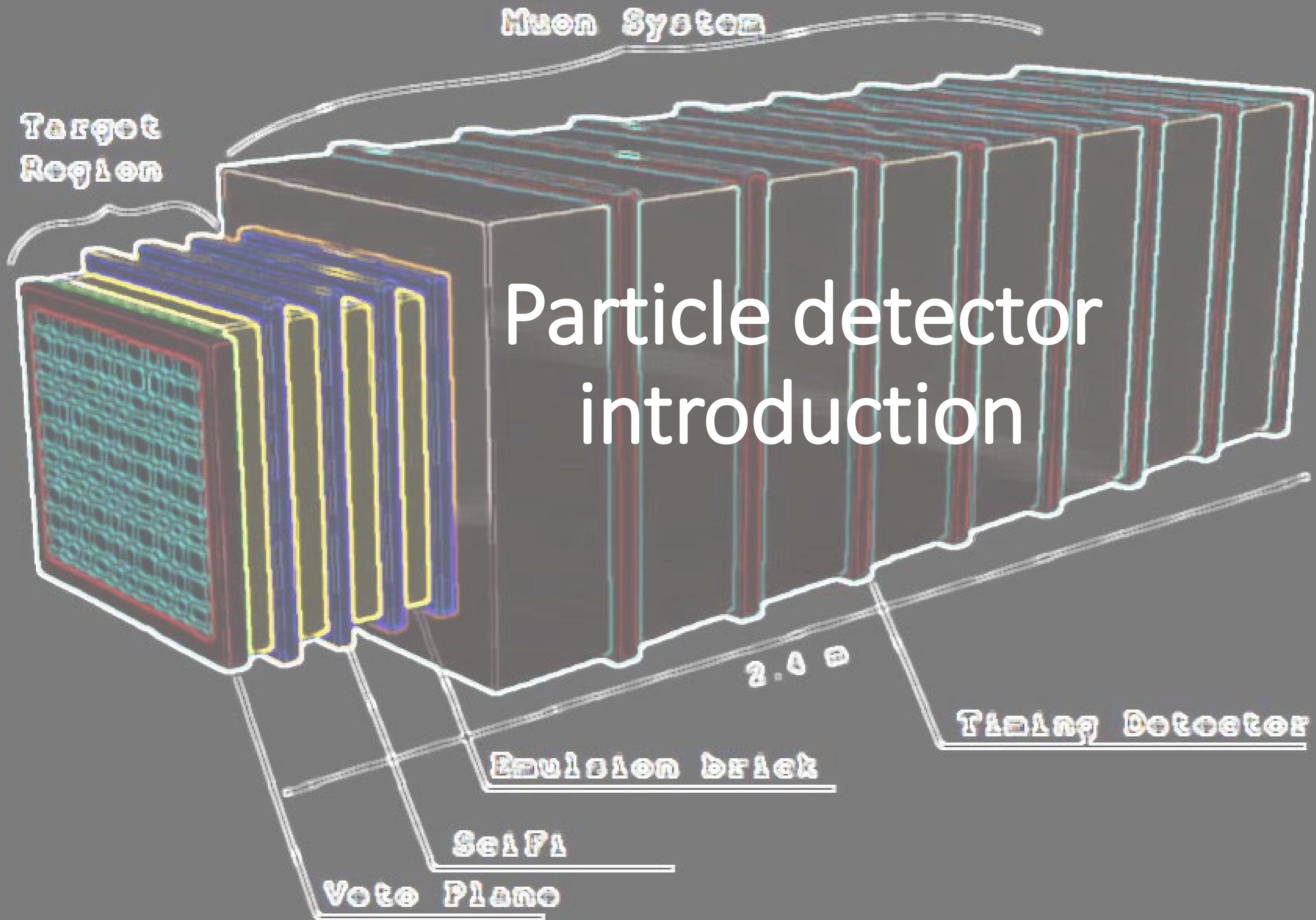
Lecture 1

Particle detector introduction

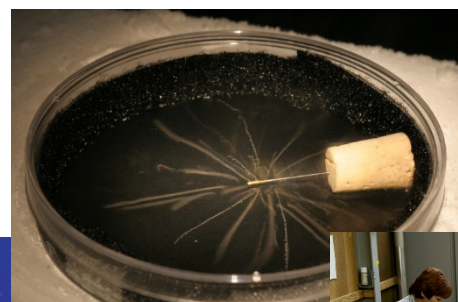


Guido.Haefeli@epfl.ch
Website: http://lphe.epfl.ch/~ghaefeli/Particle_Detectors_EPFL/2020/index.htm

Major historical discoveries with new particle detectors

Many discoveries in history were enabled by new instruments. Some examples:

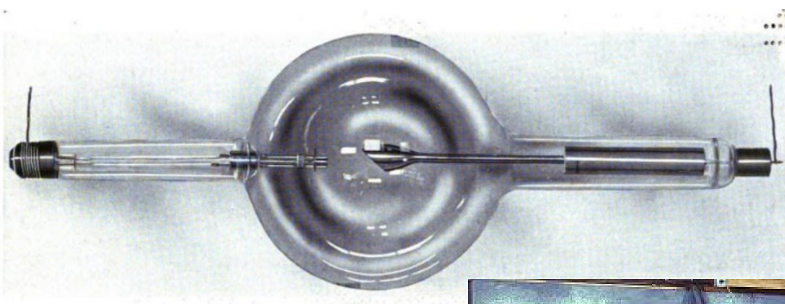
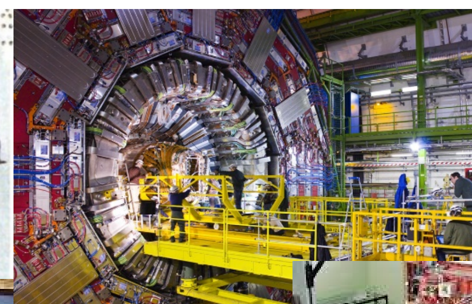
- 1896 Discovery of X-rays w. photographic plate (Nobel prize W.C. Röntgen 1901)
- 1912 Invention of the cloud chamber (Nobel prize C.T.R. Wilson 1927)
- 1953 First observations of charged particle tracks in a bubble chamber (Nobel prize D.A. Glaser 1960. For his invention of the bubble chamber")
- 1968 Invention of the Multiwire Proportional Chamber (MPC) (Nobel prize G. Charpak 1992. For his invention and development of particle detectors, in particular the multiwire proportional chamber")
- 1986 Neutrino oscillations in solar and atmospheric neutrinos (Nobel prize R. Davies and T.Koshiba 2002. Development of neutrino detection techniques")

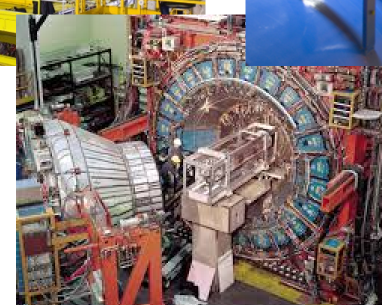


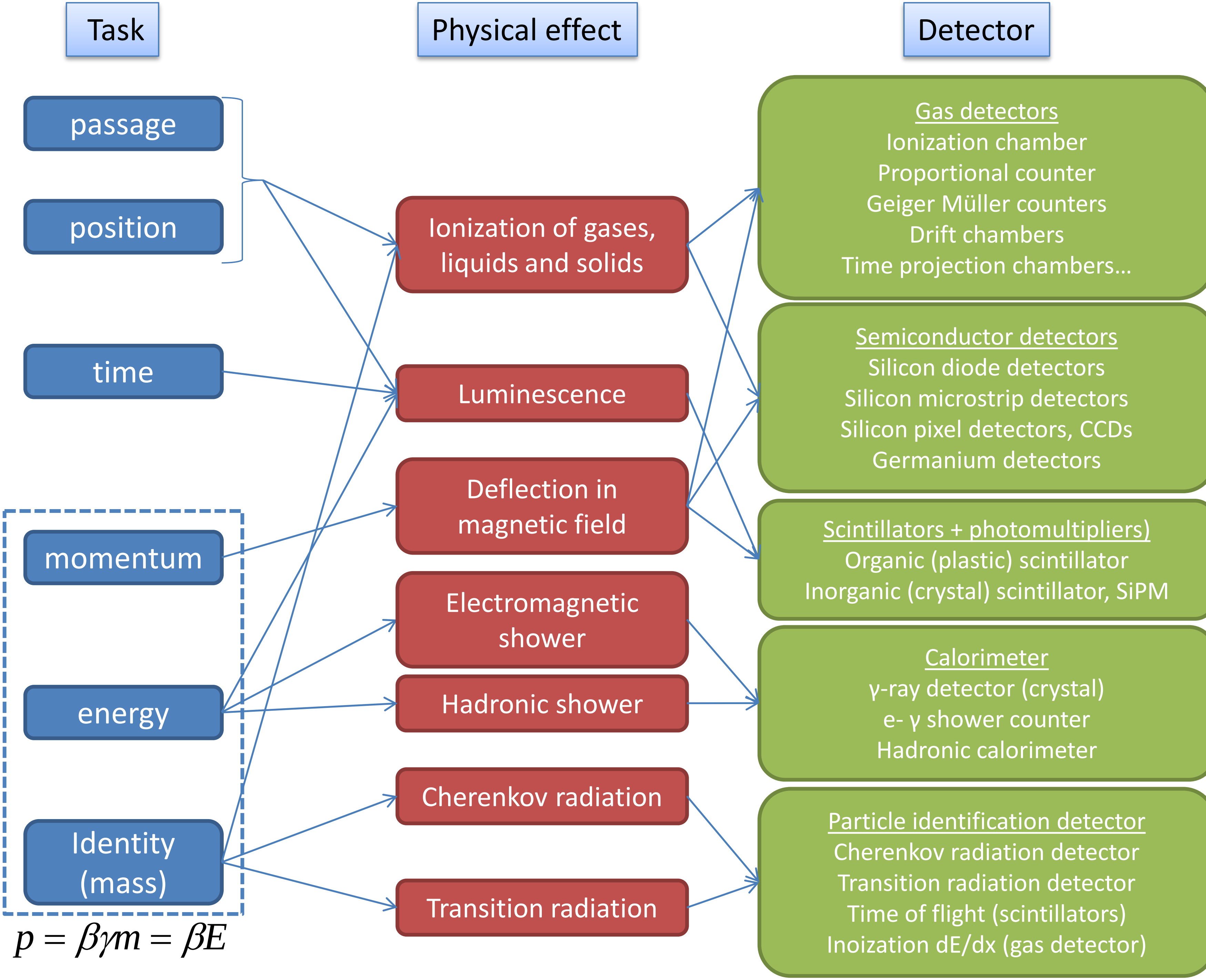
Major historical discoveries with new particle accelerators

Particle accelerators in the history. Some examples:

- 1896 X-rays tube (Nobel prize W.C. Röntgen 1901)
- 1931 Lawrence proposal: Cyclotron (Nobel prize E.O. Lawrence 1939. Invention and development of cyclotron")
- 1989-2000 Precision measurements at LEP test QCD and establish the precise form of asymptotic freedom (Nobel prize D.J. Gross, H.D. Politzer, F. Wilczek For the discovery of asymptotic freedom")
- 1995 Discovery of the top quark by D0 and CDF, first pp collisions at ps = 1.8 TeV at the Tevatron
- 2013 Discovery of a Higgs boson by ATLAS and CMS, first pp collisions at ps = 7 TeV at the LHC 2010 (Nobel prize P. Higgs and F. Englert 2013. For the theoretical discovery of a mechanism . . . recently confirmed through the discovery of the predicted fundamental particle . . . ")



Task
Physical effect
Detector
passage
position
time
momentum
energy
Identity (mass)
$p = \beta\gamma m = \beta E$
Ionization of gases, liquids and solids
Luminescence
Deflection in magnetic field
Electromagnetic shower
Hadronic shower
Cherenkov radiation
Transition radiation
Gas detectors
Ionization chamber
Proportional counter
Geiger Müller counters
Drift chambers
Time projection chambers…
Semiconductor detectors
Silicon diode detectors
Silicon microstrip detectors
Silicon pixel detectors, CCDs
Germanium detectors
Scintillators + photomultipliers)
Organic (plastic) scintillator
Inorganic (crystal) scintillator, SiPM
Calorimeter
γ-ray detector (crystal)
e- γ shower counter
Hadronic calorimeter
Particle identification detector
Cherenkov radiation detector
Transition radiation detector
Time of flight (scintillators)
Inoization dE/dx (gas detector)

High energy particle source

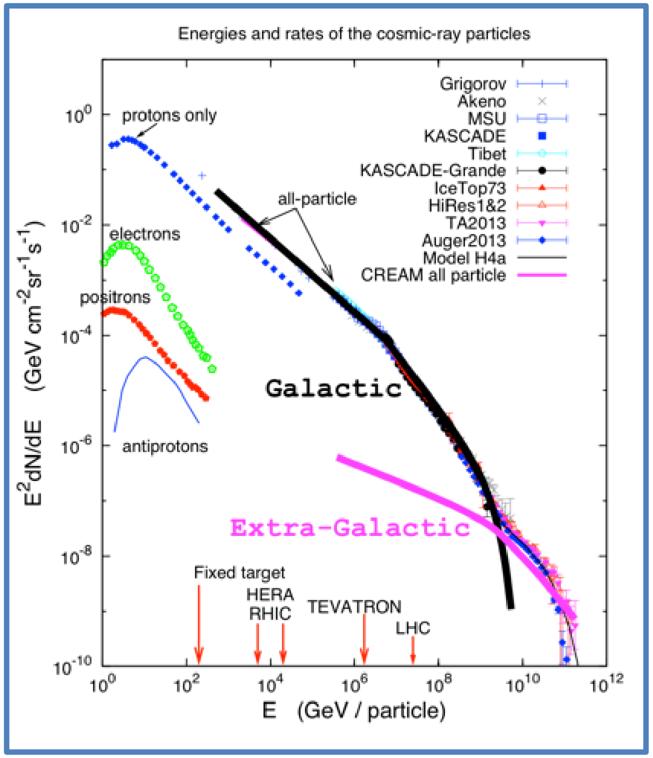
- Cosmic rays - they have the highest energy but very low collision rate
- Linear colliders - RF cavity resonators for accelleration, typically 8 MV/m, future: e.g. ILC > 35 MV/m, high cost due to length, ~100km
- Storage ring, circular accelerator, particle traverses the same potential difference many times (eg. LHC). Circular accelerators are also called (cyclotron, synchrotron), the particle traverses the same potential difference many times, magnetic field keeps particles on circular orbit.
  - Conventional coils: 1.5T
  - Superconducting: LHC 10T (most challenging technological part of the circular accelerators

The particle looses energy by synchrotron radiation, electrons with the same energy loose much more than protons.

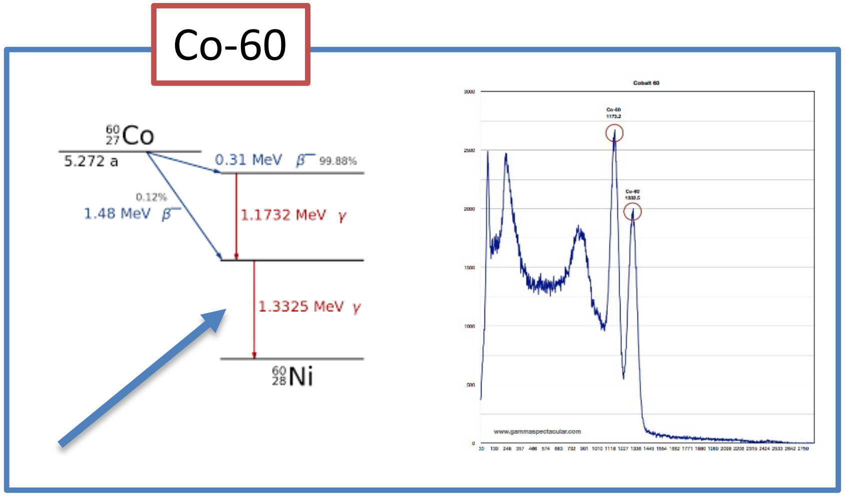
$$\Delta E = \frac{4\pi}{3}\frac{\gamma^4 e^2}{R}$$

LEP: Energy loss per turn R=4.3km, E=100GeV, m_0=0.5MeV, $\gamma=2*10^5$ -> ΔE=2.24GeV

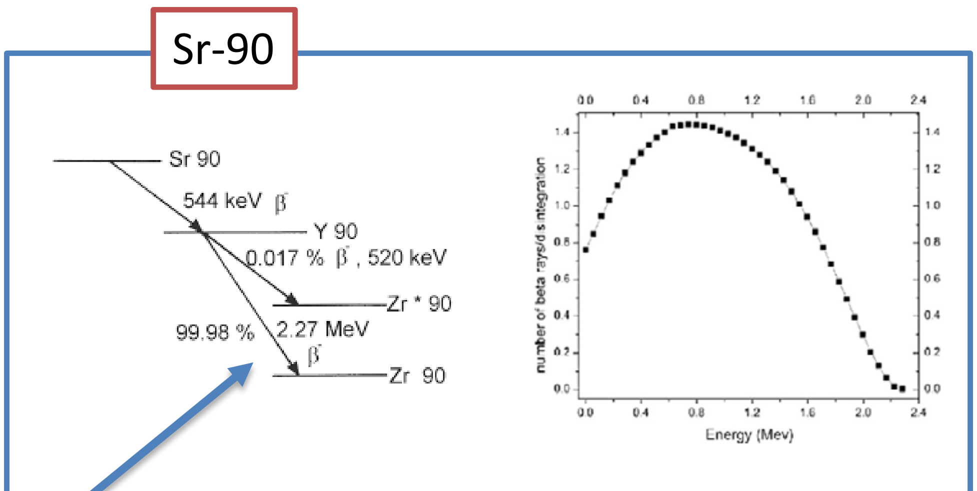
LHC: Energy loss per turn R=4.3km, E=7TeV, $\gamma=7*10^3$-> ΔE=3.4keV

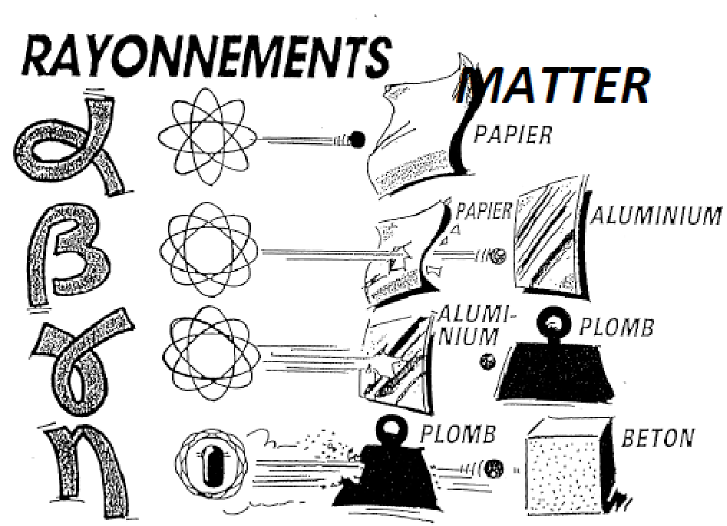


Radioactive sources



Particles	Radiation	Isotopes examples
${}^{4}_{2}He$	α	${}^{241}_{95}Am$
$e^{\pm}$	$\beta^{\pm}$	${}^{90}_{38}Sr$, ${}^{22}_{11}Na$
γ	γ	${}^{137}_{55}Cs$, ${}^{60}_{27}Co$
n	n	${}^{241}_{95}Am/Be$





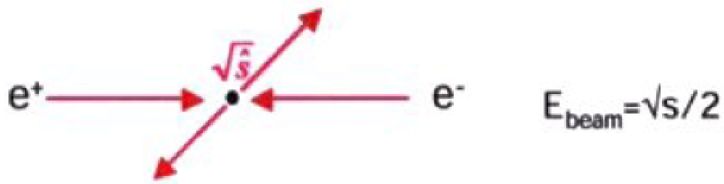
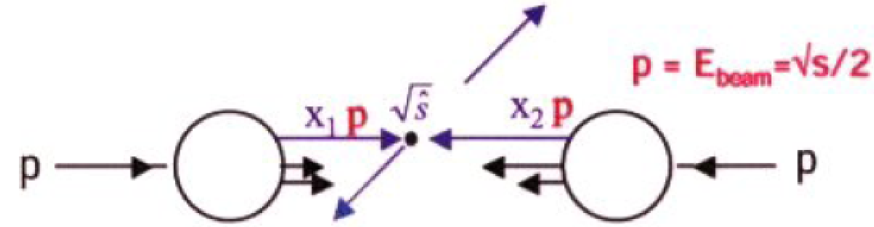
http://pdg.lbl.gov/2019/reviews/rpp2019-rev-commonly-used-radioactive-sources.pdf

Muons from cosmic rays on the surface (sea level) and underground

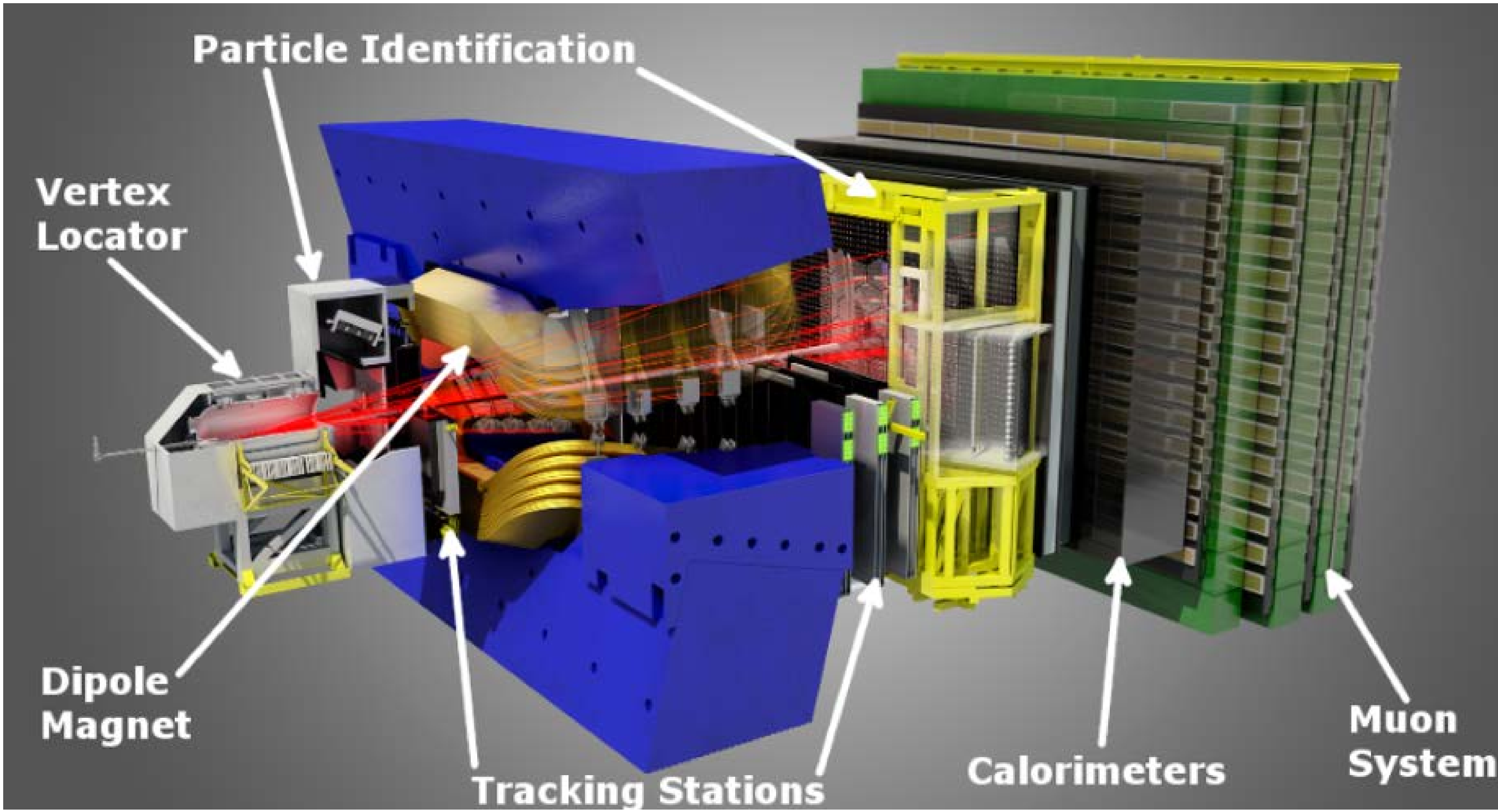
A summary for all cosmic rays is given in:
http://pdg.lbl.gov/2019/reviews/rpp2019-rev-cosmic-rays.pdf

- Muons are produced in the high atmosphere (15km) and have a mean energy of ≈4GeV at the sea level.
- The muon rate is I ≈1 cm^{-2} min^{-1} ≈ 1.7 sm^{-2} s^{-1} for horizontal detectors, I ∝ $\cos^2 \Theta$ (zenith angle Θ) for 3GeV muons
- Muons underground, dominant energy loss by ionisation

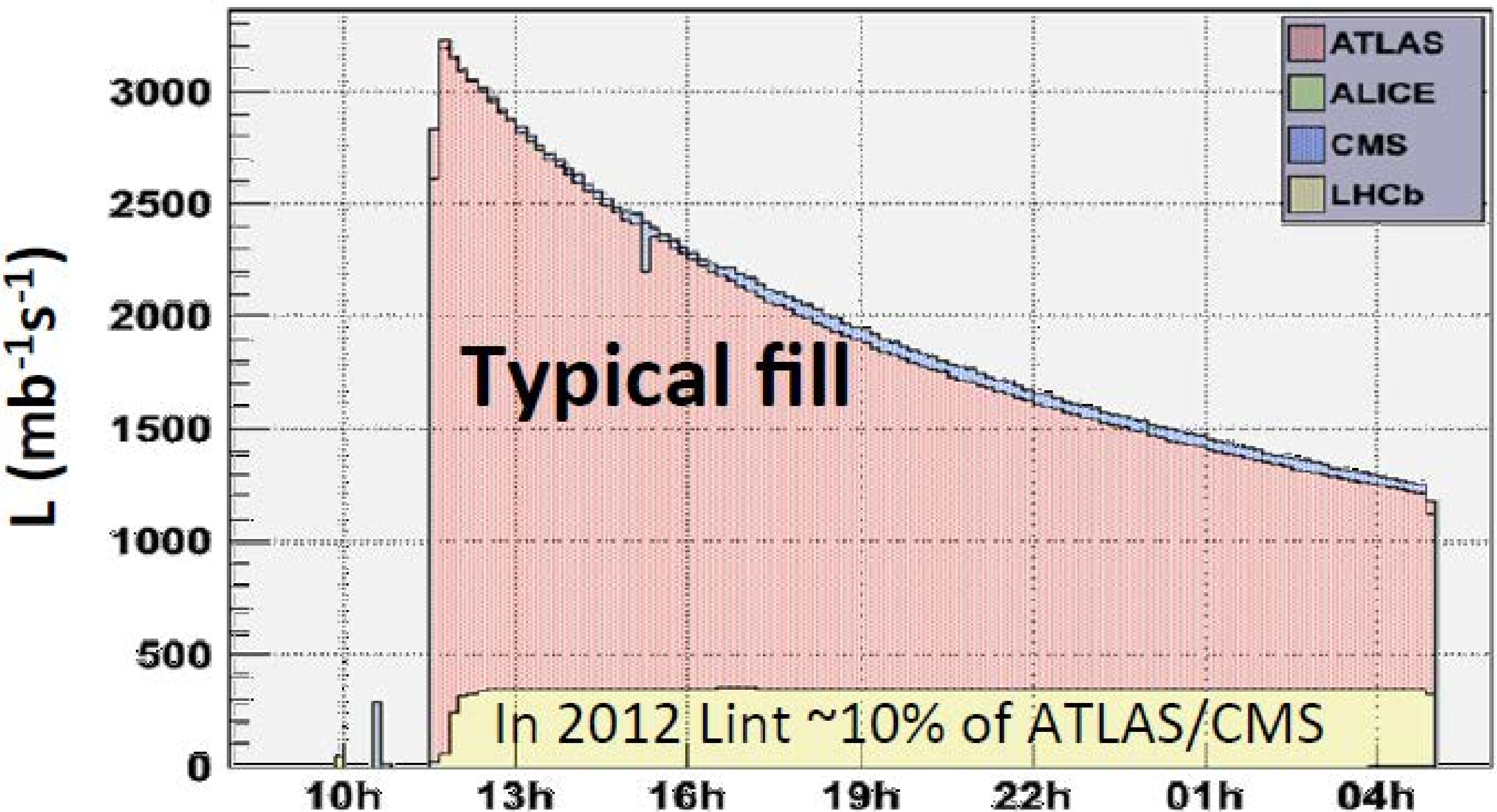
E_μ GeV	R km.w.e.	a MeV g^{-1} cm^2	b_{brems}	b_{pair}	b_{nucl} 10^{-6} g^{-1} cm^2	$\sum b_i$	$\sum b_{\text{ice}}$
10	0.05	2.17	0.70	0.70	0.50	1.90	1.66
100	0.41	2.44	1.10	1.53	0.41	3.04	2.51
1000	2.45	2.68	1.44	2.07	0.41	3.92	3.17
10000	6.09	2.93	1.62	2.27	0.46	4.35	3.78

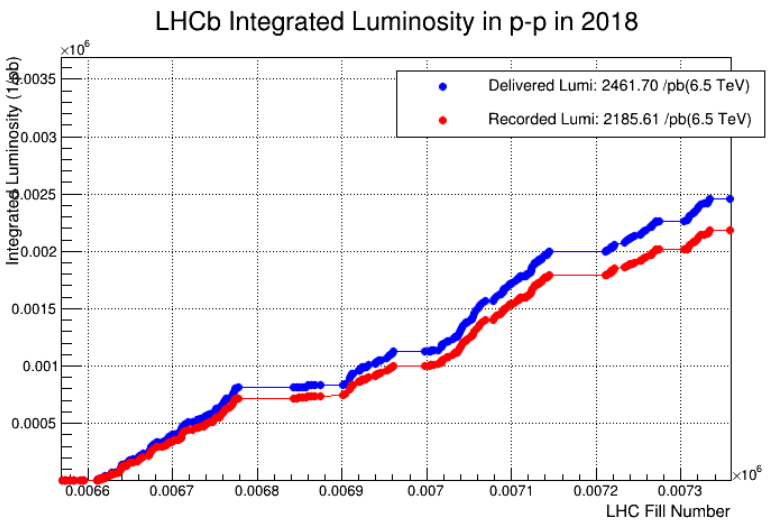
e^+e^- **Colliders**	$pp/p\bar{p}$ **Colliders**
	
Energy of elementary interaction known $\sqrt{\hat{s}} = E(e^-) + E(e^+) = \sqrt{s}$	Energy of elementary interaction not known $\sqrt{\hat{s}} = \sqrt{x_1 x_2 s} < \sqrt{s}$
Only two elementary particles collide $\rightarrow$ clean final states	Elementary interaction (hard) + interaction of "spectator" q,g (soft) overlapp in detector
Mainly EW processes	EW processes suffer from huge backgrounds from strong processes
$\sqrt{s}$ limited by $e^{\pm}$ synchrotron radiation: $E_{\rm loss} \sim \frac{E^4_{beam}}{R}\frac{1}{m_e^4}$ $E_{\rm loss} \sim 2.5$ GeV/turn LEP 2 ($E_{\rm beam} \sim 100$ GeV)	Synchrotron radiation is $\sim (m_p/m_e)^4 \sim 10^{13}$ smaller
- high energy more difficult $\rightarrow$ next machine: Linear Collider (ILC, CLIC, $\sqrt{s} = 800(3000?)$ GeV?) - clean environment $\rightarrow$ precision measurement machines	- high energy easier $\rightarrow$ discovery machines current machine: LHC, pp , $\sqrt{s} = 14$ *TeV* in the LEP ring more "dirty" environment

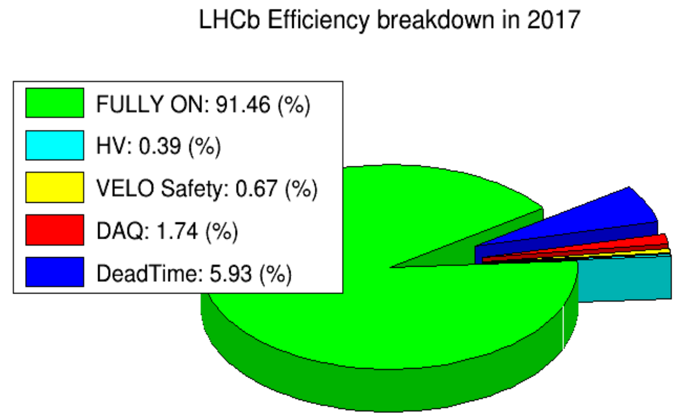
The LHCb detector for Run1&2

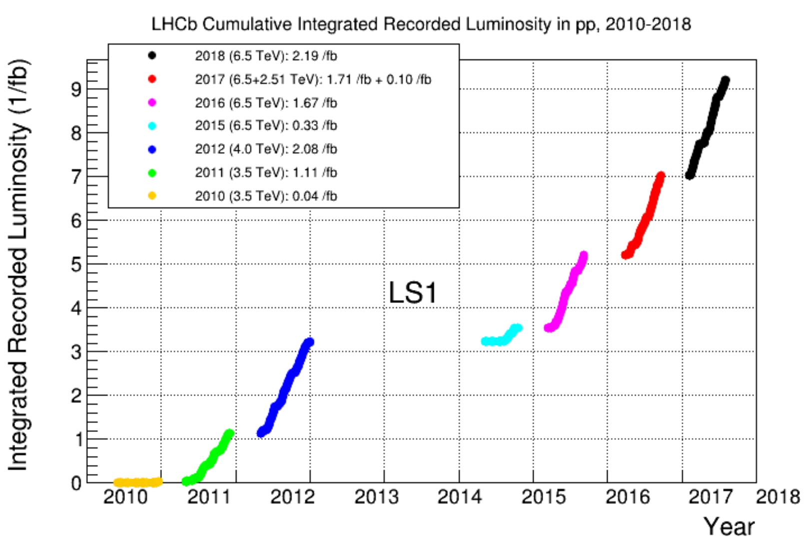


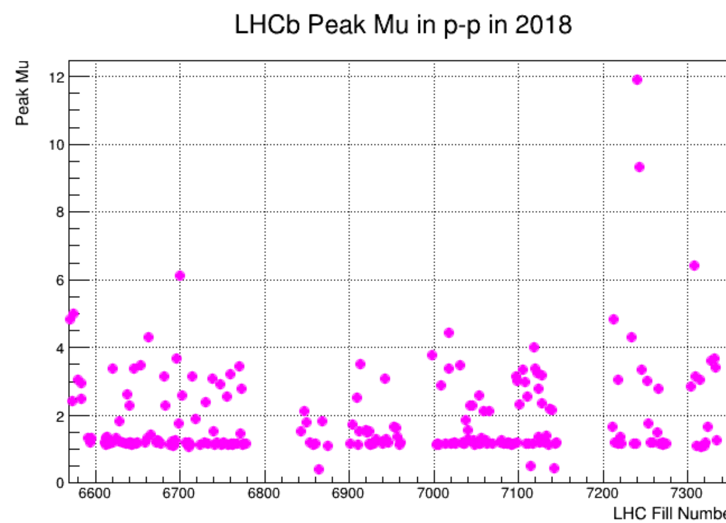
The LHCb detector luminosity compared with ATLAS and CMS

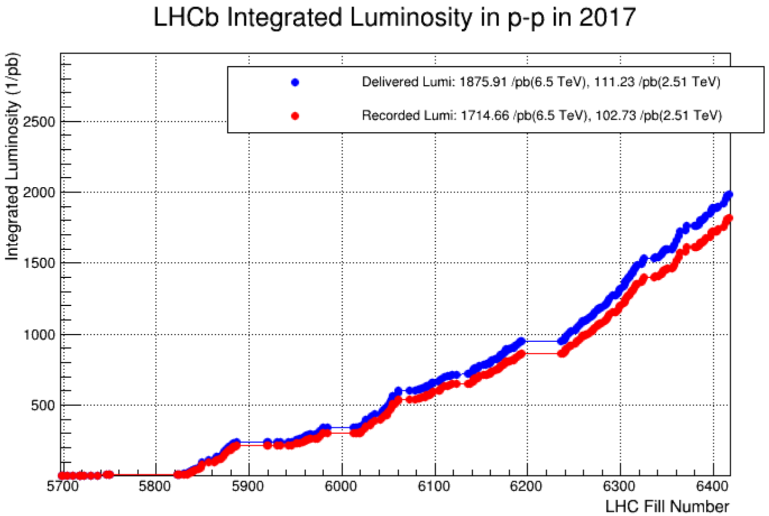


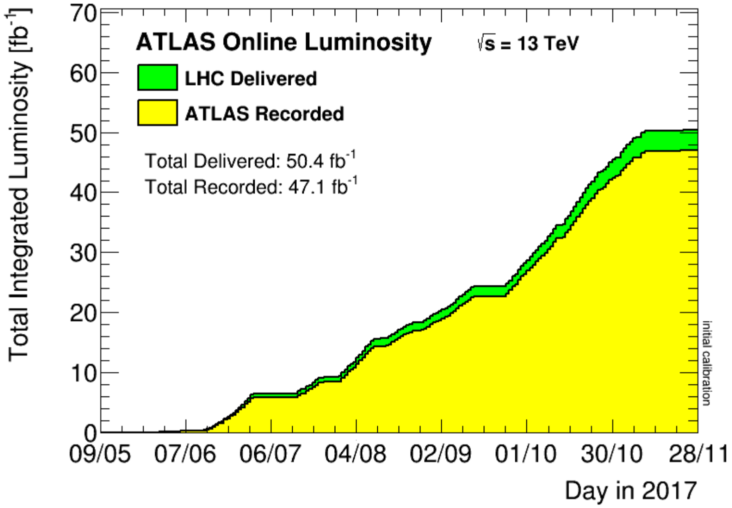

LHCb Integrated Luminosity in p-p in 2018
Delivered Lumi: 2461.70 /pb(6.5 TeV)
Recorded Lumi: 2185.61 /pb(6.5 TeV)
Integrated Luminosity (1/pb)
LHC Fill Number

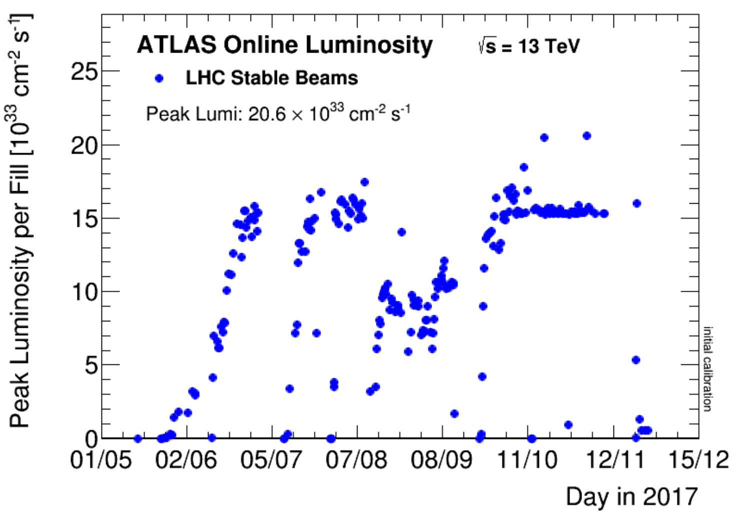

LHCb Efficiency breakdown in 2017
FULLY ON: 91.46 (%)
HV: 0.39 (%)
VELO Safety: 0.67 (%)
DAQ: 1.74 (%)
DeadTime: 5.93 (%)

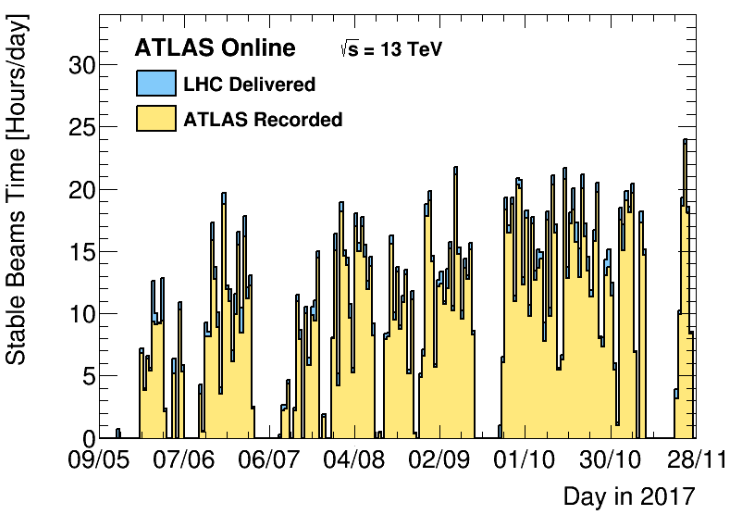

LHCb Cumulative Integrated Recorded Luminosity in pp, 2010-2018
2018 (6.5 TeV): 2.19 /fb
2017 (6.5+2.51 TeV): 1.71 /fb + 0.10 /fb
2016 (6.5 TeV): 1.67 /fb
2015 (6.5 TeV): 0.33 /fb
2012 (4.0 TeV): 2.08 /fb
2011 (3.5 TeV): 1.11 /fb
2010 (3.5 TeV): 0.04 /fb
LS1
Integrated Recorded Luminosity (1/fb)
Year


LHCb Peak Mu in p-p in 2018
Peak Mu
LHC Fill Number


LHCb Integrated Luminosity in p-p in 2017
Delivered Lumi: 1875.91 /pb(6.5 TeV), 111.23 /pb(2.51 TeV)
Recorded Lumi: 1714.66 /pb(6.5 TeV), 102.73 /pb(2.51 TeV)
Integrated Luminosity (1/pb)
LHC Fill Number


ATLAS Online Luminosity
√s = 13 TeV
LHC Delivered
ATLAS Recorded
Total Delivered: 50.4 fb-1
Total Recorded: 47.1 fb-1
Total Integrated Luminosity [fb-1]
Day in 2017
initial calibration


ATLAS Online Luminosity
√s = 13 TeV
LHC Stable Beams
Peak Lumi: 20.6 × 10^33 cm^-2 s^-1
Peak Luminosity per Fill [10^33 cm^-2 s^-1]
Day in 2017
initial calibration

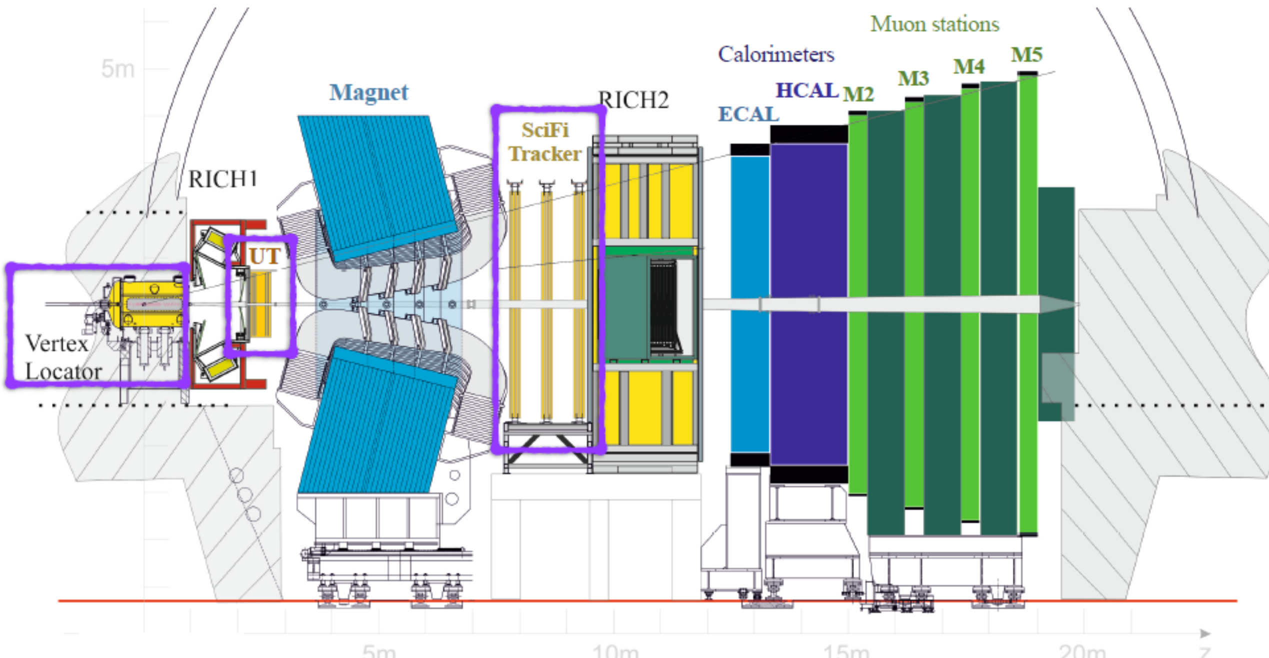

ATLAS Online
√s = 13 TeV
LHC Delivered
ATLAS Recorded
Stable Beams Time [Hours/day]
Day in 2017

The LHCb Upgrade

$\longleftarrow$ 9 fb^{-1} $\longrightarrow$ $\longleftarrow$ Goal: 50 fb^{-1} $\longrightarrow$

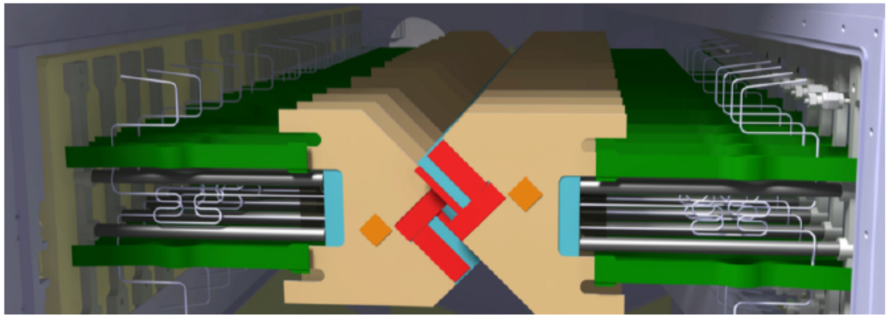
Run 1	**LS1**	Run 2	**LS2**	Run 3	**LS3**	Run 4
2010 2011 2012	2013 2014	2015 2016 2017 2018	2019 2020	2021 2022 2023	2024 2025	2026 2027 2028 2029

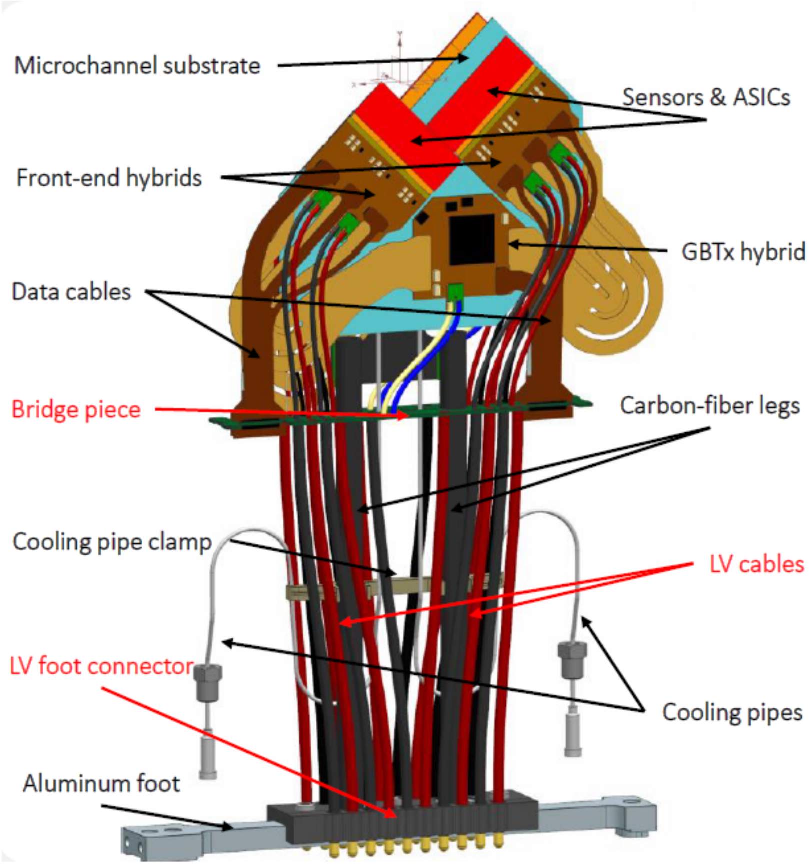
- **Remove hardware trigger** limitation
  - **All new electronics** to read all data at **40 MHz**
- **Increase granularity** and **longevity**
  - **3 new trackers**
  - New RICH optics
  - Lower PMT gain in CALO



Vertex Locator (VELOPix)

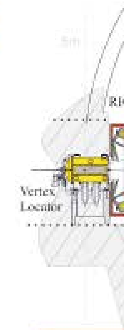
- **Replace Si strips** with **55 μm×55 μm pixels**
  - ➡ 72k strips → 41M pixels with 40 MHz readout
- **Improved IP resolution** by moving sensor **closer to beam** and thinner RF foil
  - ➡ 8.1 mm → 5.1 mm (active area, module down to 3.5 mm)
- **20× more rad-hard** (8×10^{15} MeV$\cdot n_{eq}/cm^{-2}$)
- **Sophisticated cooling** for VELOPix ASICs
  - ➡ Bi-phase CO_2 passes under chips via **microchannels etched on the silicon substrate**

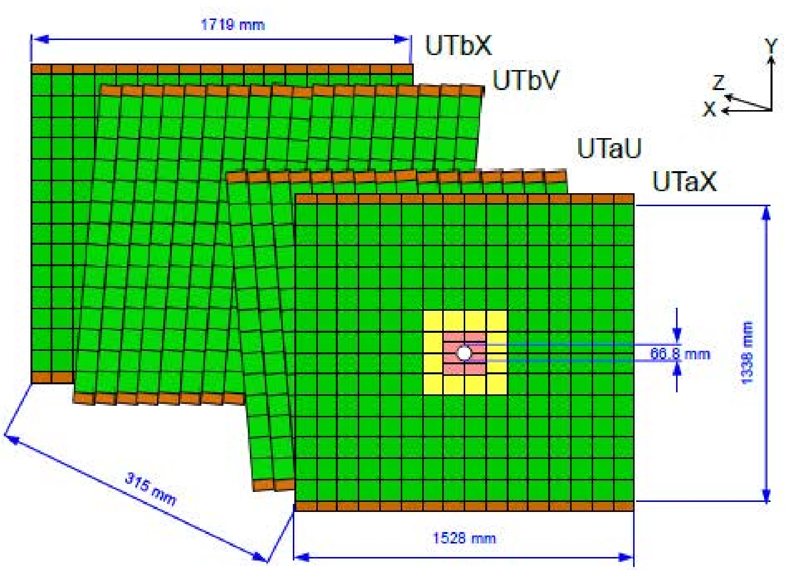




Upstream Tracker (UT)

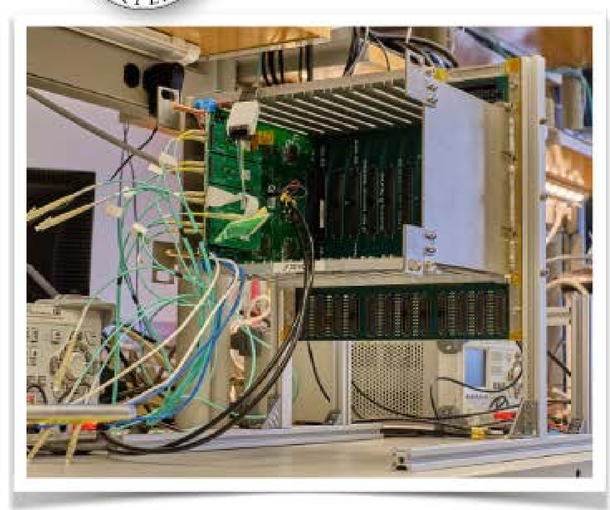
- **4 layers of silicon strips** with same arrangement as TT but
  - **Finer granularity** (95 μm close to the beam)
  - **Improved coverage**
  - **Less material budget**
- Crucial for **triggering** and for **long-lived particle reco**



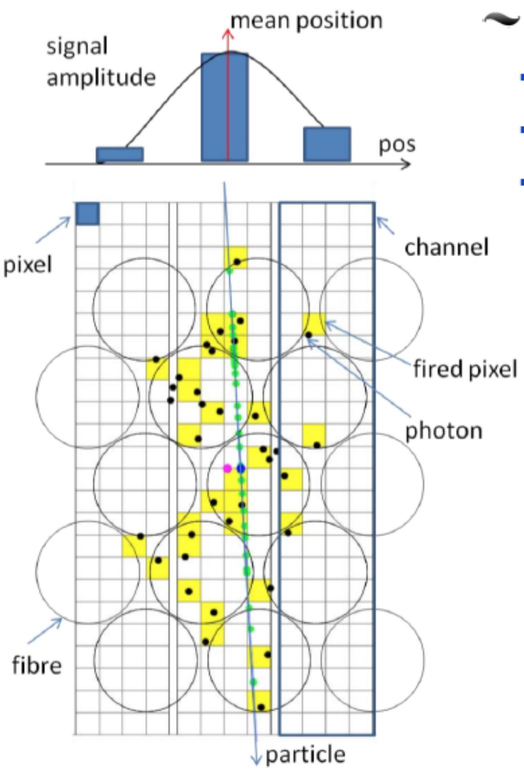


Sensors
+ staves

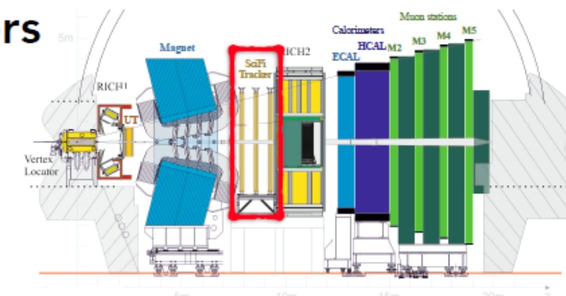
Readout
electronics +LV

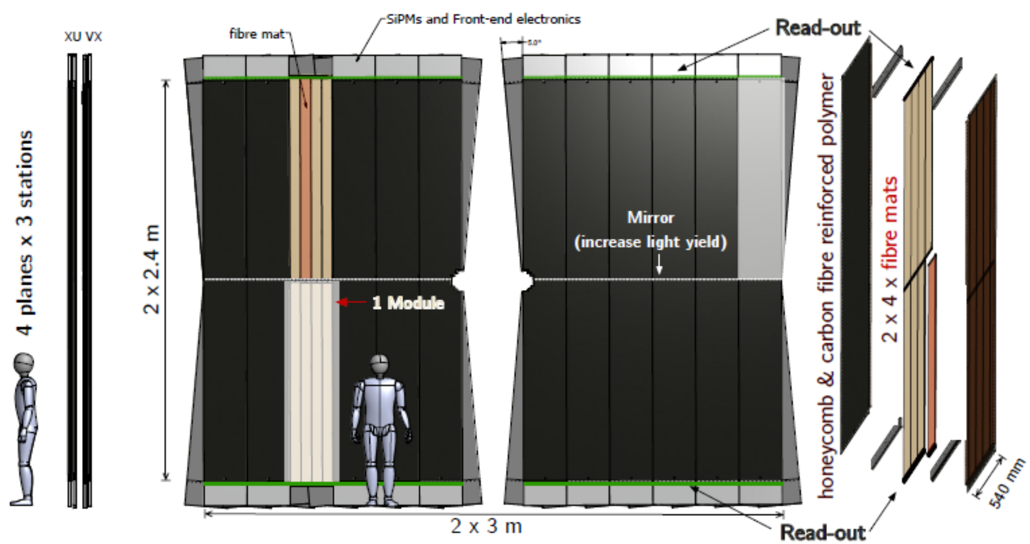


Scintillating Fibre Tracker (SciFi)



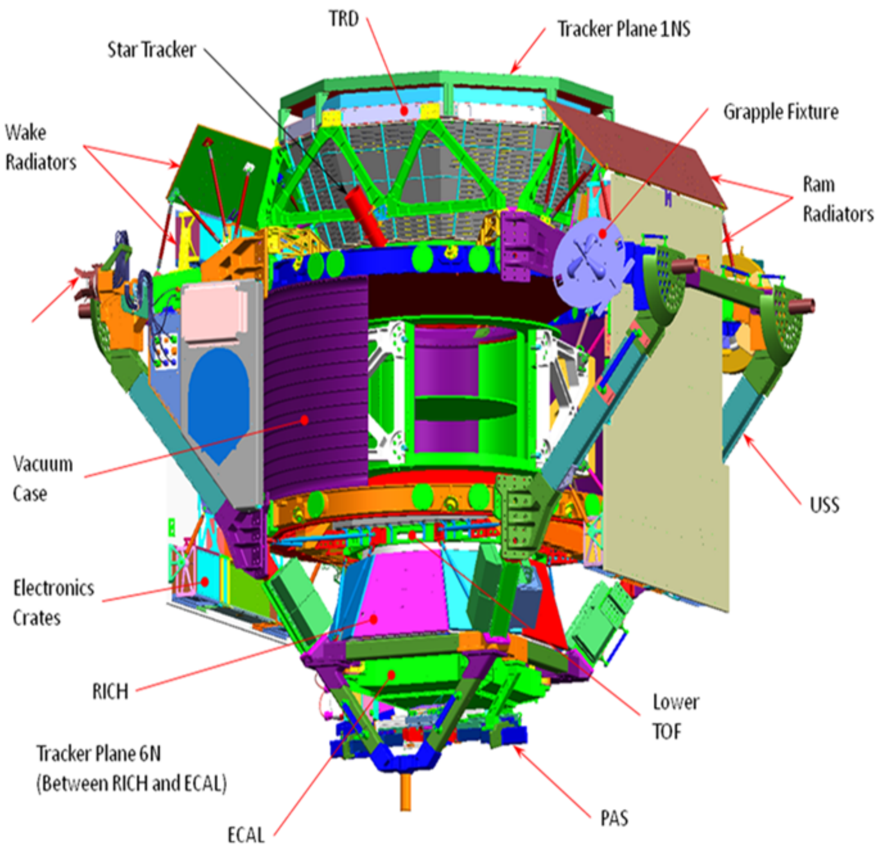
- ~12 layers of 250 μm scintillating fibers
  - ➡ Readout with SiPMs
  - ➡ 80 μm resolution
  - ➡ Replace straw tubes and silicon Outer Tracker
    - ✦ Slow drift time of tubes limit occupancy





The **Alpha Magnetic Spectrometer** on the International Space Station

AMS-02



Magnet *bends in opposite directions charged particles/antiparticles*

Transition Radiation Detector (TRD) *identifies electrons and positrons among other cosmic-rays*

Time-of-Flight System (ToF) *warns the sub-detectors of the incoming of a cosmic-ray*

Silicon Tracker (Tracker) *detects the particle charge sign, separating matter from antimatter*

Ring-Imaging Cherenkov Detector (RICH) *measures with high precision the velocity of cosmic-rays*

Electromagnetic Calorimeter (ECAL) *measures energy of incoming electrons, positrons and γ-rays*

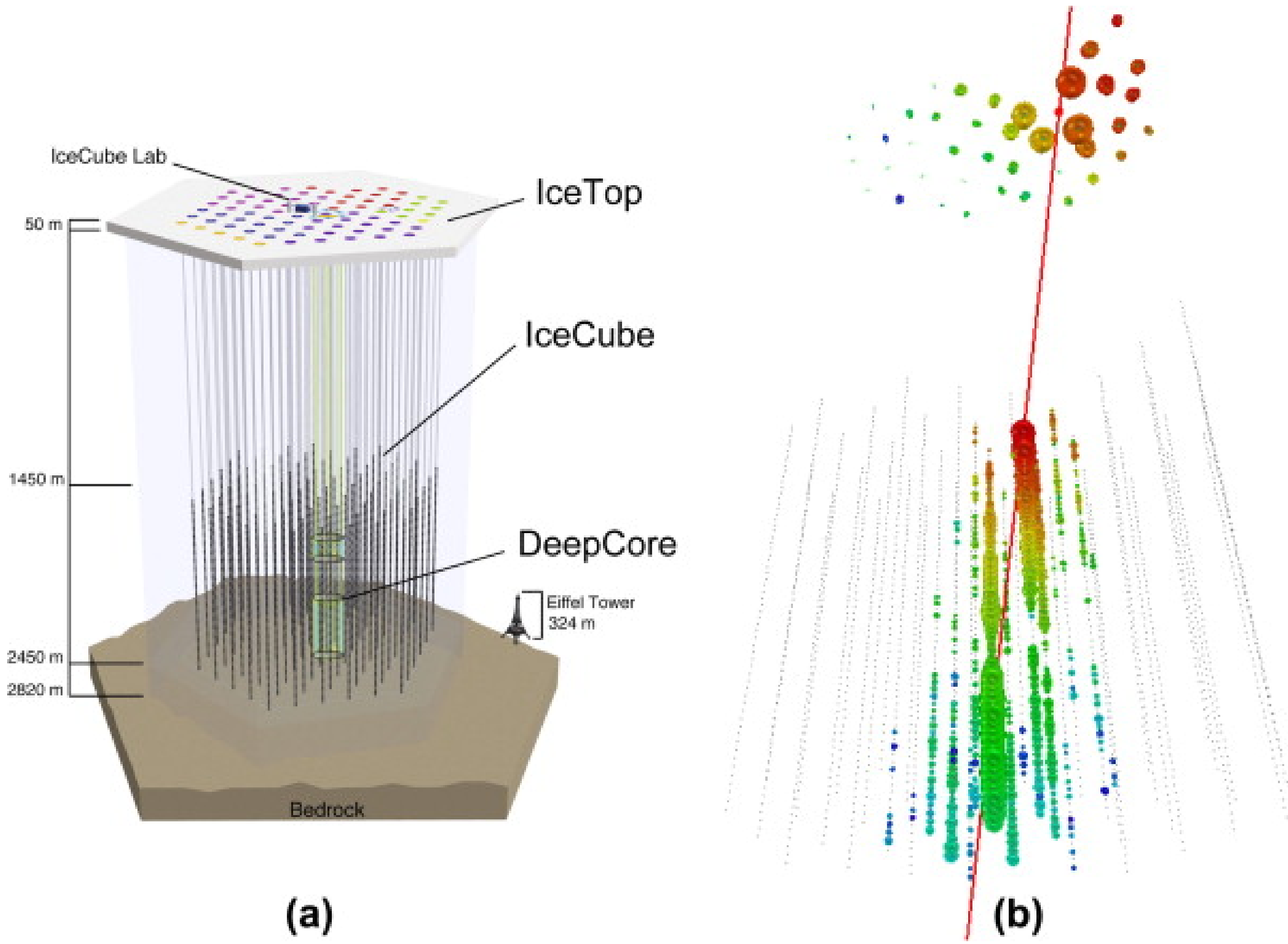
Anti-Coincidence Counter (ACC) *rejects cosmic rays traversing the magnet walls*

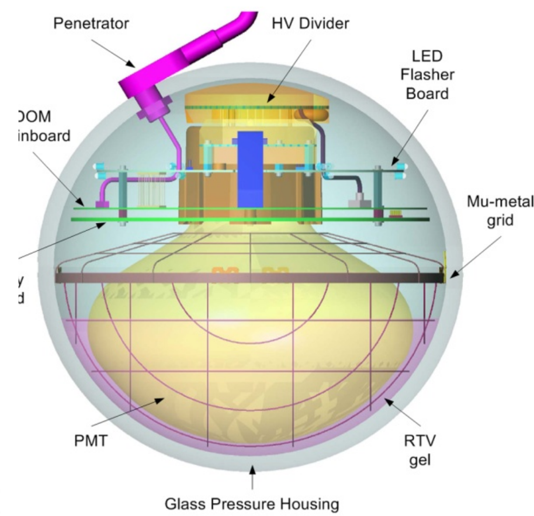
Tracker Alignment System (TAS) *checks the Tracker alignment stability*

Star Tracker and GPS *defines the position and orientation of the AMS-02 experiment*

ICE cube

- http://icecube.wisc.edu/gallery/view/140





Useful relations of relativistic Kinematics

$\beta \equiv v/c$ $\gamma \equiv \dfrac{1}{\sqrt{1-\beta^2}}$ $m \equiv m_0\,\gamma$

m_0: rest mass
γ : Lorentz boost

- Momentum $\vec{p} = m_0\gamma\vec{v}$
- Kinetic energy $E_{kin} = (\gamma - 1)m_0c^2$
- Total energy $E = \sqrt{(pc)^2 + (m_0c^2)^2}$

Massless particles:
$E = pc$

$E = E_{kin} + m_0c^2 = m_0\gamma c^2 = \mathrm{m}c^2$ $\gamma = E/(m_0c^2)$

Units:

$[E] = eV$ $[m] = eV/c^2$ $[p] = eV/c$

Natural Units

There are 4 primary SI units: three kinematical (meter, second, kilogram) and one electrical (Ampere[1])

It is common in the realm of the elementary particle physics to redefine units so that speed of light and Plank's constant become equal to one: c=1 and $\hbar$=1. This imposes two constraints on the three kinematical units and, therefore, leaves us a free choice for one of the three kinematical units. The units of electrical charge, also, can be and are redefined (see below). Such system of units is often referred to as Natural Units (natural for the elementary particle physics, that is).

The kinematical unit of the choice is energy, E, and it is usually measured in eV (keV, MeV, GeV, TeV). Once we fixed c=1 and $\hbar$=1, all other kinematical units can now be expressed in terms of units of energy. E.g., one can easily see:

$E^2=m^2c^4+p^2c^2$:	with c=1, units of mass and momentum are E
$\Psi = Ce^{-i\left(\frac{Et-px}{\hbar}\right)}$:	with $\hbar$=1, units of time and length are 1/E
$L_z = \hbar n$:	with $\hbar$=1, angular momentum is dimensionless

In SI system, units of current and charge can be *effectively* defined by choosing the value of ε_0 in the Coulomb's Law:

$$F = \frac{qq}{r^2}\frac{1}{4\pi\varepsilon_0}, \text{ where } \varepsilon_0=8.8\times10^{-12}\ C^2m^{-3}kg^{-1}c^2.$$

In the Natural Units, the units of charge are defined by choosing ε_0=1. This automatically sets μ_0=1, since $c^2=1/(\varepsilon_0\mu_0)$. Since the units of force and distance in Natural Units are E^2 and 1/E, the electric charge turns out to be dimensionless in these units.

The value of the fine structure constant, being dimensionless, is the same in all units. In SI units it has the following form: $\alpha = \frac{e^2}{4\pi\varepsilon_0\hbar c} = \frac{1}{137}$, where e is the elementary charge $e=1.6\times10^{-19}$ C. In Natural Units, the fine structure constant becomes $\alpha = \frac{e^2}{4\pi} = \frac{1}{137}$. This clearly shows that an electric charge e has no dimensions in the Natural Units and now equals to 0.303.

Table. Units for major physical quantities in SI and Natural Units with conversion factors.

Quantity	Dimensions		Conversions
	SI Units	Natural Units	
mass	kg	E	1 GeV = 1.8×10^{-27} kg
length	m	1/E	1 GeV^{-1} = 0.197×10^{-15} m
time	s	1/E	1 GeV^{-1}= 6.58×10^{-25} s
energy	$kg\cdot m^2/s^2$	E	1 GeV = 1.6×10^{-10} Joules
momentum	$kg\cdot m/s$	E	1 GeV = 5.39×10^{-19} kg·m/s
velocity	m/s	none	1 = 2.998×10^{8} m/s (c)
angular momentum	$kg\cdot m^2/s$	none	1 = 1.06×10^{-34} J·s ($\hbar$)
cross-section	m^2	$1/E^2$	1 GeV^{-2} = 0.389 mb = 0.389×10^{-31} m^2
force	$kg\cdot m/s^2$	E^2	1 GeV^2 = 8.19×10^{5} Newton
charge	C=A·s	none	1 = 5.28×10^{-19} Coulomb; e=0.303=1.6×10^{-19} C

Possible subjects for the presentations during the exercises 2020

Photo detectors:

- Comparison of PD, APD, SiPM
- Timing detectors comparison of SiPM, MCP and LGAD

Tracking detectors:

- Emulsion tracking detectors
- Spark Chamber (possible outreach detector)
- Gas detectors for tracking

Calorimeter:

- Comparison of ECAL and HCAL

Detector systems and experiments:

- FASER vs SND@LHC
- Time of Flight PET
- ???

Presentation mode:

- 35’ presentation, slides, material
- No marks, it is an occasion to present in front of the class and discuss!

Points to pay attention during the presentation:

- What is the detector principle?
- What type of particles at what energy range can be detected?
- What is the interaction type?
- Illustrate the detected signal and how much signal is expected, intrinsic gain or amplification?
- For experiments: What is the goal physics goal of the experiment? What are the achieved measurements in the past? What is the role of particular detectors in the system (for example the RICH detectors in LHCb are required to separate the hadronic particles at different energy ranges)?