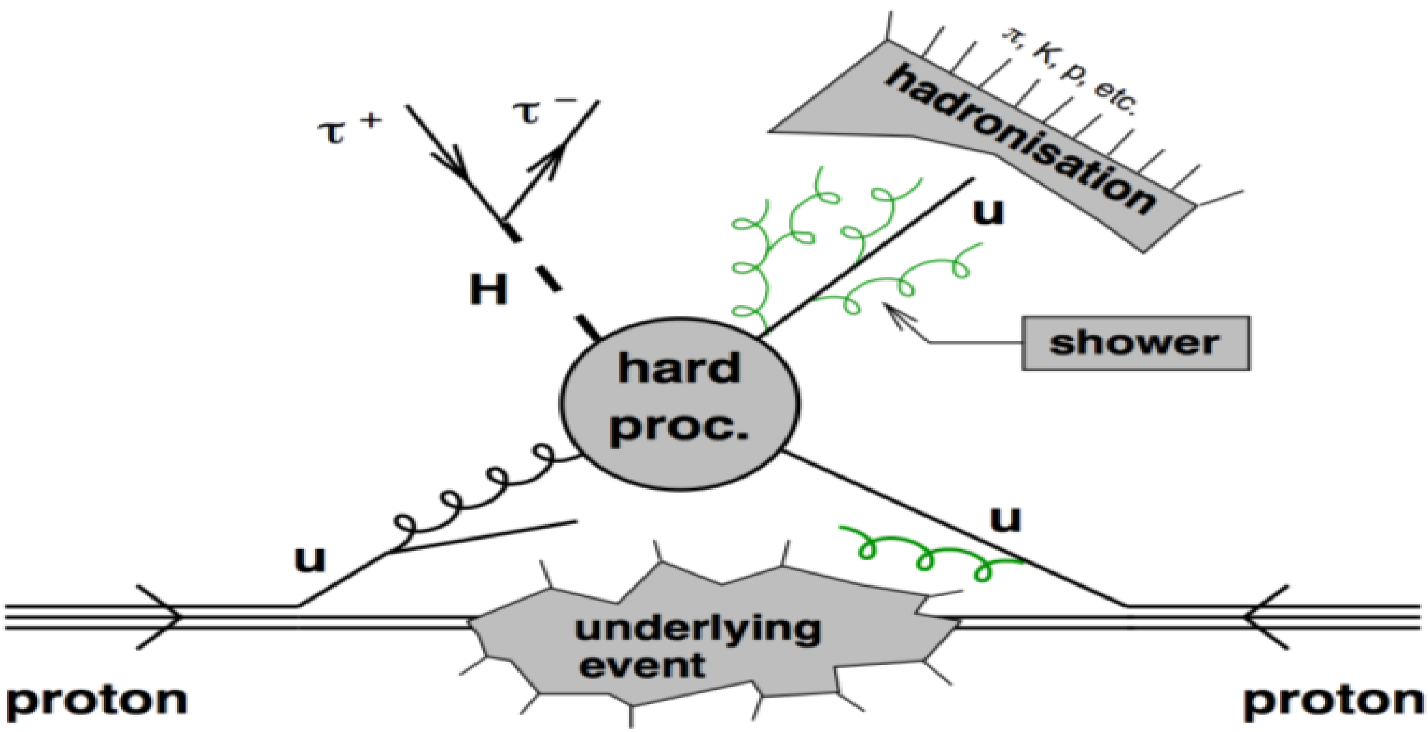


Simulation and Experiment

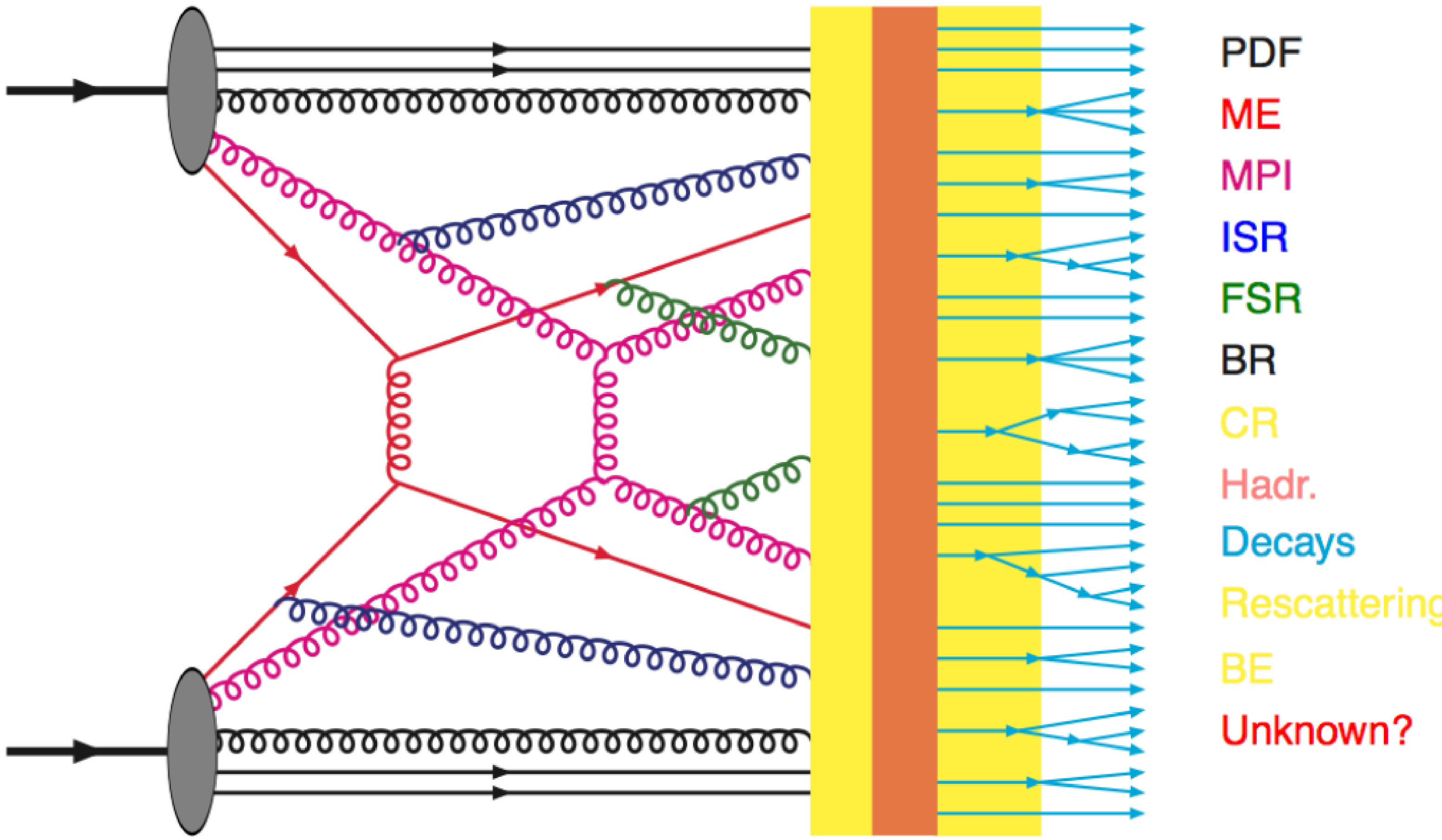


The structure of an event – 1

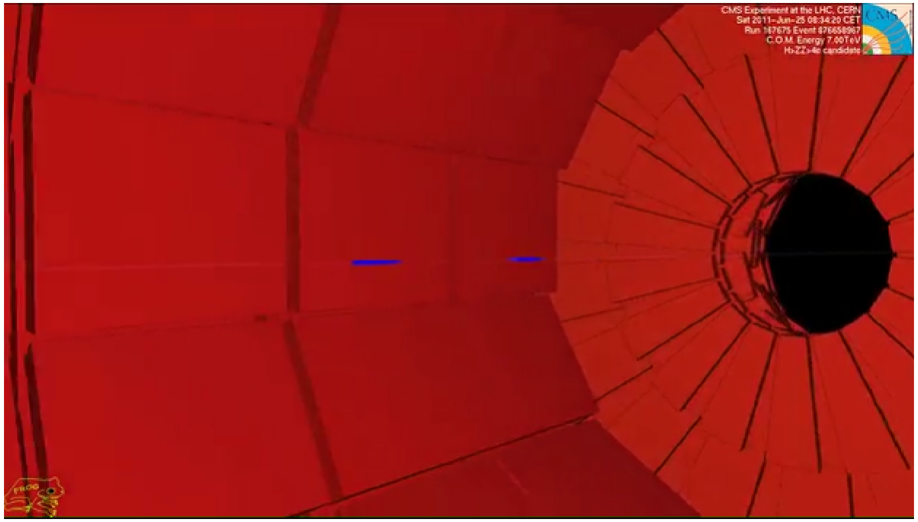
The structure of an event – 2
The structure of an event – 3
The structure of an event – 4
The structure of an event – 5
The structure of an event – 6
The structure of an event – 7
The structure of an event – 8
The structure of an event – 11

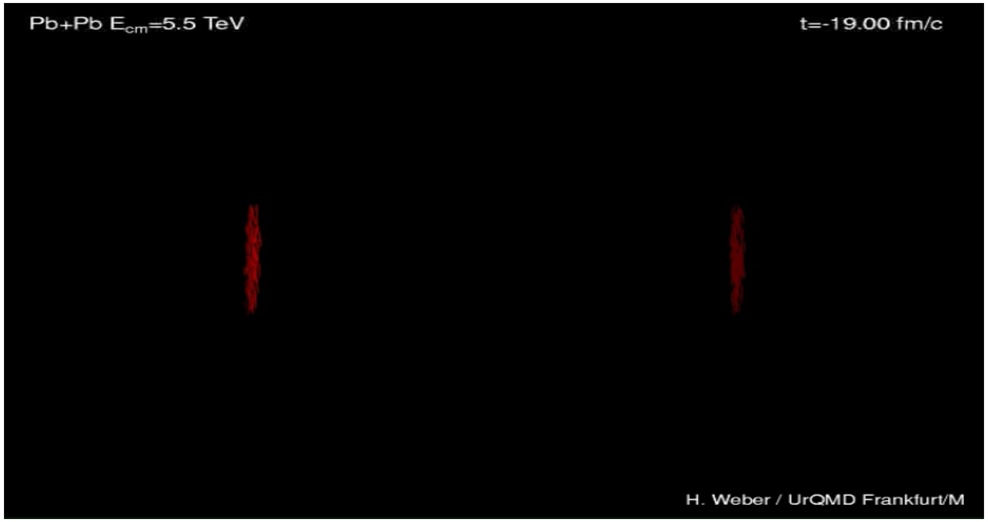


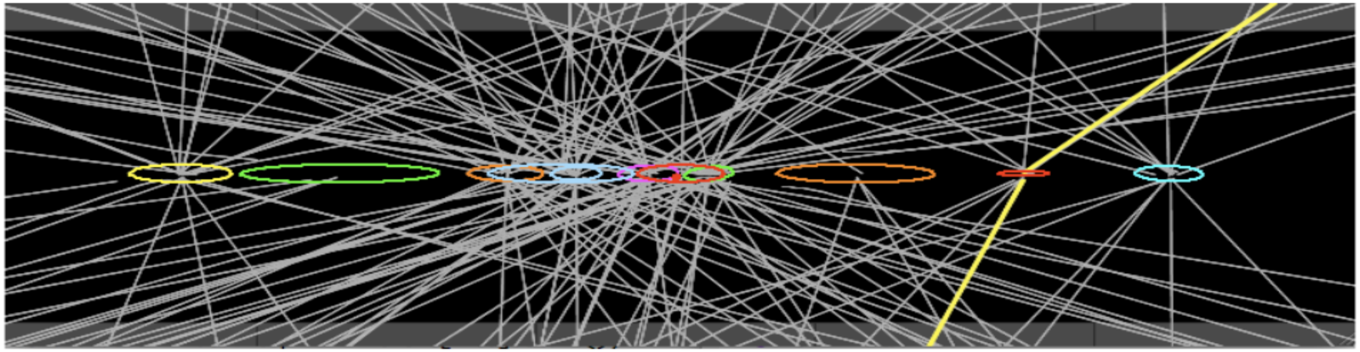
An event consists of many different physics steps, which have to be modeled by event generators.



What happened for real data?



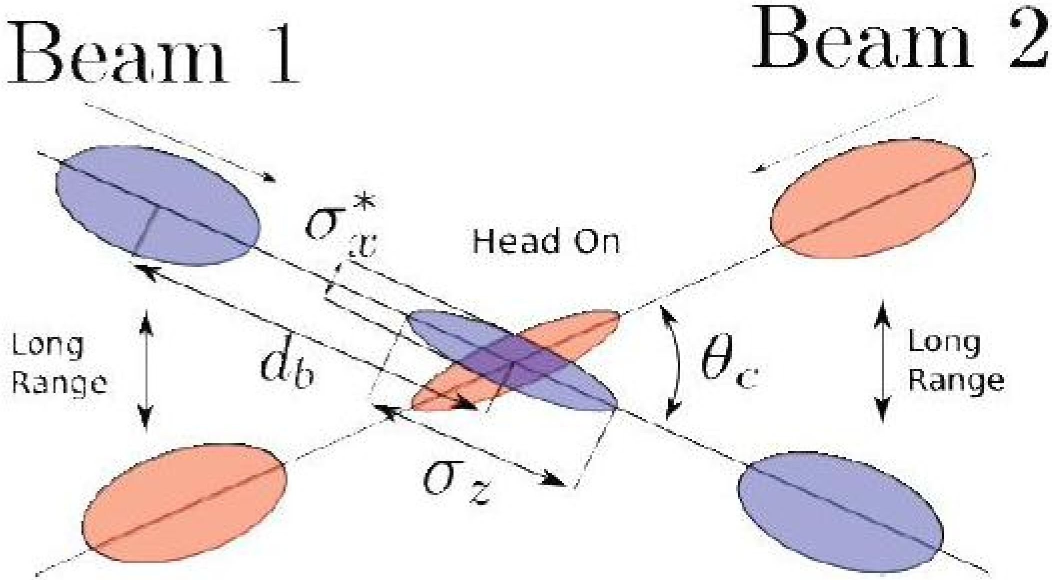


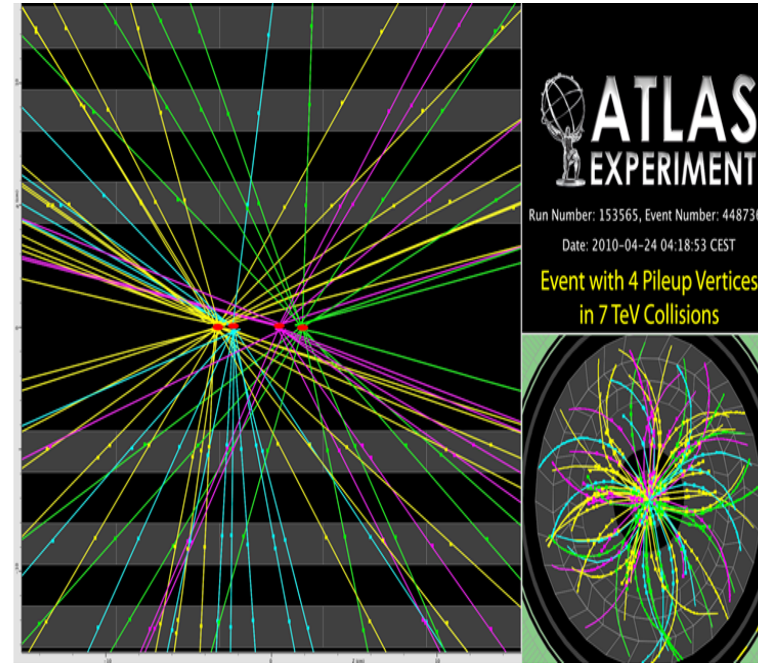


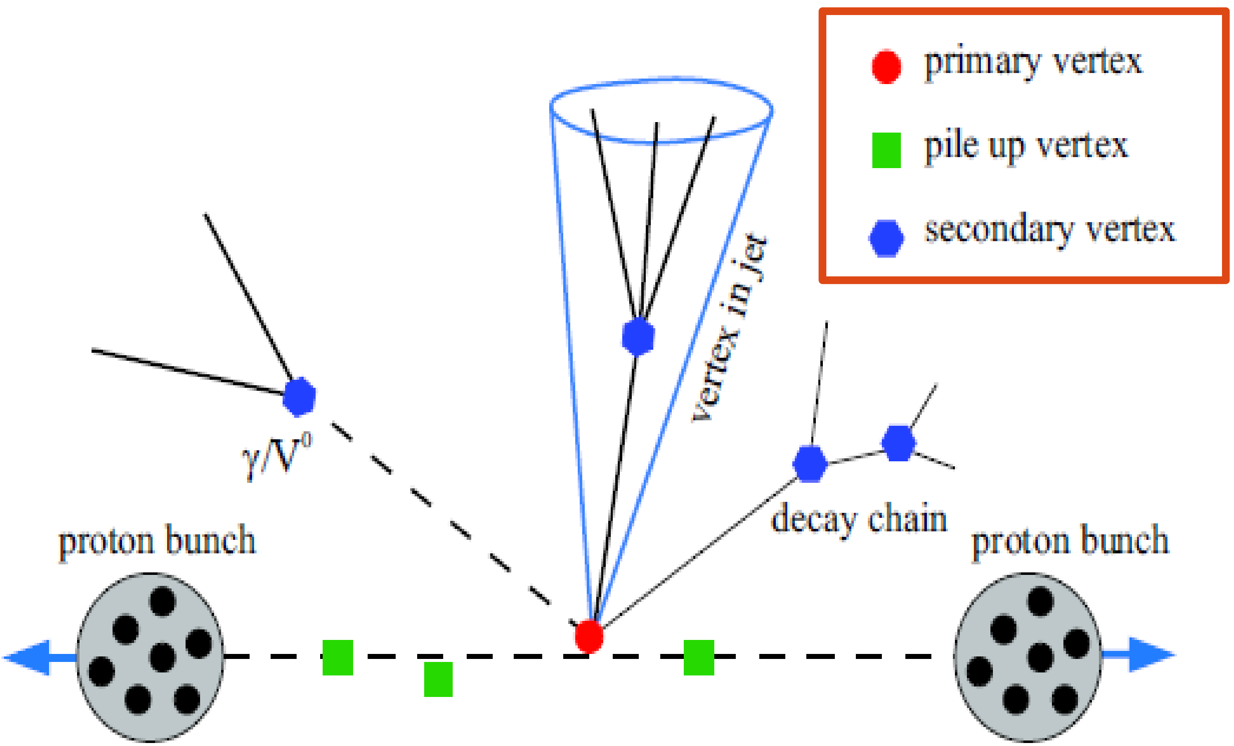
$$\langle n \rangle = \overline{\mathcal{L}}\,\sigma$$

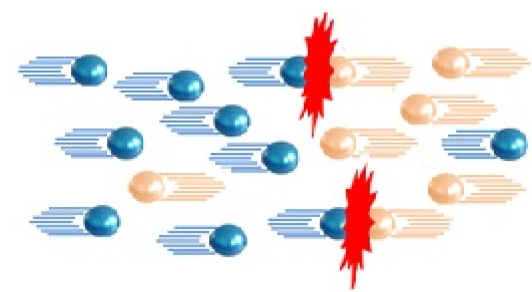
- The L parameter is machine luminosity per bunch crossing, **$L \sim n_1.n_2 /A$** and $\sigma \sim \sigma_{tot} \approx 100$ mb.
- Current LHC machine conditions ⇒ n ∼ 10−20.

Pileup introduces no new physics and keep in mind concept of bunches of hadrons leading to multiple collisions.









http://www.lhc-closer.es/taking_a_closer_look_at_lhc/0.lhc_p_collisions

Analysis techniques

-An often faced problem is to predict the answer to a question based on different input variables
- Two different problems:

Classification
■ Predict only a binary response
  Do I need an umbrella today? Yes/No
  What is the measured data?   Signal/Background

Regression
■ Predict an exact value as an answer
● What will be the temperature tomorrow? -19 °C, 7 °C, 38 °C, ...
This session will only cover the classification problem

Event Classification

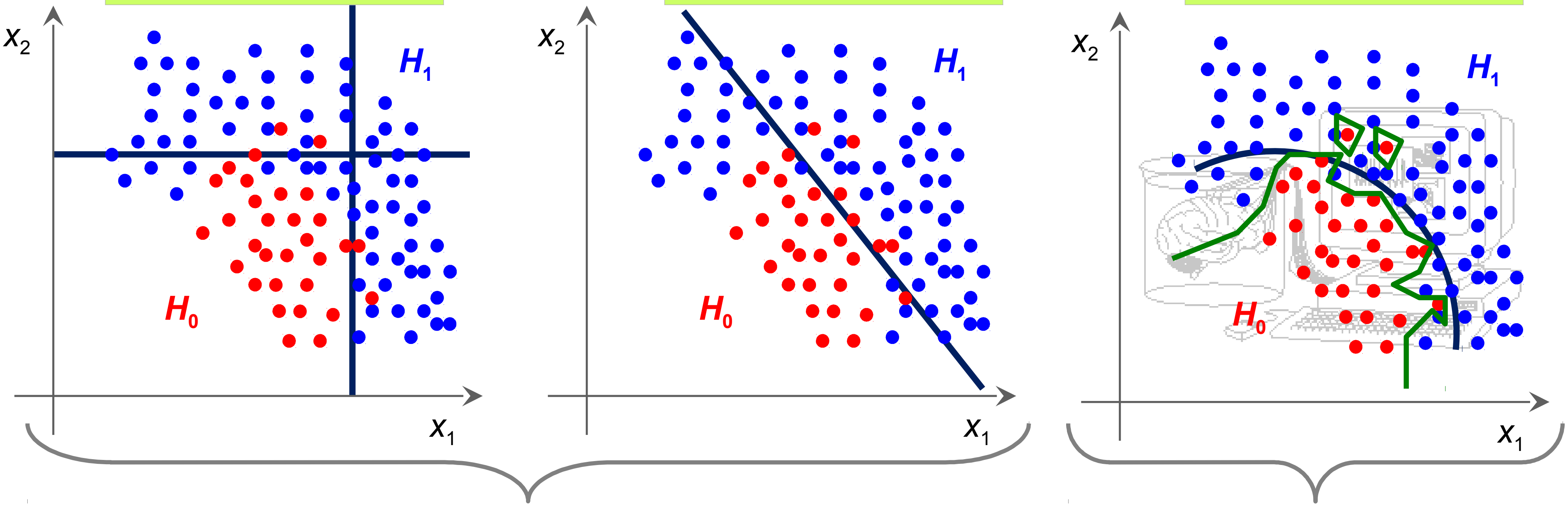
Optimal analysis uses information from all (or in any case many) of the measured quantities → Multivariate Analysis (MVA)

Each event yields a collection of numbers $\vec{x} = (x_1, \ldots, x_n)$

x_1 = number of muons, $x2 = pt$ of jet, ...

- Suppose data sample with two types of events: H_0, $H1$
  - We have found discriminating input variables $x1$, $x2$, …
  - What decision boundary best separates the two classes??

Rectangular cuts? | A linear boundary? | A nonlinear one?



Low variance (stable), high bias methods

High variance, small bias methods

- How can we decide this in an optimal way ? → Let the machine learn it !

Event Classification in High-Energy Physics (HEP)

Allows to combine several discriminating variables into one final discriminator $R^d \rightarrow R$
Better separation than one variable alone Correlations become visible

- Most HEP analyses require discrimination of signal from background:
  - Event level (Higgs searches, …)
  - Cone level (Tau-vs-jet reconstruction, …)
  - Track level (particle identification, …)
  - Lifetime and flavour tagging (*b*-tagging, …)
  - etc.
- The multivariate input information used for this has various sources
  - Kinematic variables (masses, momenta, decay angles, …)
  - Event properties (jet/lepton multiplicity, sum of charges, …)
  - Event shape (sphericity, Fox-Wolfram moments, …)
  - Detector response (silicon hits, *dE*/*dx*, Cherenkov angle, shower profiles, muon hits, …)
  - etc.

Available methods:

-Boosted Decision Trees
-Neural Networks
-Likelihood Functions
...

Top quark physics