An introduction to Instrumentation

Christina Agapopoulou - LPNHE / CNRS

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Disclaimers

- This is a twisted view of instrumentation from the eyes of a particle physicist
- I’ve spent my whole career working for LHC experiments
- 25 minutes is not enough to cover everything, apologies if I left out your favourite detector / technology
- I’m looking forward to learning from you!

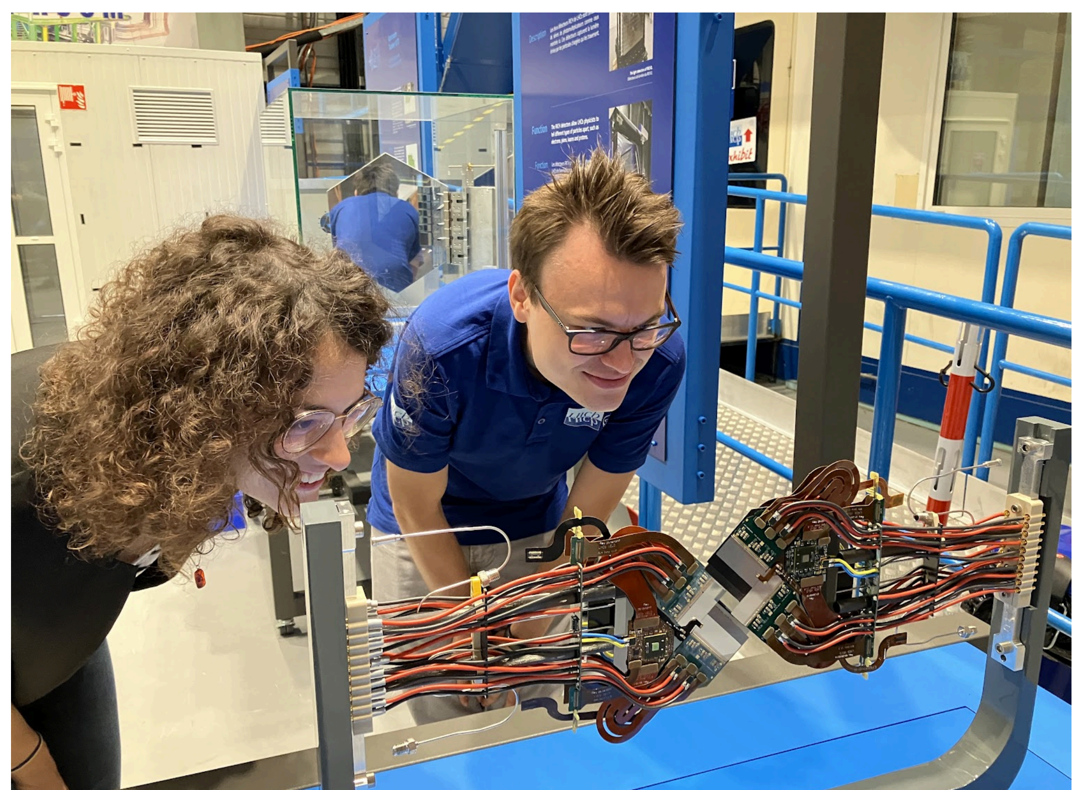
Instrumentation 101

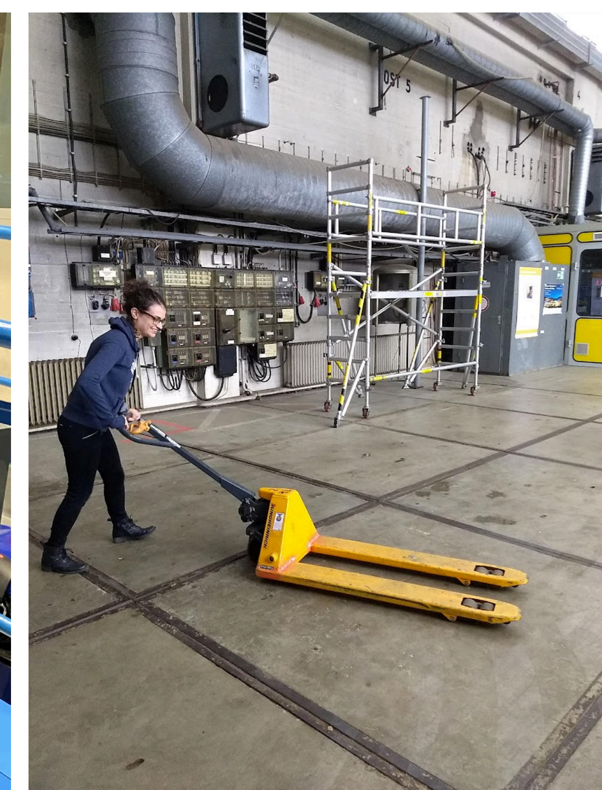
Experiment: A test under controlled conditions that is made to demonstrate a known truth, examine the validity of a hypothesis, or determine the efficacy of something previously untried.

Instrumentation: a collective term for measuring instruments that are used for indicating, measuring and recording physical quantities.

Wikipedia definitions

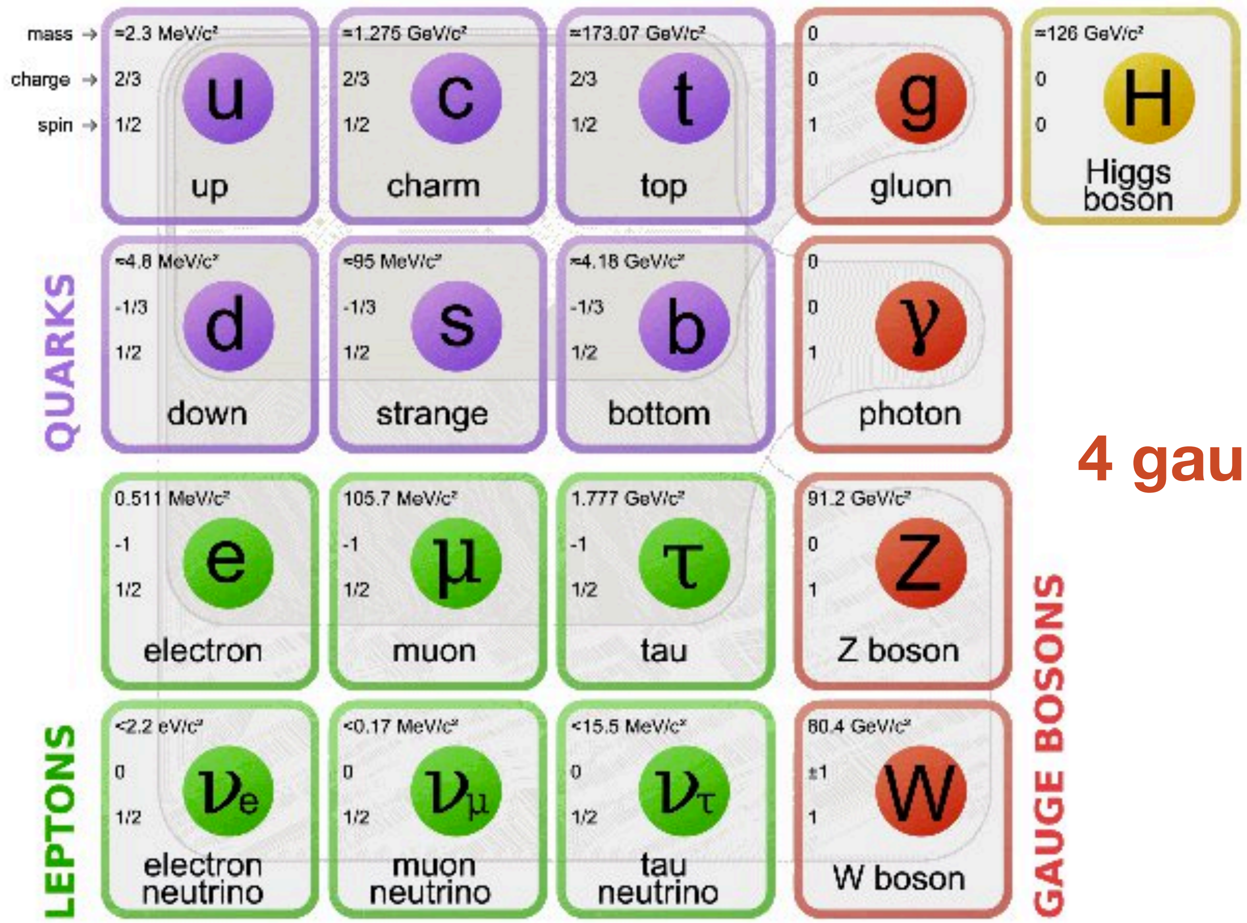
But it's also a lot of fun!





Is it a particle zoo?

6 types of quarks

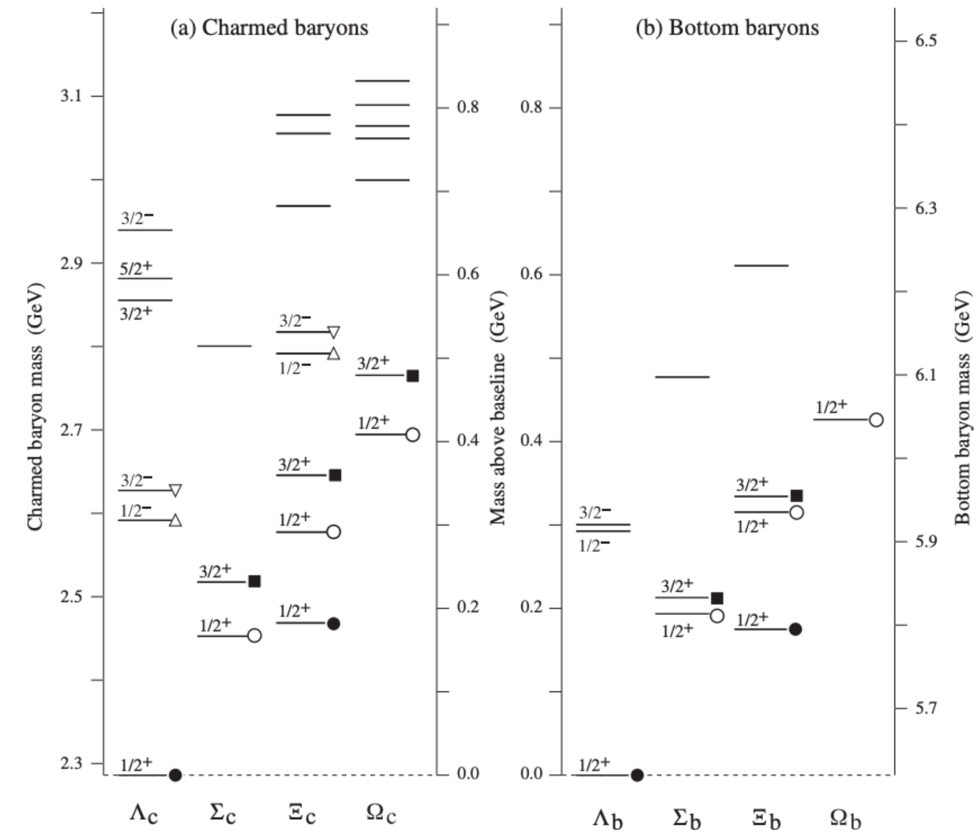


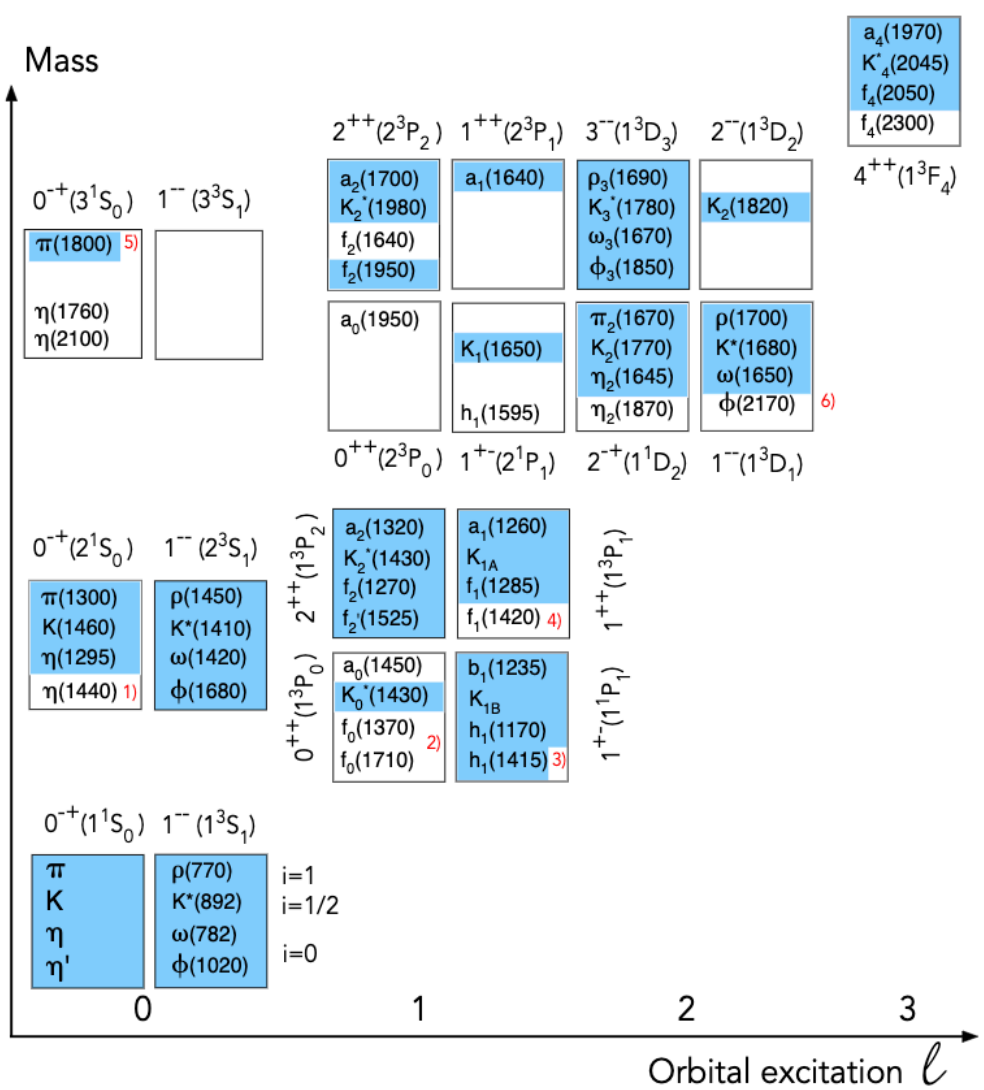
4 gauge bosons + 1 scalar

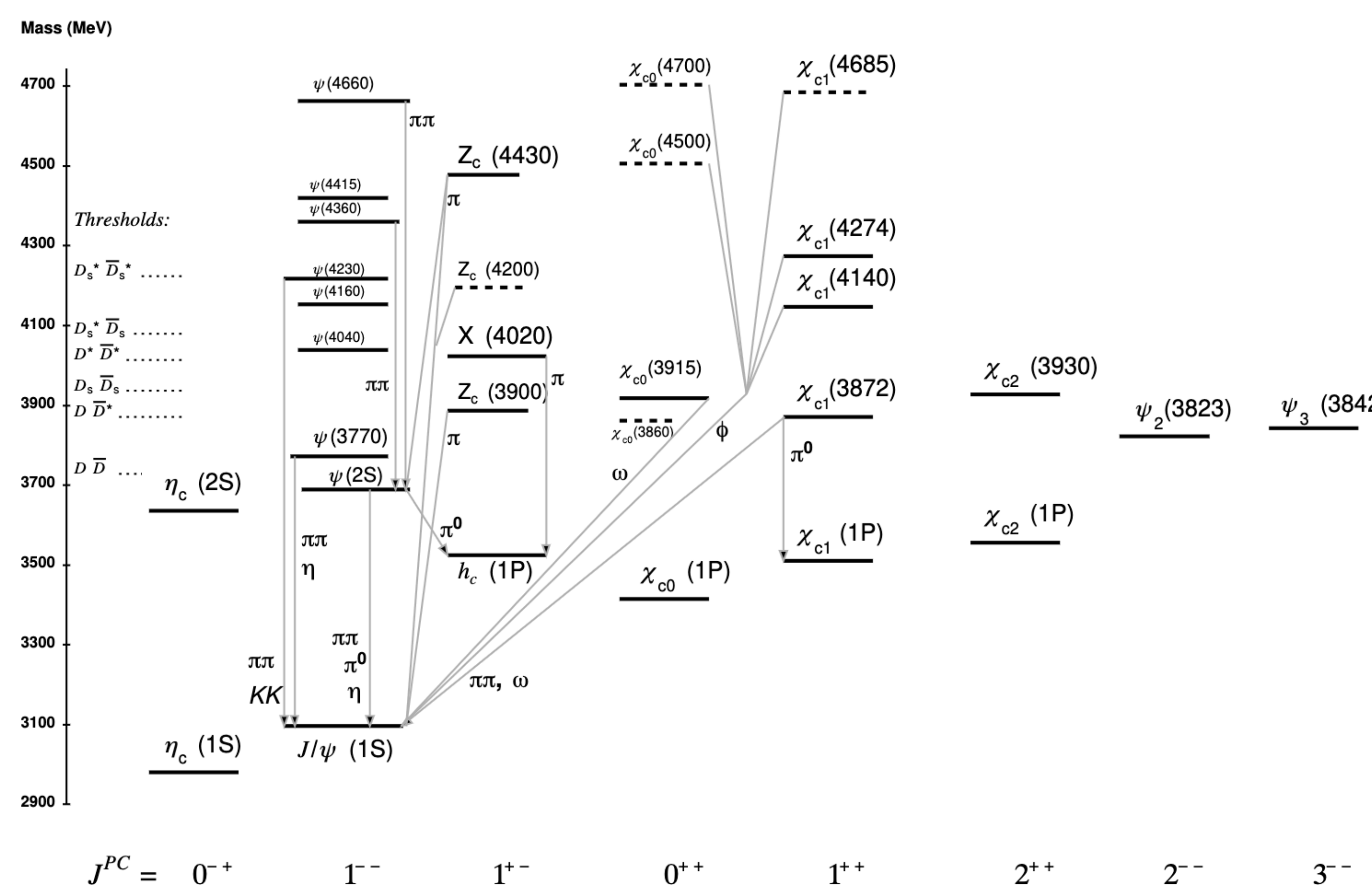
3 charged and 3 neutral leptons

Or a particle jungle?

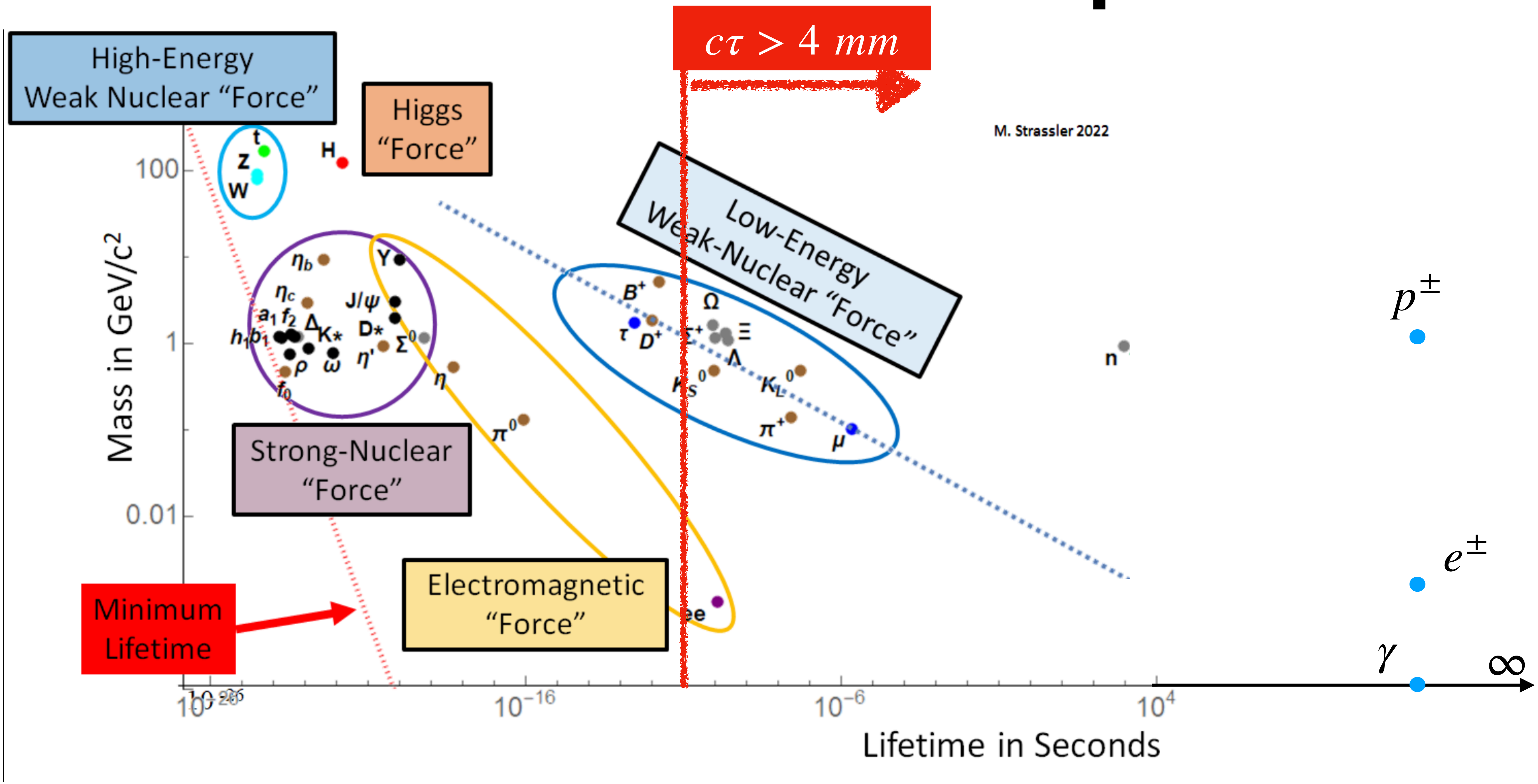
- Thanks to the strong interaction: More than 200 mesons + baryons have been found
- + a few exotics (tetraquarks & pentaquarks)
- + the yet un-observed ones!







And the domesticated particles?



- Among all the observed particles, only ~13 can travel more than a few mm before decaying: $e^{\pm}, \mu^{\pm}, \gamma, \pi^{\pm}, K^{\pm}, p^{\pm}, K^0, n$
- Closest detectors to a p-p collision can reach 2 mm
- Particle detectors rely on detecting these particles, **measuring their properties** and using conservation laws to reconstruct their "lost" parents

Hello, I love you, will you tell me your name?

Caserolle of delicious beans

Hello, I love you, will you tell me your name?

Caserolle of delicious beans

But what kind of beans were used?

Hello, I love you, will you tell me your name?

Caserolle of delicious beans

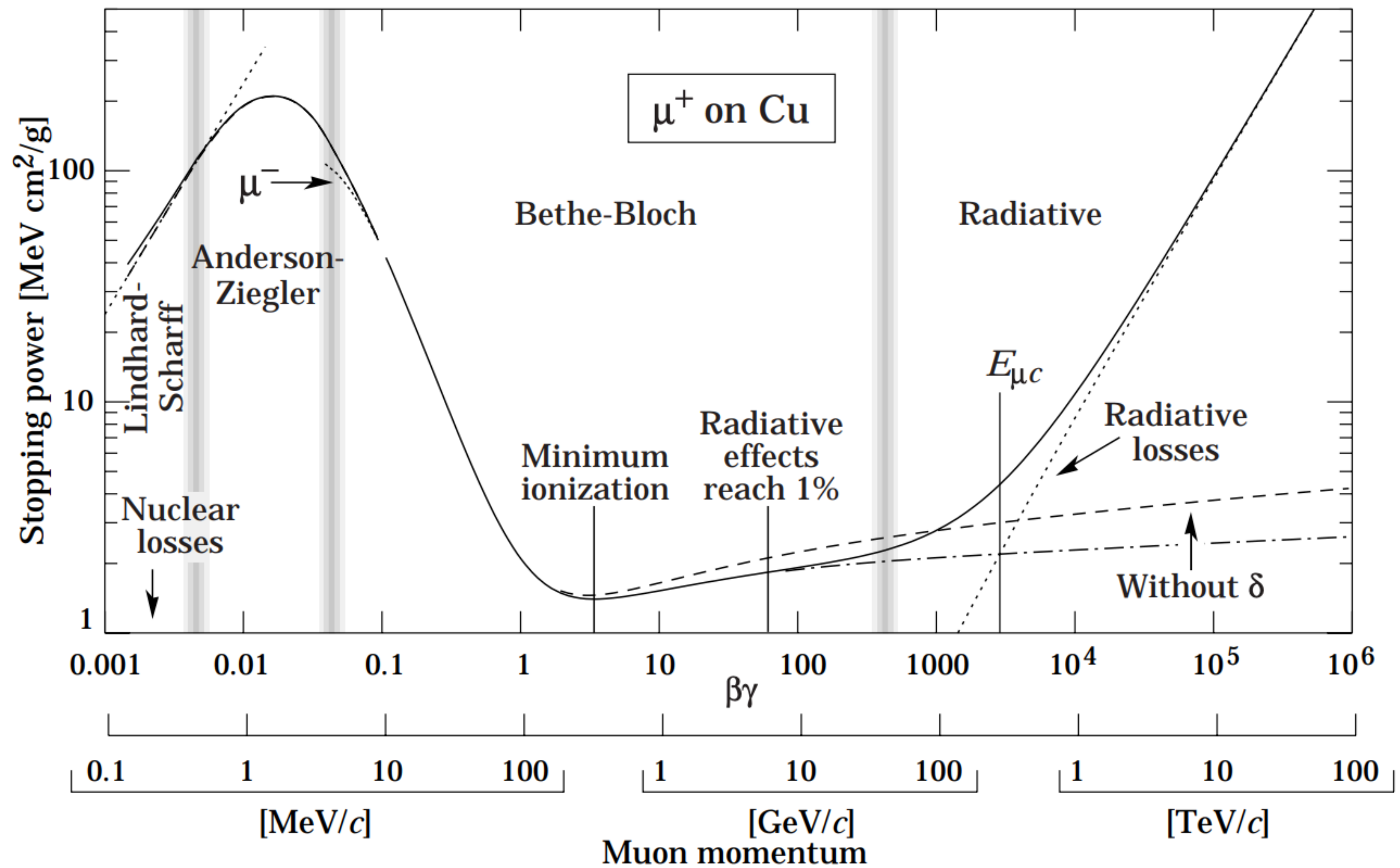
But what kind of beans were used?

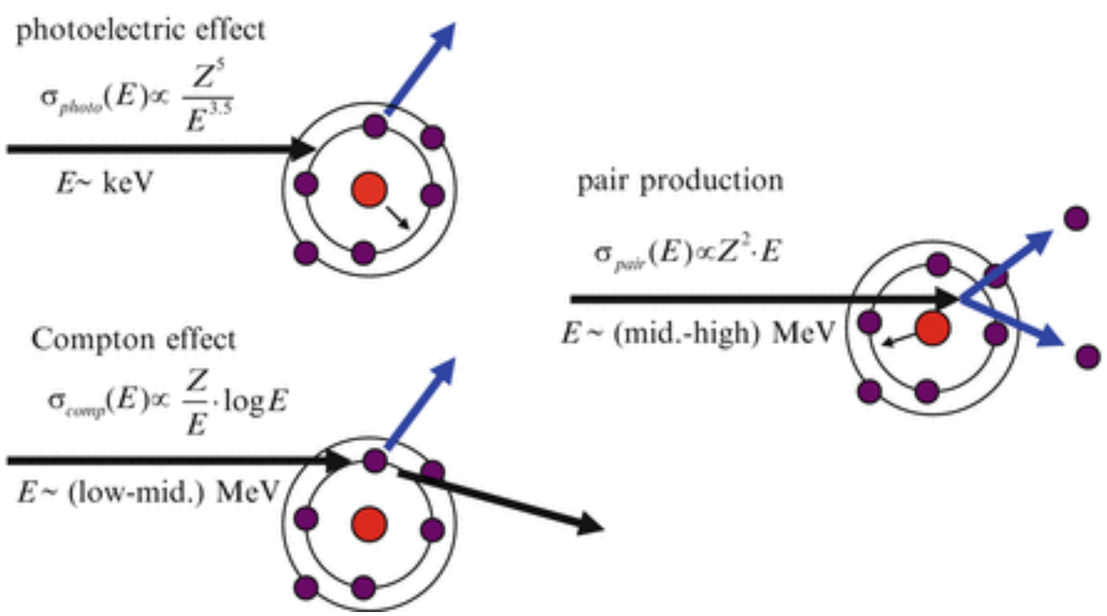
And more importantly… was there some mogette?

It’s all about material interaction

We need a “visible” signal from the passage of particles through our detector material

- **Charged particles:** ionisation, Cherenkov, Bremsstrahlung → continuous energy loss in medium
- **Photons:** photo-electric effect, Compton scattering, pair production → instantaneous full energy loss
- **Hadrons:** nuclear interactions
- **Neutrinos:** weak interactions





Bethe-Bloch

$$-\frac{dE}{dx} = K z^2 \frac{Z}{A} \frac{1}{\beta^2} \left[\frac{1}{2} \ln \frac{2 m_e c^2 \beta^2 \gamma^2 T_{\max}}{I^2} - \beta^2 - \frac{\delta}{2} \right]$$

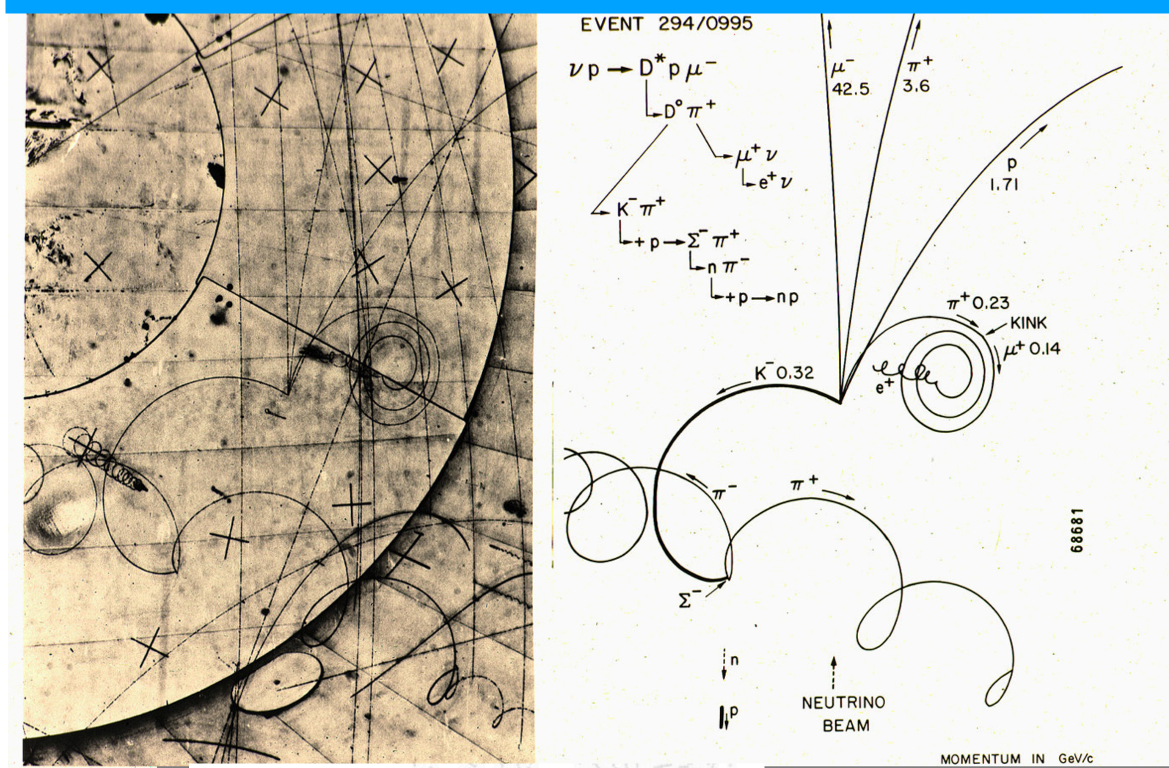
Hello, I love you, will you tell me your name?

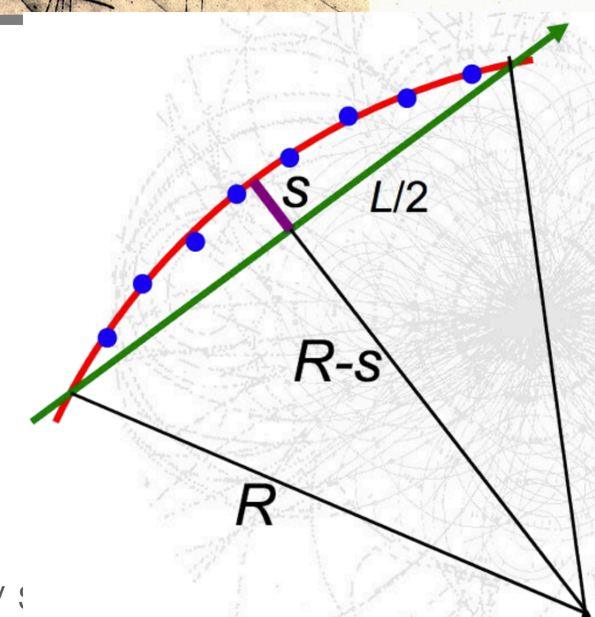
- The answer for charged particles: make them bend!

$$\frac{d\overrightarrow{p}}{dt} = q\overrightarrow{\beta} \times \overrightarrow{B} \ldots \;\rightarrow p[GeV] = 0.3B[T]\rho[m]$$

- Having the measurement of β and p $\rightarrow$ particle mass & charge
- Measuring the curvature under B-field gives access to momentum -**tracking**
- And can lead us back to the interaction vertices
- Momentum resolution: $\frac{\sigma p_T}{p_T} \sim \frac{\sigma_y p_T}{\sqrt{n}BL^2}$
- Good measurement:
  - High B-field, lever arm, number of hits
  - Good single-hit resolution, not too high p_T (low bending)

Production and decay of a charmed meson state in the Big European Bubble Chamber

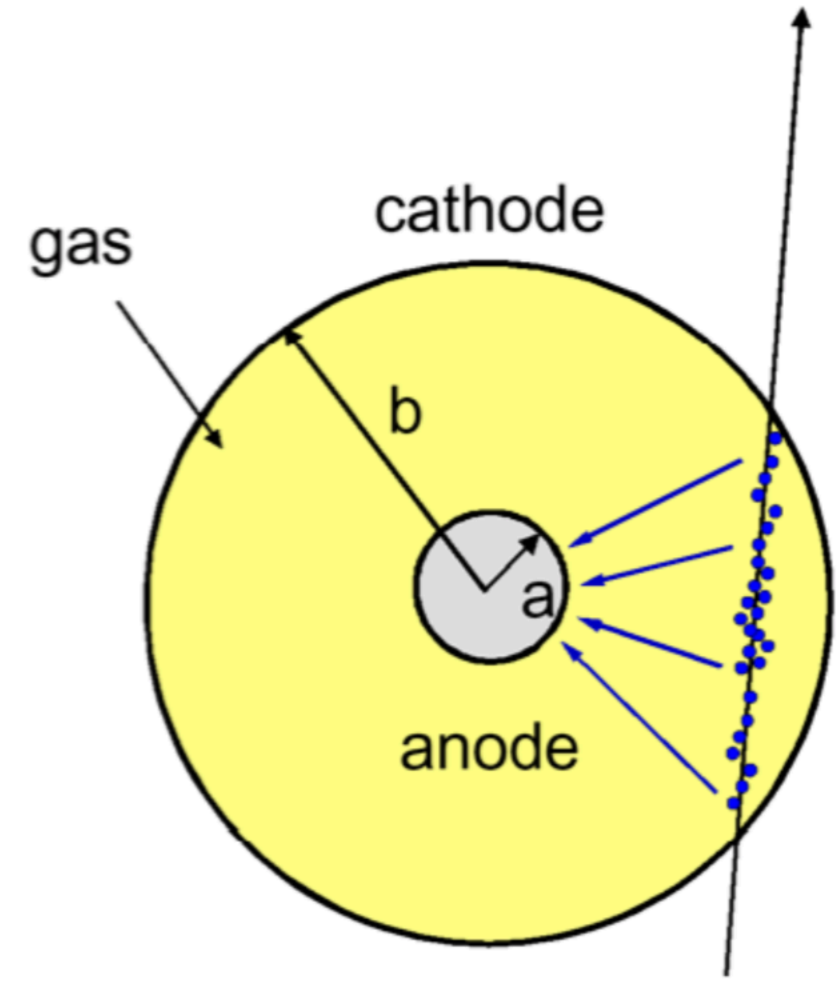




Gas detectors

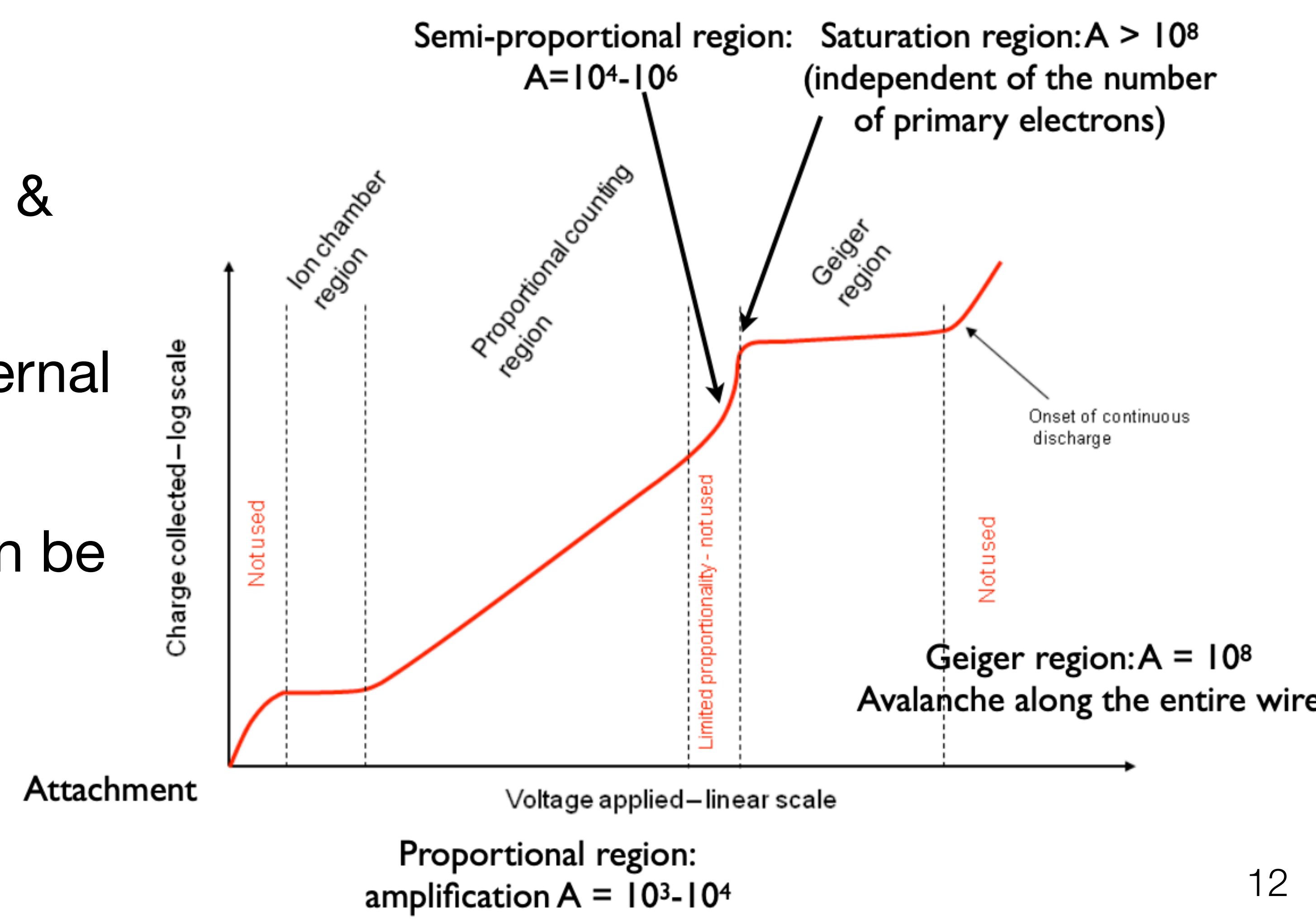
Principle of operation

- Particle traverses a gas volume (gas choice very important!) ionising it
- Created electron/ion pairs drift in electric field that we apply
- Towards collection anode/cathode → generated current



Some properties

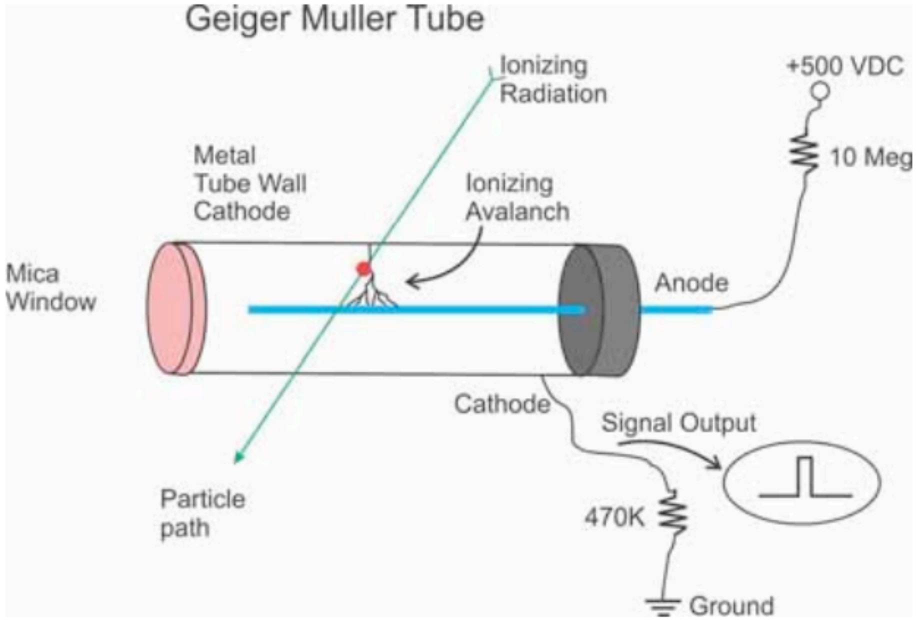
- Large coverage, good position resolution & low material budget
- Low yield of created pairs → Require internal amplification
- Long collection time due to ion tail → can be handed by filtering electronics



Gas detectors

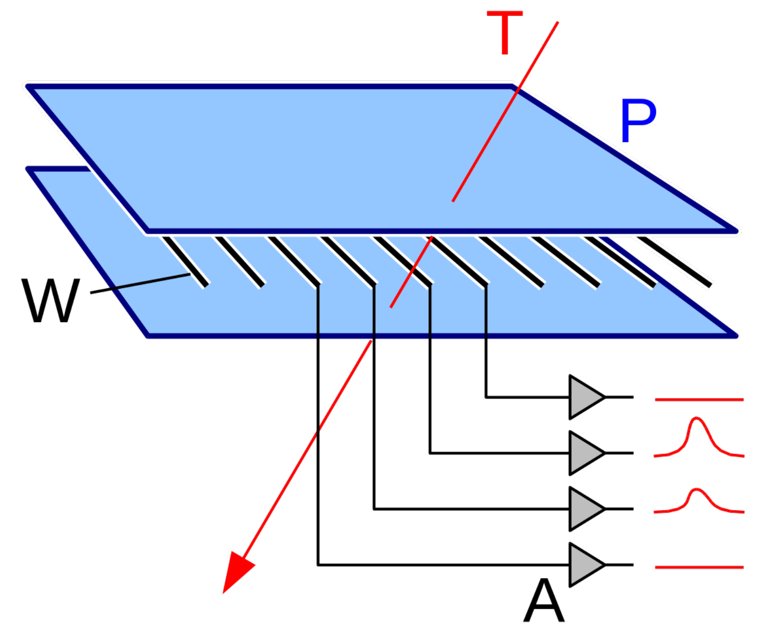
First generation: the good-old single-wire:

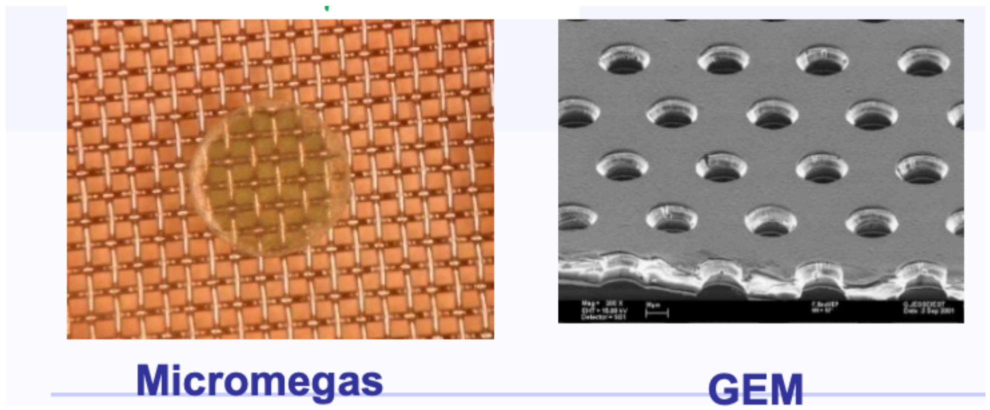
- Geiger-Muller tube: high voltage → avalanche, saturation of charge (no particle ID). First electrical signal from a particle!
- Also single-wire proportional & ionisation counters



Adding some more wires makes all the difference

- **Multi-Wire Proportional Counter (MWPC):** spacial resolution achieved by combining signals from all wires - revolutionised data collection rate
- Adaptations: thin gap, resistive plate and drift chambers
- **Time Projection Chamber (TPC):**
  - full 3-D reconstruction, x-y from wires and segmented cathode of MWPC
  - z = vdrift x tdrift from drift time
  - Not only gases, but also liquid scintillators!
- New generation of **MicroPattern** gaseous detectors (MicroMegas, GEMs) → higher segmentation & rates





Solid-state detectors

Solid-state sensors:

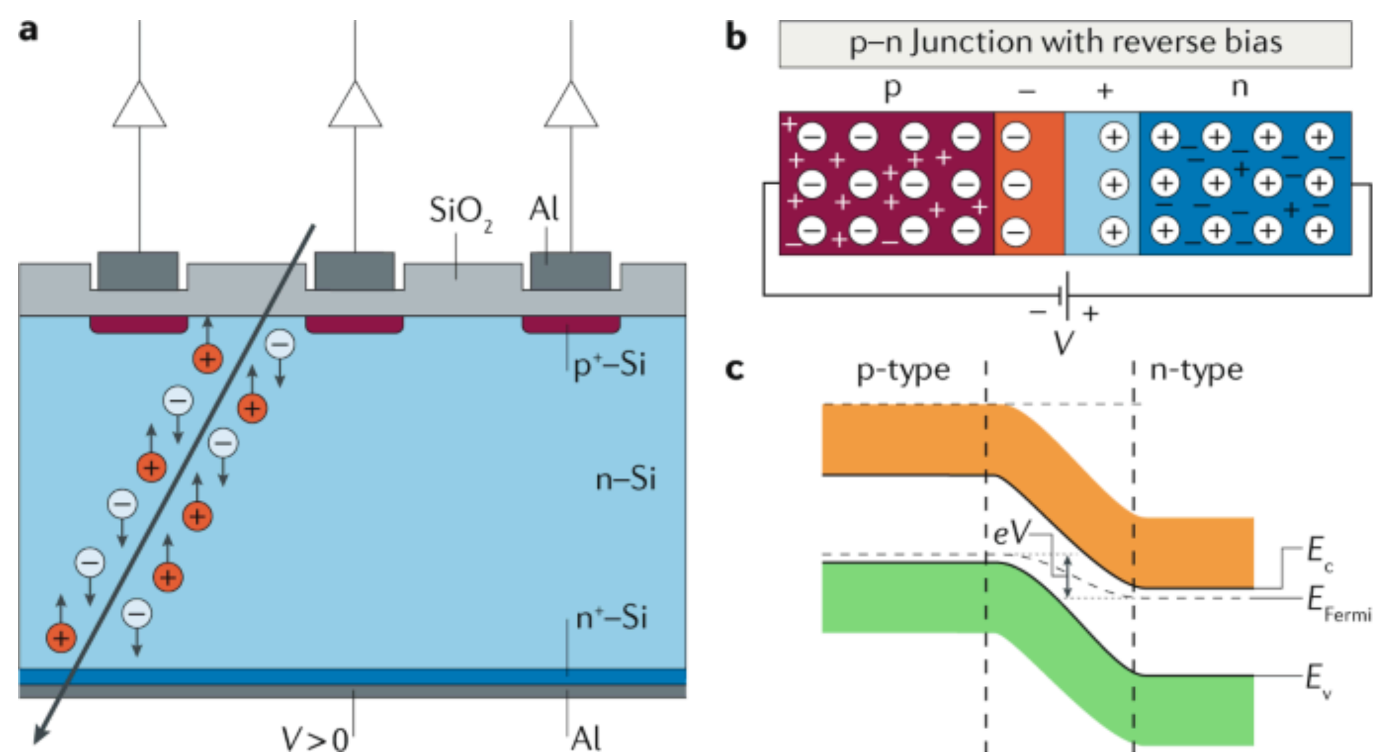
- Semiconductors like Silicon, Germanium and Diamond
- Two sides, one negative charge carriers/electrons (n-type) and one with positive carriers/holes (p-type)
- Put them together (p-n junction) → intermediate region without carriers (depletion region)
- Apply some voltage; forward bias - large current / **reverse bias → low transient current (our preference in HEP!)**

Principle of operation:

- When a particle passes through, it generates electron - hole pairs
- Again, carriers drift due to the electric field
- Signal generation according to **Shockley - Ramo** theorem

Some properties:

- High yield of created pairs -> No/little internal amplification
- O(μm) segmentation & short (O(ns-ps)) signals -> can withstand very high particle rates
- Radiation hard
- Expensive & difficult to manufacture

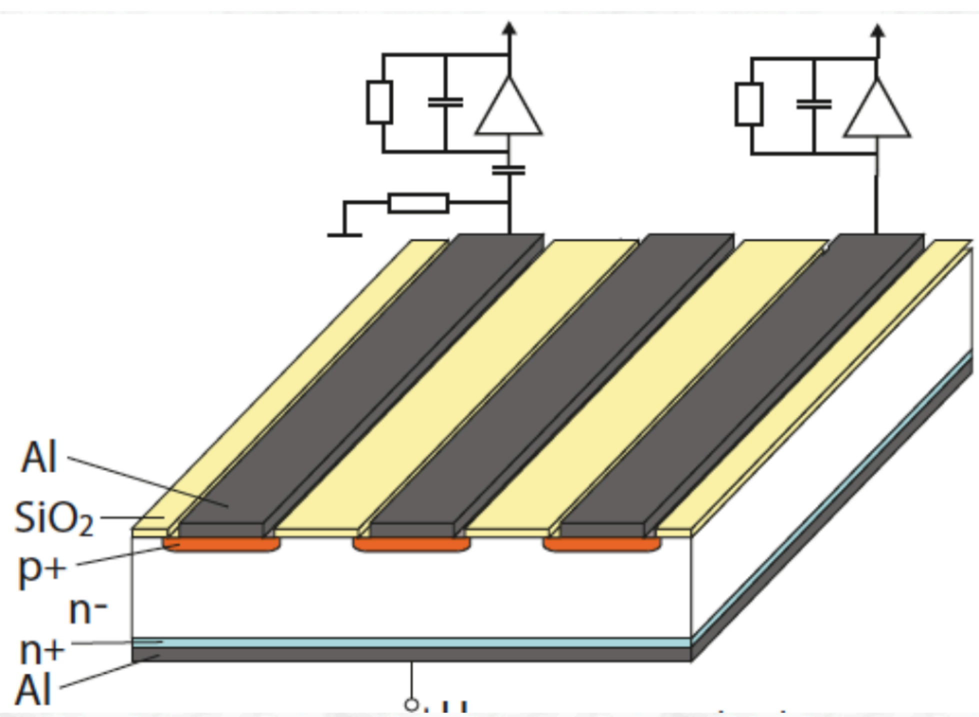


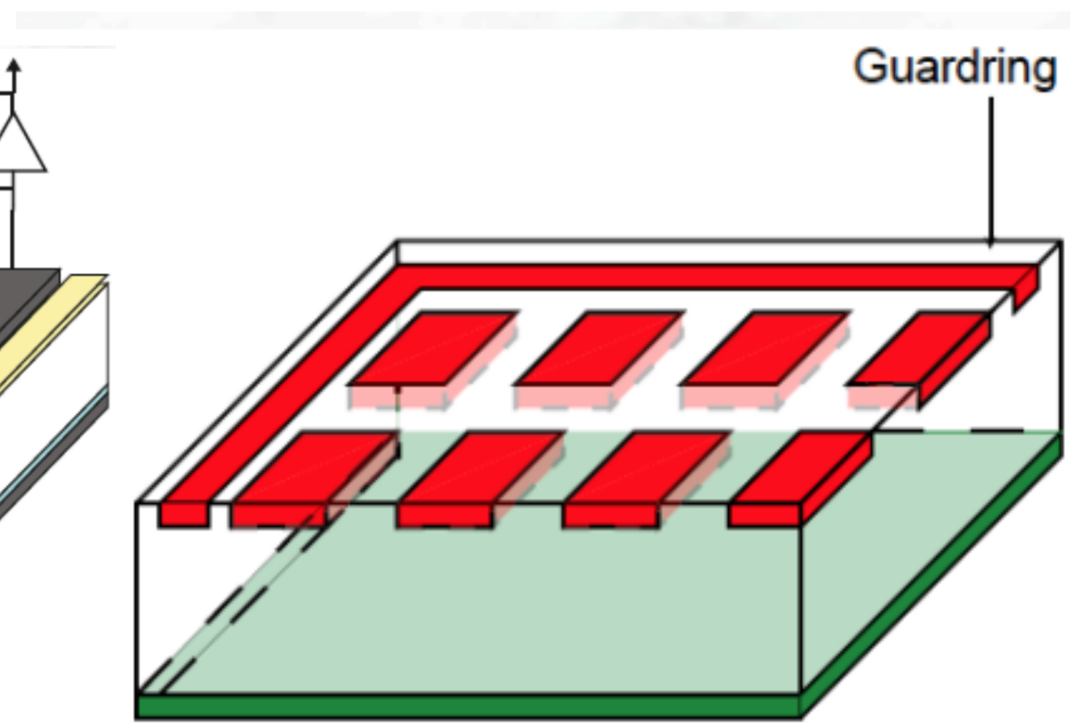
A few considerations

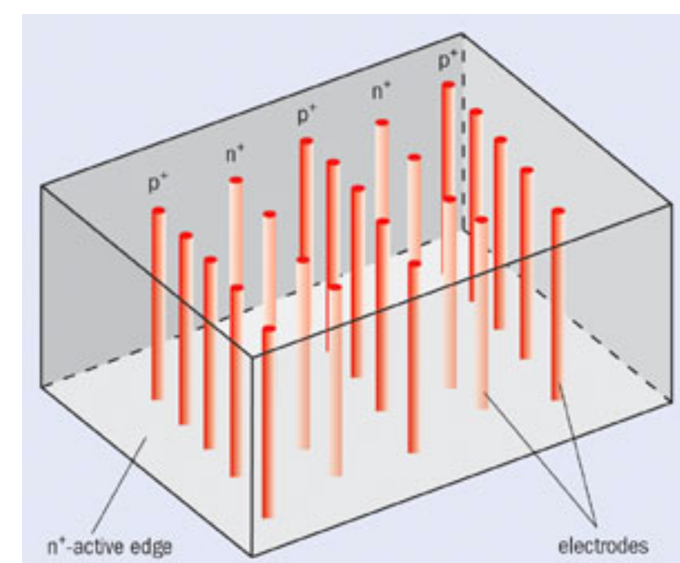
Strips and pixels

- Strips: 2-D tracking, can be recovered by smart detector design choices (tilting/overlapping layers)
- Pixels: full 3-D tracking, but large amount of read-out channels, high power consumption
- Usual compromise in HEP: pixels in the innermost layers, strips in the larger outermost area

Some more considerations: 3-D vs planar, timing (4-D tracking)…



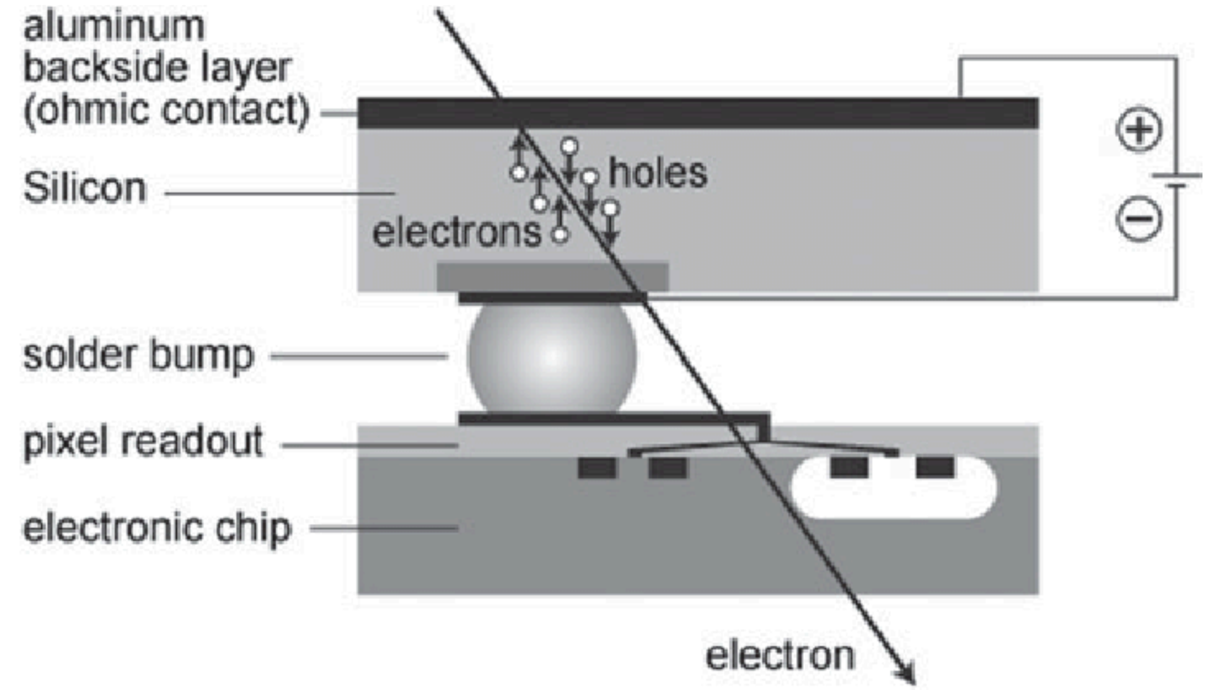




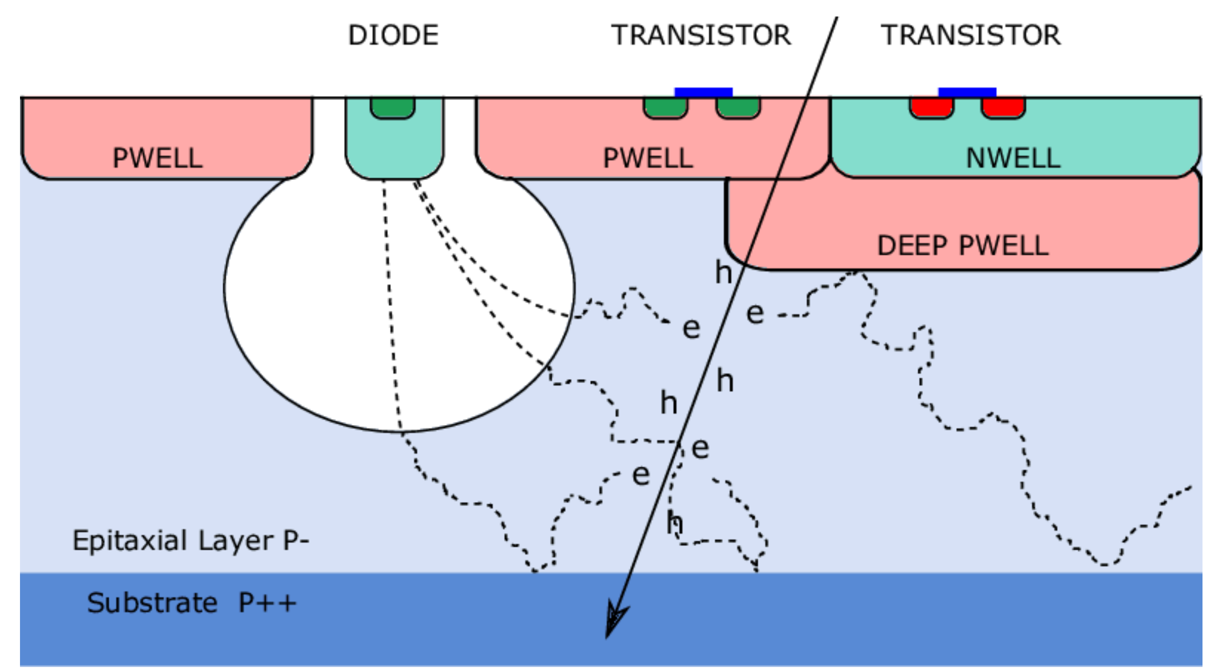
A few considerations

Hybrid or monolithic?

- **Hybdrid sensors:** typical connection of sensor to front-end electronics chip through wire and bump-bonds
    - Radiation hard, fast timing
    - difficult and expensive (and you might have to do thousands of them!)



- **CMOS technology:** integrate signal-processing circuits on sensor substrate (sensor & electronics become one)!
    - Cheap, easy to produce and assemble
    - Radiation hardness & timing being worked on



Hello, I love you, will you tell me your name?

We measured p … And what about β ?

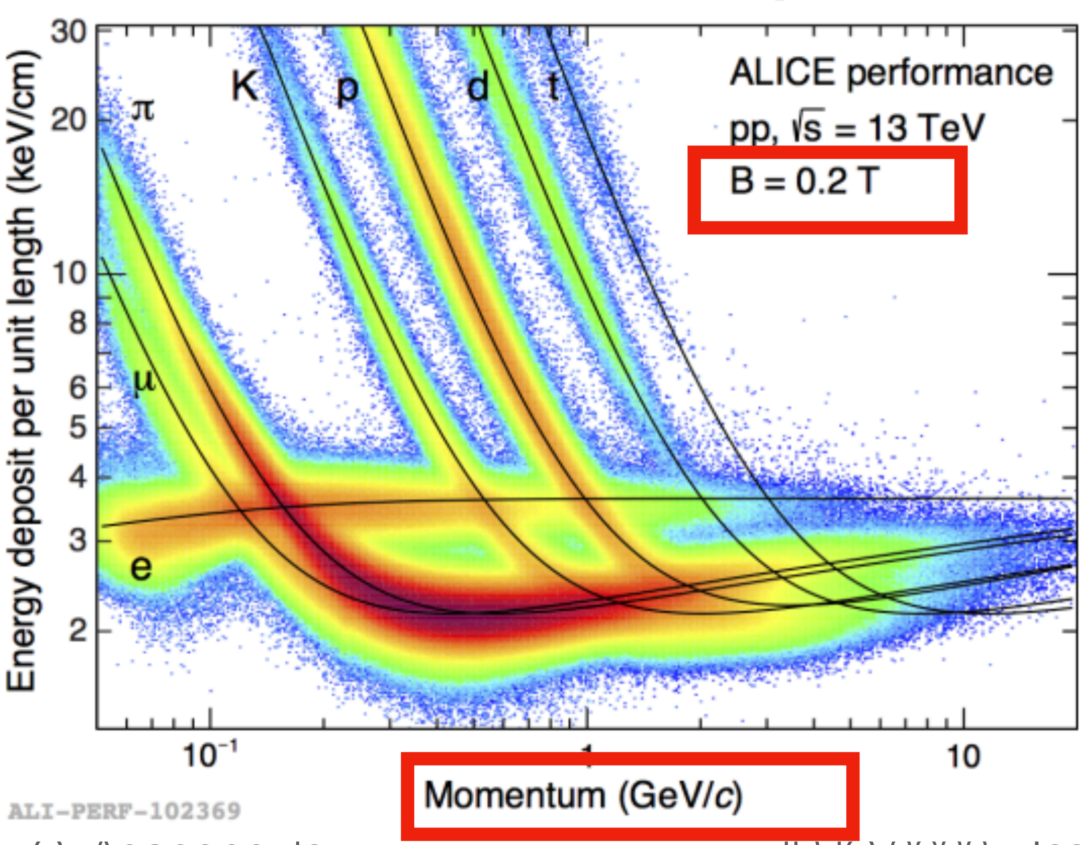
▸ **Measuring the energy loss $\frac{dE}{dx}$**

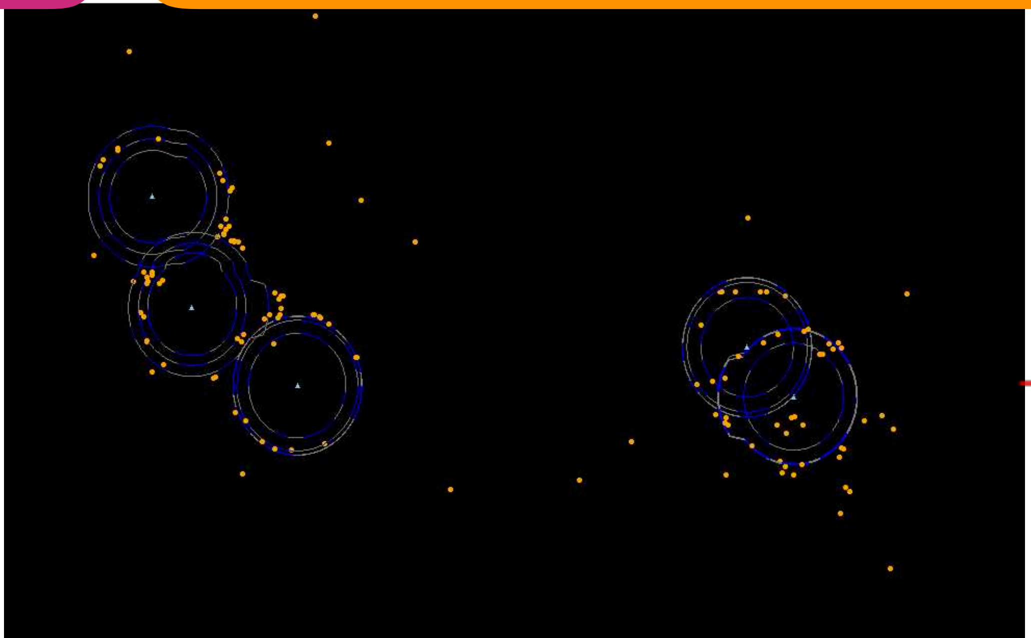
- Remember the Bethe-Bloch?
- Excellent for $p \leq 1$ GeV/c
- Multi-wire proportional chambers, Time-projection chambers

▸ **Cherenkov radiation**

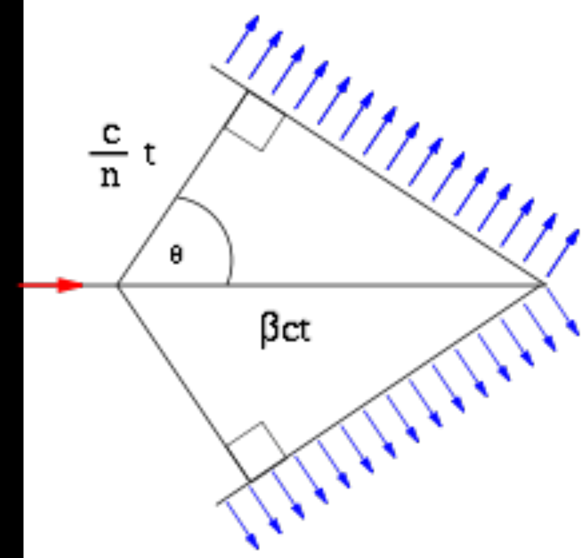
- Radiation from charged particle crossing medium at speed greater than speed of light within the medium
- Emission angle reversely proportional to β
- PID for 1 - 100 GeV/c

ALICE's TPC PID power





Rings from LHCb's RICH

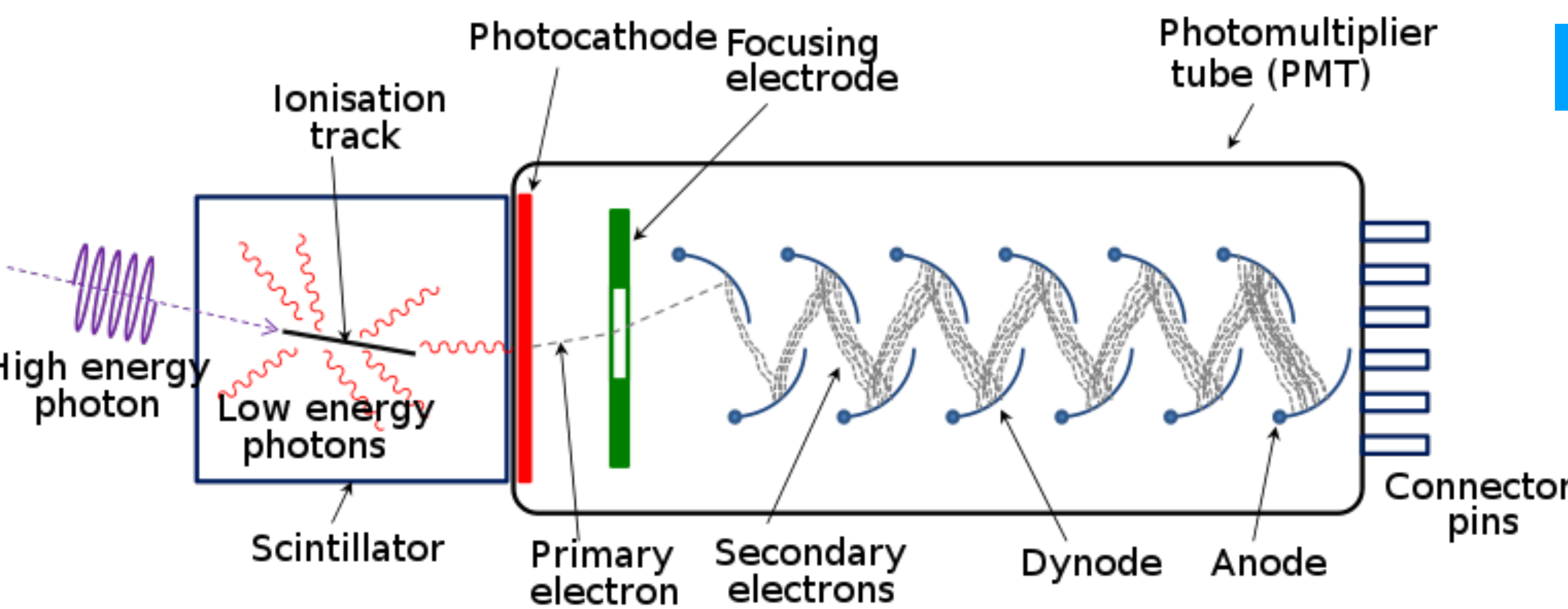


- \+ Direct measurement with Time-of-Flight (TOF)
- \+Transition Radiation

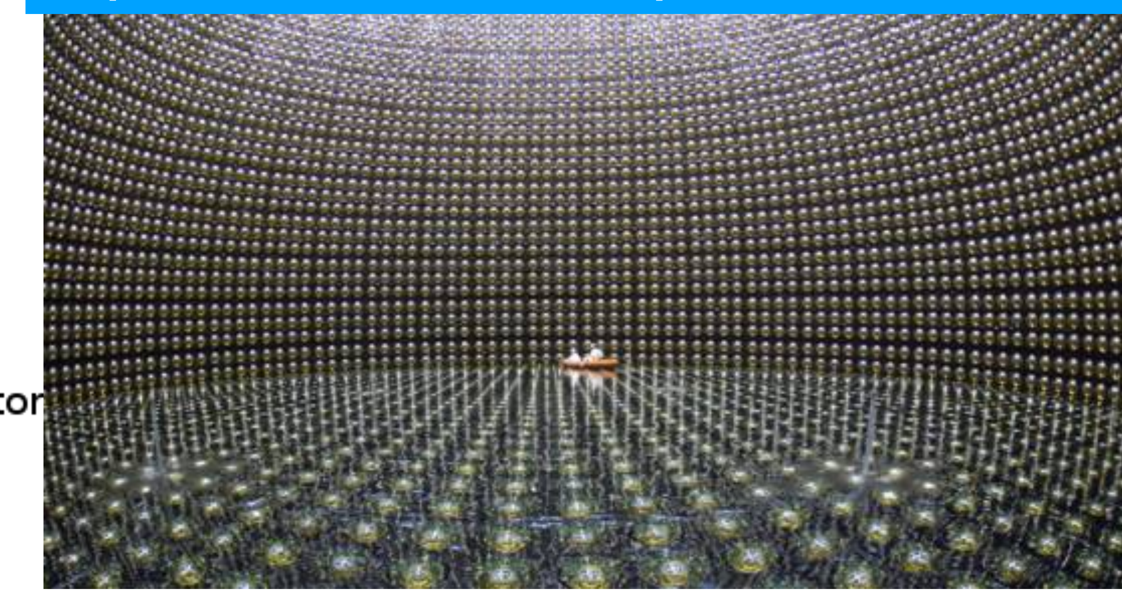
And what if you're a photon?

Photomultipliers

- Primary high energy photon → primary electron
- Electrons accelerated in electric field through a dynode chain producing more electrons → internal amplification!
- Important properties: gain, quantum efficiency, spectral range, single photon detection…



SuperKamiokande in Japan, ~13000 PMTs



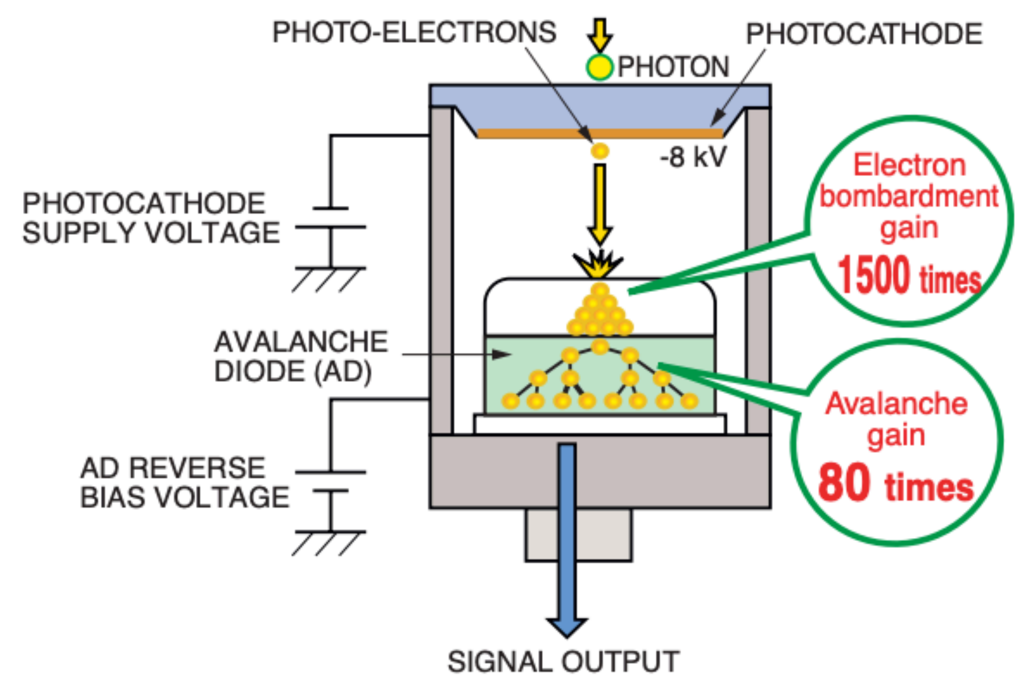
Can be vacuum

- Old technology, but still used in many experiments
- Quantum efficiency ~ 20-30% @ 400 nm
- High gain, low noise, good timing, radiation hard
- Segmenting the anode readout can give position sensitivity (MAPMTS)
- Some disadvantages: bulky, sensitive to magnetic field (and expensive)

Photomultipliers

- Primary high energy photon → primary electron
- Electrons accelerated in electric field through a dynode chain producing more electrons → internal amplification!
- Important properties: gain, quantum efficiency, spectral range, single photon detection…

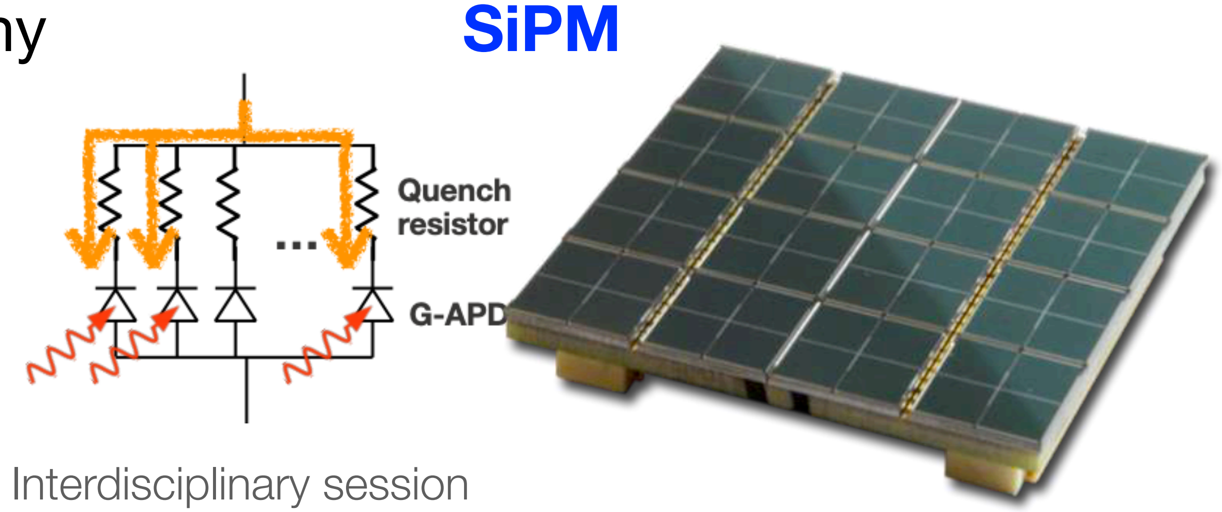
APD



Or solid state photodetectors

- Usually Si, but also Ge
- Photon induces electron-hole pairs → photocurrent
- Quantum efficiency ~ 100 %
- Originally no internal gain (photo-diode)
- Can be induced by operating at high reverse voltage → **Avalanche Photo-Diode (APD)**
- Even higher gain by connecting in parallel many APDs together → **Silicon Photomultipliers (SiPMs)**

SiPM

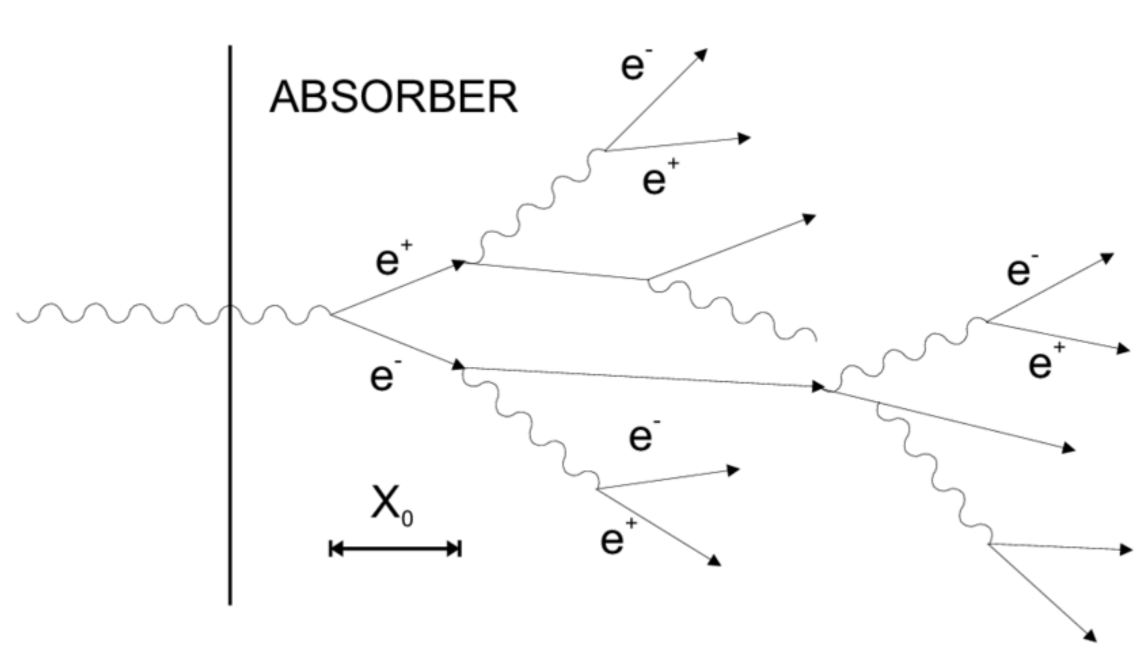


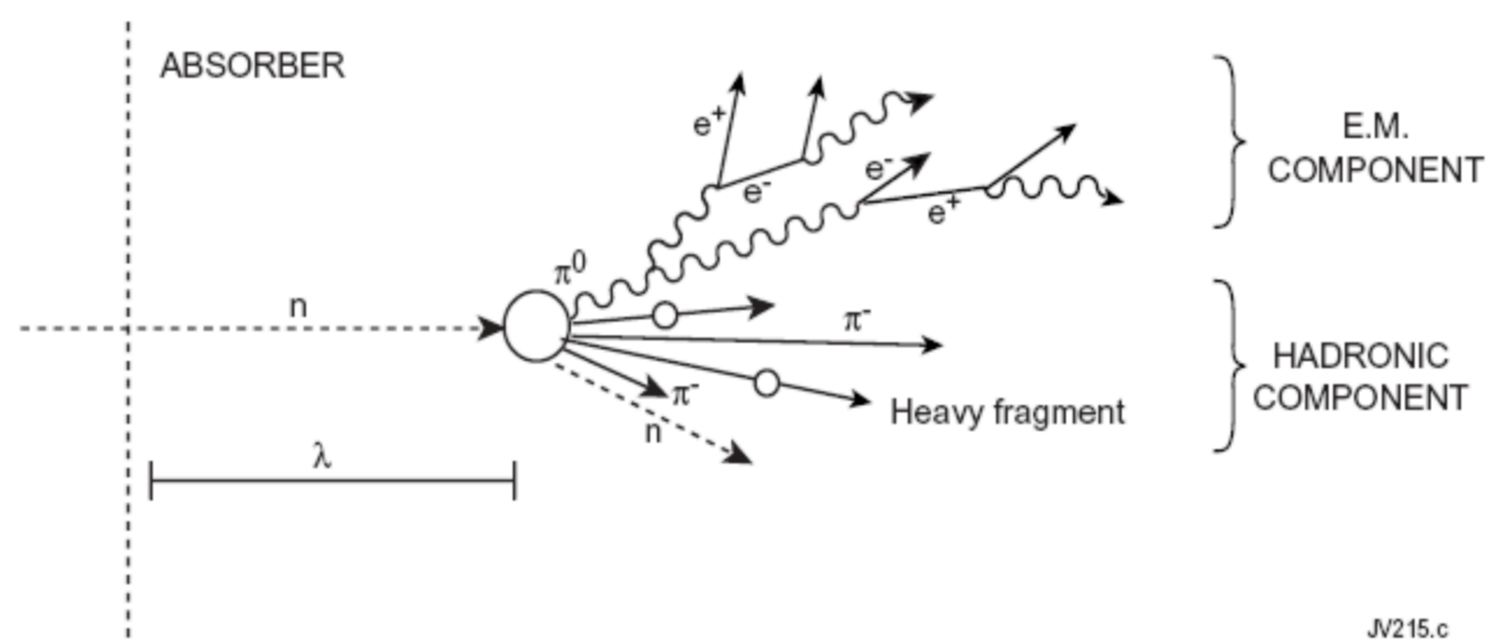
Measuring energy

- Up to now, we've measured the momentum of only charged particles - what about neutrals?
- We can take advantage of electromagnetic and hadronic cascades /showers in thick "absorber" materials →**Calorimeters!**
- Destructive measurement → original particle is **lost** (only muons and neutrinos can survive)
- Measuring the shower size gives the original particle energy

EM showers:
- Produced by electrons and photons
- Sequence of pair production & Brem.
- Shower size described by radiation length X_0

Hadronic showers:
- Produced by hadrons (strong interactions)
- Contains EM component
- Shower size described by interaction length λ_{int}

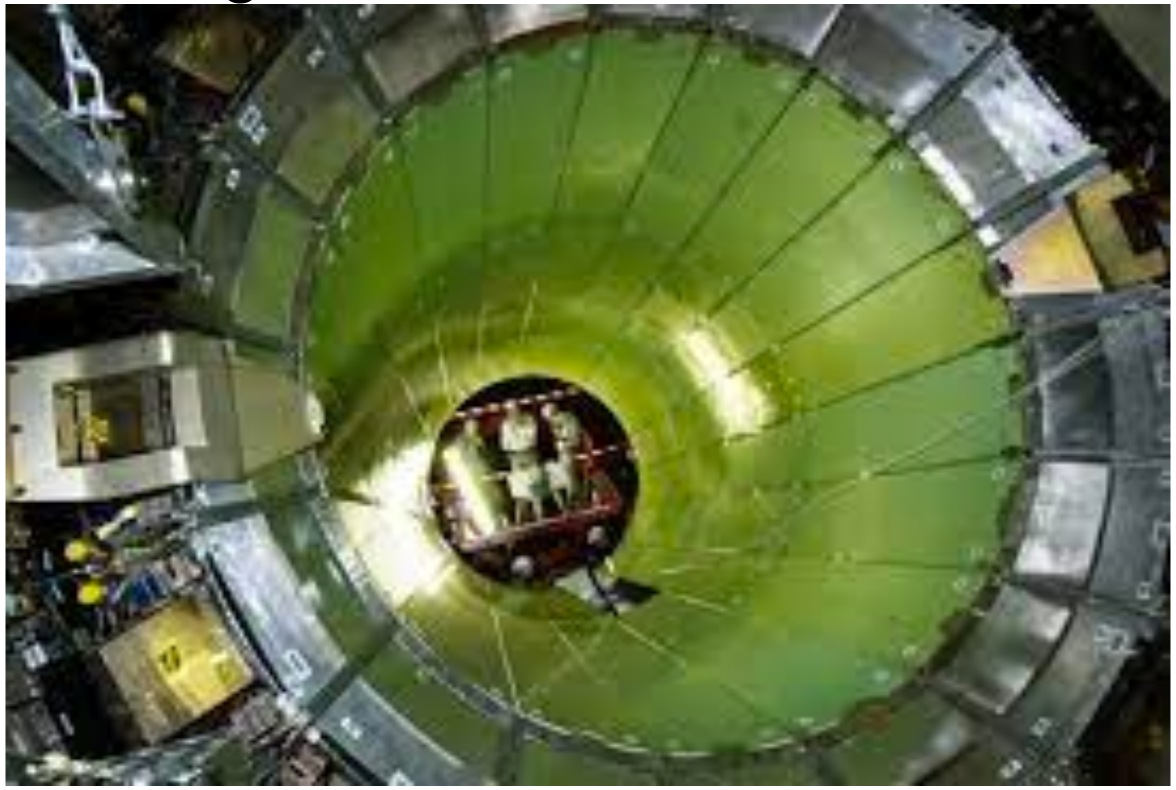




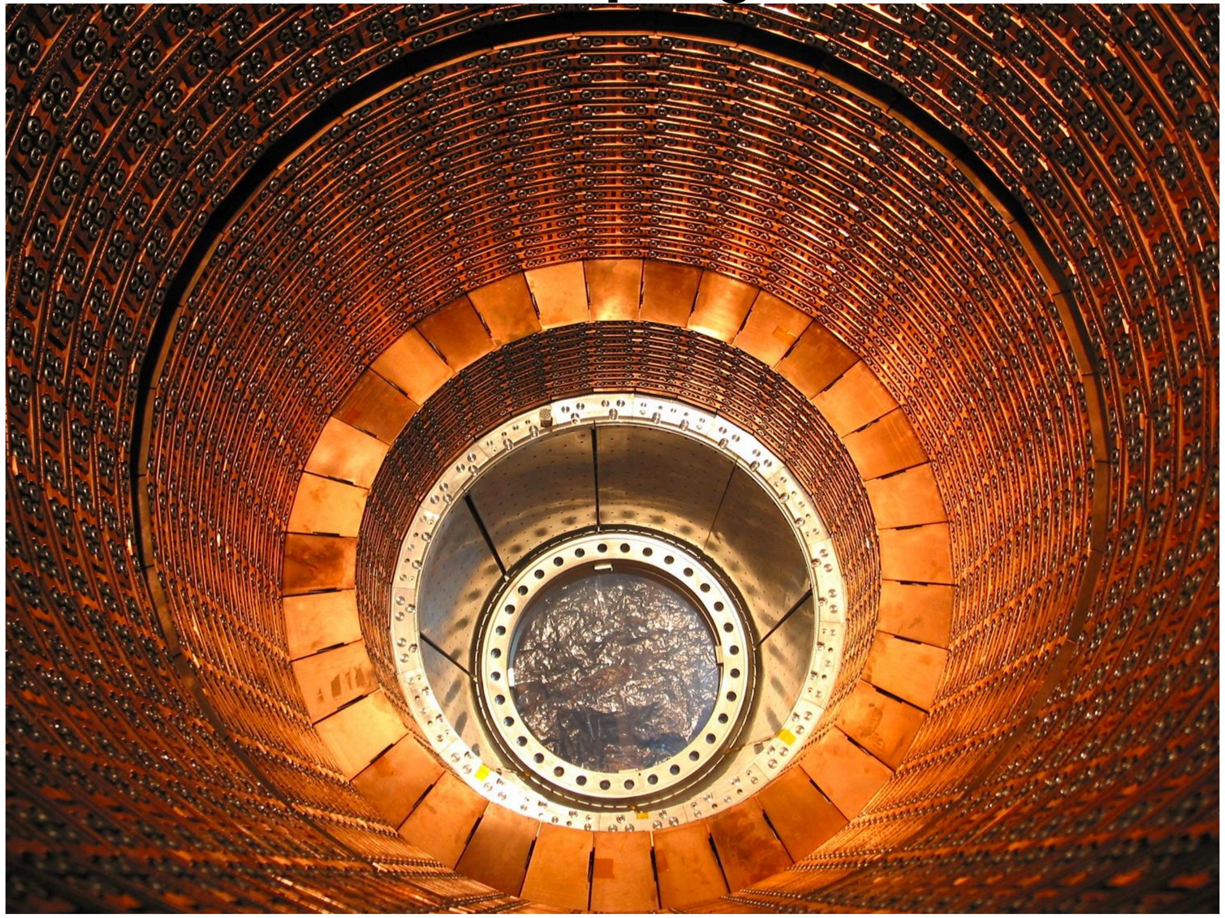
Large calorimeters

- Homogeneous calorimeters:
  - Active medium (the material that records the showers) also acts as absorber (the material that helps develop the shower)
  - Excellent energy resolution
  - But no longitudinal information on shower development

CMS homogeneous PbWO4 EM calorimeter

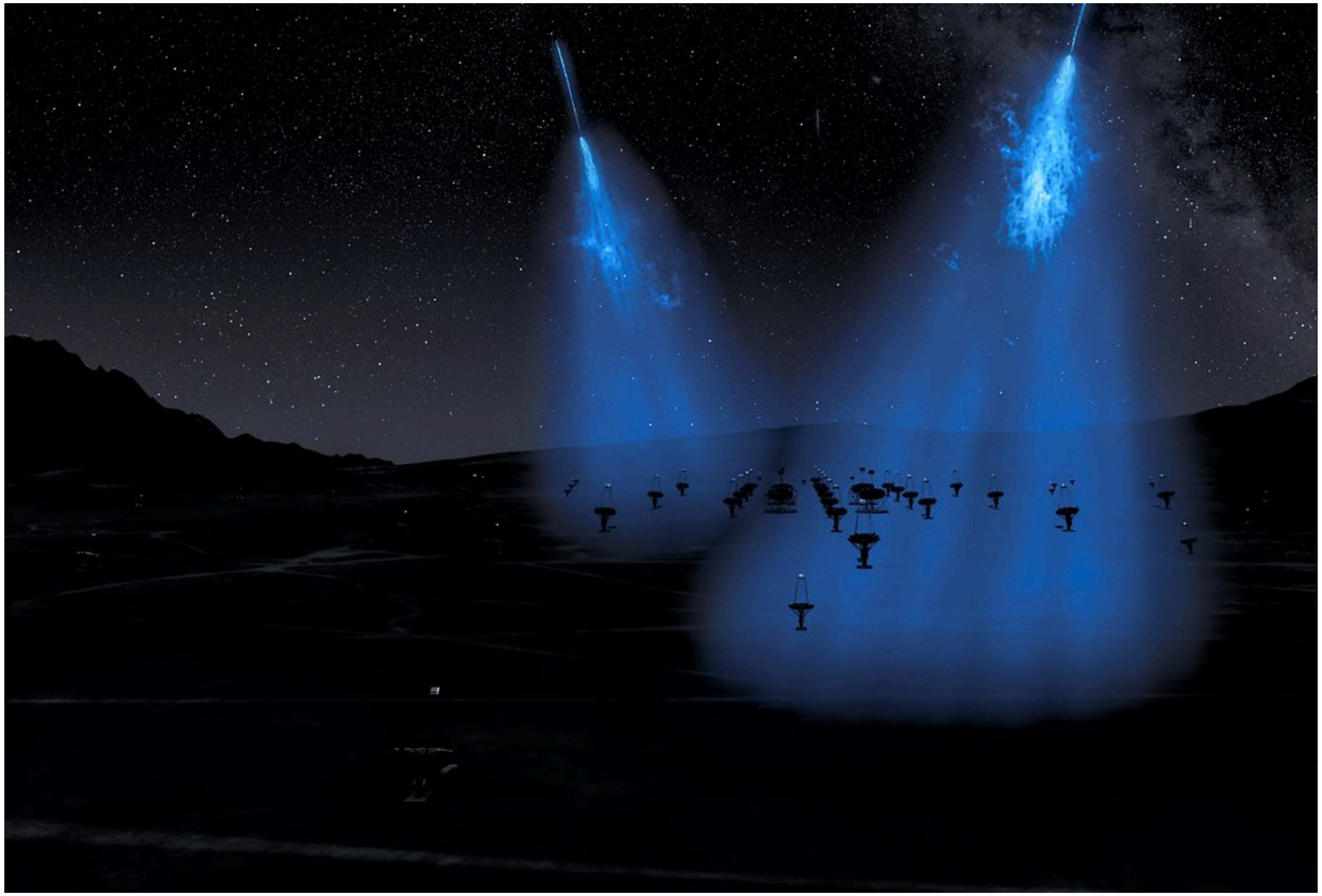


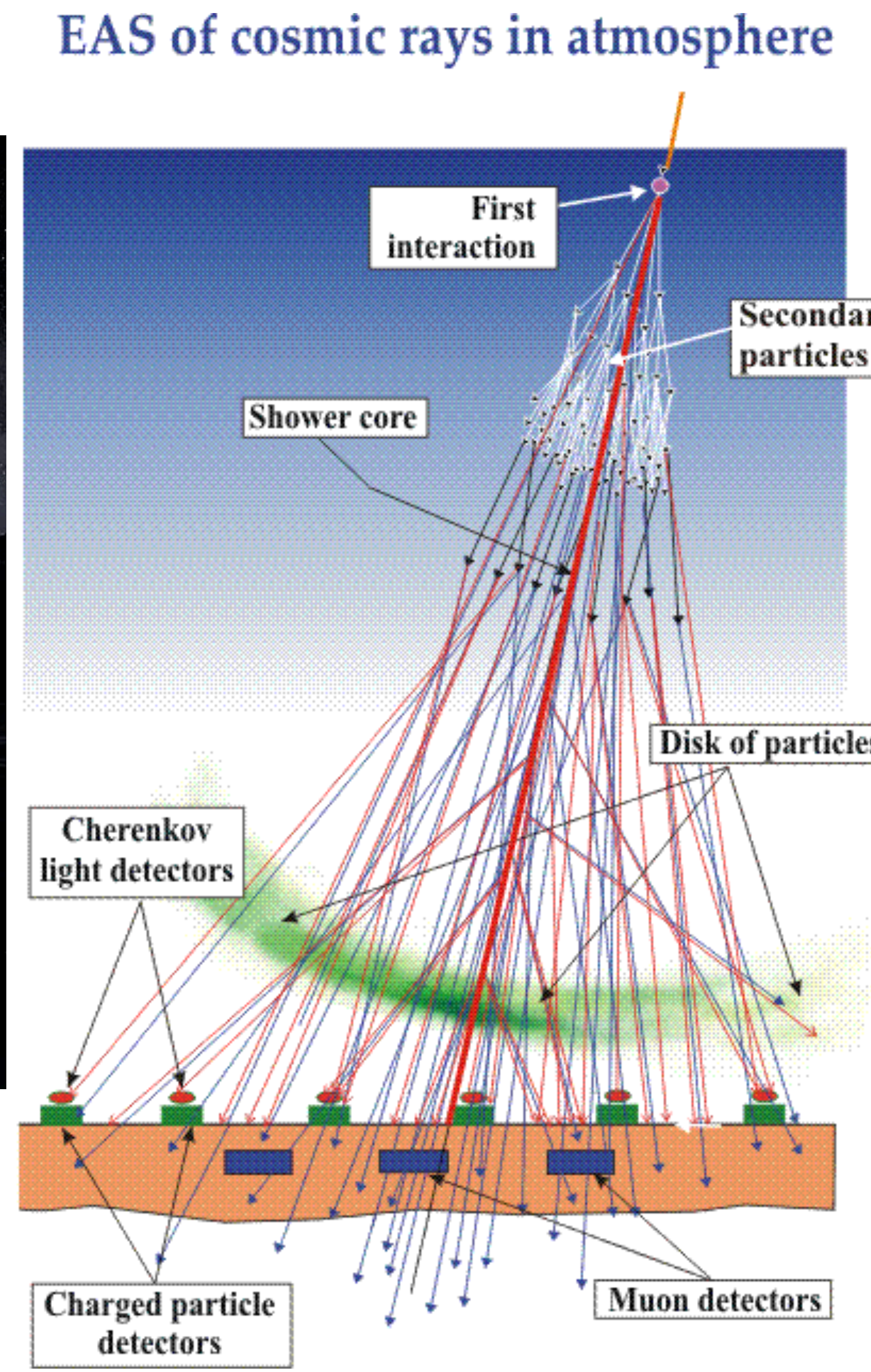
ATLAS LAr EM sampling calorimeter



- Sampling calorimeters:
  - Active medium separate from the absorber (usually placed in alternating layers)
  - Some energy is always lost in the absorber → limited energy resolution
  - But, information on longitudinal shower development

And giant ones





Earth's atmosphere acts as a giant absorber for cosmic rays

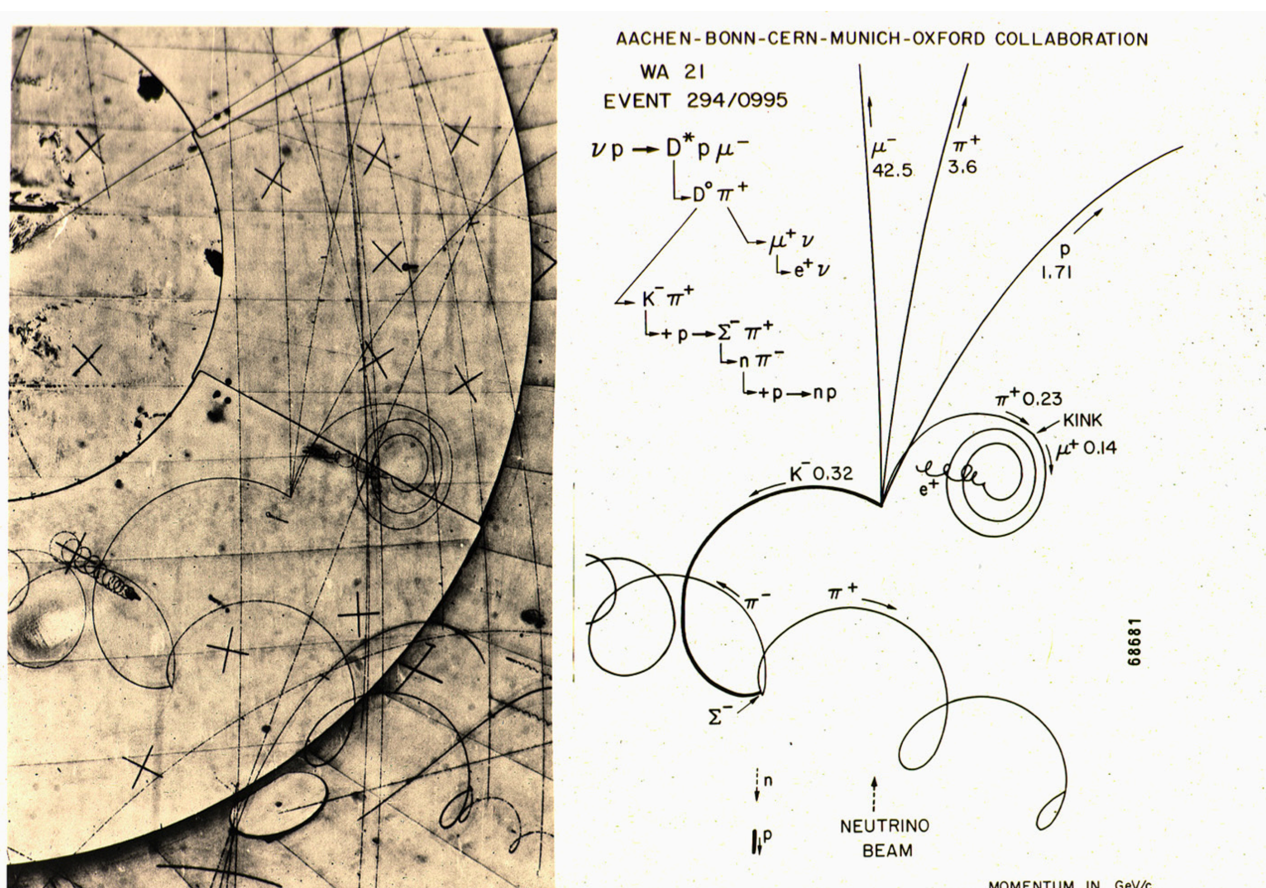
X0 & $\lambda_{int} \sim 2000$ x LAr , but, we have a lot of air!

Atmospheric and ground-based detectors measure the shower, similar to calorimeters!

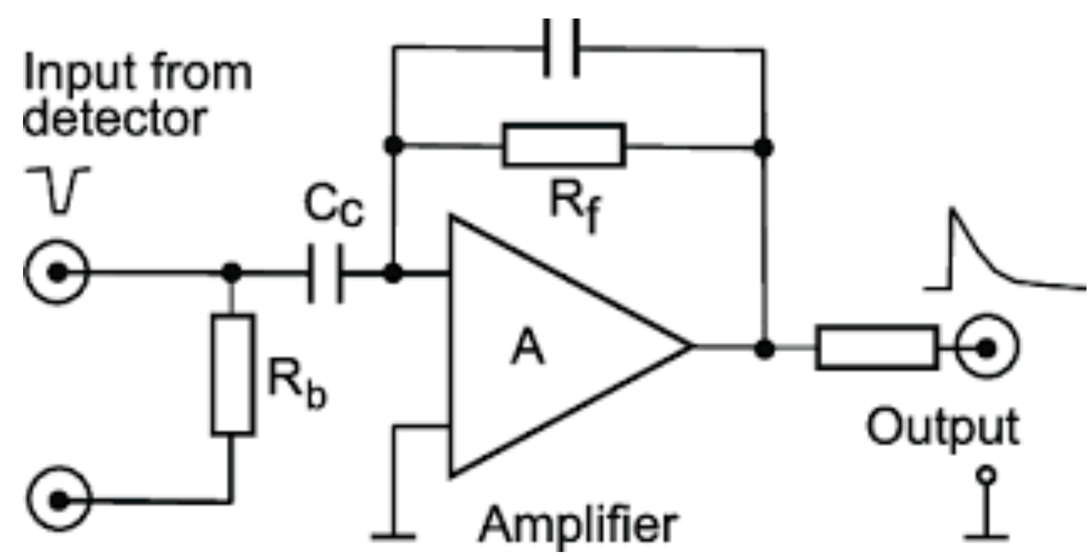
And what to do with all these signals?

First of all, record it

- **In the bubble-chamber era: Photographic methods**
  - Quite precise but…
  - Very low rate ~ few HZ → can't operate in a modern collider!
  - Automation of data analysis is hard

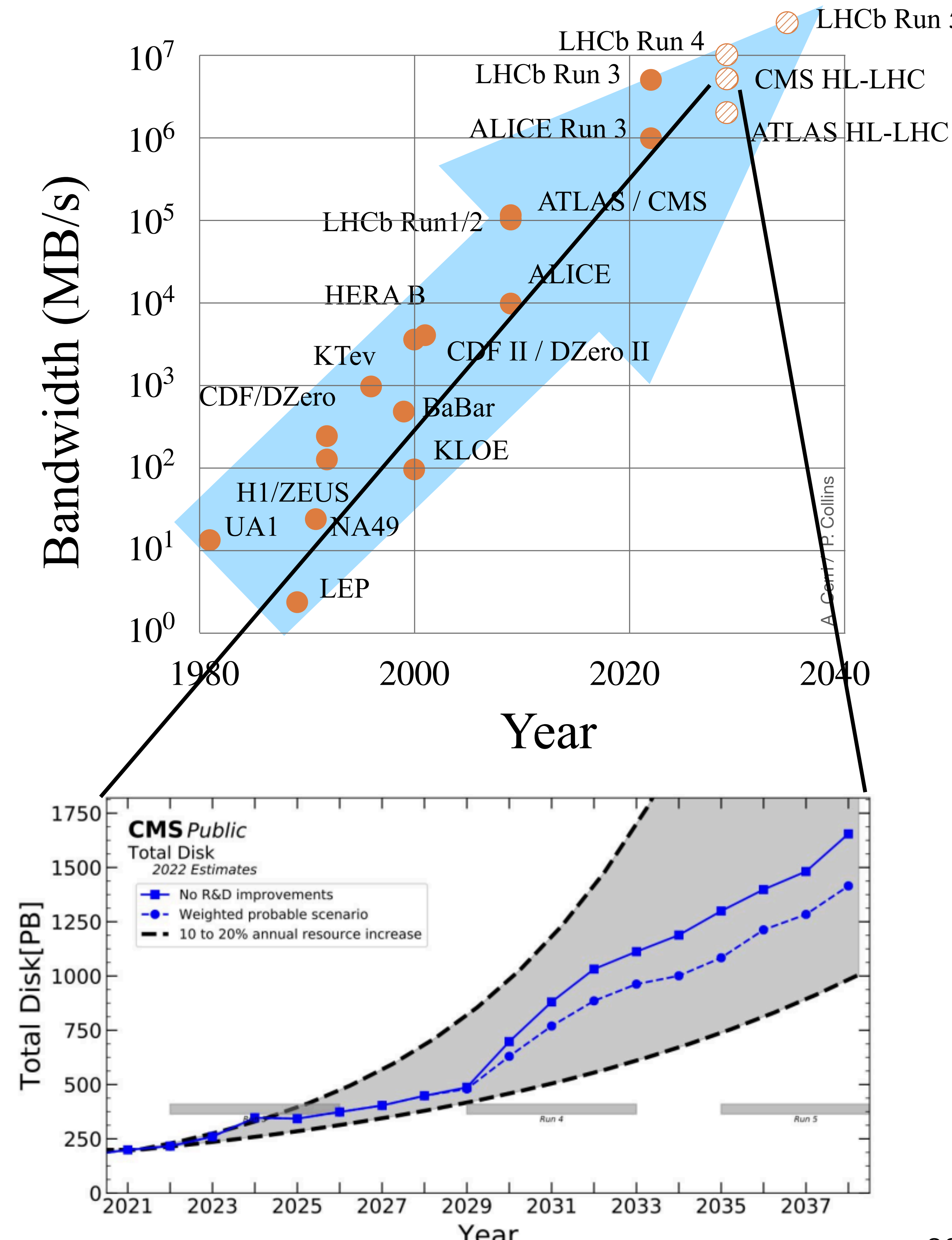


- **Today: Integrated electronics (ASICs)**
  - Allow us to go down to O(MHz) rates
  - What we get: electronic signals, usually digital
  - A wide variety of circuits for position, energy and time measurement
  - Same requirements as the active material (radiation hard, compact & not too power consuming)



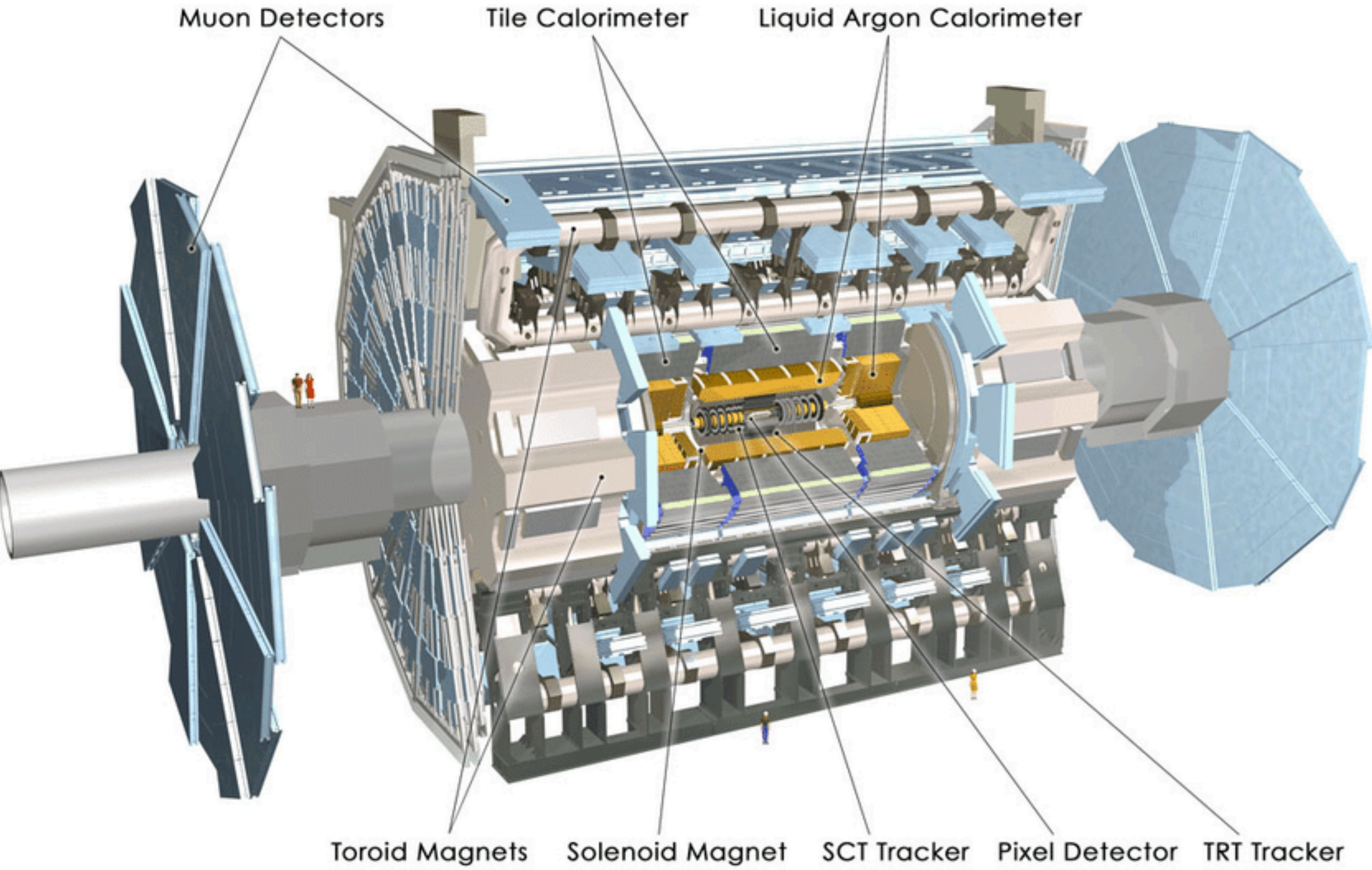
Then, process it…

- Technological breakthroughs in material and electronics have improved signal yields and detection times → we're at the picosecond era!
- At the same time, demand for precision is increasing
- Many experiments need to process TB of data every second!
- Traditionally, this has been handled by fast electronics making decisions based on topical signals - **Triggers**
- However, new strategies are now emerging:
    - **Software triggering** based on heterogeneous architectures (GPUs, FPGAs)
    - **Machine-learning** developments for topological event reconstruction, faster simulation and inclusive selections

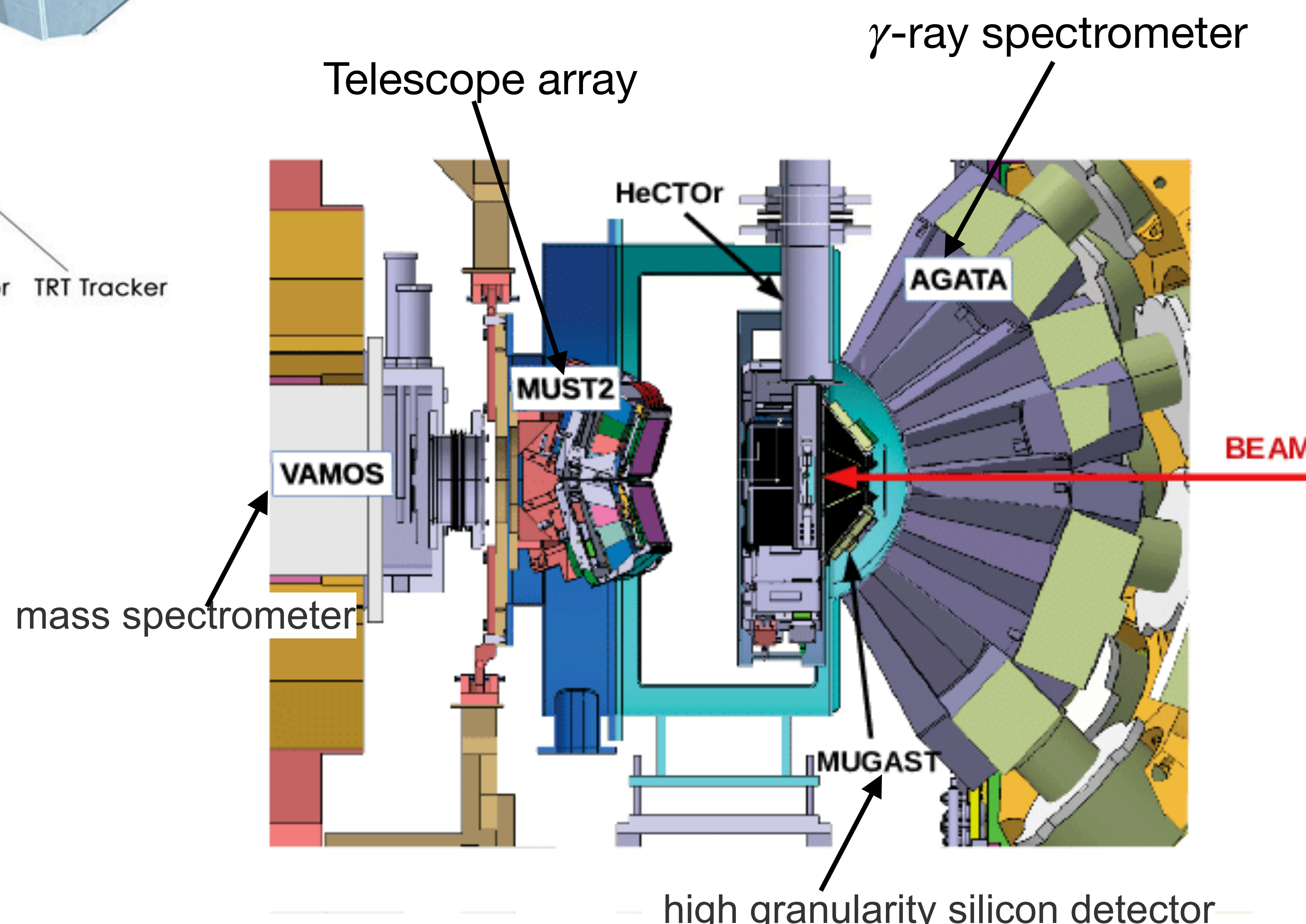


Putting everything together

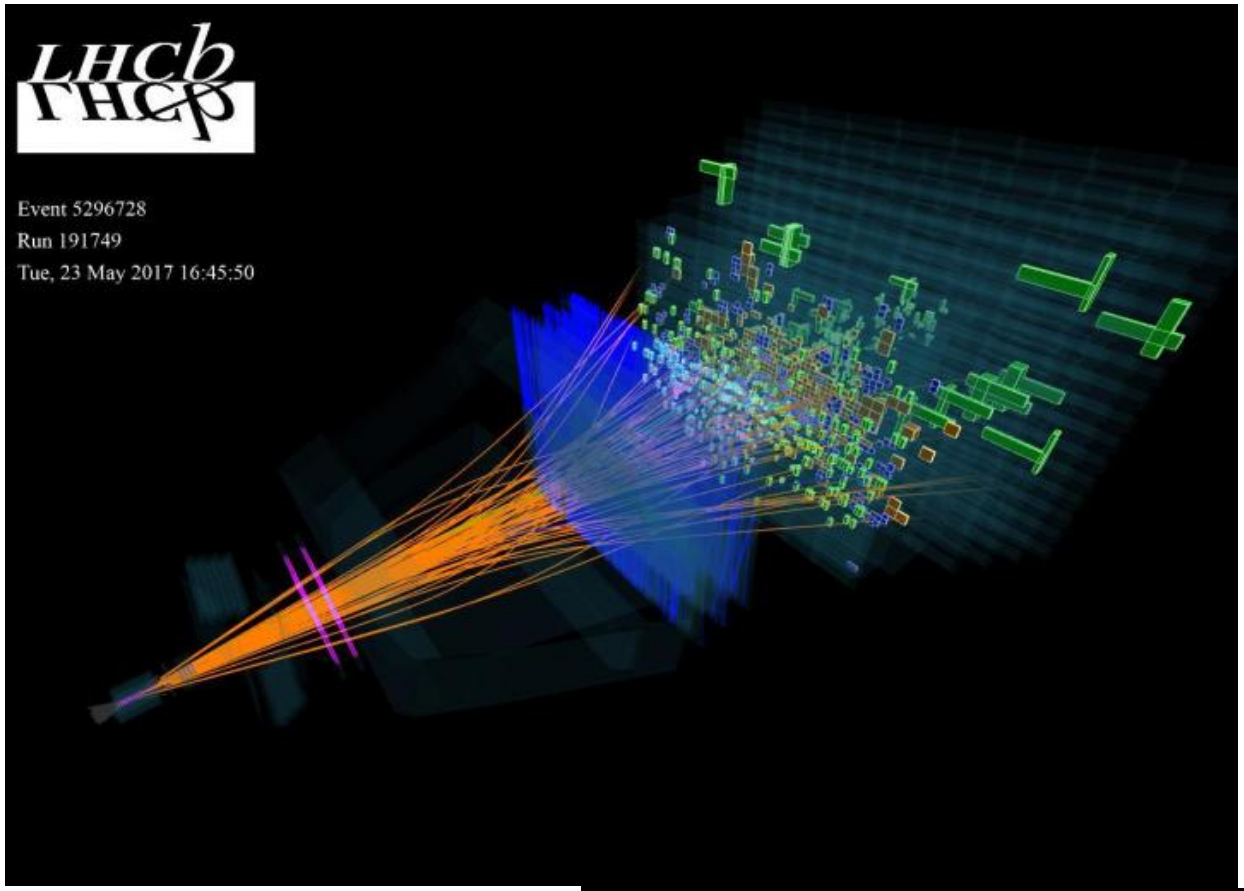
ATLAS experiment @ CERN

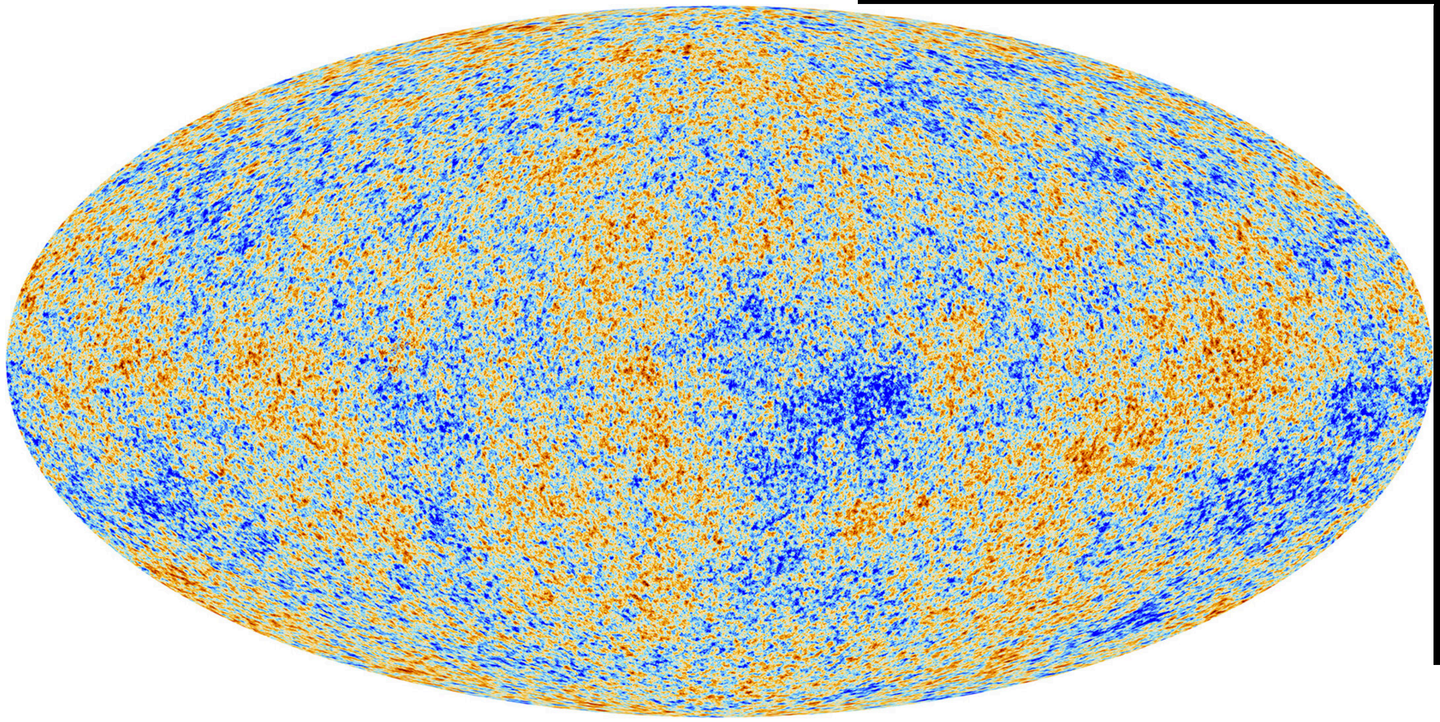


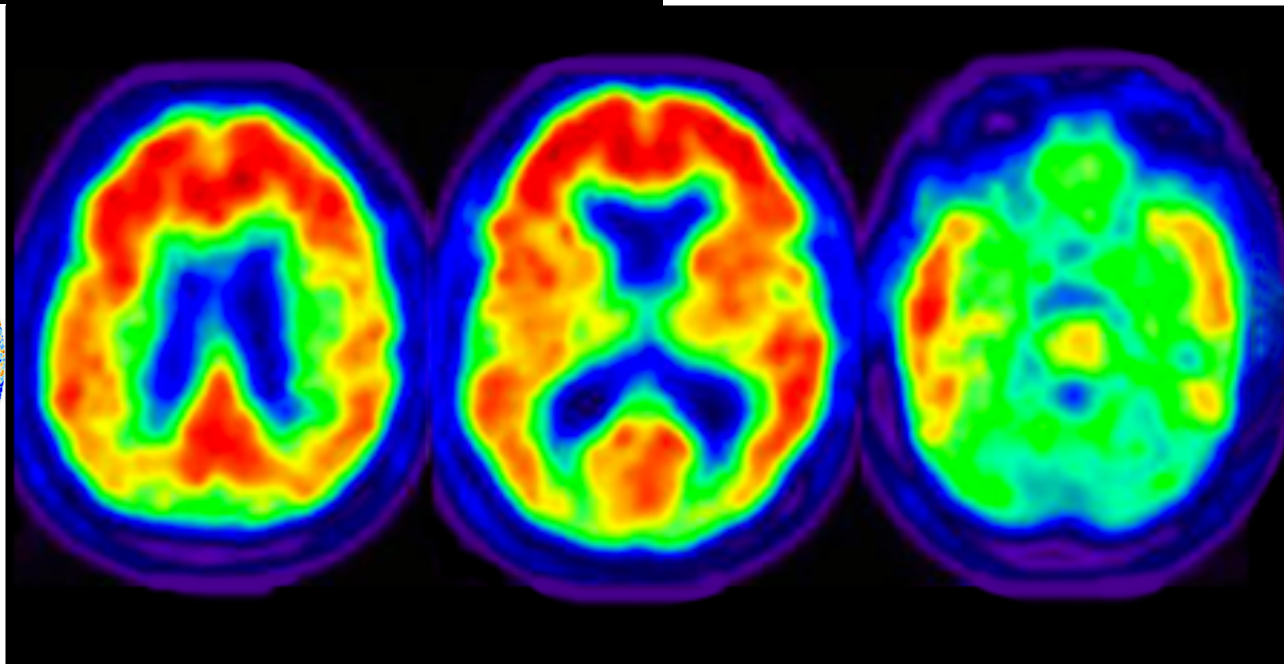
GANIL @ Caen



In the end







These images are thanks to the instruments, and you!

Credits

- I. Wingerter's CERN summer school lectures
- EDIT 2020 Lectures on detectors
- Wikipedia
- And more…