Particle Detectors

Aurelijus Rinkevicius

Cornell U., Vilnius U.

2019-03-08

Motivation from My Research

$t\bar{t}H$ Importance

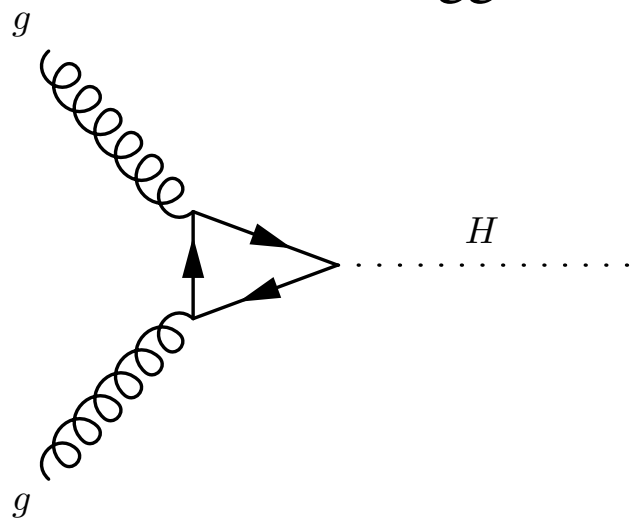
- Only way to directly probe $t\bar{t}H$ vertex:
  - ggH vertex depends on other fields.
  - Way to probe $f\bar{f}H$ Lorentz structure.
  - Critical piece of Higgs properties.
- Bridge to $t\bar{t}X$ searches.

Mode	gg	VBF	VH	$t\bar{t}H$	$b\bar{b}H$
σ, pb	43.9	3.7	2.2	0.5	0.5

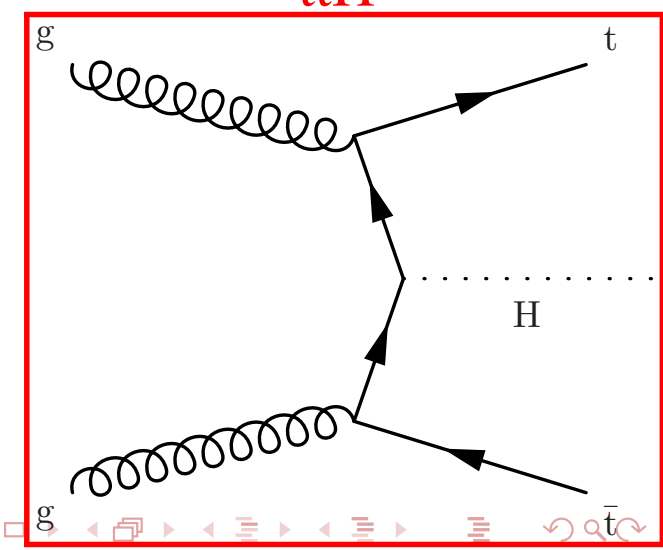
$\sqrt{s}$, TeV	7	8	13
σ, fb	89	133	507

Almost $4\times$ better with 13 TeV!

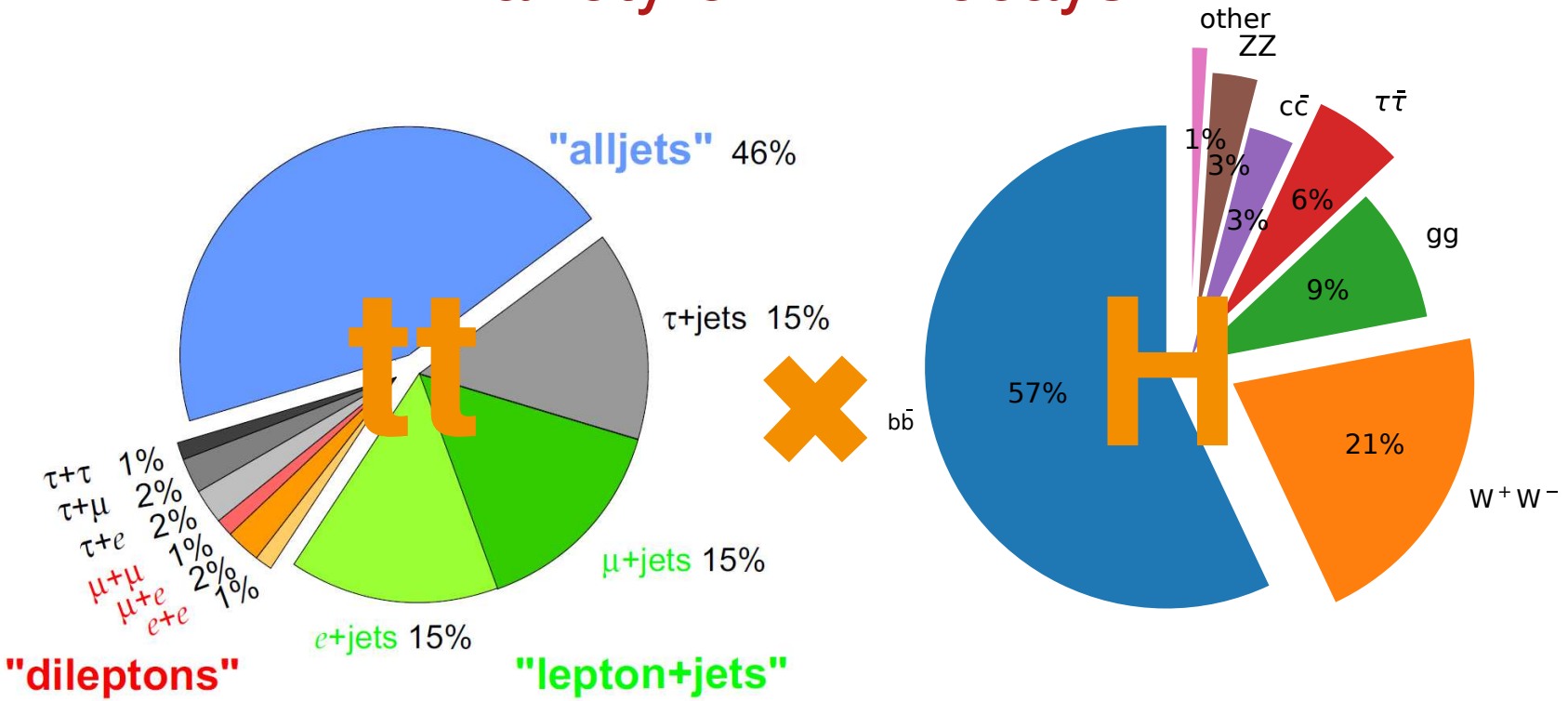
Dominant gg



$t\bar{t}H$



Variety of $t\bar{t}H$ Decays



- $t\bar{t}H, H \to b\bar{b}$: dileptonic, ℓ+jets [, hadronic]
- $t\bar{t}H, H \to \tau\bar{\tau}$: universal ("inclusive") categories
- $t\bar{t}H, H \to \ell_i$ (multileptonic): dileptonic, ℓ+jets
- $t\bar{t}H, H \to \gamma\gamma$: leptonic (dileptonic, ℓ+jets), hadronic
- $t\bar{t}H, H \xrightarrow{ZZ^*} 4\ell$: one special category

More events ↑

Fewer backgrounds ↓

Contents

Introduction

Detector Interactions

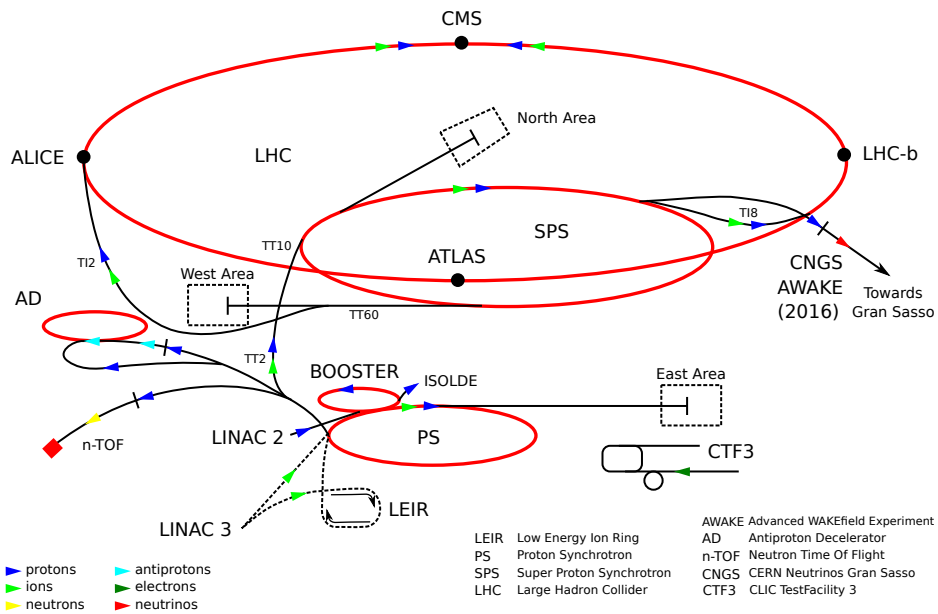
Detectors

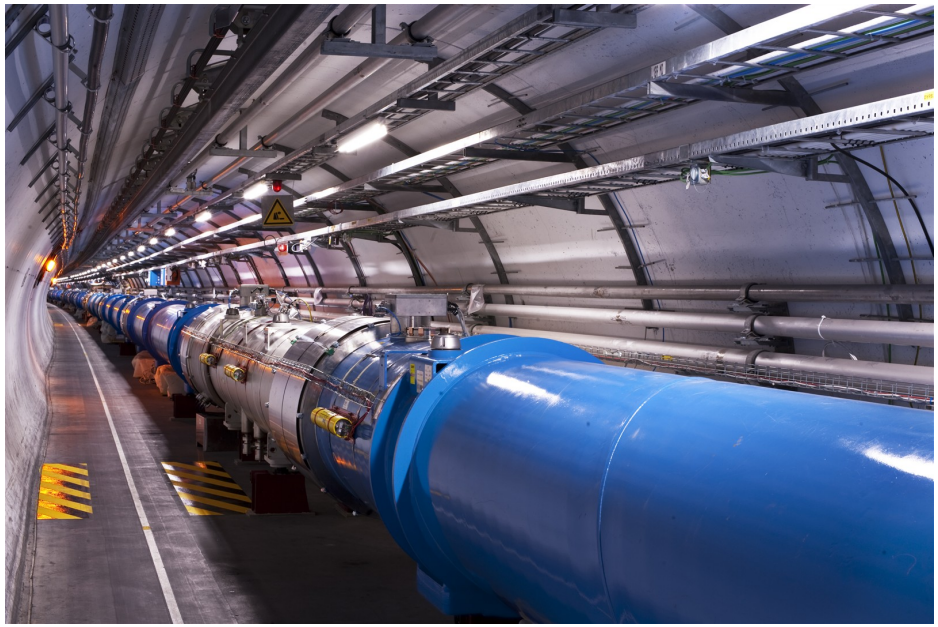
Anatomy

Observations

Introduction

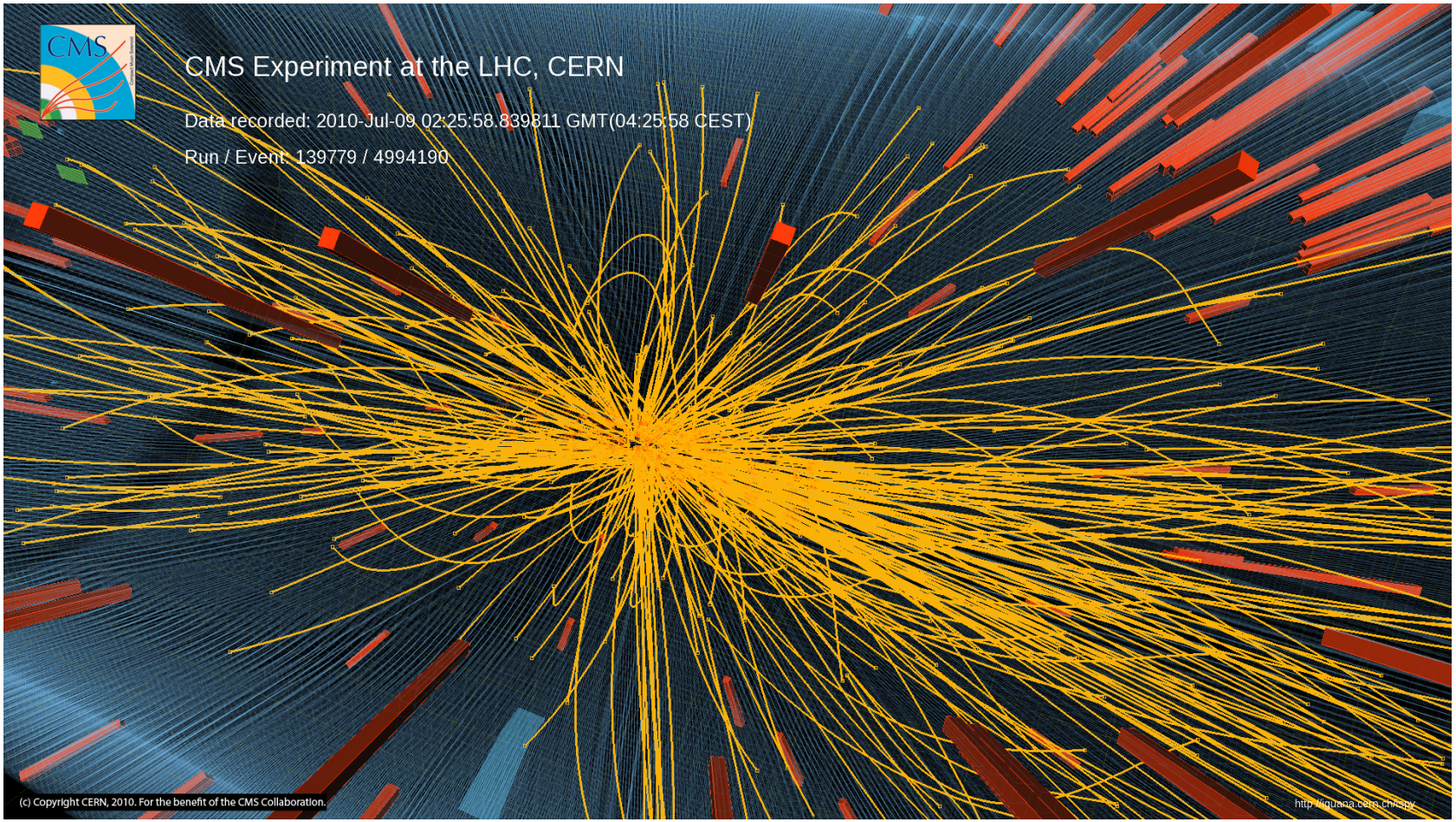
Accelerator Complex



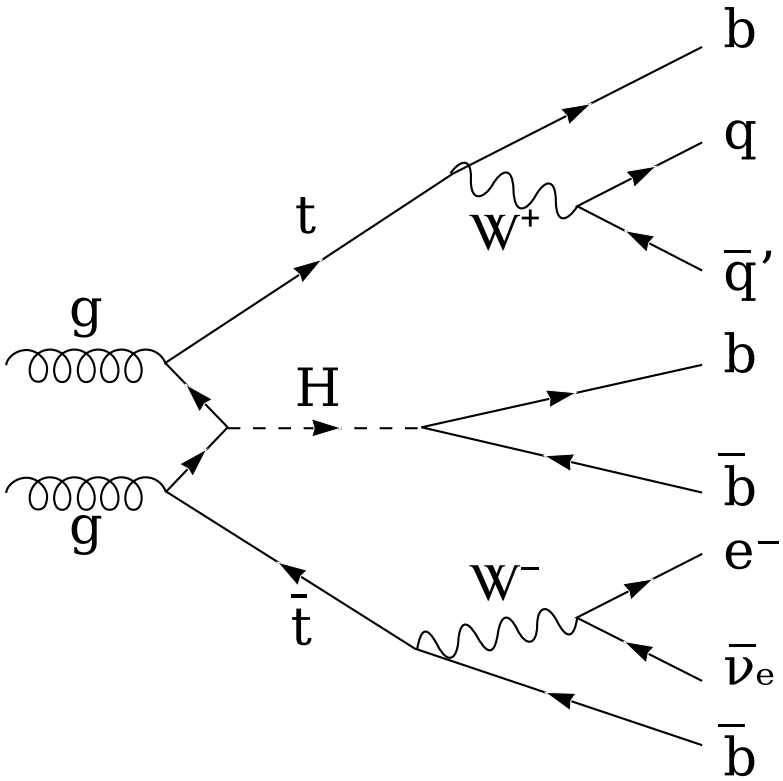


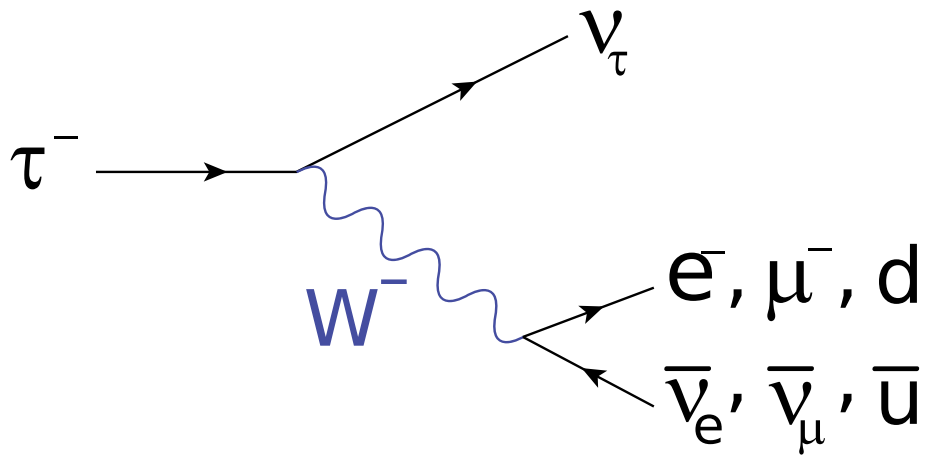
All is needed in order to ...

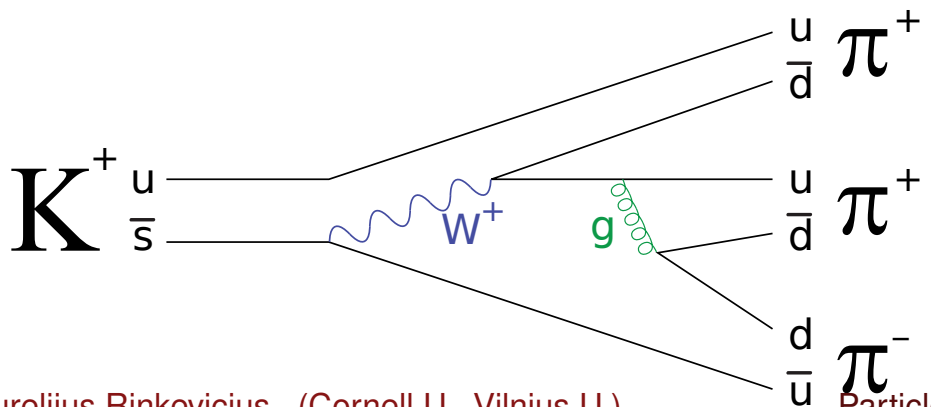
Energetic Collisions (1)

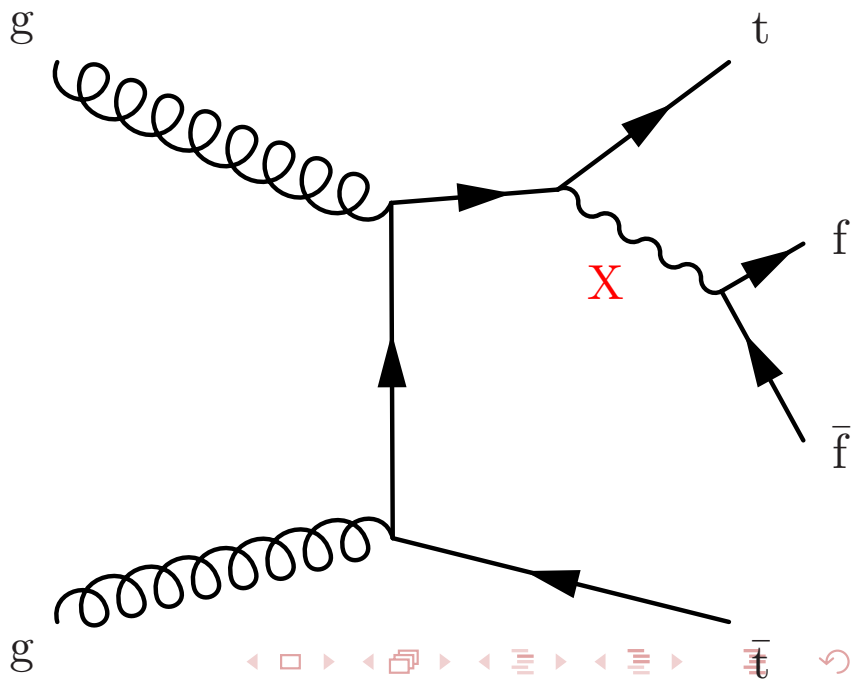


Energetic Collisions (2)









Detectors

Detector — device for collecting experimental “results”/data.

Needed for:

- Registering physical reality in action

Helps to:

- Understand “hidden” processes/nature

Can:

- “See” depending on our understanding of the nature

Detectors

Detector — device for collecting experimental “results”/data.

Needed for: (Experiment)

- Registering physical reality in action

Helps to: (Theory)

- Understand “hidden” processes/nature

Can: (Theory+technologies)

- “See” depending on our understanding of the nature

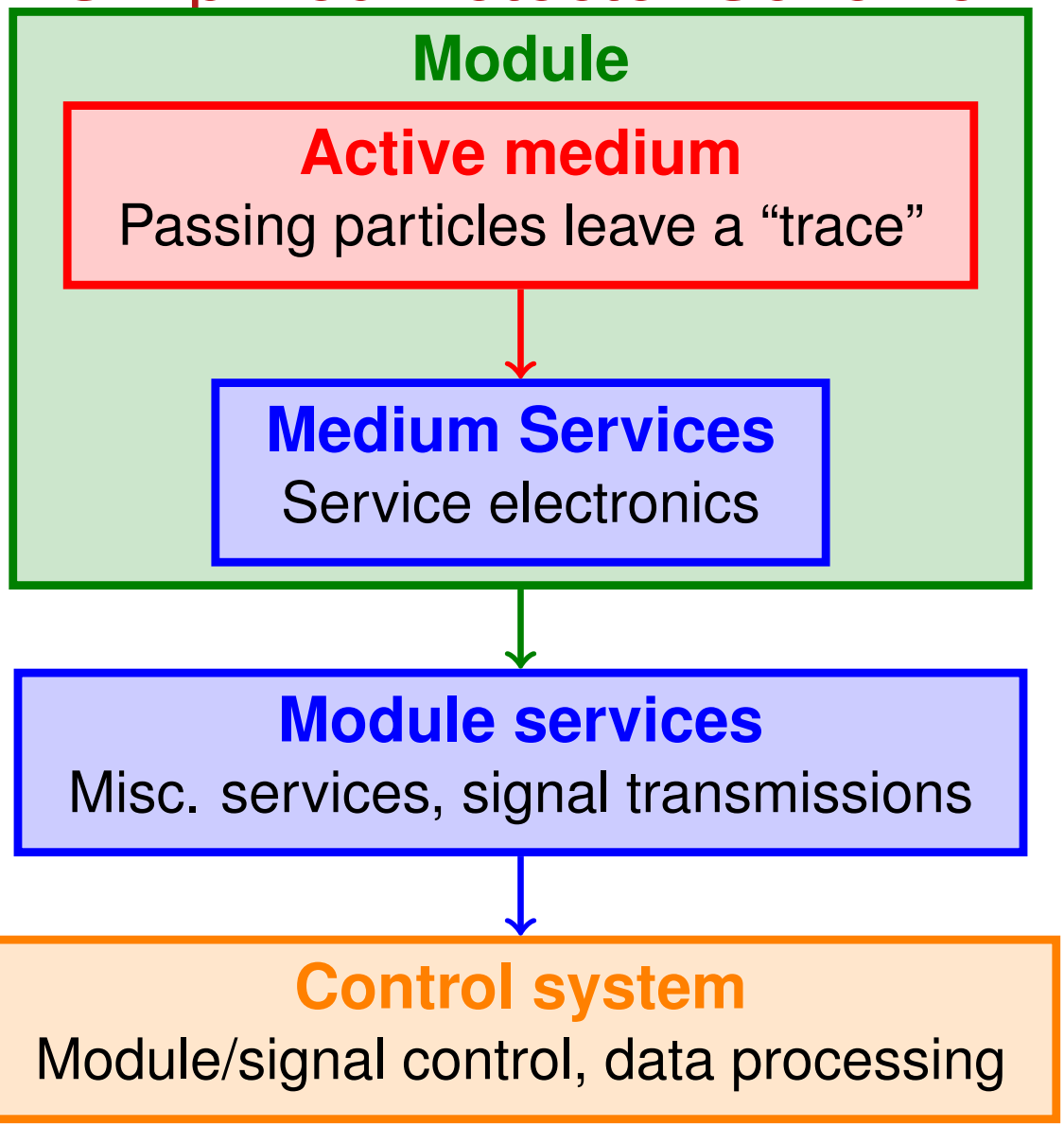
Detectors

In this talk, let's

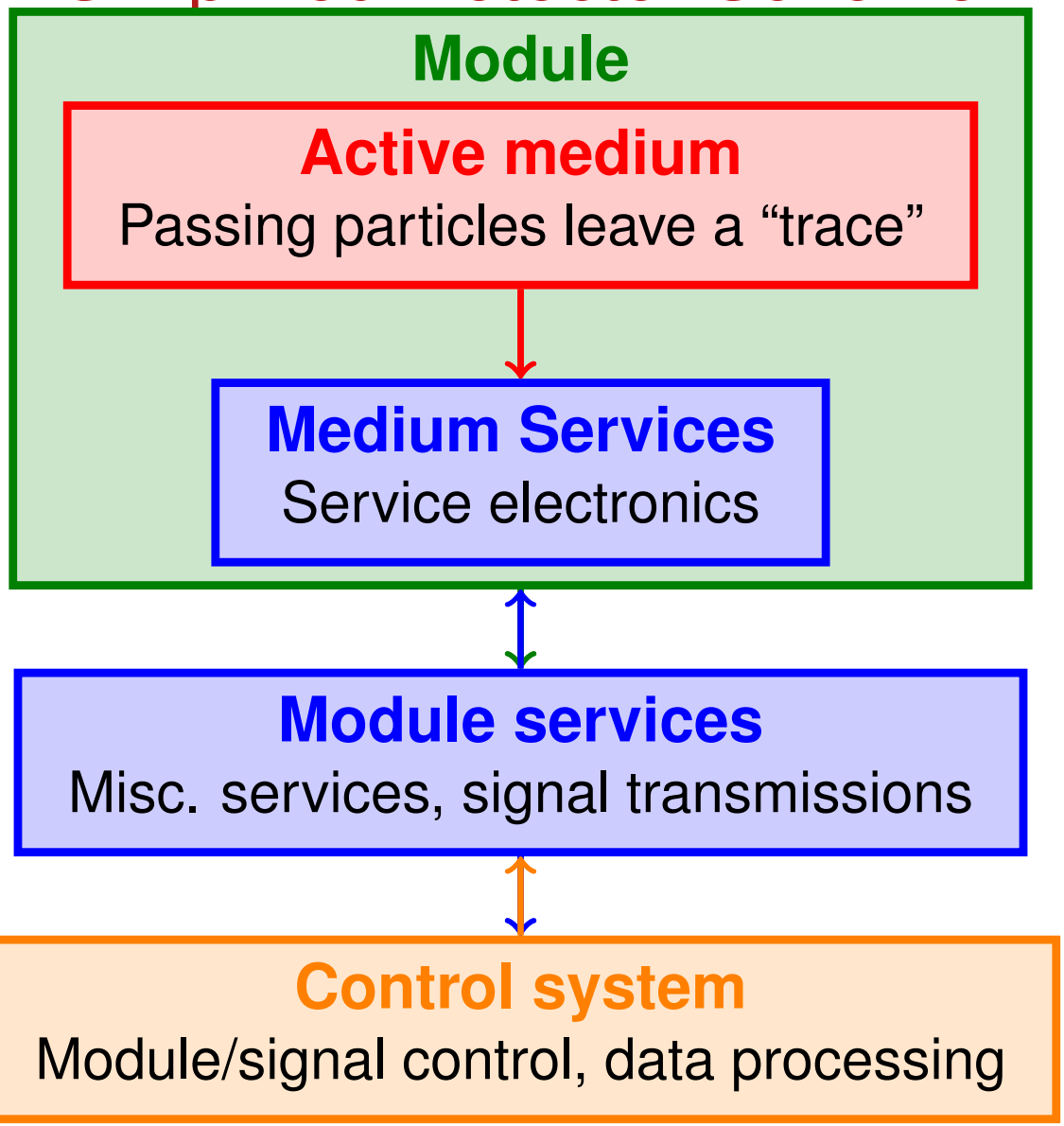
overview detectors — discuss what they **can** and **why**.

Detector Interactions

Simplified Detector Scheme



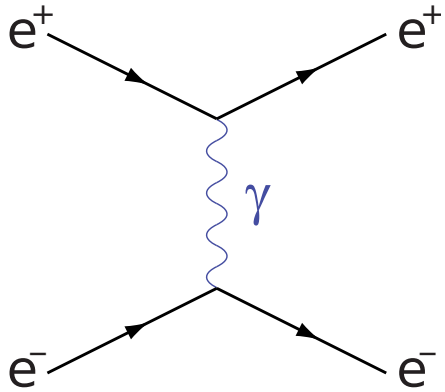
Simplified Detector Scheme



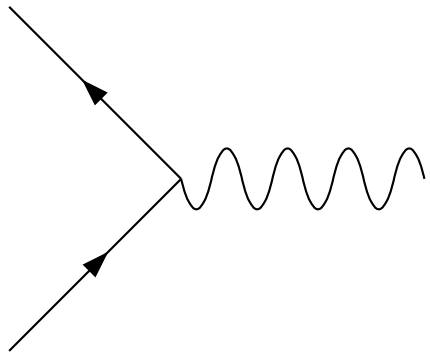
Possible Elementary Interactions

Possible Elementary Interactions

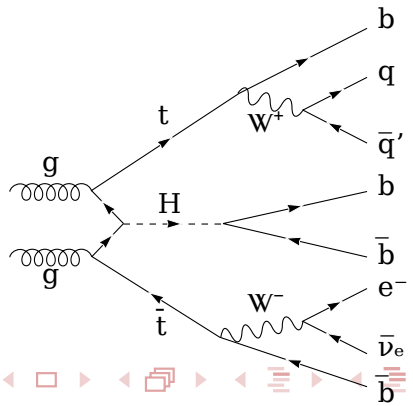
- Scattering



- Annihilation



- New particle production



Macrointeractions (1)

Photons:

- Compton Scattering
- Photoelectic effect
- Pair production

Charge carriers:

- Scattering — highly unwanted
- Ionization (kicking off electron off atom)
- Excitation (excites electron to higher energy states)
- Photon emission:
  - Bremsstrahlung (accelerated charge carriers)
  - Transition radiation
  - Cherenkov radiation ($>$light's phase speed in medium)

Macrointeractions (2)

Hadron interactions:

- Strong interaction due to inelastic nuclear interactions: resulting charged particles are detected.

Neutrinos:

- Do no interact.
- Appear as missing energy/momentum.

How to Construct a Detector?

One needs to know:

- Physics goal
- Physical objects/particles
- Technologies
- Data acquisition needs
- Detector load
- Detector conditions
- Plans of other colleagues
- Budget

Detectors

Detector Types (1)

Categorized by

- Type
  - Tracker
  - Calorimetry (uniform, sampling)
- Technology (based on)
  - Gasses
  - Crystals
  - Semiconductors
  - Metal
  - Scintillating crystals or fibers
  - Exotic

Detector Types (2)

Categorized by

- Physical objects/particles
  - Electromagnetic
  - Hadron
  - Muon
  - Charge tracker
- Location
  - Inner
  - Outer
  - Barrel
  - Endcap

All combinations are possible using mentioned ingredients

Composite Detectors (“Experiments”)

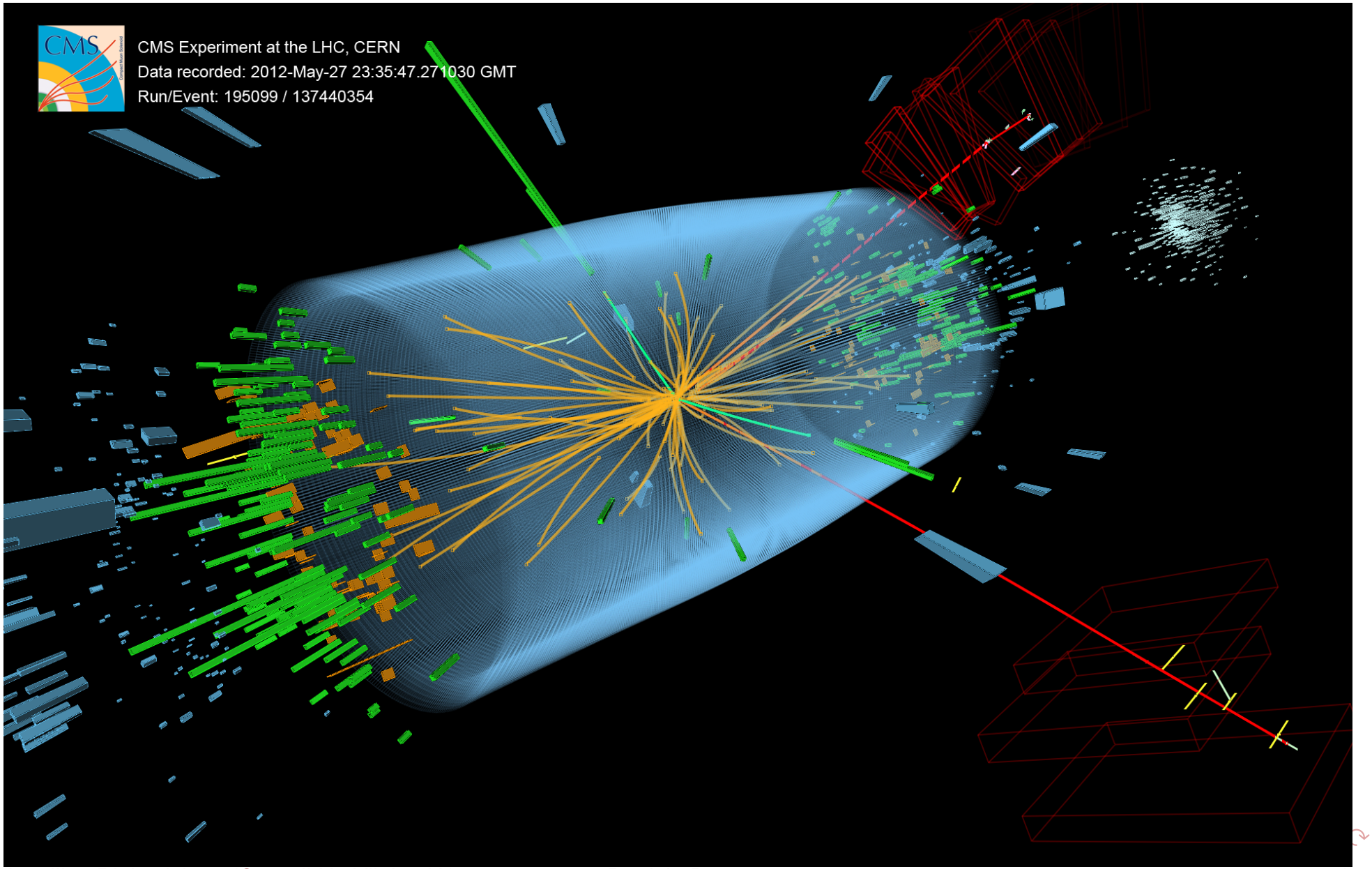
Classified by

- **Physics goals**
  - General purpose
  - Heavy ions
  - Precision studies
  - Specialized

Given the context:
noncomposite: subdetectors, systems, subsystems.

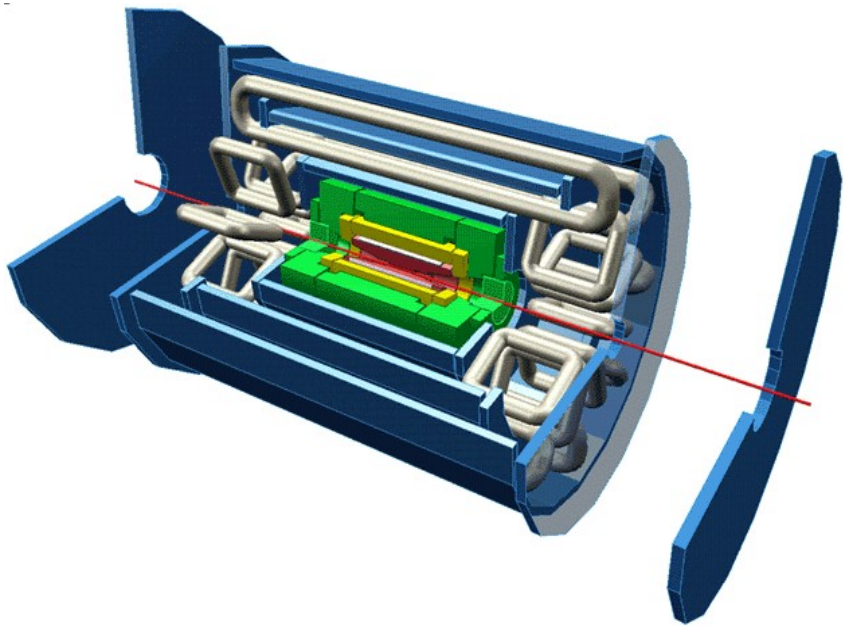
Composite detectors usually detect all particle types.

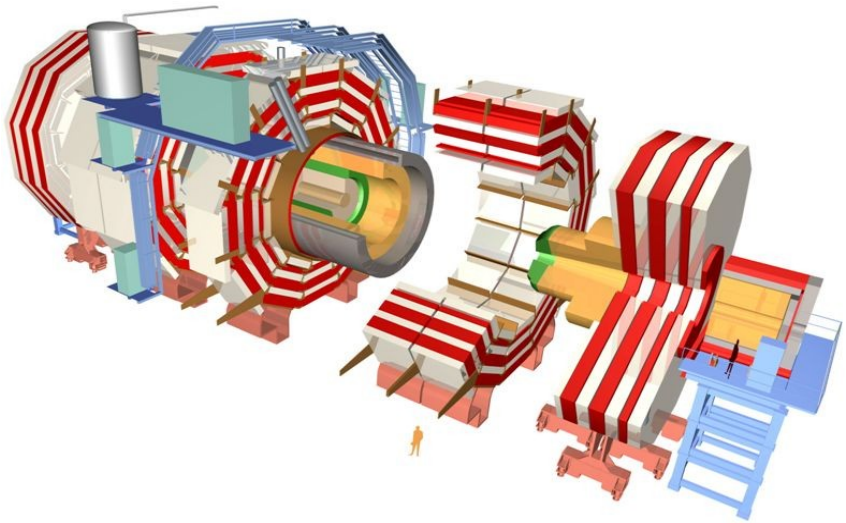
Recorded “Picture”

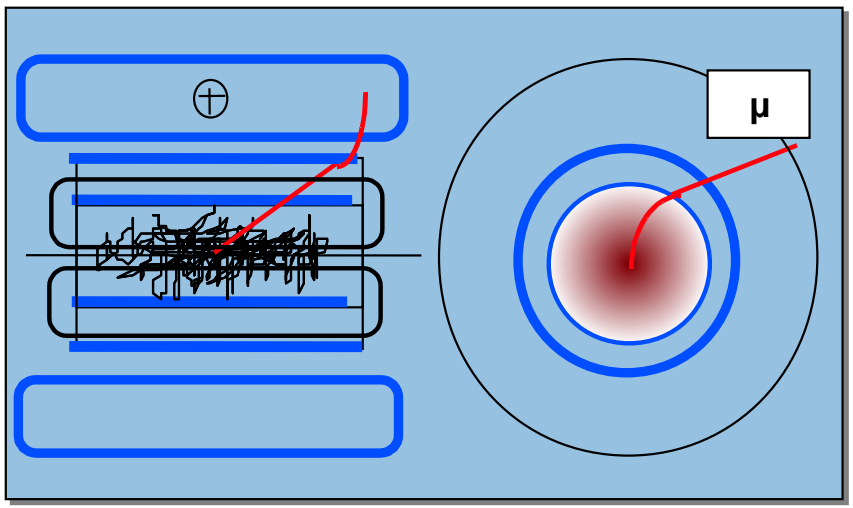


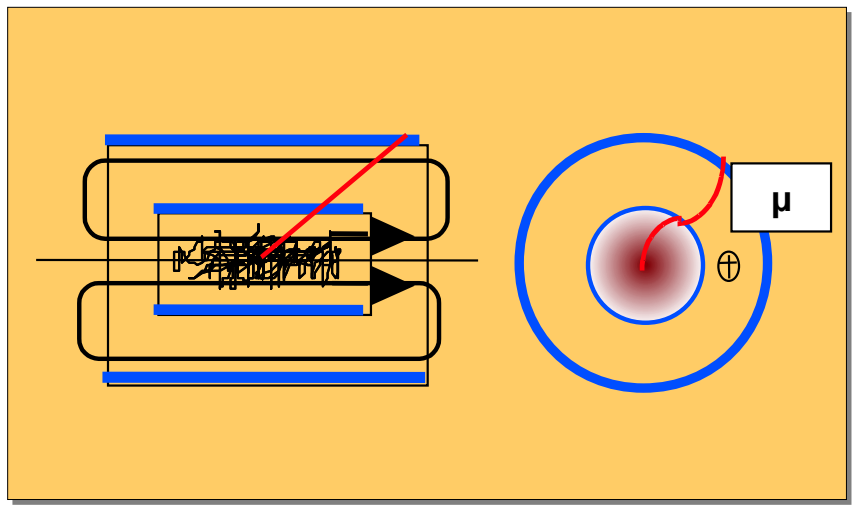
Detector Magnets — Special Ingredient

A Toroidal LHC Apparatus (ATLAS) Compact Muon Solenoid (CMS)



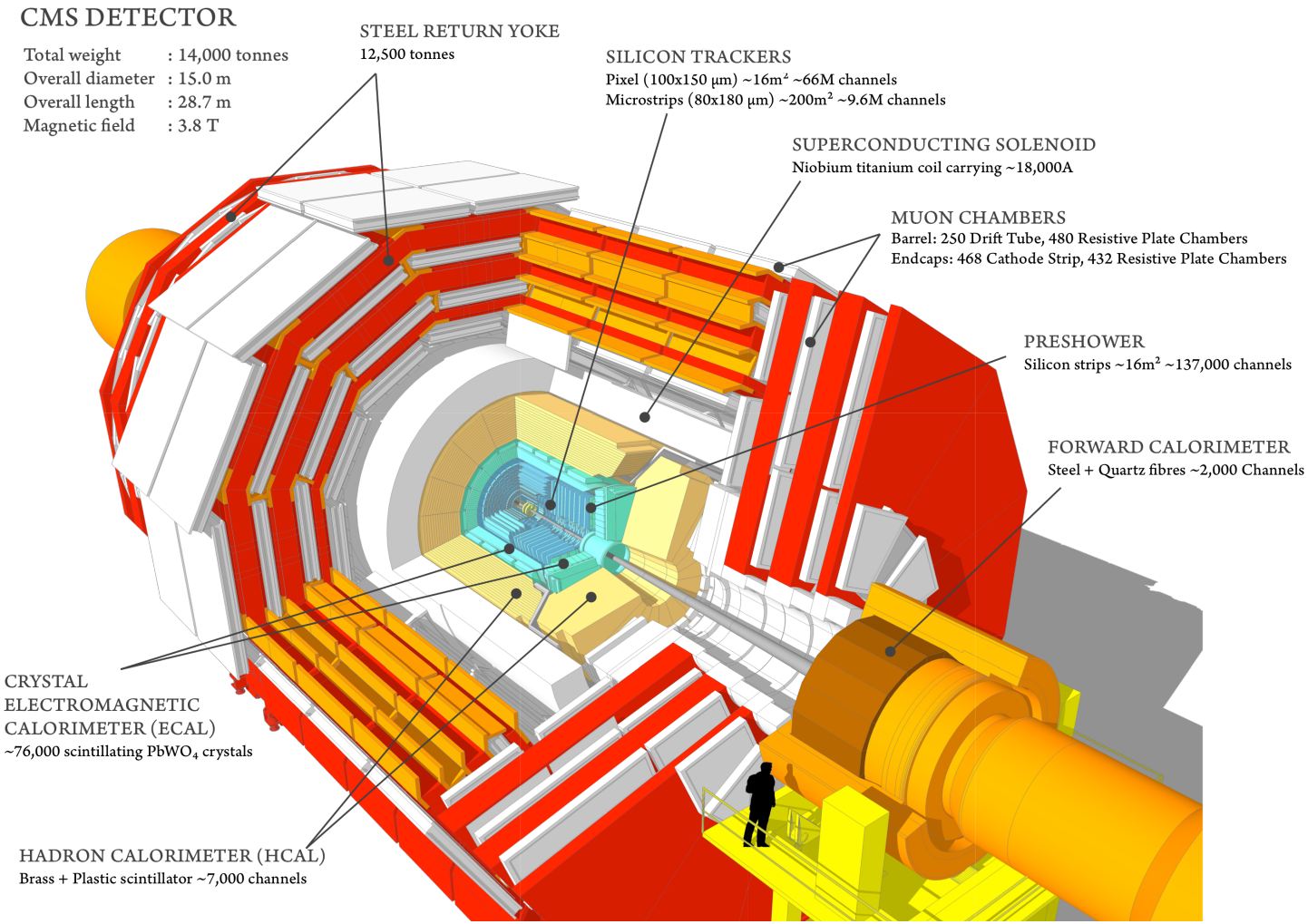






Detector: Compact Muon Solenoid

CMS detector with cut



40 MHz

×

~30 p–p collisions

×

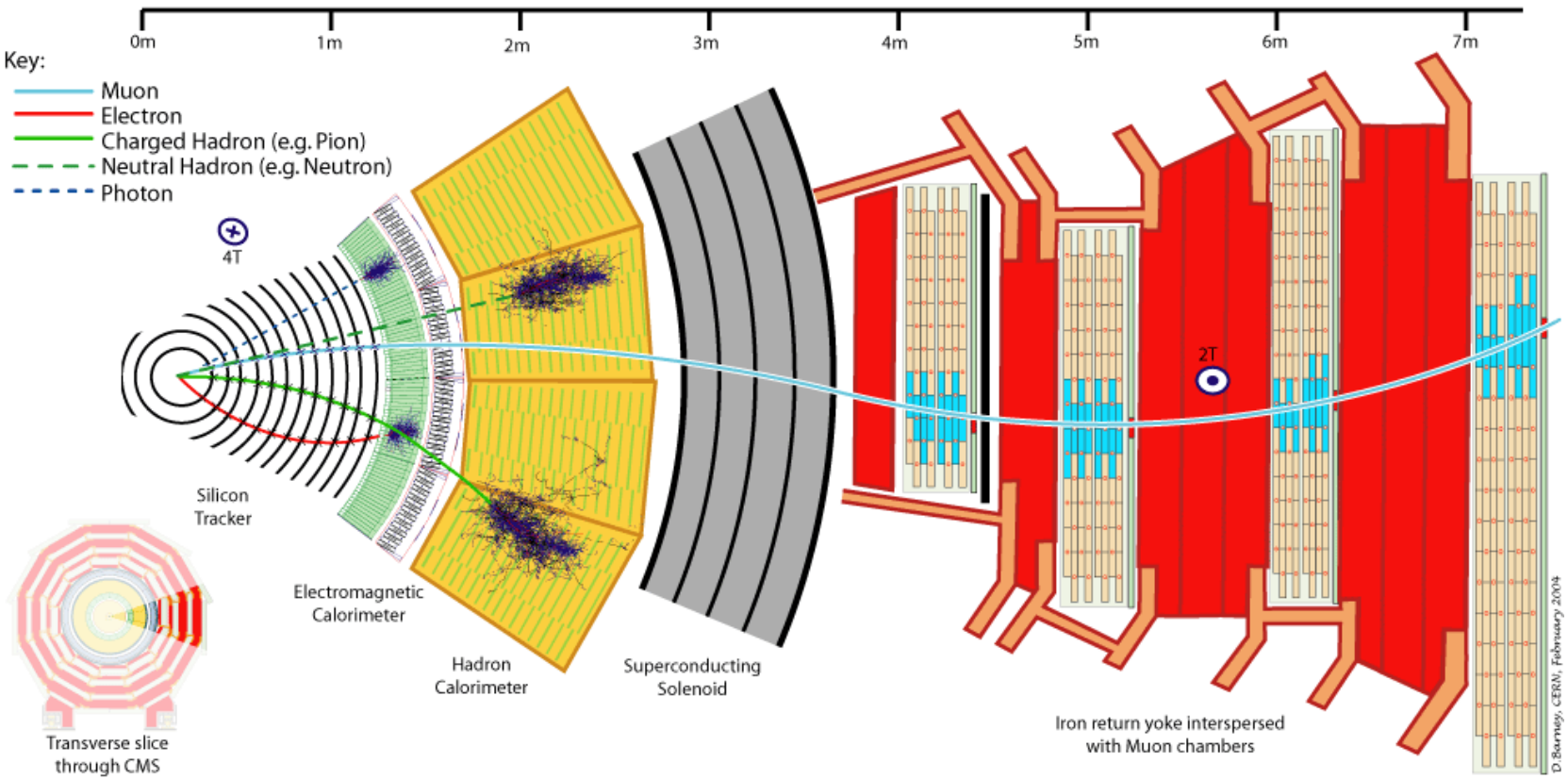
p–p = ~200 **final** partic.

=

~100 Tb/s

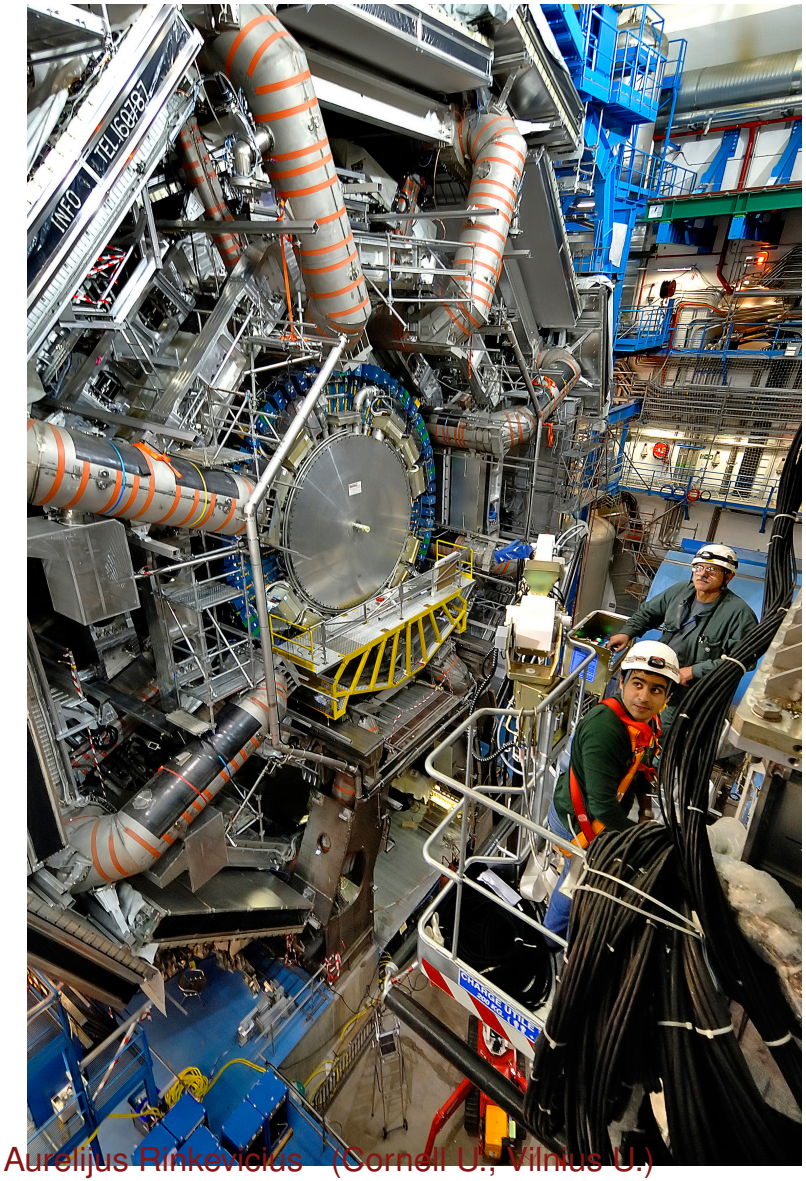
Final particle	Resolution
γ	1.5–5% @ 60 GeV
e	2–4% @ 10 GeV
μ	1–1.5% @ 10 GeV
j	o(10)%

Particle Identification

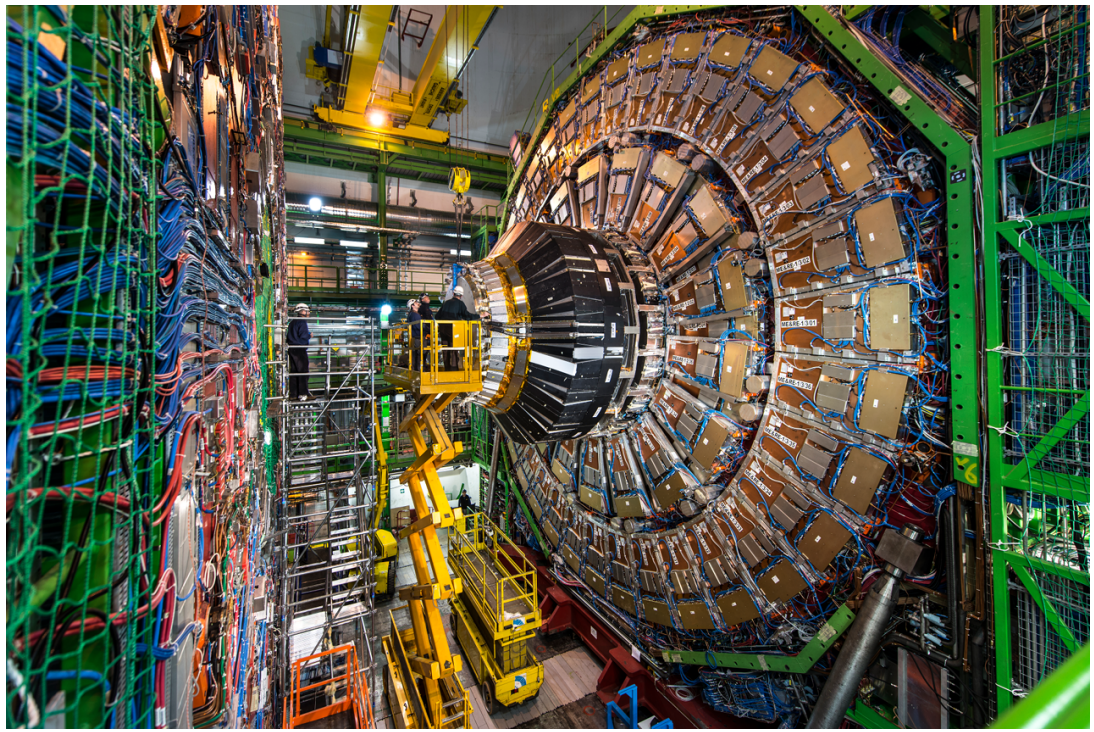


General Purpose Detectors

ATLAS

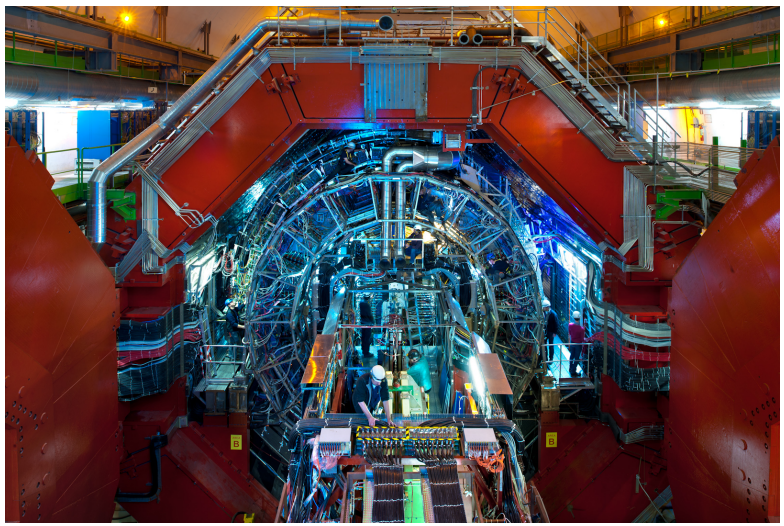


CMS



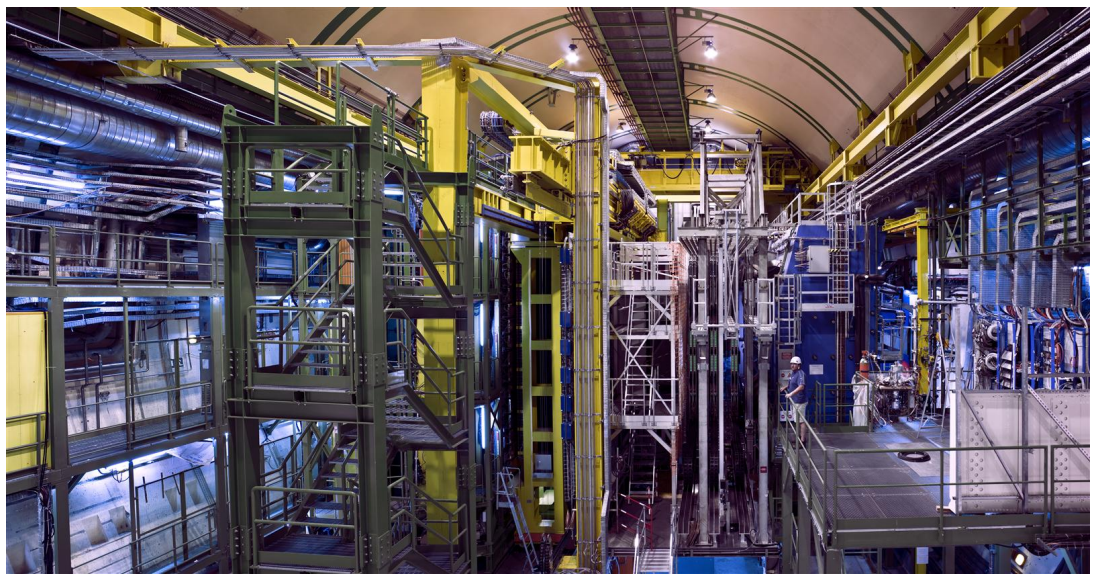
Specialized Detectors

ALICE



- Heavy-ion research

LHCb



- Precision studies

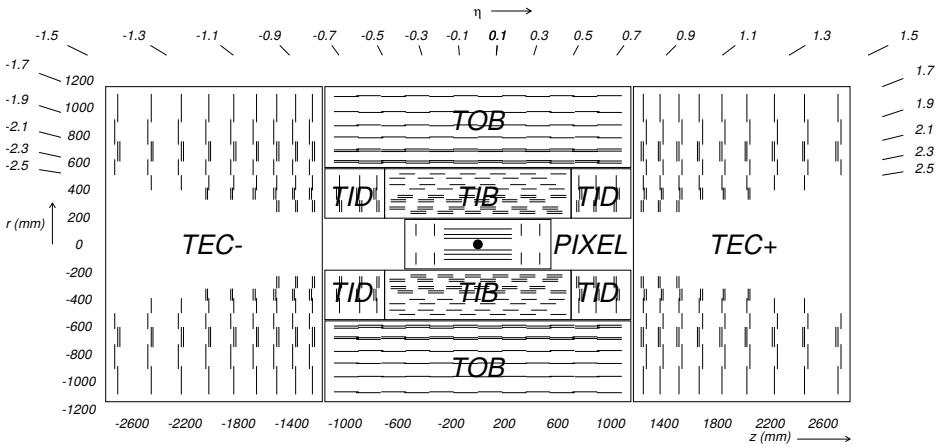
Anatomy or Subdetectors

(Focusing on CMS)

CMS Magnet

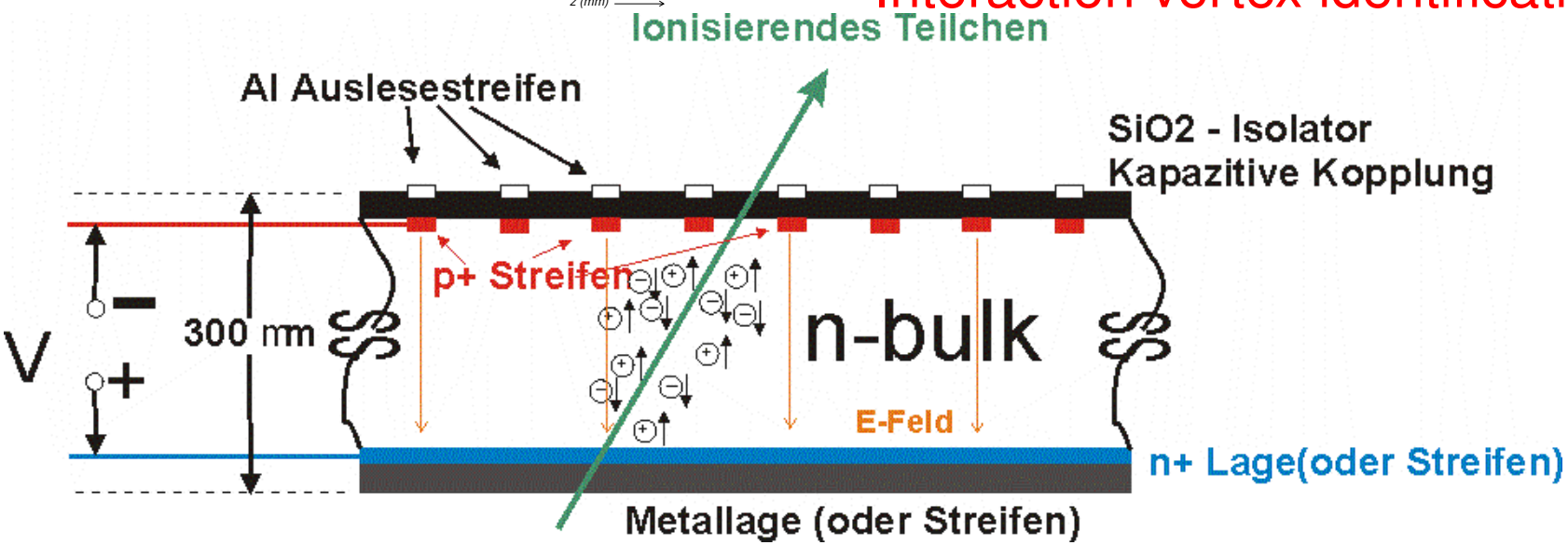
- Superconducting solenoid magnet, $B = 4$ T
- Current intensity: 20 kA
- Superconductor: NbTi ($\sim$4 K)
- Dimensions: 13 $\times$ 4 m — holds tracker and calorimeters
- Cost $\sim$80 MCHF

Semiconducting Tracker

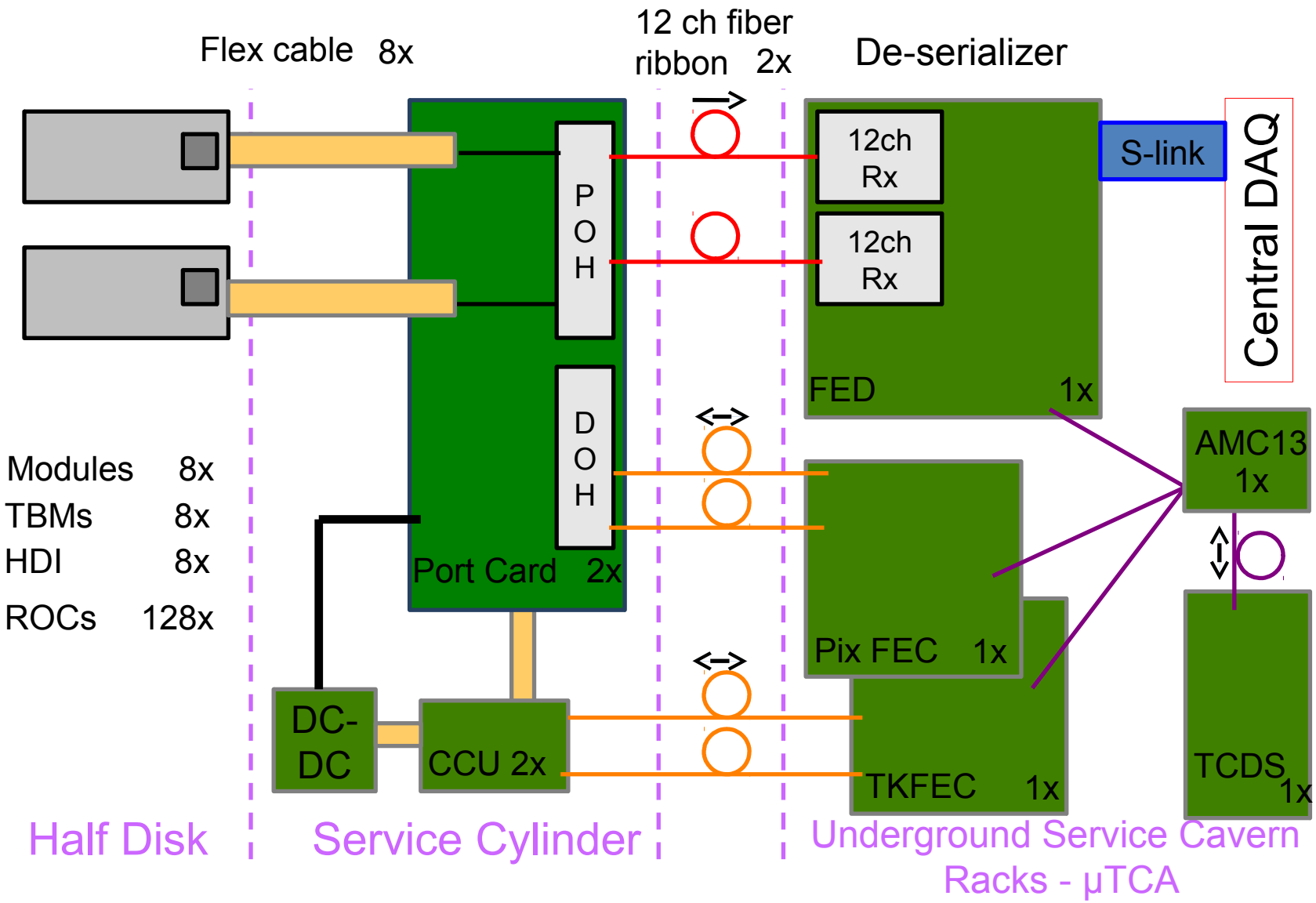


Highlights:

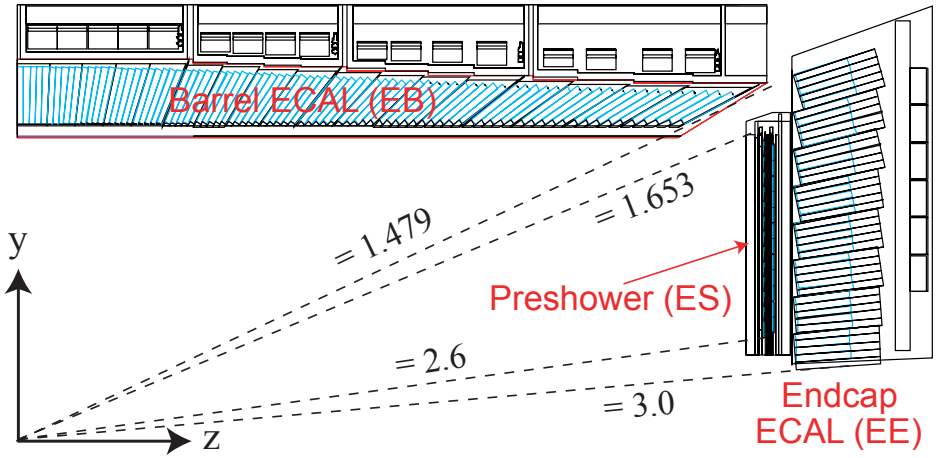
- Si sensors (strips, pixels).
- "Feel" charged p.: $e^{\pm}$, $\mu^{\pm}$,...
- Measures momentum.
- Interaction vertex identification.



Phase-1 Pixel Readout Scheme

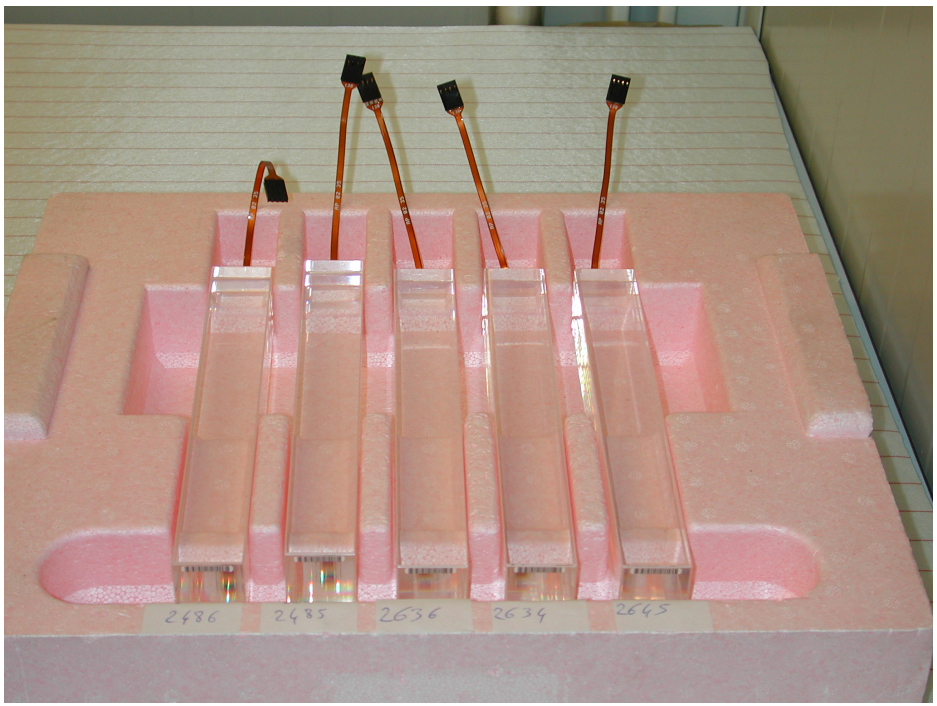


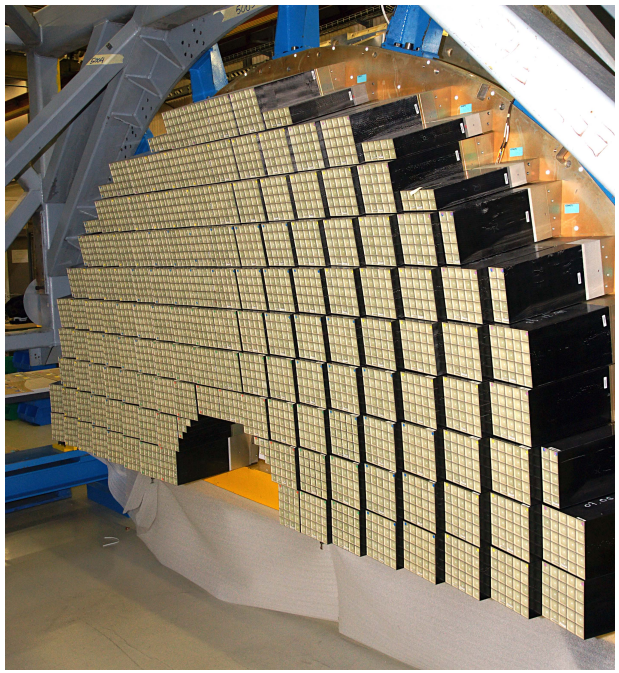
Electromagnetic Calorimeter (ECAL)



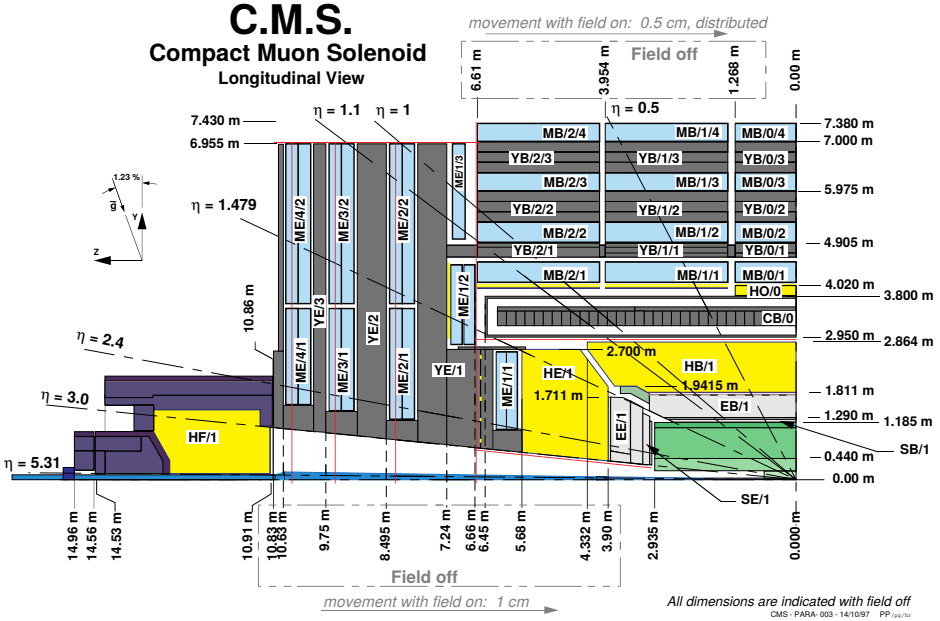
Highlights:

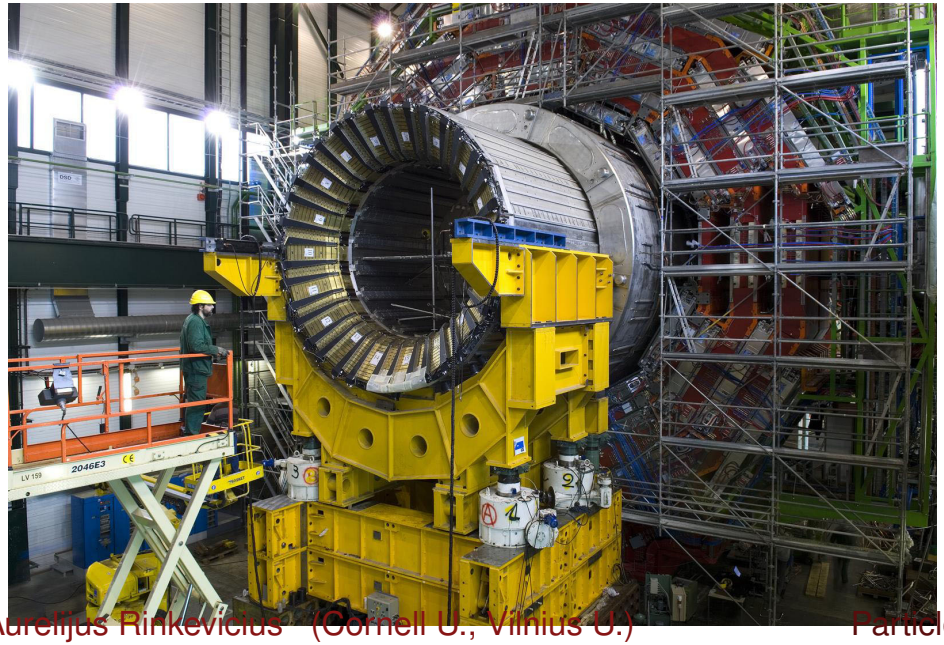
- Lead tungstate crystals ($PbWO_4$).
- Measures energy: $e^{\pm}$, γ (radiation length: $25X_0$).





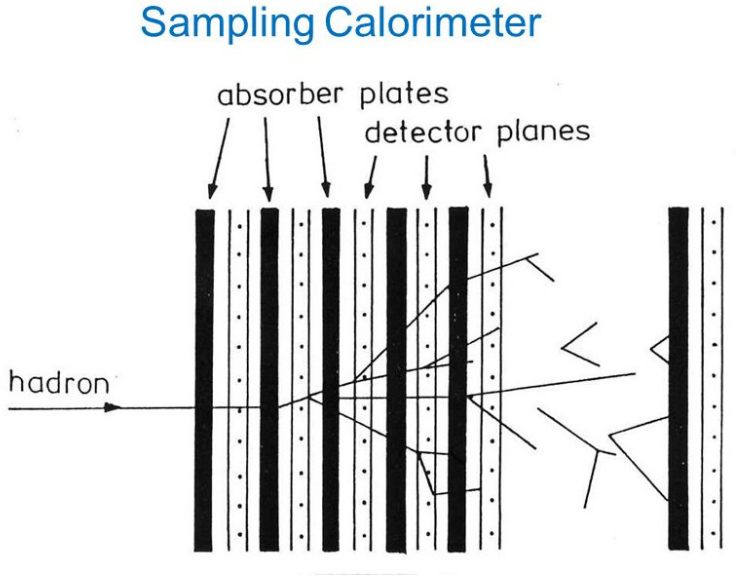
Hadron Calorimeter (HCAL)



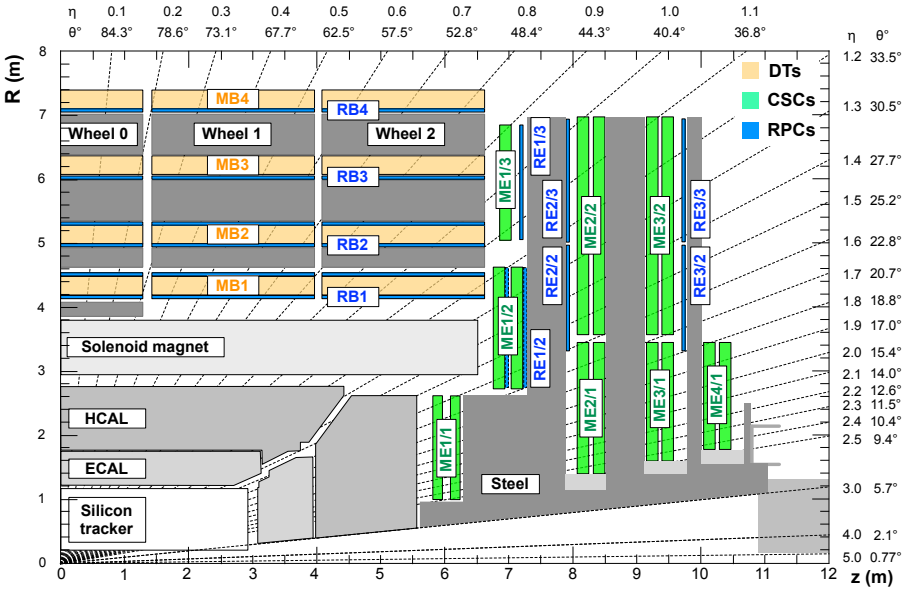


Highlights:

- Plastic scintillators in brass absorbers.
- Measures (hadron) energy: p^+, n^0, $\pi^\pm$, K mesons.

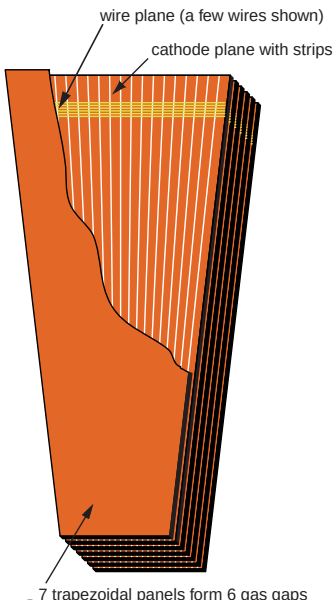


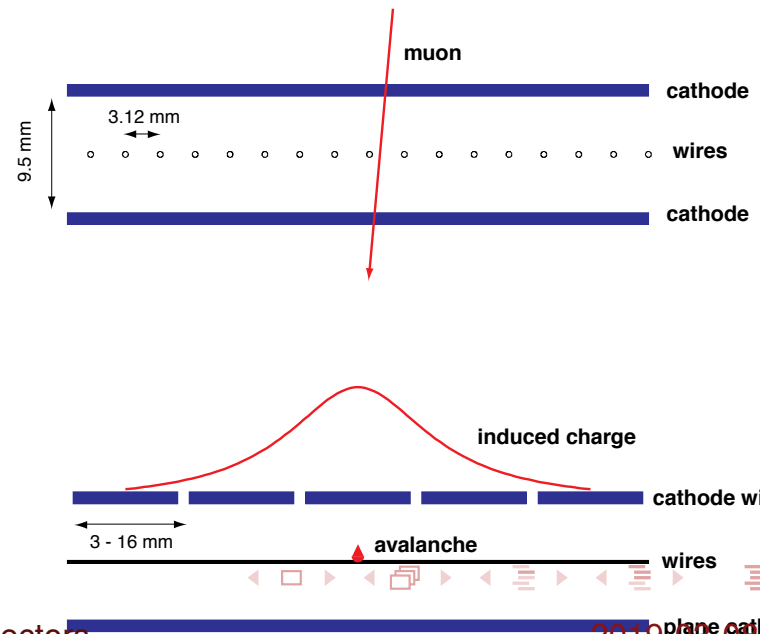
Muon Detector



Highlights:

- Gaseous detectors.
- Important for muon identification.
- Used in fast filtering/trigger.



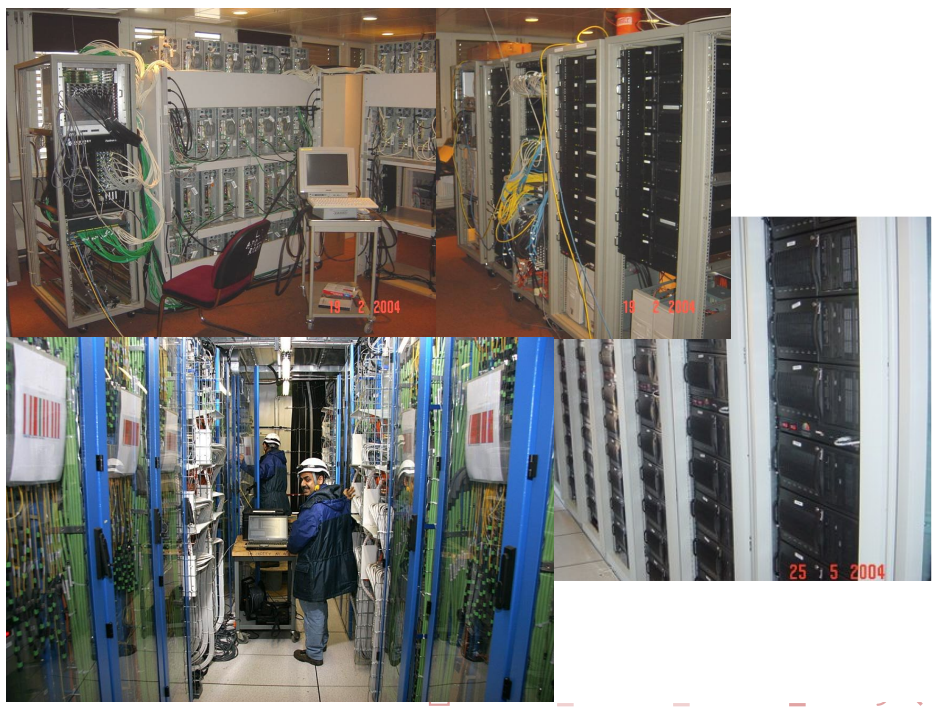


Trigger (Event Filter)

One collision/event $\sim O(1)$ Mb of data.

- Collisions happen at 40 MHz.
- Level-1 “hot” filter (online): 100 kHz.
  Subdetectors used: muon, ECAL, HCAL.
- High-level filter is more sophisticated ($\sim$offline): 300 Hz.
  All systems are used. Approx. “full” reconstruction.

Now and then:



Schematically

All 25 ns

40 MHz
COLLISION RATE

100 kHz
LEVEL-1 TRIGGER

DAQ accepts
Level-1 rate of 100kHz

1 Terabit/s
(50000 DATA CHANNELS)

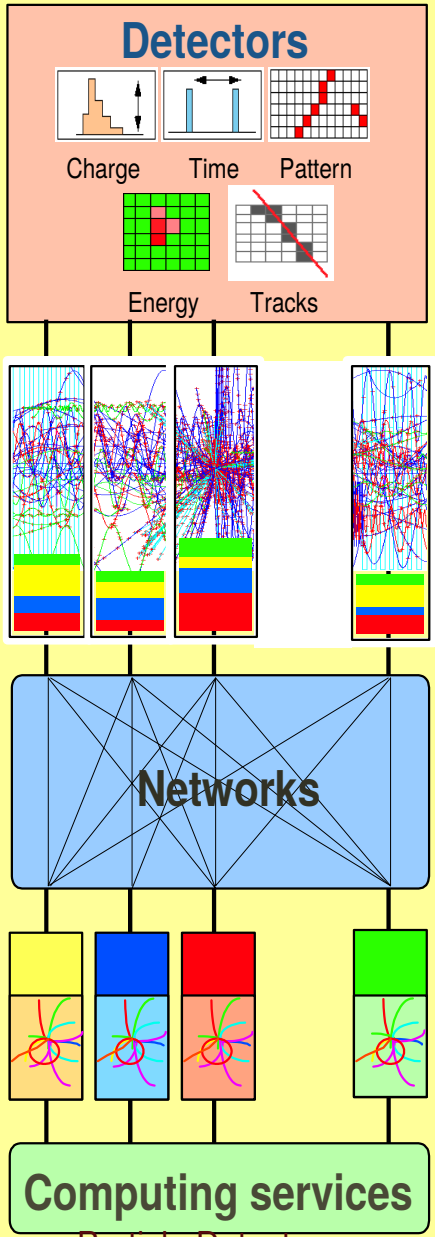
500 Gigabit/s

HLT (High Level Trigger) designed for about 100Hz

- Reduction factor 1000

~2000 CPUs

Gigabit/s SERVICE LAN



16 Million channels
3 Gigacell bu ers

1 Megabyte EVENT DATA

200 Gigabyte BUFFERS
500 Readout memories

EVENT BUILDER. A large switching network (512+512 ports) with a total throughput of approximately 500 Gbit/s forms the interconnection between the sources (Readout Dual Port Memory) and the destinations (switch to Farm Interface). The Event Manager collects the status and request of event lters and distributes event building commands (read/clear) to RDPMs

5 TeraIPS

EVENT FILTER. It consists of a set of high performance commercial processors organized into many farms convenient for on-line and o -line applications. The farm architecture is such that a single CPU processes one event

Petabyte ARCHIVE

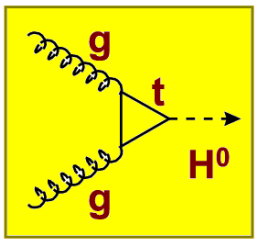
Various Observations

Do It Yourself (DIY)

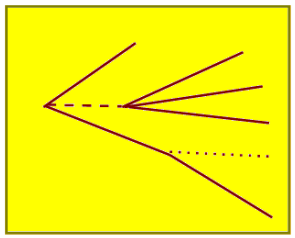
- Equipment @LHC is DIY:
  - From parts... till software (hardware, firmware, software)
- Each part/component — prototype (calibration is critical)
- Designing/building is tough: some features are ill-known.
- Experimental conditions change with time: 8, 13 TeV, ...

Running target

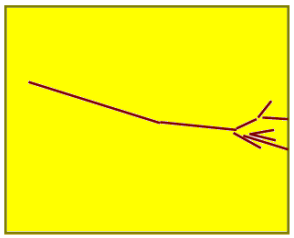
From Physics to Raw Data



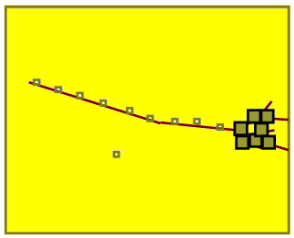
Basic physics



Fragmentation, Decay



Interaction with detector material
Multiple scattering, interactions



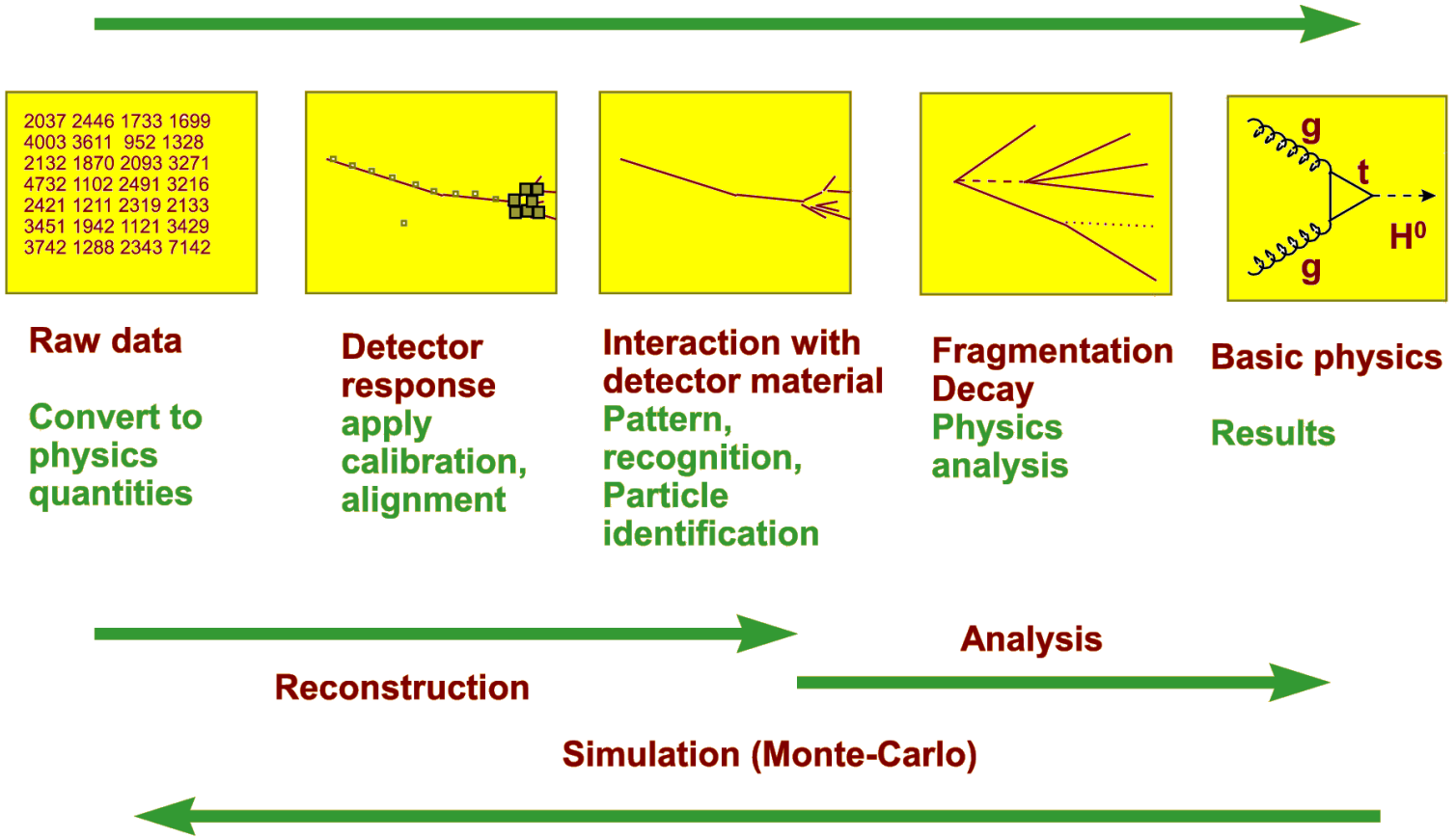
Detector response
Noise, pile-up, cross-talk, inefficiency, ambiguity, resolution, response function, alignment

Raw data

Read-out addresses, ADC, TDC values, Bit patterns

- Really recorded raw data for ATLAS/CMS ~400 MB/s
  - mainly electronics numbers
    - e.g. number of detector element where ADC (Analog-to-Digital converter) saw signal with x counts...

From Physics to Raw Data



- We need to go from raw data back to physics
  - reconstruction + analysis of the event(s)

Summary

- Mostly, “useful” detectors are composite.
- Detector reach depends on knowledge and technologies.
- Data collection and analysis is multistage process.

Thanks for your attention!