Detector technologies

A brief overview

Many thanks to Erik Butz, Simon Spannagel, Freya Blekman, Peter Schleper, Erika Garutti

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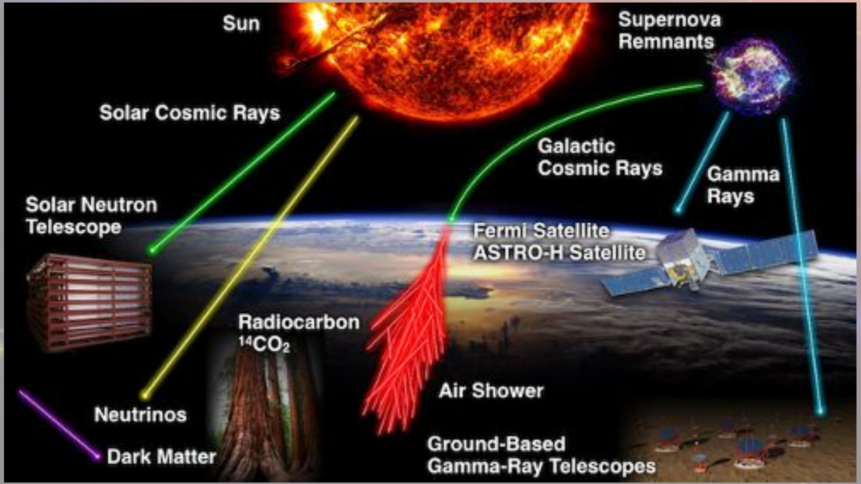
Photo courtesy of Erik Butz

Particles from outer space

10000 times a second you have particles from cosmic rays passing through you

What are these particles and how do they behave?
What are we and what is the universe made of?



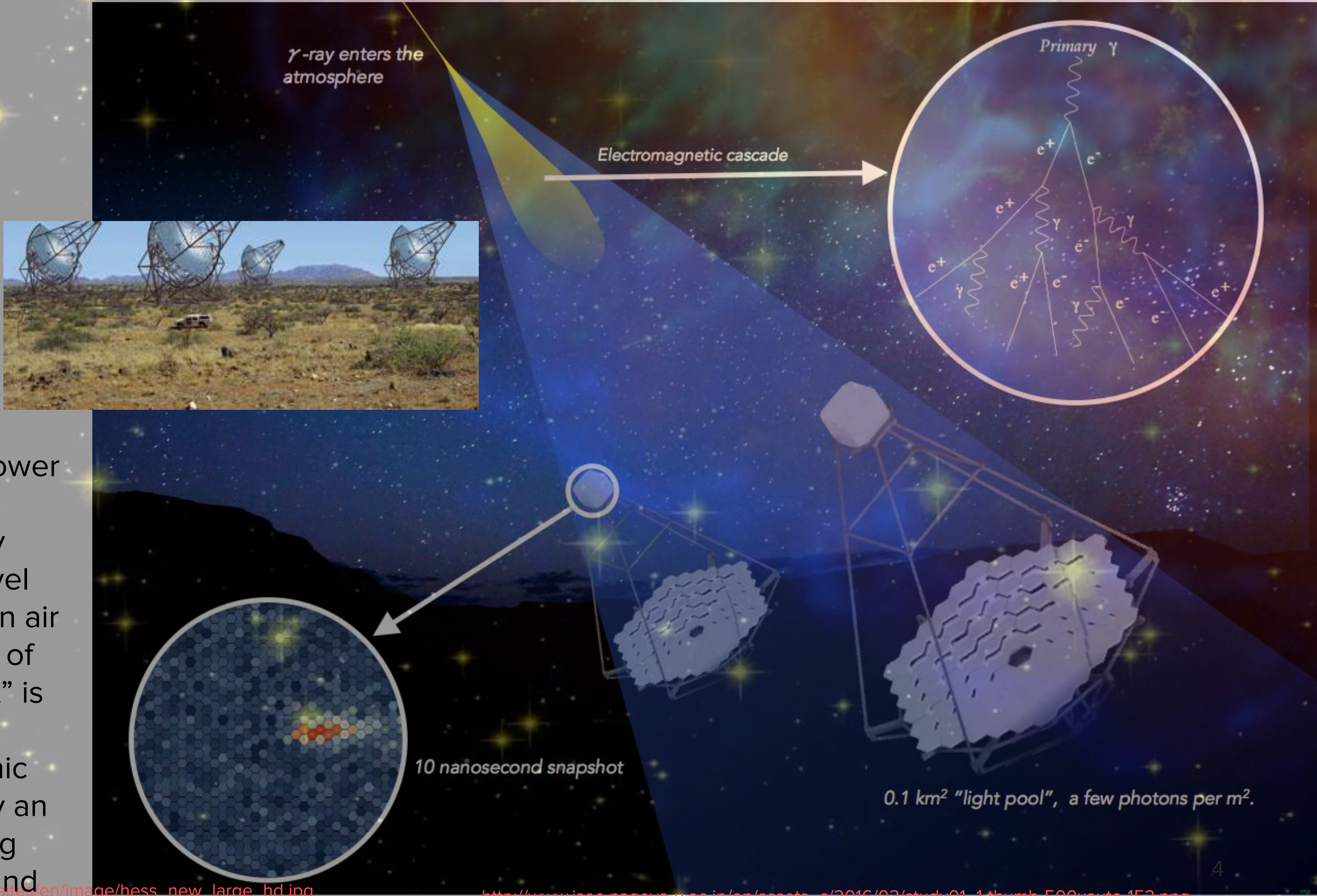
HESS: high energy stereoscopic system, in Namibia, can detect gamma rays

http://www2.cnrs.fr/sites/en/image/hess_new_large_hd.jpg

http://www.isee.nagoya-u.ac.jp/en/assets_c/2016/03/study01_1-thumb-500xauto-153.png

How to detect a particle?

γ rays



Cherenkov telescope:

- light is 0.03 % slower in air
- ultra-high energy particles can travel faster than light in air
- then a blue flash of "Cherenkov light" is created
- similar to the sonic boom created by an aircraft exceeding the speed of sound

http://www2.cnrs.fr/sites/en/image/hess_new_large_hd.jpg

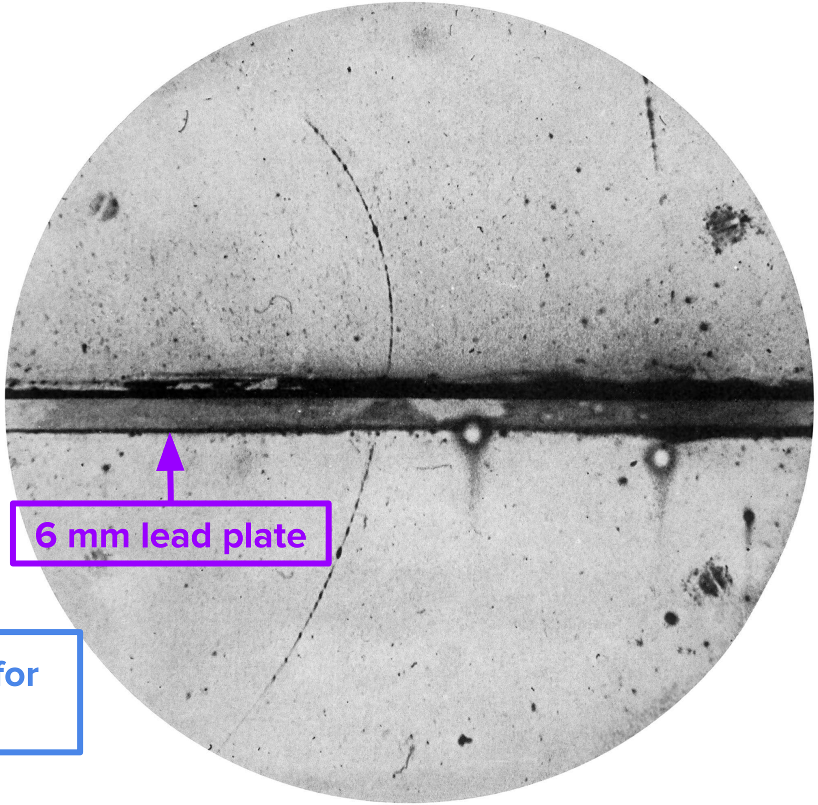
http://www.isee.nagoya-u.ac.jp/en/assets_c/2016/03/study01_1-thumb-500xauto-153.png

Discovery of antimatter

https://upload.wikimedia.org/wikipedia/commons/6/69/PositronDiscovery.jpg
C.D. Anderson https://journals.aps.org/pr/pdf/10.1103/PhysRev.43.491

The first positron ever observed!

Wilson cloud chamber: gaseous mixture of supersaturated water or alcohol. Energetic particle ionizes gas and ions form condensation centers visible as a ‘cloud’.



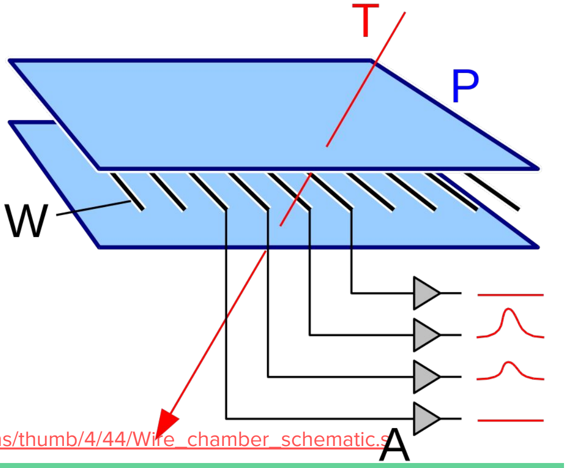
15000 Gauss = 1.5T magnetic field Wilson chamber for detecting cosmic rays

Gluon discovery

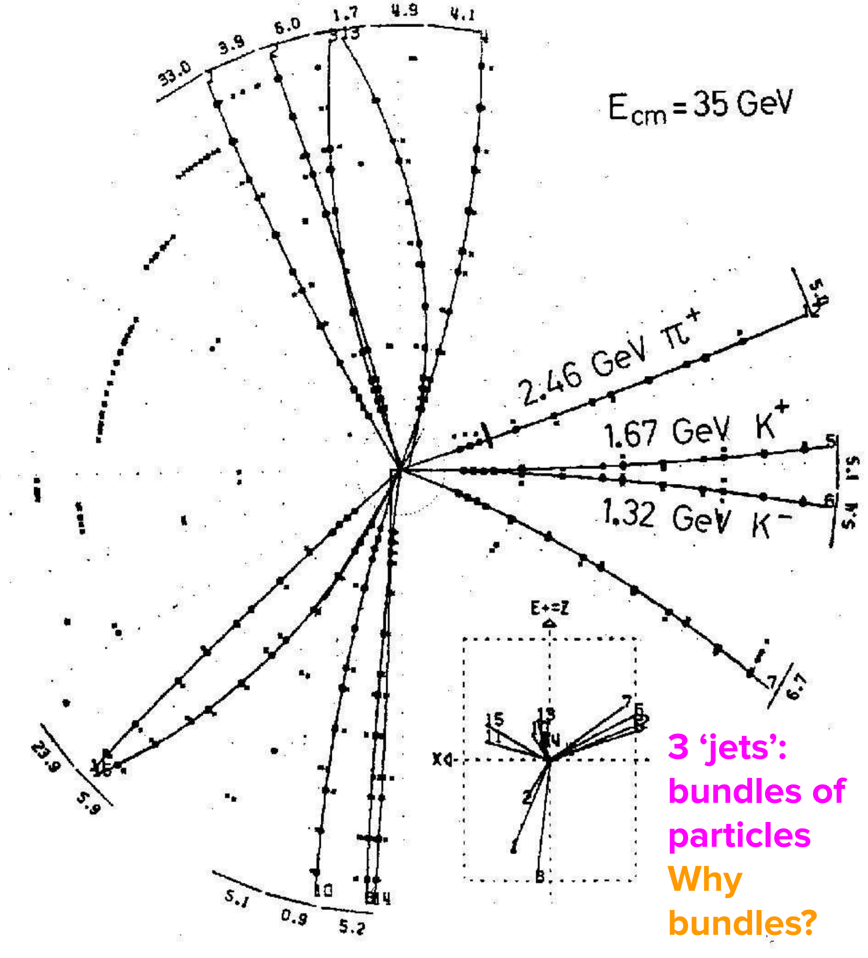
Event in *drift chamber* of JADE experiment at PETRA collider at DESY.

Such events were used to prove the existence of gluons: $e^+e^- \rightarrow q\bar{q}g$.

Wire chamber: particle T passes through grounded plate P and ionizes gas in chamber. Charge drifts in electric field to high voltage wires W and is collected at an amplifier A.



https://upload.wikimedia.org/wikipedia/commons/thumb/4/44/Wire_chamber_schematic.svg/1024px-Wire_chamber_schematic.svg.png



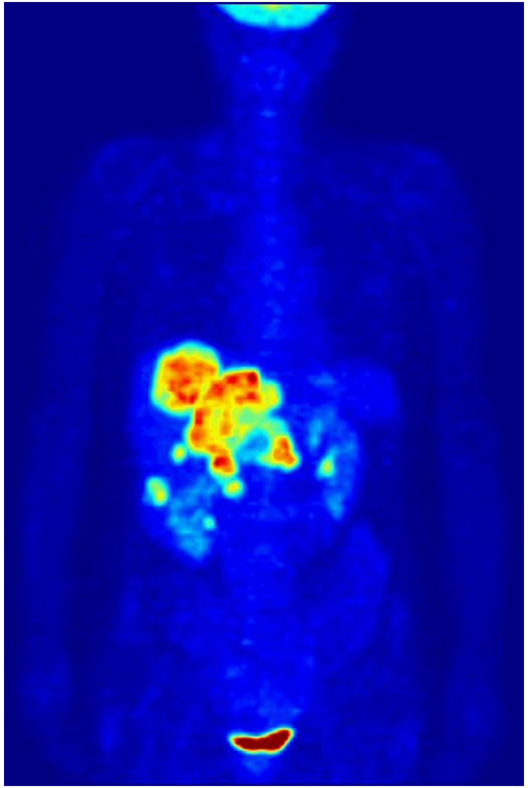
3 'jets': bundles of particles

Why bundles?

From http://www.desy.de/sites2009/site_www-desy/content/e409/e287332/e287337/e287345/1980-09-22_TASSO-Event_Gluon_Entdeckung_sw_ger.jpg

https://www.desy.de/~schleper/lehre/physik5/WS_2018_19/Physik_5_72-95.pdf

More detectors



https://upload.wikimedia.org/wikipedia/commons/3/3d/PET-MIPS-anim.gif

Magnetic resonance imaging

(b)

https://upload.wikimedia.org/wikipedia/commons/3/35/113abcd_Medical_Imaging_Techniques.jpg

Positron emission tomography

https://upload.wikimedia.org/wikipedia/commons/thumb/d/d9/Smoke_detector.JPG/1920px-Smoke_detector.JPG

https://dosimetry.web.cern.ch/sites/dosimetry.web.cern.ch/files/field/image/201404-071_01_cut4x2_0.jpeg

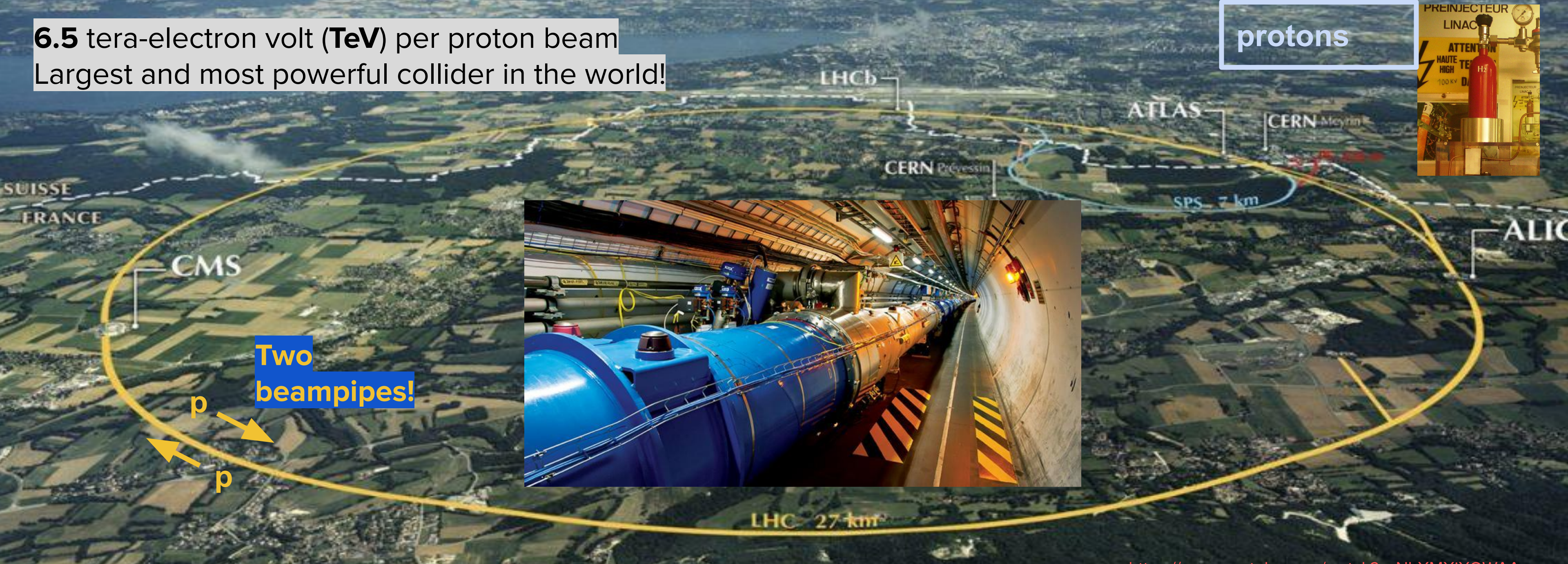
CERN and the Large Hadron Collider

Large Hadron Collider

Hadron: composite particle made of quarks held together by the strong force

6.5 tera-electron volt (**TeV**) per proton beam
Largest and most powerful collider in the world!

protons

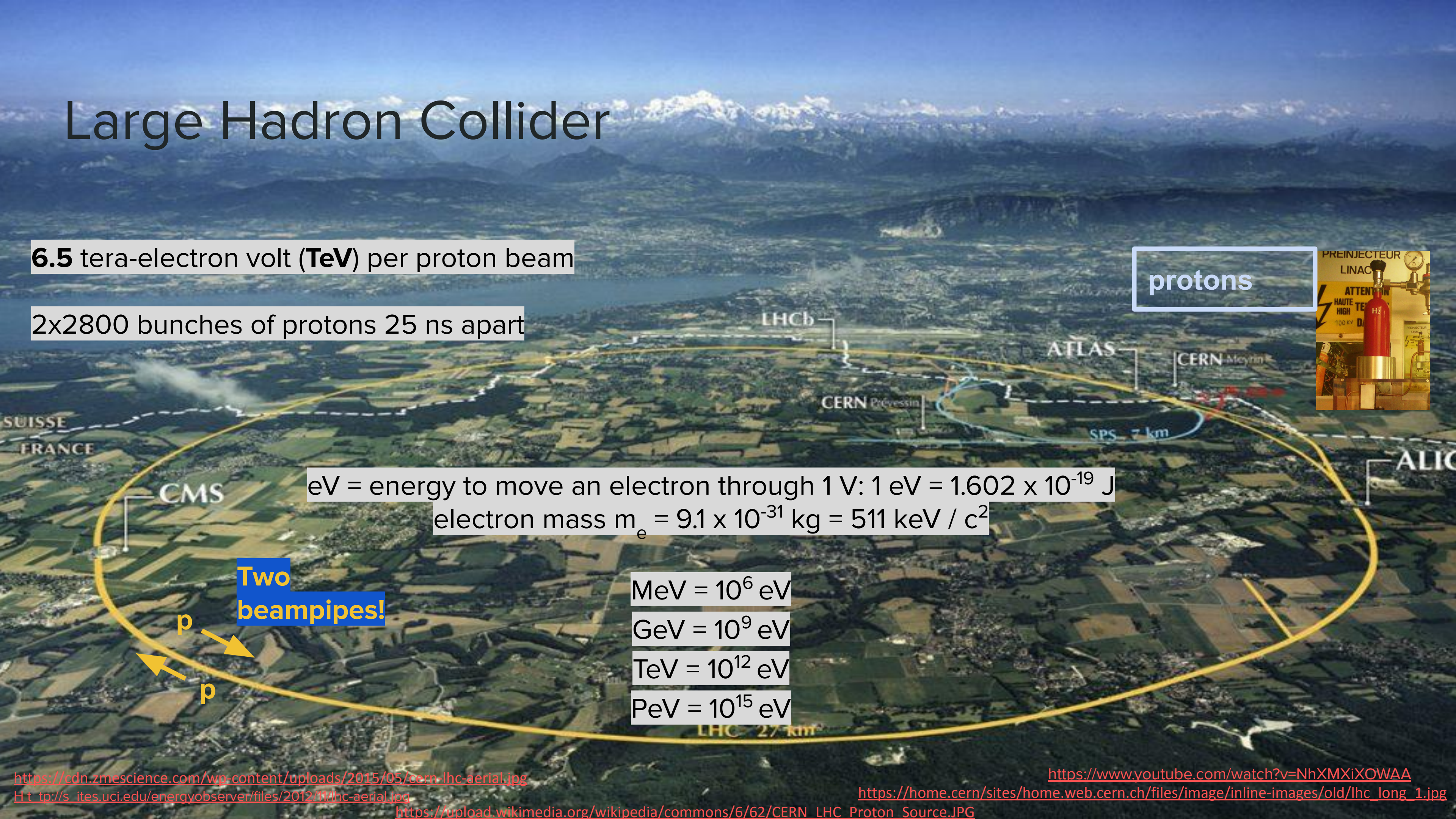


https://cdn.zmescience.com/wp-content/uploads/2015/05/cern-lhc-aerial.jpg
H t tp://s ites.uci.edu/energyobserver/files/2012/11/lhc-aerial.jpg
https://upload.wikimedia.org/wikipedia/commons/6/62/CERN_LHC_Proton_Source.JPG
https://www.youtube.com/watch?v=NhXMXiXOWAA
https://home.cern/sites/home.web.cern.ch/files/image/inline-images/old/lhc_long_1.jpg

Large Hadron Collider

6.5 tera-electron volt (**TeV**) per proton beam

2x2800 bunches of protons 25 ns apart



eV = energy to move an electron through 1 V: 1 eV = 1.602×10^{-19} J

electron mass $m_e = 9.1 \times 10^{-31}$ kg = 511 keV / c^2

MeV = 10^6 eV

GeV = 10^9 eV

TeV = 10^{12} eV

PeV = 10^{15} eV

https://cdn.zmescience.com/wp-content/uploads/2015/05/cern-lhc-aerial.jpg
H t tp://s ites.uci.edu/energyobserver/files/2012/11/lhc-aerial.jpg
https://upload.wikimedia.org/wikipedia/commons/6/62/CERN_LHC_Proton_Source.JPG
https://www.youtube.com/watch?v=NhXMXiXOWAA
https://home.cern/sites/home.web.cern.ch/files/image/inline-images/old/lhc_long_1.jpg

Large Hadron Collider

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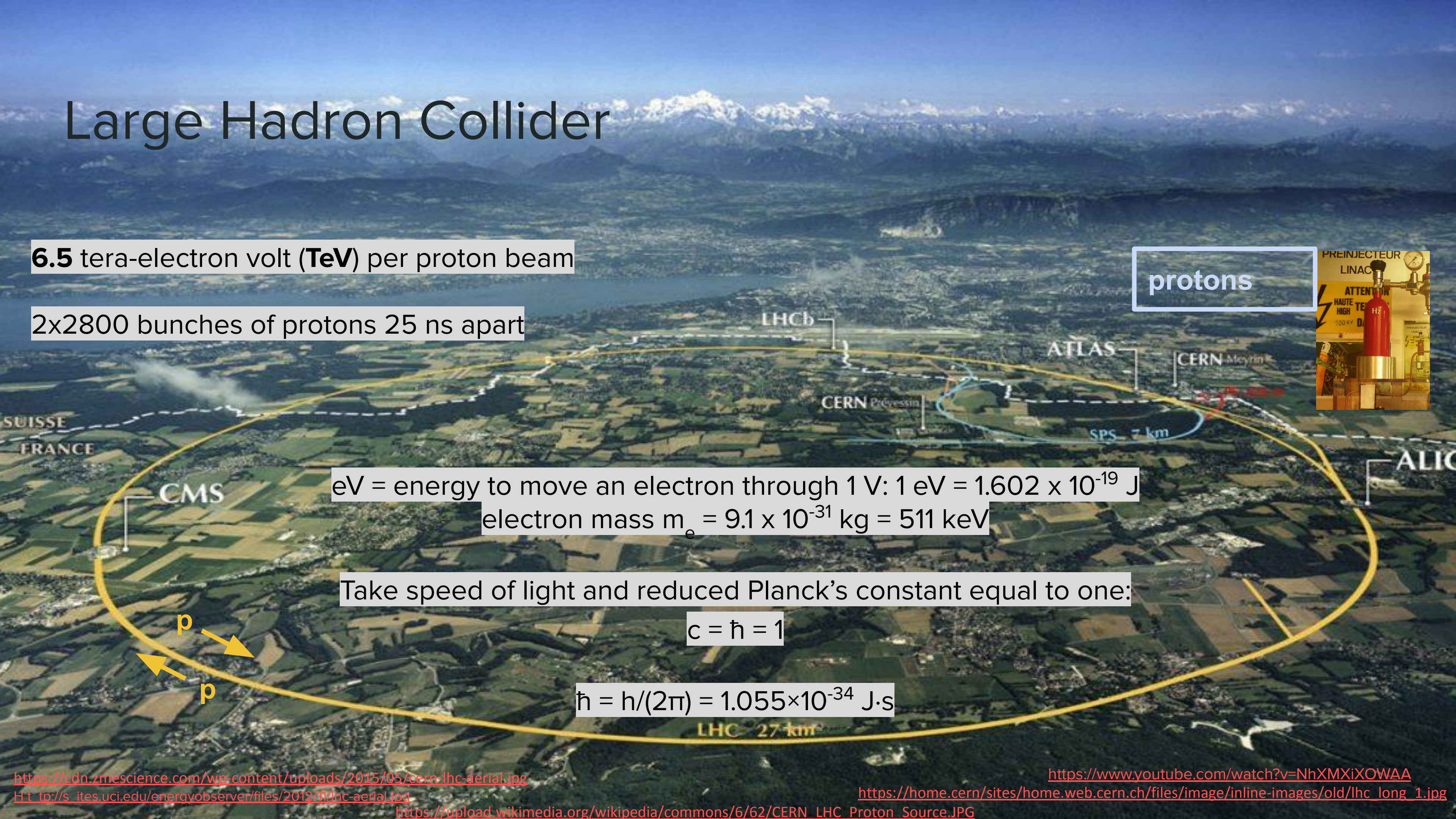
eV = energy to move an electron through 1 V: 1 eV = 1.602×10^{-19} J

electron mass $m_e = 9.1 \times 10^{-31}$ kg = 511 keV

Take speed of light and reduced Planck's constant equal to one:

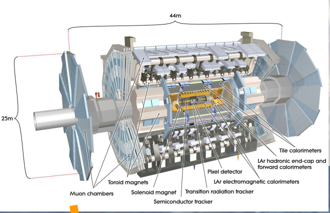
$c = \hbar = 1$

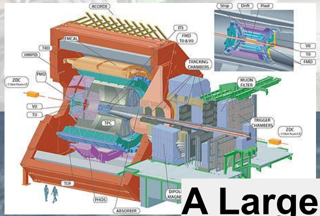
$\hbar = h/(2\pi) = 1.055\times10^{-34}$ J·s



https://cdn.zmescience.com/wp-content/uploads/2015/05/cern-lhc-aerial.jpg
H t tp://s ites.uci.edu/energyobserver/files/2012/11/lhc-aerial.jpg
https://upload.wikimedia.org/wikipedia/commons/6/62/CERN_LHC_Proton_Source.JPG
https://www.youtube.com/watch?v=NhXMXiXOWAA
https://home.cern/sites/home.web.cern.ch/files/image/inline-images/old/lhc_long_1.jpg

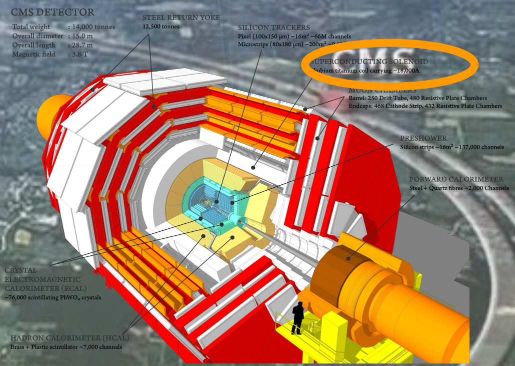
Detectors at the LHC



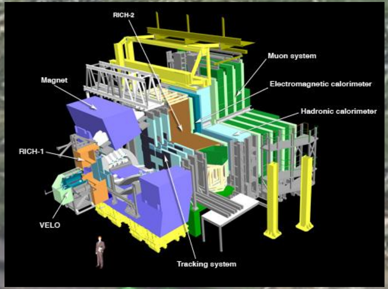


A Large Ion Collider Experiment: specialized in heavy ion collisions and quark-gluon plasma: fraction of second after big bang!

Compact Muon Solenoid
14000 tons: 1.5* Eiffel tower weight, half the size of ATLAS: 15 m x 15 m x 21 m very compact!
Largest superconducting solenoid magnet ever made



A Toroidal LHC ApparatuS:
25 m x 25 m x 46m
The inner detector has 3 air core **toroidal magnets** and one solenoidal magnet .

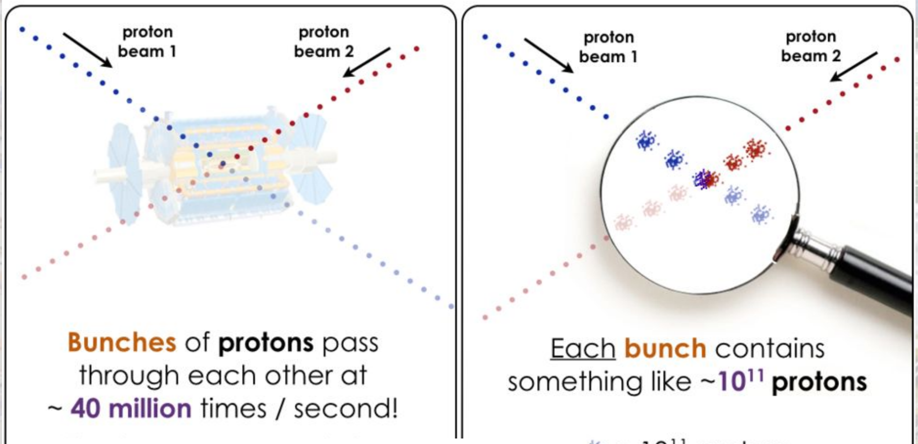


LHC beauty:
A single-arm **forward** spectrometer designed for the study of particles containing b or c quarks.

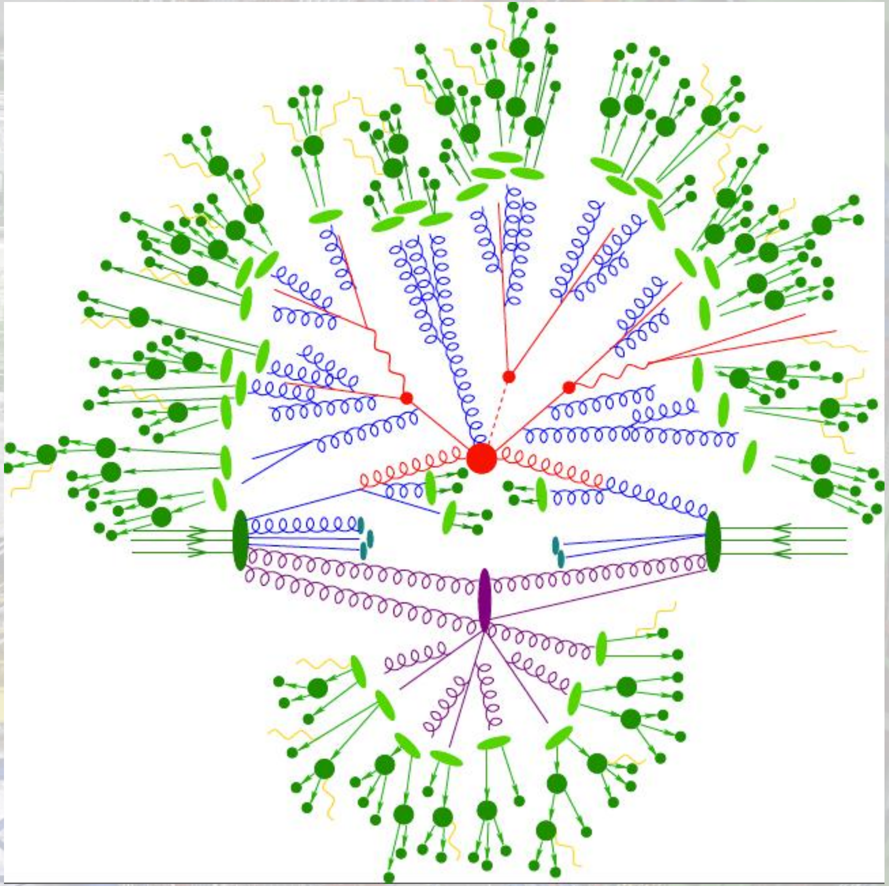
Other detectors: MoEDAL, TOTEM, LHCforward

https://cms-docdb.cern.ch/cgi-bin/PublicDocDB/RetrieveFile?docid=11514&version=1&filename=cms_120918_03.png

Proton-proton collisions



The beams are made to cross at the **center** of CMS, ATLAS detectors and **end** of LHCb and ALICE



https://sciencenode.org/feature/sherpa-and-open-science-grid-predicting-emergence-jets.php

Trigger system:
Choose what events are interesting
How do we choose?

Jet: quarks and gluons hadronized to kaons, protons, pions in a collimated stream

https://inspirehep.net/record/805147/files/crosssections2008.png
https://static1.squarespace.com/static/568f0767d82d5ee322f9bbcc/t/57bac2e99f7456e36f33b505/1471857390507/
https://image.slidesharecdn.com/rojo-slac-nnpdfs-150406131730-conversion-gate01/95/the-structure-of-the-proton-in-the-higgs-boson-era-8-638.jpg?cb=1428344507

http://wlcg-public.web.cern.ch/sites/wlcg-public.web.cern.ch/files/WLCG-snapshot-28112013.jpg

What do we detect?

Not all known elementary particles

Directly detect:

Decay products

jets

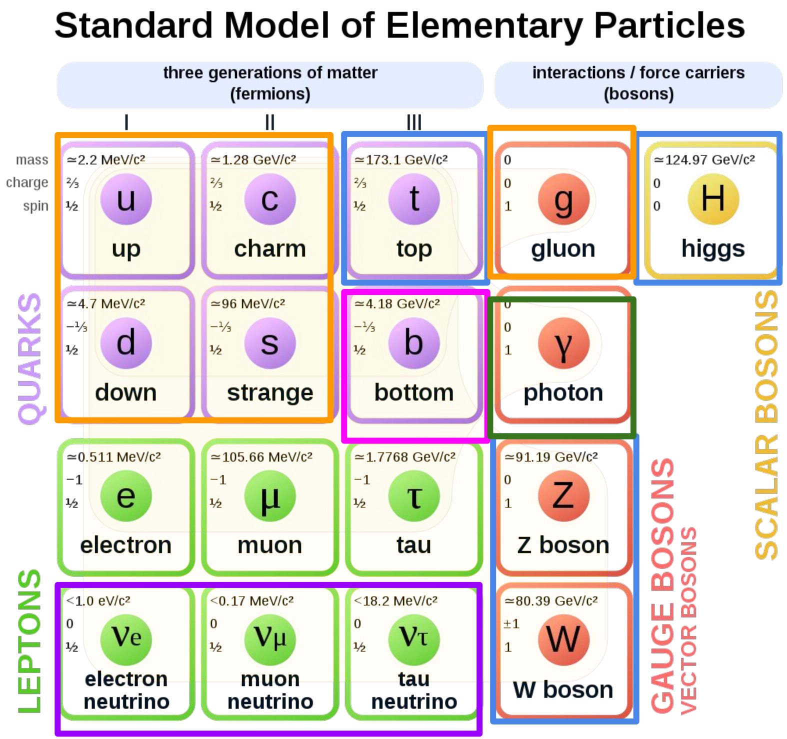
Indirectly detect:

Missing energy

Secondary vertex + jets

Neutral particles

Should be able to detect and identify:
$e^{\pm}$, $\mu^{\pm}$, γ, $\pi^{\pm}$, $K^{\pm}$, $p^{\pm}$, K^{0}, n
using mass, charge, interaction



From https://upload.wikimedia.org/wikipedia/commons/0/00/Standard_Model_of_Elementary_Particles.svg

What do we measure and how?

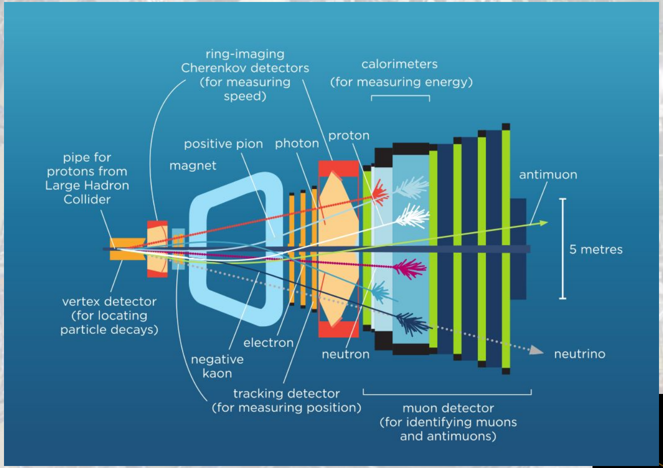
Observable	**Measurable quantity**
Momentum (p)	Bending radius in magnetic field
Speed (v)	Time of flight, Cherenkov radiation
Charge (Q)	Bending in magnetic field
Lifetime (τ)	Distance traveled before decay
Energy (E)	Absorption in calorimeters
Mass (m)	Indirectly from momentum
Spin	Angular distributions

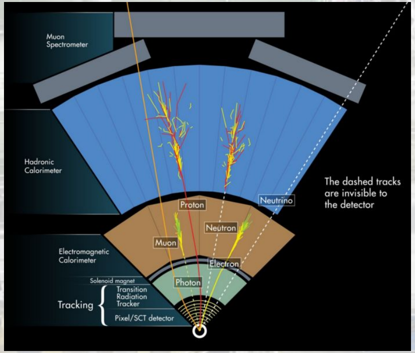
- $d = c\tau\gamma$
- $\gamma = 1/\sqrt{(1-\beta^2)}$
- $\beta = v/c$
- $E^2 = m^2c^4 + p^2c^2$
- $p = \gamma mv = mv/\sqrt{(1-v^2/c^2)}$

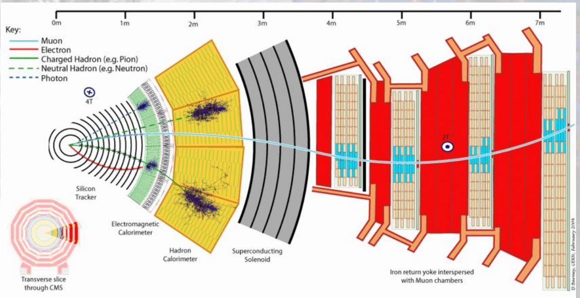
For some examples of measuring spin see https://arxiv.org/pdf/1202.6660.pdf and http://moriond.in2p3.fr/QCD/2013/proceedings/Muehlleitner.pdf

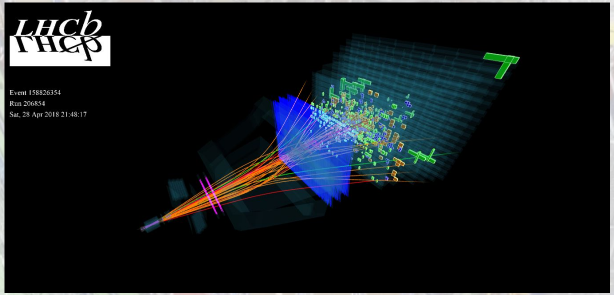
Need 1) a magnetic field and 2) interaction with material

Detecting particles at the LHC

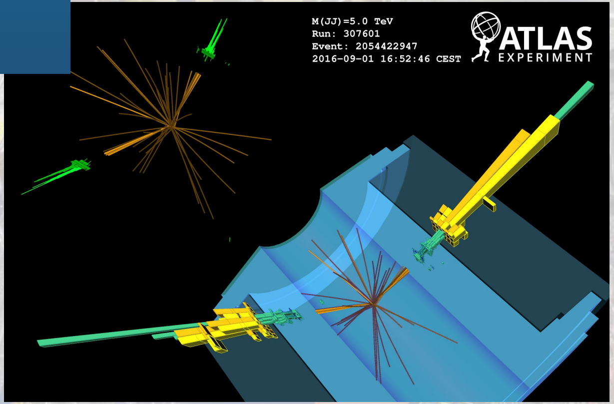




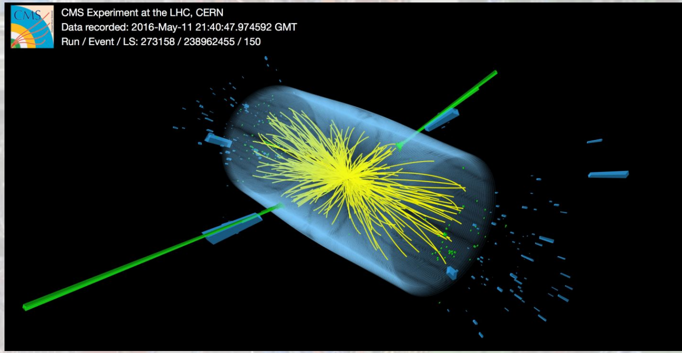




LHCb b-jet event



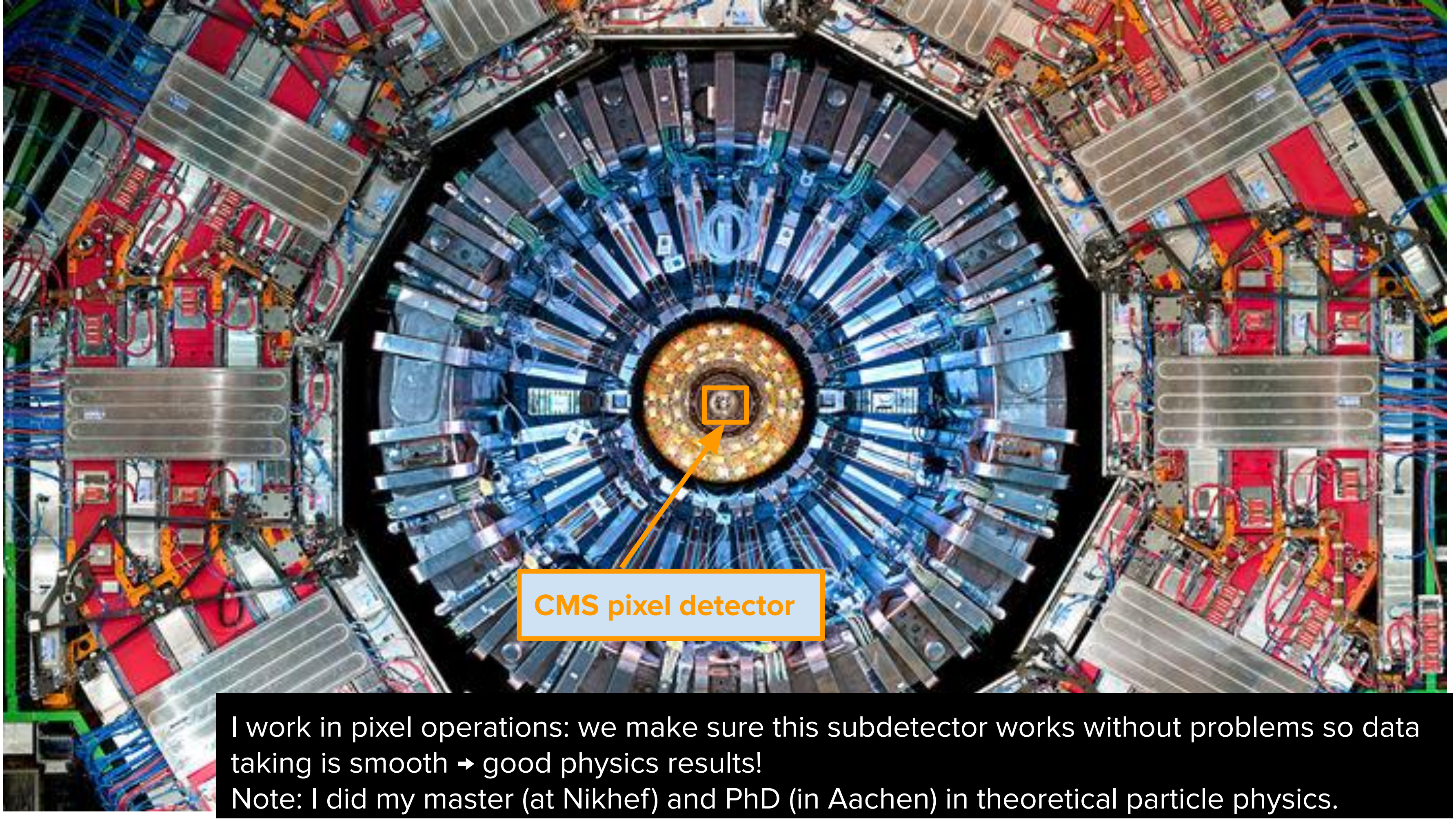
ATLAS dijet event



CMS dijet event

https://www.researchgate.net/profile/Raquel_Gomez-Ambrosio/publication/323966523/figure/fig17/AS:607356689842176@1521816527028/Transverse-section-of-the-CMS-detector.png

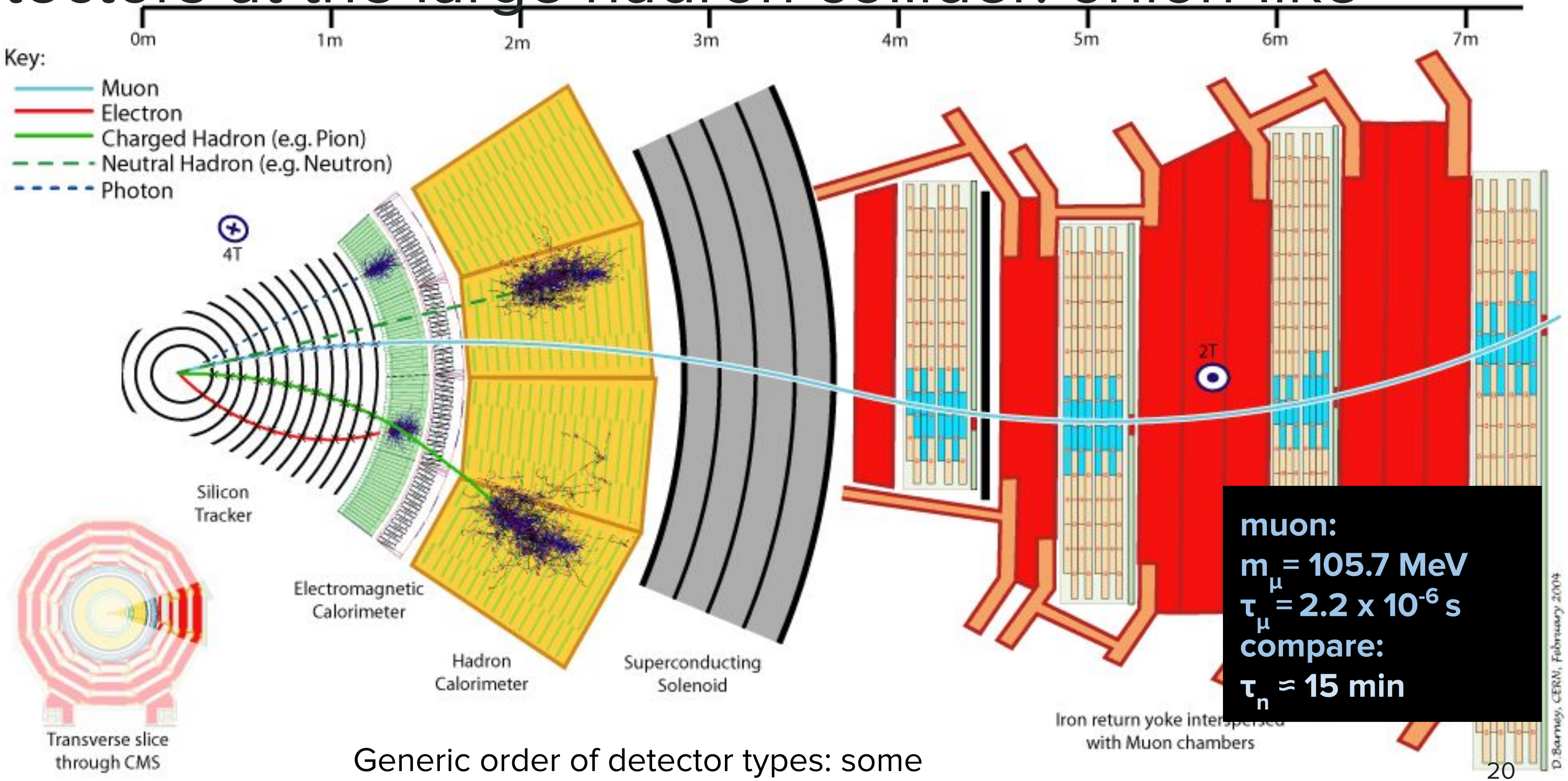
https://www.sciencemag.org/sites/default/files/styles/inline__699w__no_aspect/public/ca_0914NID_CMS_Detector_online.jpg?itok=EzPQHklv



I work in pixel operations: we make sure this subdetector works without problems so data taking is smooth ➜ good physics results!
Note: I did my master (at Nikhef) and PhD (in Aachen) in theoretical particle physics.

https://www.sciencemag.org/sites/default/files/styles/inline__699w__no_aspect/public/ca_0914NID_CMS_Detector_online.jpg?itok=EzPQHklv

Detectors at the large hadron collider: onion-like



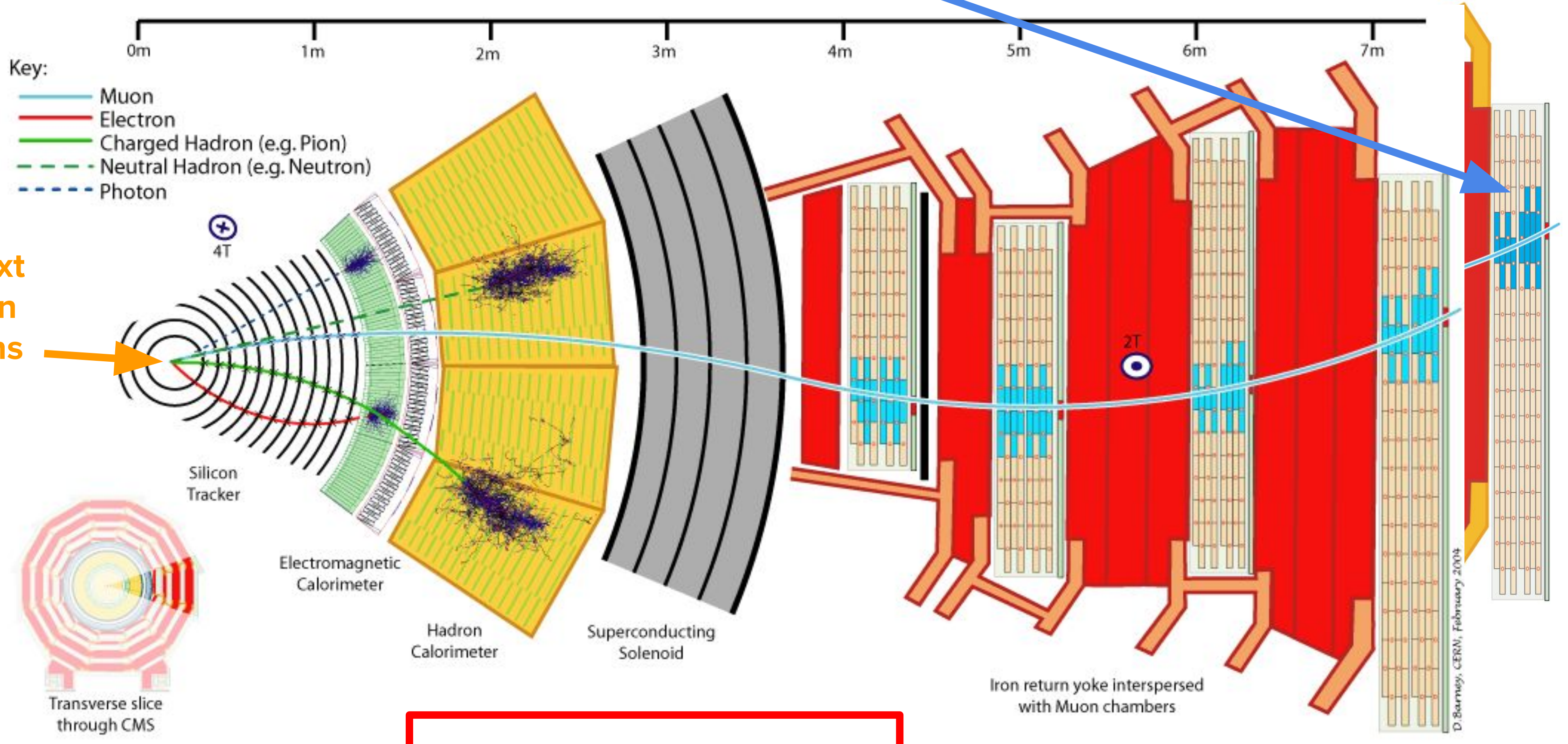
http://inspirehep.net/record/826852/files/EPS_CMS_Slice.png

muon:
m_μ = 105.7 MeV
τ_μ = 2.2 x 10^{-6} s
compare:
$\tau_n \approxeq$ 15 min

Generic order of detector types: some measurements destructive!

Note when the muon arrives here

The next collision happens here:



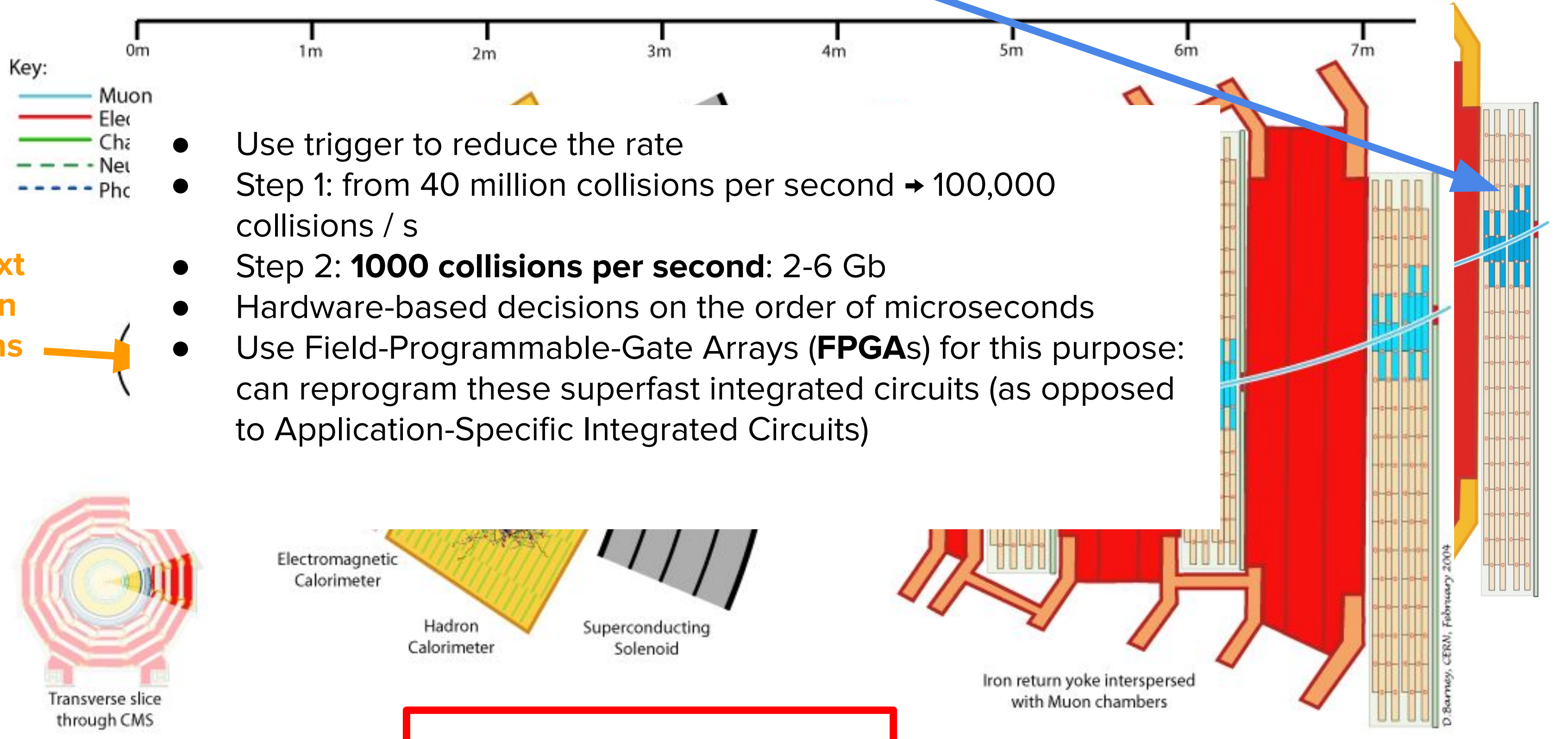
http://inspirehep.net/record/826852/files/EPS_CMS_Slice.png

25 ns • c ≅7.5m

Note when the muon arrives here

- Use trigger to reduce the rate
- Step 1: from 40 million collisions per second → 100,000 collisions / s
- Step 2: **1000 collisions per second**: 2-6 Gb
- Hardware-based decisions on the order of microseconds
- Use Field-Programmable-Gate Arrays (**FPGA**s) for this purpose: can reprogram these superfast integrated circuits (as opposed to Application-Specific Integrated Circuits)

The next collision happens here:



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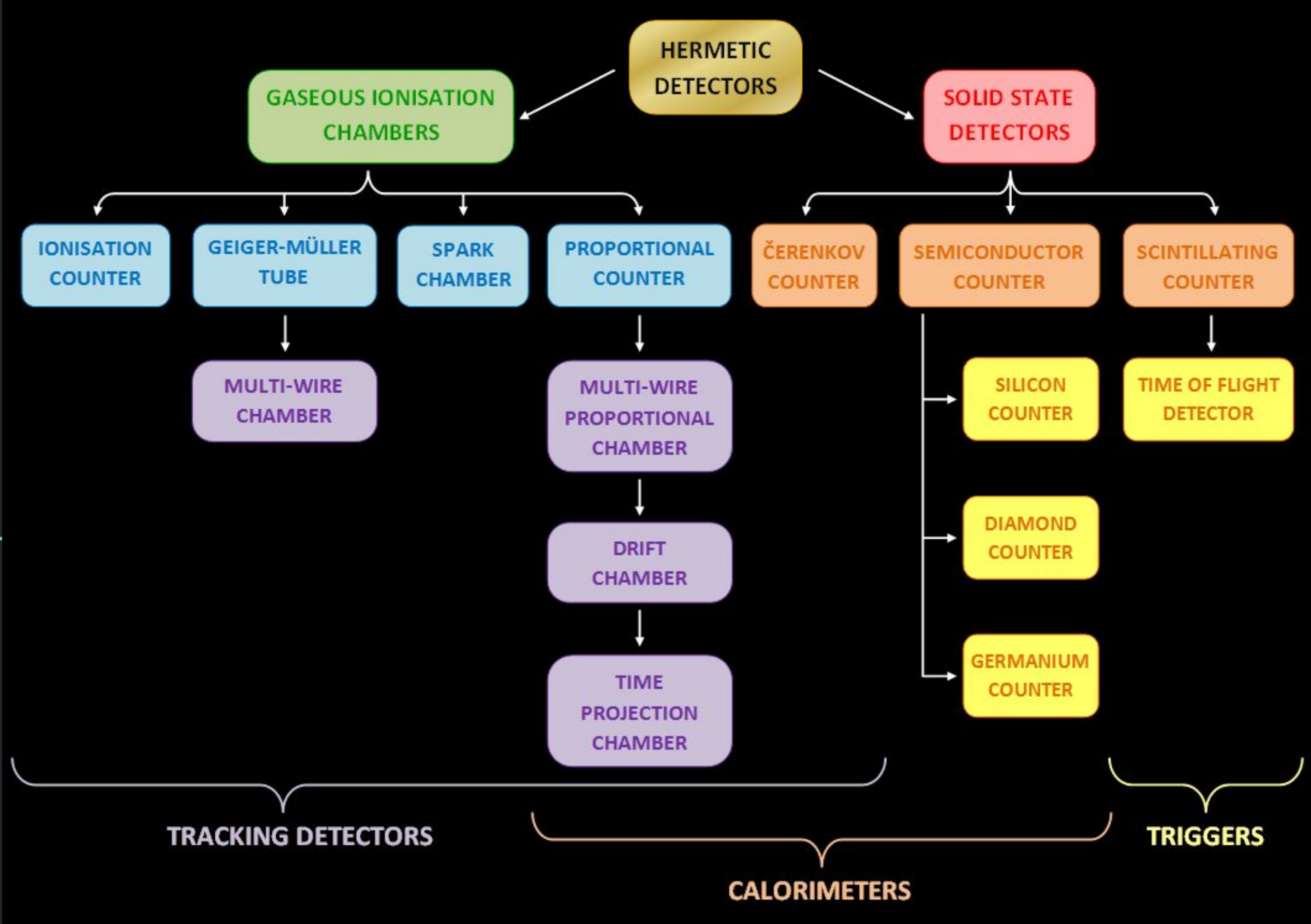
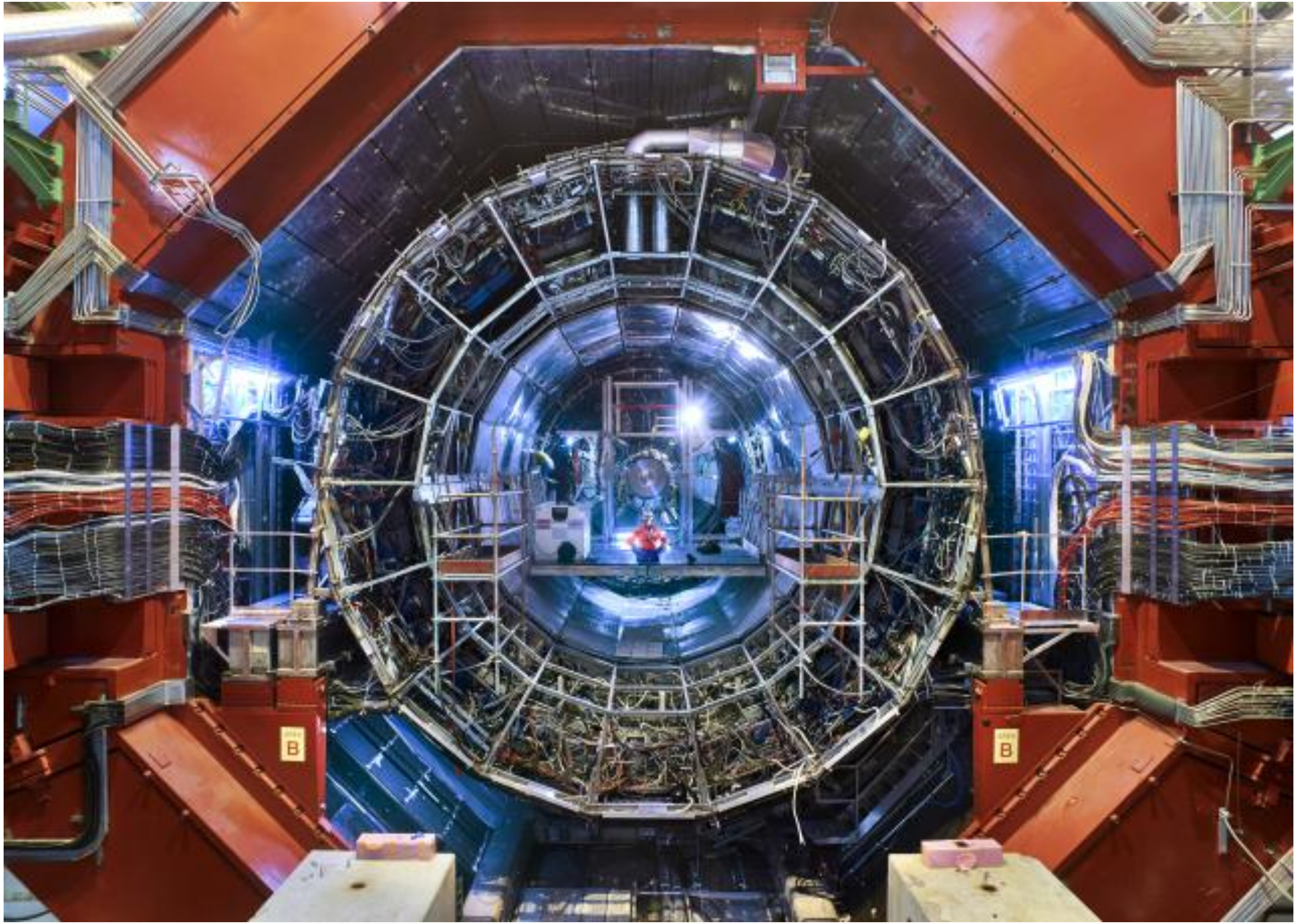
25 ns • c ≅7.5m

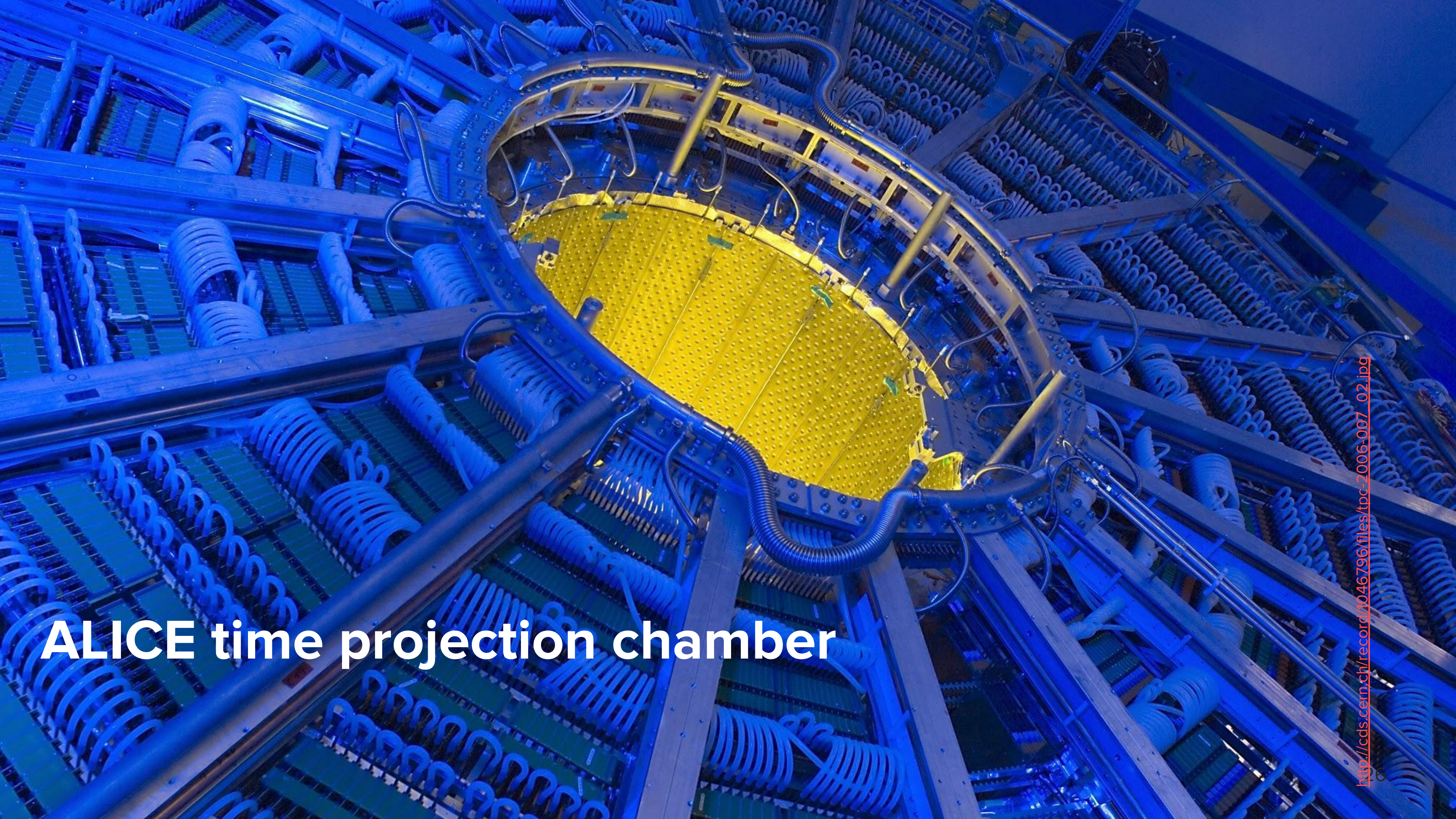


https://upload.wikimedia.org/wikipedia/commons/c/c0/Detectors_summary_3.png

Gaseous detectors



https://cds.cern.ch/record/2665476/files/201902-053_01.jpg?subformat=icon-640

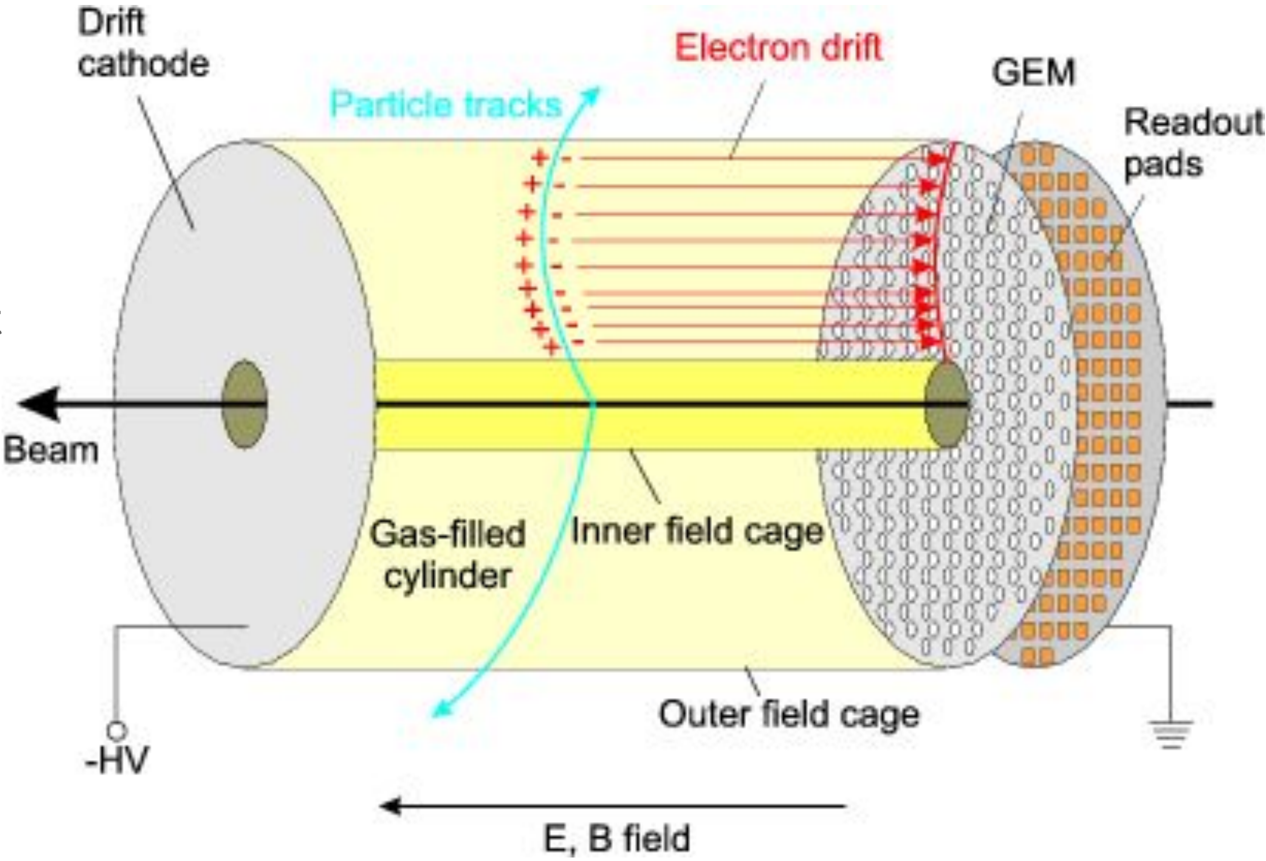


ALICE time projection chamber

http://cds.cern.ch/record/1046796/files/tpc-2006-007_02.jpg

TPC

1. Ionization of gas in **chamber** with electric field causes electron drift
2. Signal gets amplified, in this case by gas electron multipliers ➜ electron avalanche
3. Readout pads can detect signal that can be **projected** onto trajectory
4. z (along beam) information from **timing**



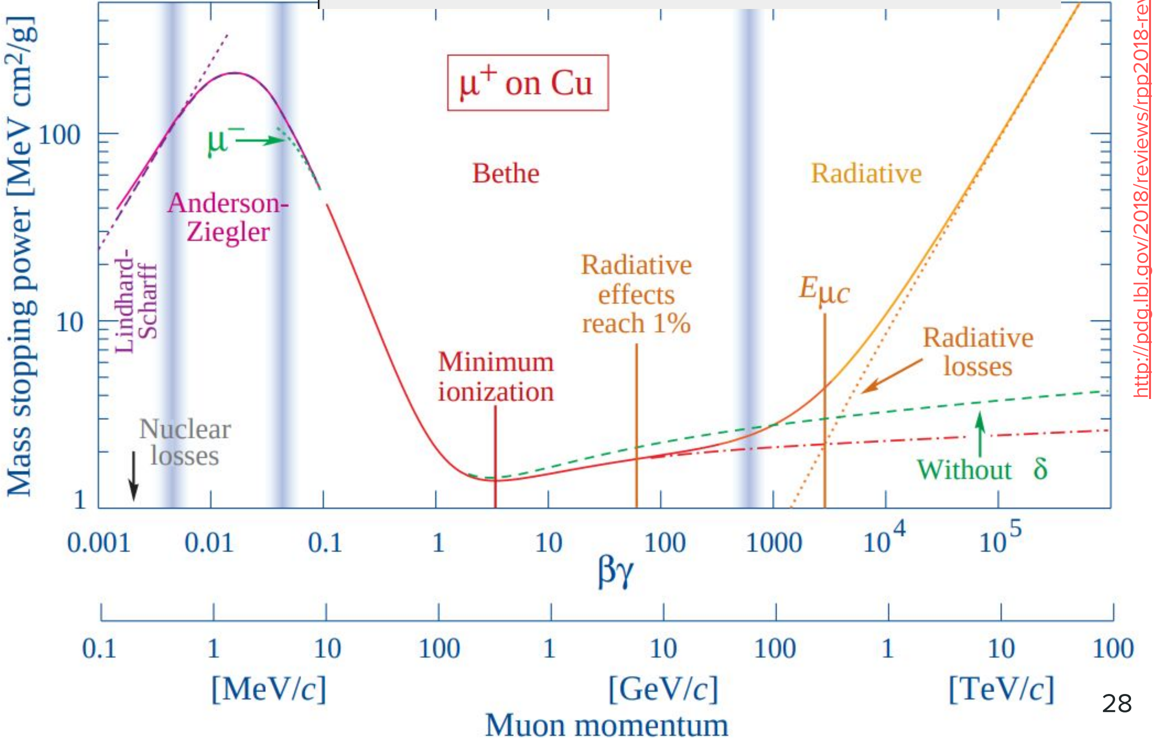
http://aliceinfo.cern.ch/Public/Objects/Chapter2/DetectorComponents/tpc_operation.gif

Ionization loss

- Can measure ionization loss dE/dx
- K is a coefficient: K = .307 MeV mol^{-1}cm^{-2}
- I is the mean excitation energy

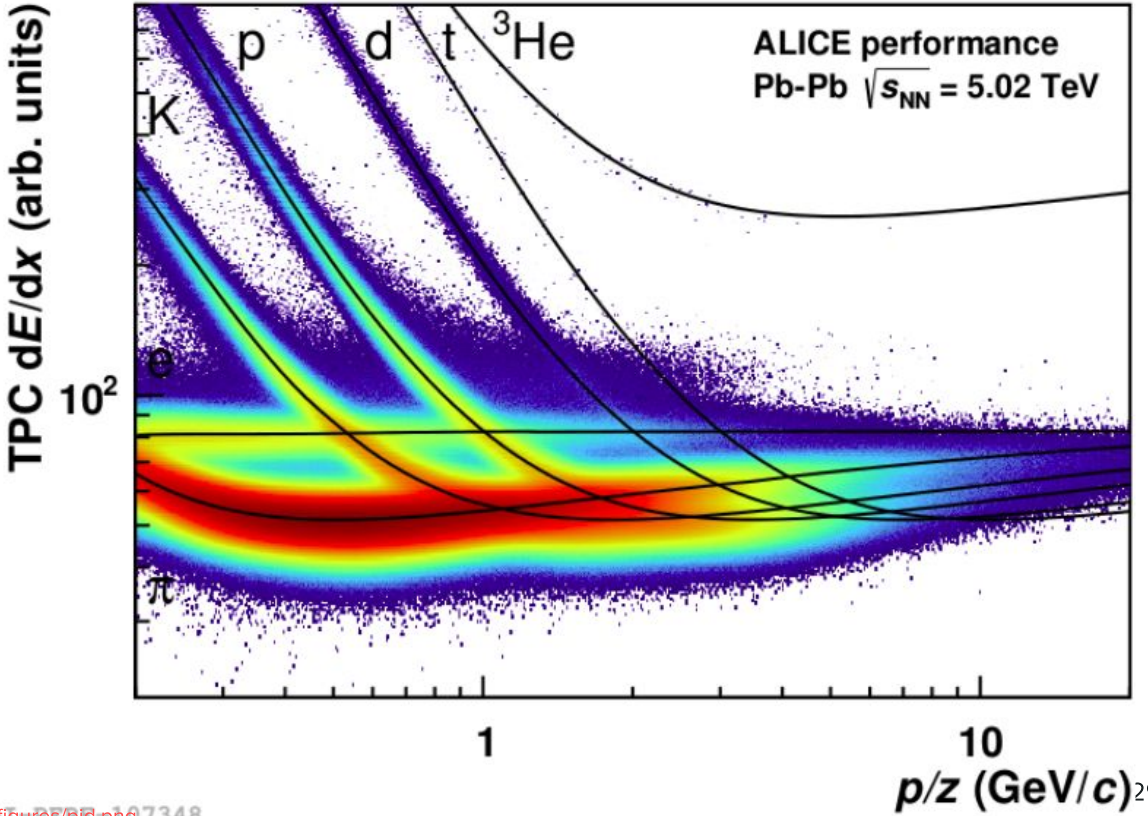
Depends on charge, atom number, ionization energy, density

$$-\left\langle \frac{dE}{dx} \right\rangle \approx K q^2 \frac{1}{\beta^2} \frac{Z}{A} \left[\ln\left(\frac{2 m_e c^2}{I} \beta^2 \gamma^2 \right) - \beta^2 \right]$$



http://pdg.lbl.gov/2018/reviews/rpp2018-rev-passage-particles-matter.pdf

- Every point is one measurement!
- Can identify particles for low momenta
- For higher momenta, all particles behave like a minimum ionizing particle (MIP)



https://scx1.b-cdn.net/csz/news/800/2015/55d25b5d82741.png

https://alice-doc.github.io/alice-analysis-tutorial/analysis/figures/pid.png

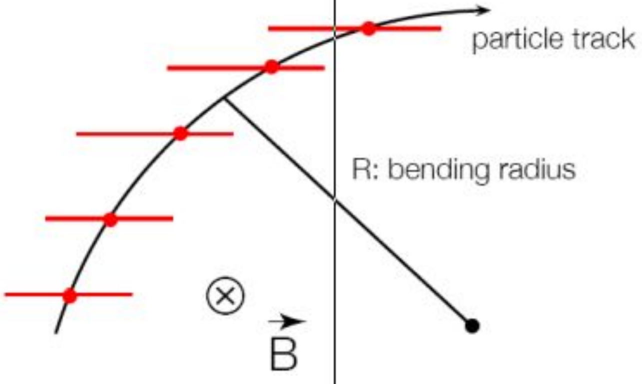
Tracking detectors

Momentum determination

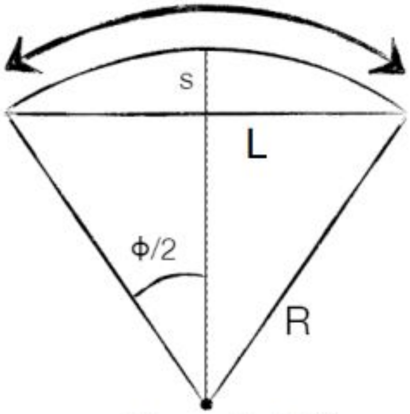
in a cylindrical drift chamber ...

$$\frac{mv^2}{R} = evB \quad \rightarrow \quad p = eB \cdot R$$

$$p\left[\frac{GeV}{c}\right] = 0.3\ B[T]\ R[m]$$



Magnet is important!



1T = 1kg/C/s^2
1eV/c = 0.535 10^{-27} kg m/s
1eV = 1.6 10^{-19} C

momentum component perpendicular to the B-field
transverse momentum p_t

For Sagitta s:

$$s = R - R\cos\frac{\phi}{2} \approx R\frac{\phi^2}{8} \qquad \text{with } \phi = \frac{L}{R}$$

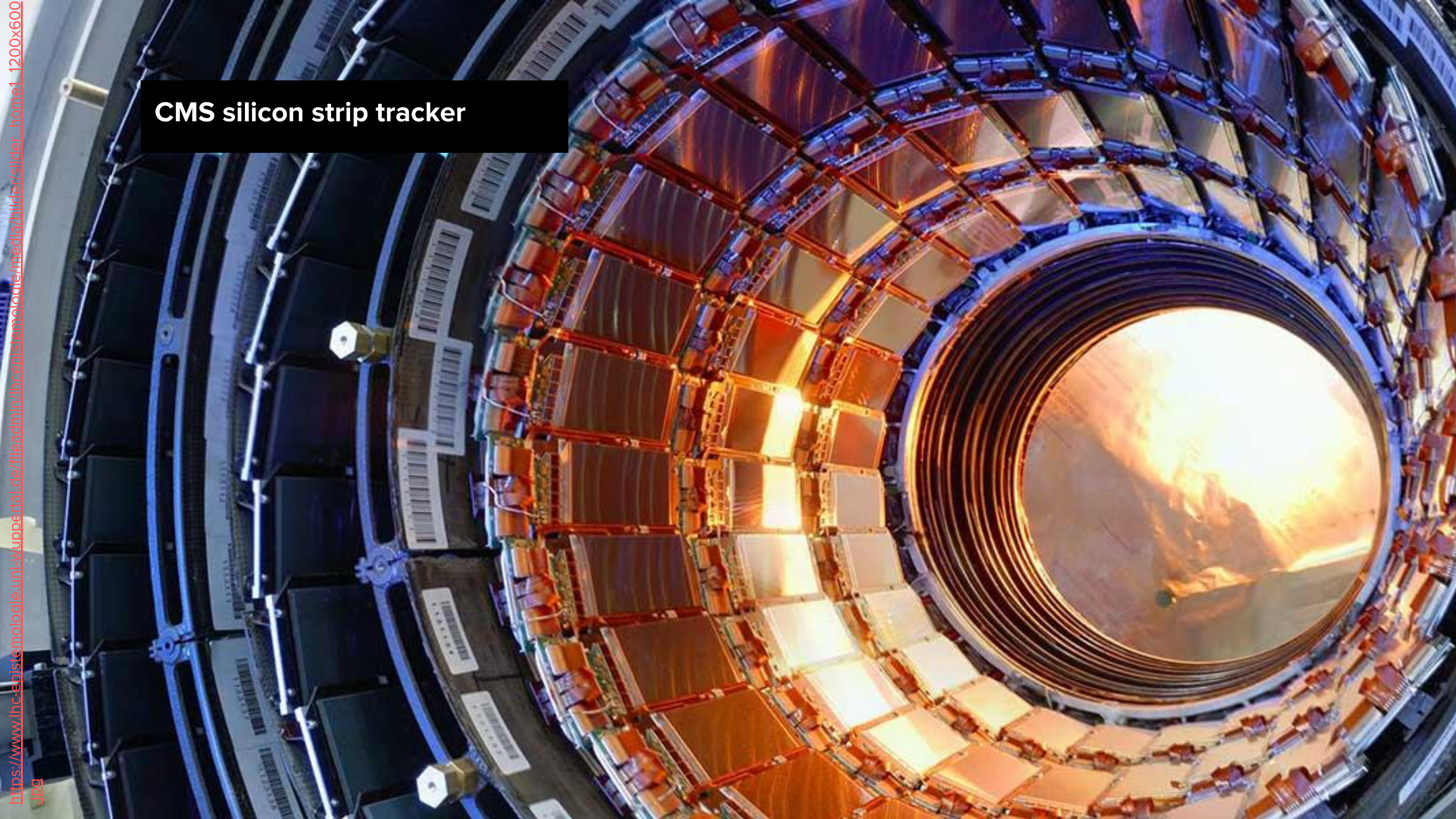
$$s = R\frac{L^2}{8R^2} = \frac{L^2}{8R} \quad \text{and} \quad R = \frac{L^2}{8s}$$

→ radius is obtained by a circle fit through measurement points along the track with point resolution $\sigma_{r\phi}$

$$\rightarrow \quad \frac{\Delta p}{p} = \frac{\Delta R}{R} = \frac{L^2}{8Rs} \cdot \frac{\Delta s}{s}$$

18

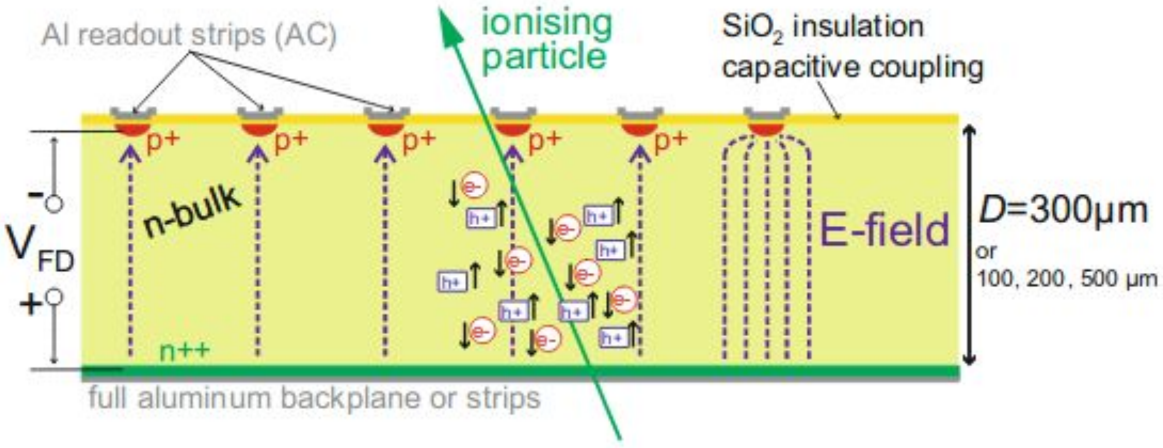
CMS silicon strip tracker



https://www.lhc-epistemologie.uni-wuppertal.de/fileadmin/lhcepistemologie/media/bilder/slider/slider_home1_1200x600.jpg

Ideal signal detection with silicon sensors

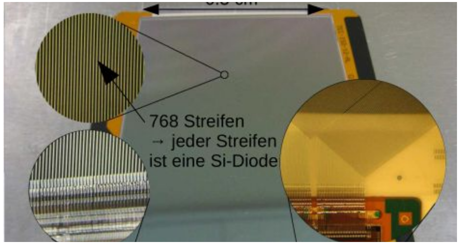
- A minimum ionizing particle (MIP) traveling through a fully depleted region (V_{FD}) creates electron hole pairs
- The charges drift to opposite directions under the electric field
- Within nanoseconds, charges are collected at the readout



p-in-n silicon sensor

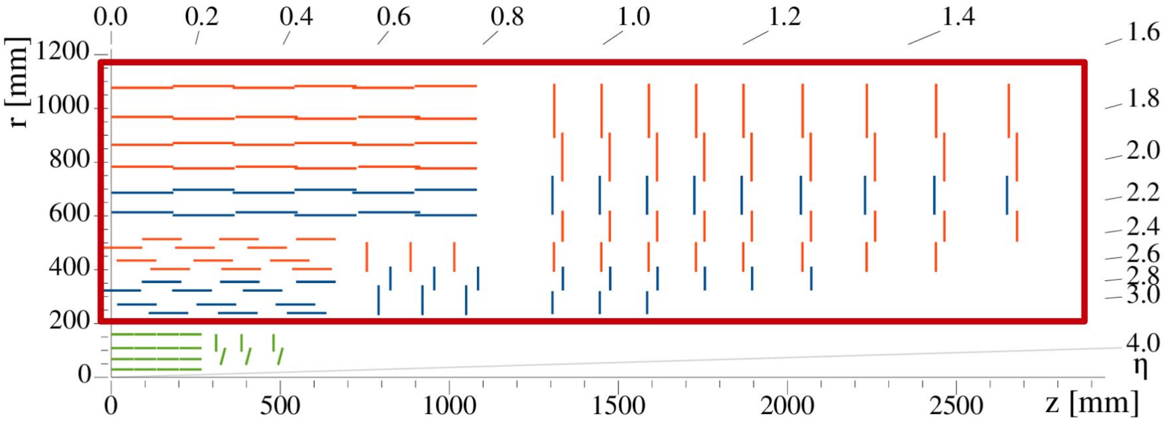
From Frank Hartmann

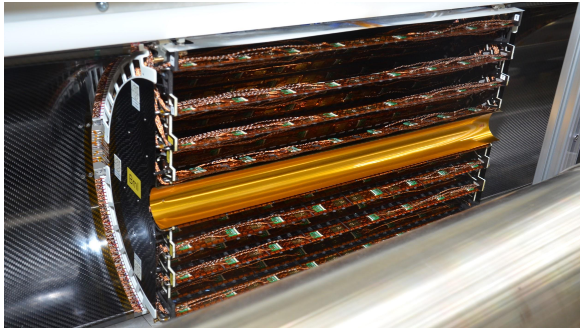
CMS silicon tracker



Strips vs pixels: how to determine location with strips?

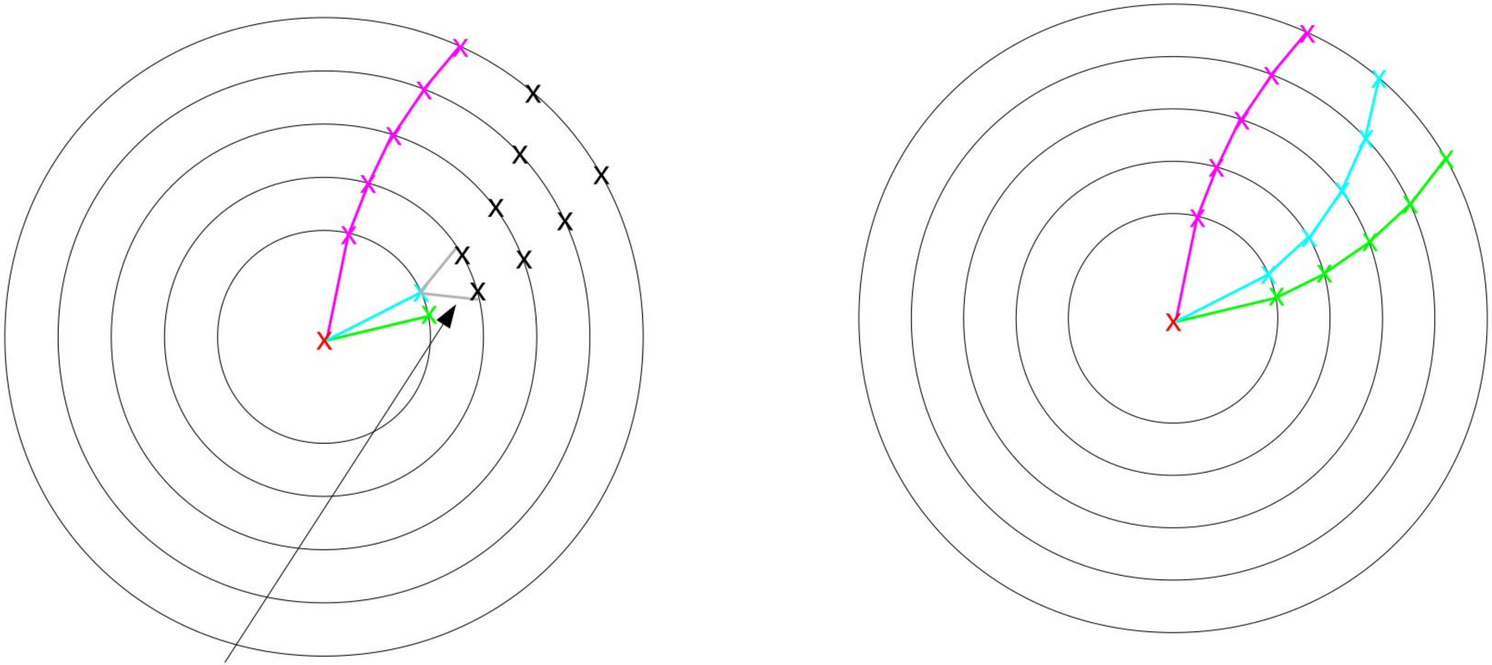
- 10-12 layers of silicon sensors
- 15148 modules
- 9.3 million electronic channels
- Operated at -20°C and < 20% humidity
- In over 10 years of beam more than a billion particles fly through detector!



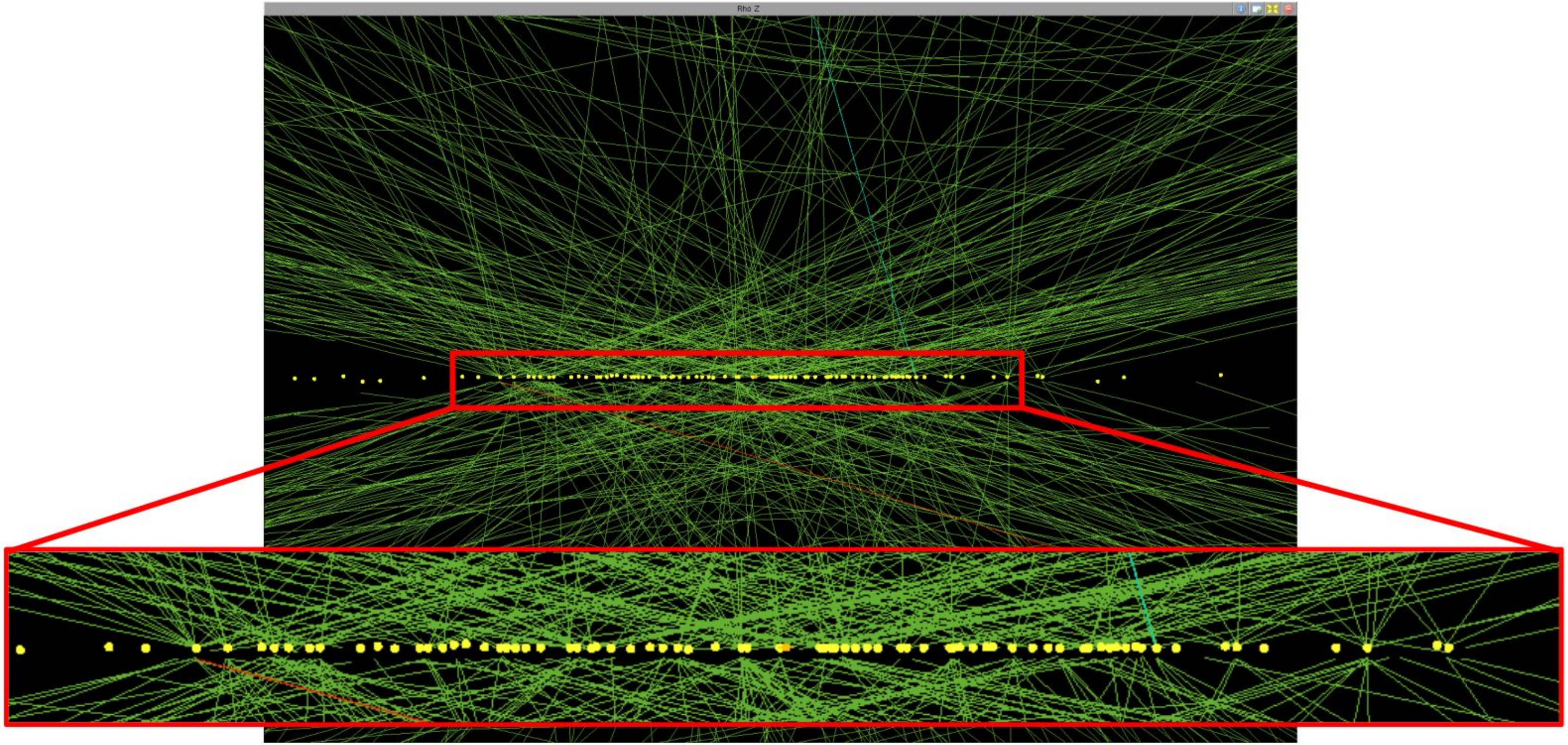


The pixel (or vertex) detector is so close to the beam pipe, it cannots survive this radiation: replaced in 2017, now inner layer will be replaced

Track reconstruction: find hits that belong to track

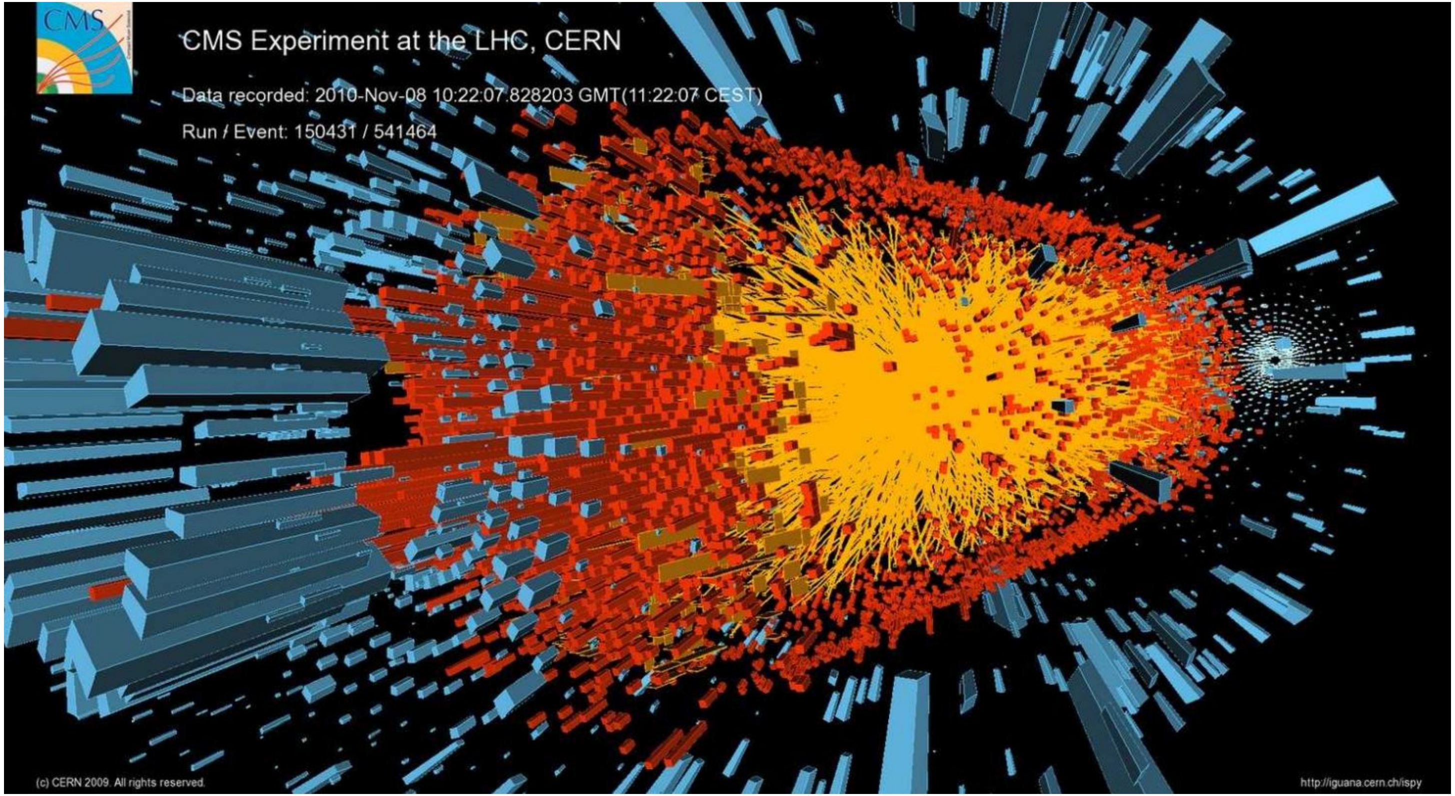


What if 78 interactions happen simultaneously?



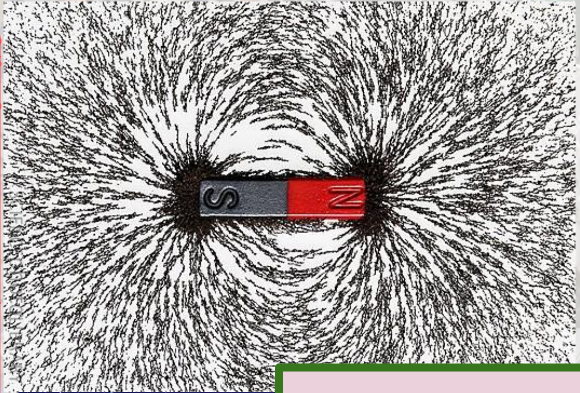
Or a collision of 2 lead nuclei?

10000 charged tracks!



Calorimeters

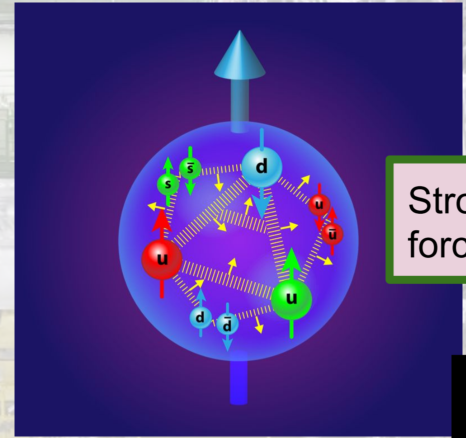
Interactions: four known forces



electromagnetism

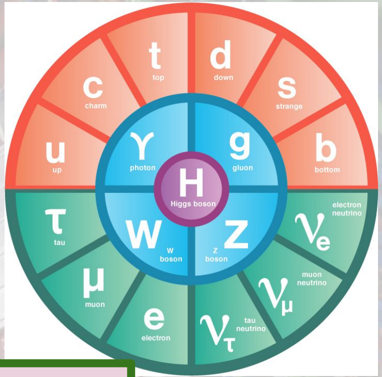
https://upload.wikimedia.org/wikipedia/commons/thumb/3/33/Lightning.0257.jpg/1200px-Lightning.0257.jpg

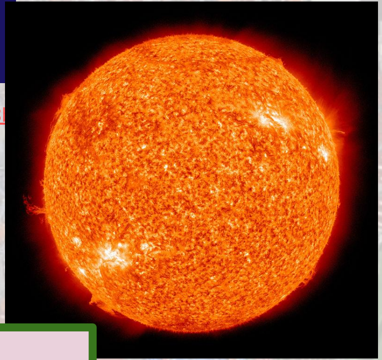
http://blog.science4you.es/wp-content/uploads/2016/08/5magnet.jpg



Strong nuclear force

https://physics.aps.org/assets/89b4f0e0-b8b70d-d90f744d1790/e23_2.png



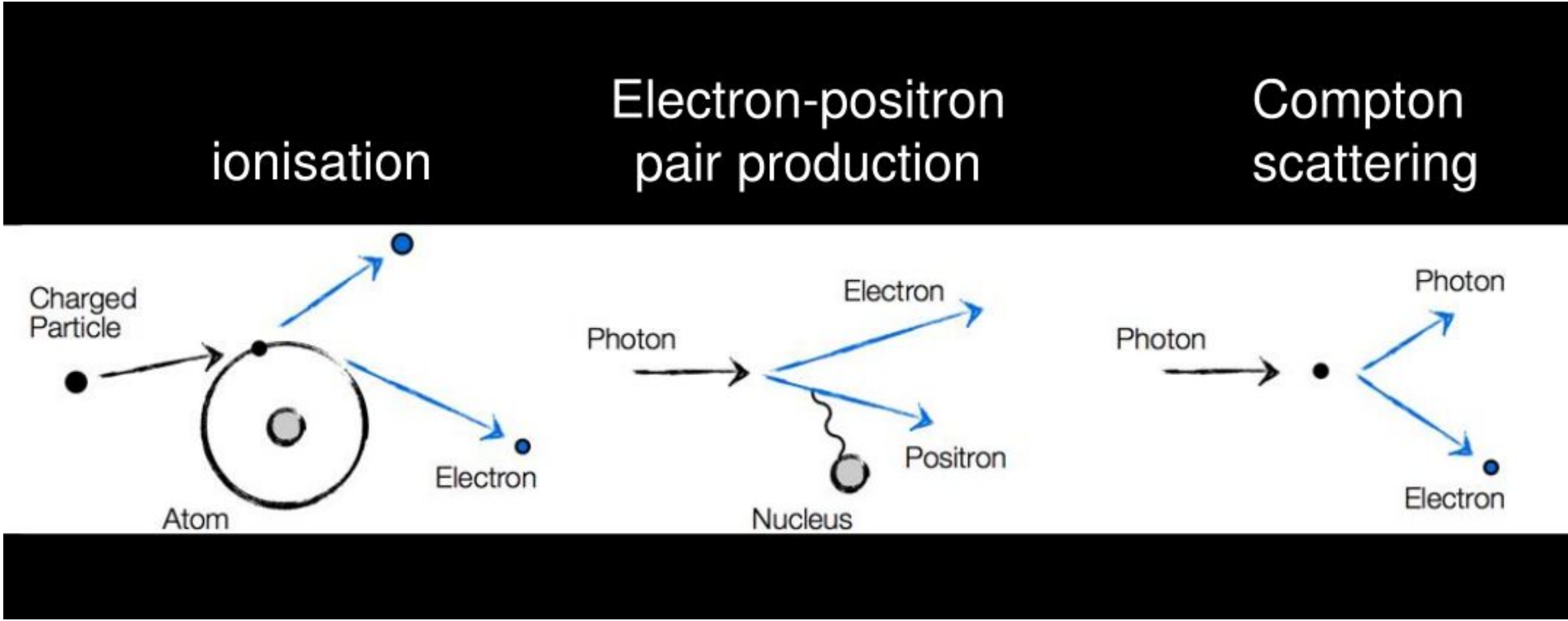


Weak nuclear force

https://upload.wikimedia.org/wikipedia/commons/thumb/b/b4/The_Sun_by_the_Atmospheric_Imaging_Assembly_of_NASA%27s_Solar_Dynamics_Observatory_-_20100819.jpg/800px-The_Sun_by_the_Atmospheric_Imaging_Assembly_of_NASA%27s_Solar_Dynamics_Observatory_-_20100819.jpg

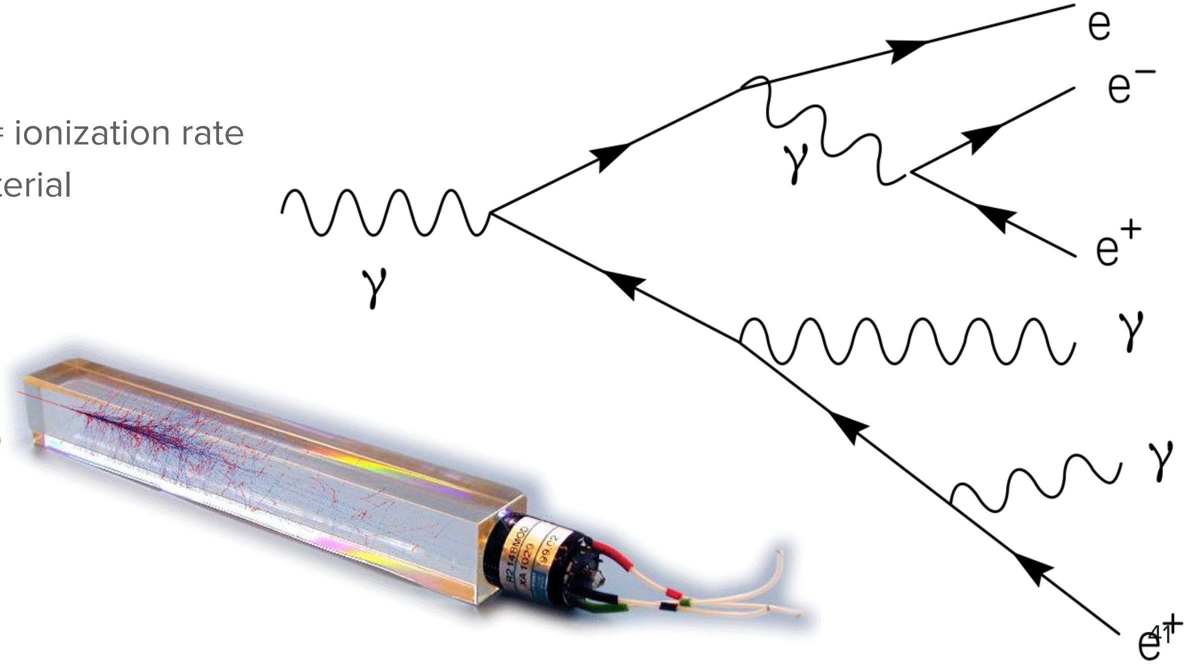
What are we made of?
How do particles get mass?
Gravity is not described by the Standard Model!

Interaction with matter: destructive measurement



Electromagnetic calorimeter

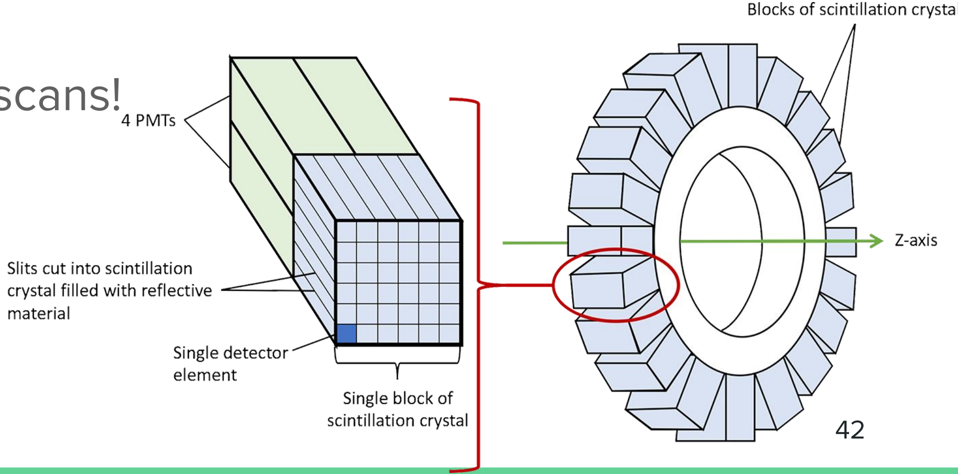
- Electromagnetic shower by interaction with material
- Depth of shower in a material is determined by
  - Energy
  - Critical energy where Brehmsstrahlung rate = ionization rate
  - Radiation length of material



$$X = X_0 \frac{\ln(E_0/E_c)}{\ln 2}$$

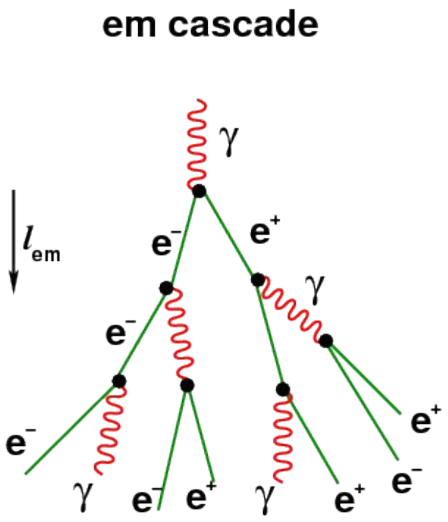
CMS electromagnetic calorimeter

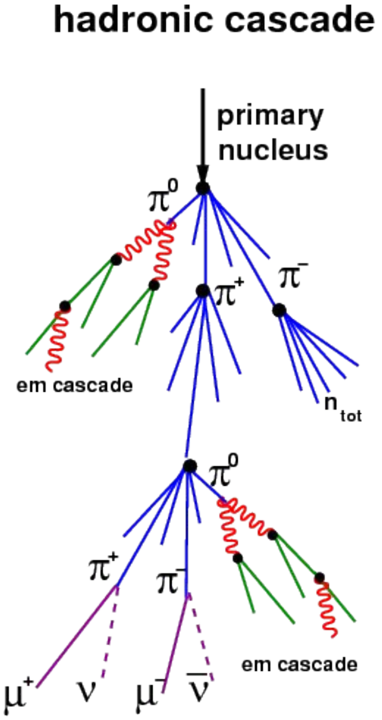
- Crystals made of lead tungstate, weighing 1.5 kg each
- 80,000 crystals each of which took 2 days to grow
- A crystal scintillates when an electron or photon passes through: produces light
- Light is read out with photomultiplier tubes: vacuum tubes that convert light into an electric signal
- Same scintillating crystals as for PET scans!



Hadronic calorimeter

	λ_{int} [cm]	X_0 [cm]
Szint.	79.4	42.2
LAr	83.7	14.0
Fe	16.8	1.76
Pb	17.1	0.56
U	10.5	0.32
C	38.1	18.8





$$X_0 \sim \frac{A}{Z^2}$$

$$\lambda_{int} \sim A^{1/3}$$

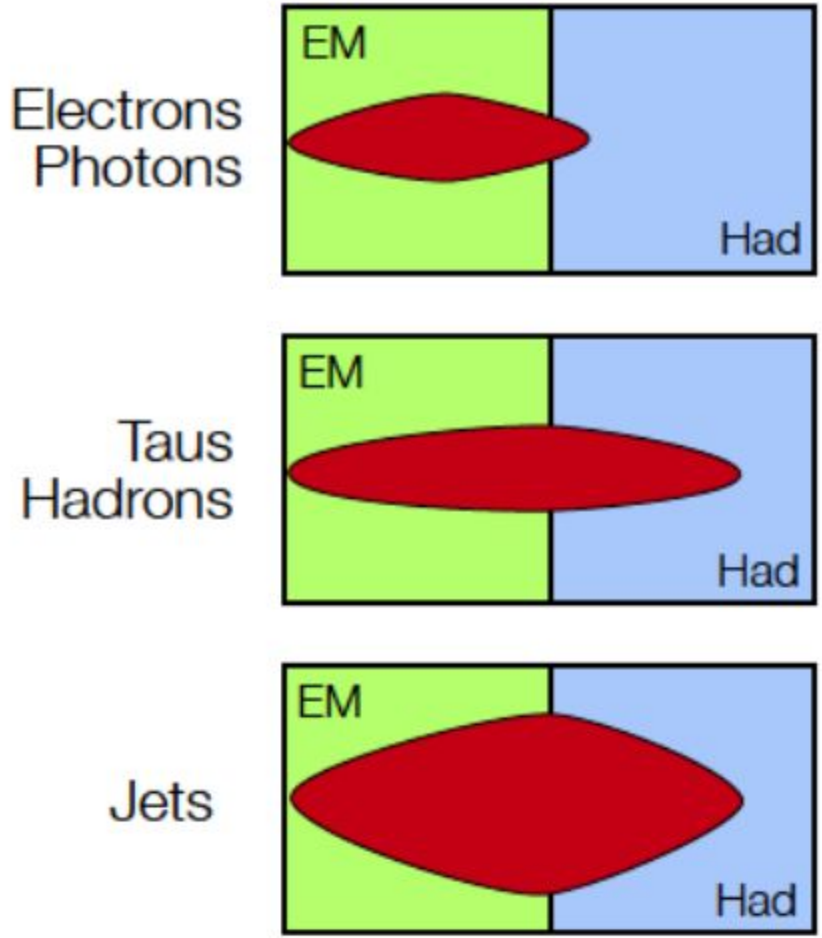
$$\rightarrow \frac{\lambda_{int}}{X_0} \sim A^{4/3}$$

$$\lambda_{int} \gg X_0$$

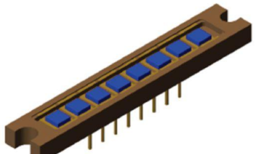
Hadronic calorimeters are much thicker: larger shower depth!

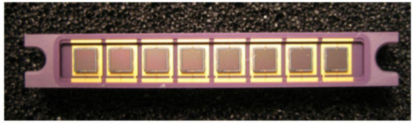
Hadronic calorimeter

Need to consider fraction of electromagnetic energy

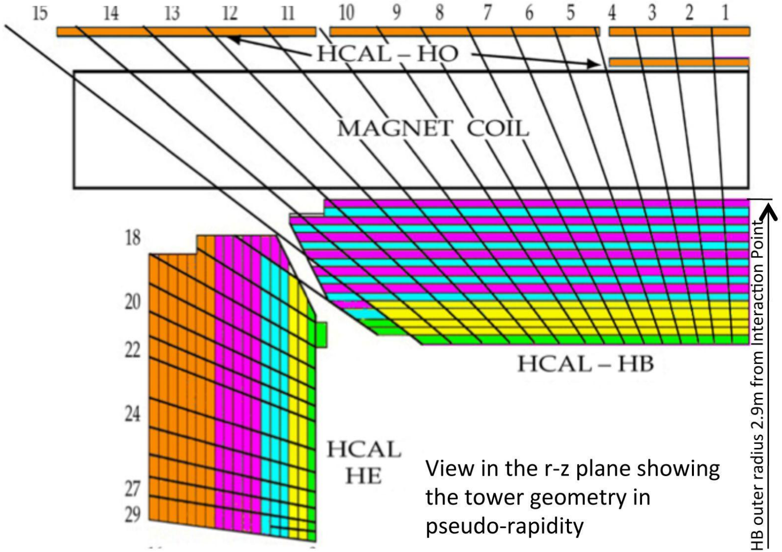


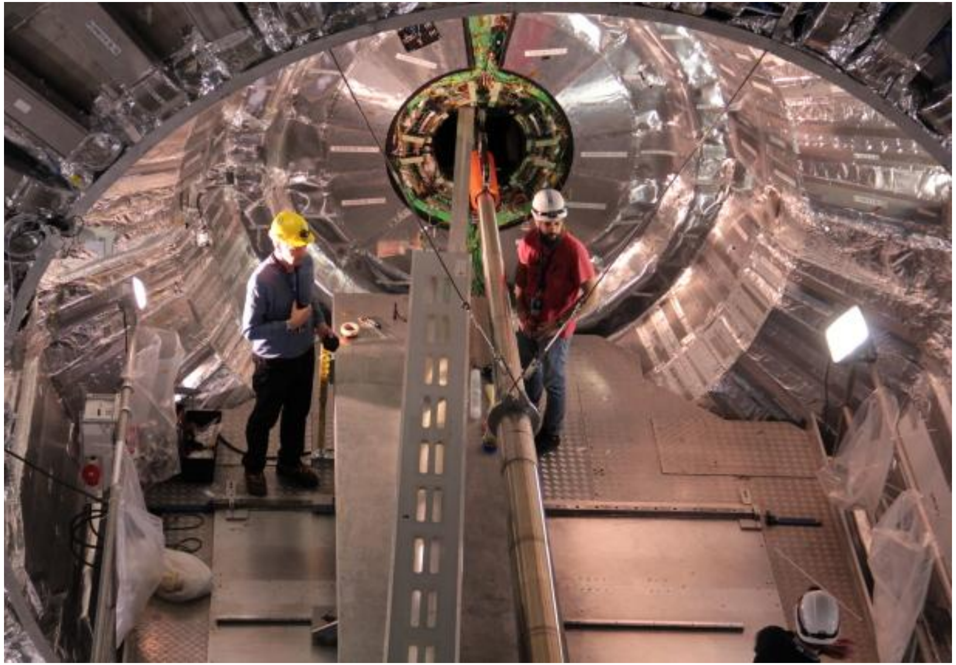
Photomultipliers ➜ silicon photomultipliers





SiPM array in ceramic holder





From hit information for 4 cells (1 tower) ➜ hit information per cell

How to measure neutrinos?

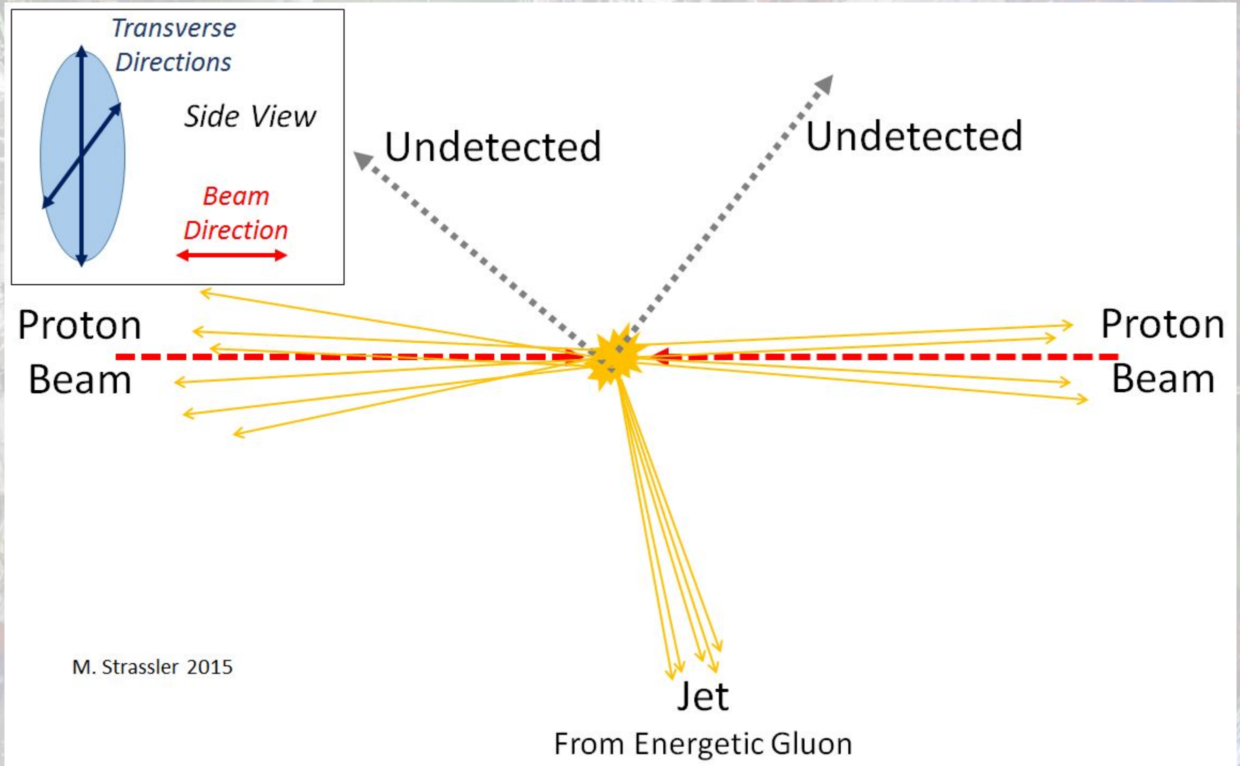
Missing transverse momentum

Neutrinos?

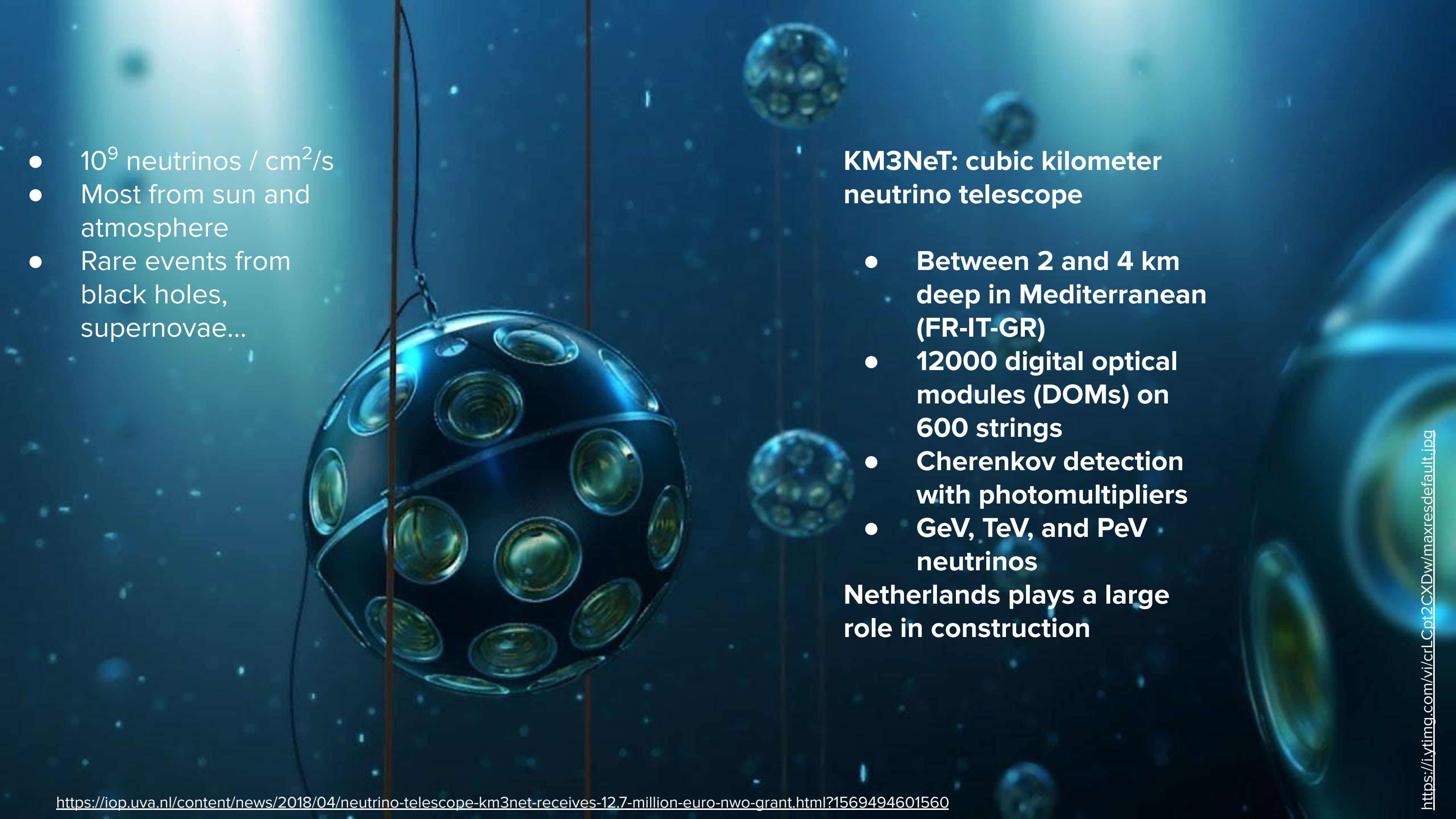
Mismeasurement?

Detector effect?

Dark matter?



https://profmattstrassler.files.wordpress.com/2015/04/pp2nunuj_side.png
https://profmattstrassler.com/articles-and-posts/relativity-space-astronomy-and-cosmology/dark-matter/searching-for-dark-matter-at-the-lhc/



- 10^9 neutrinos / cm^2/s
- Most from sun and atmosphere
- Rare events from black holes, supernovae...

KM3NeT: cubic kilometer neutrino telescope

- **Between 2 and 4 km deep in Mediterranean (FR-IT-GR)**
- **12000 digital optical modules (DOMs) on 600 strings**
- **Cherenkov detection with photomultipliers**
- **GeV, TeV, and PeV neutrinos**

Netherlands plays a large role in construction

https://i.ytimg.com/vi/crLCpt2CXDw/maxresdefault.jpg

https://iop.uva.nl/content/news/2018/04/neutrino-telescope-km3net-receives-12.7-million-euro-nwo-grant.html?1569494601560

KATRIN: neutrino mass measurement

https://www.katrin.kit.edu/img/spectrum_rdax_1200x678.jpg

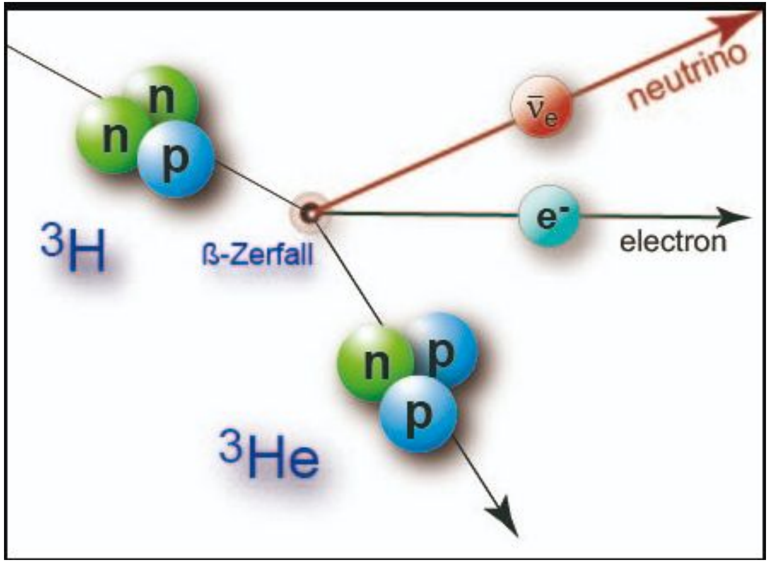
https://upload.wikimedia.org/wikipedia/commons/c/c6/Ortsdurchfahrt-Leopoldshafen.jpg

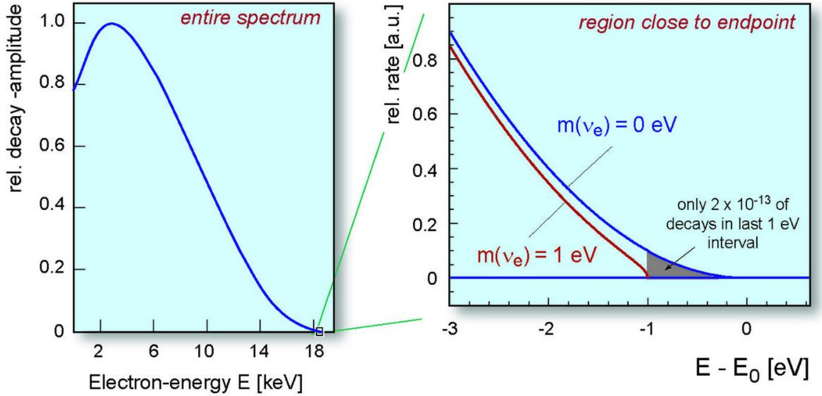
$m_\nu < 1.1$ eV (90% confidence level): twice as precise as previous measurements!

Recently published! https://arxiv.org/abs/1909.06048

KATRIN: neutrino mass measurement

Karlsruhe tritium neutrino experiment





m_ν < 1.1 eV (90% confidence level)

Derive neutrino mass information from electron energy

Recently published!
https://arxiv.org/abs/1909.06048

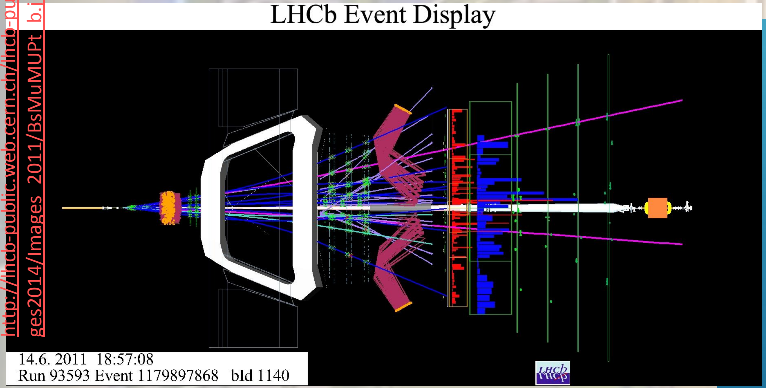
https://www.katrin.kit.edu/img/spectrum_rdax_1200x678.jpg

https://upload.wikimedia.org/wikipedia/commons/c/c6/Ortsdurchfahrt-Leopoldshafen.jpg

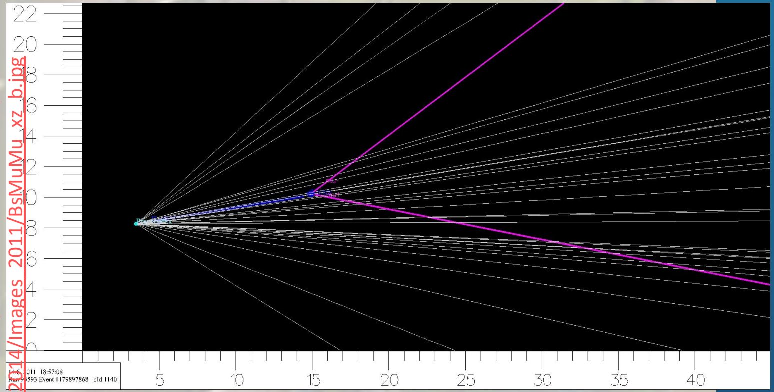
Detecting particles with LHCb

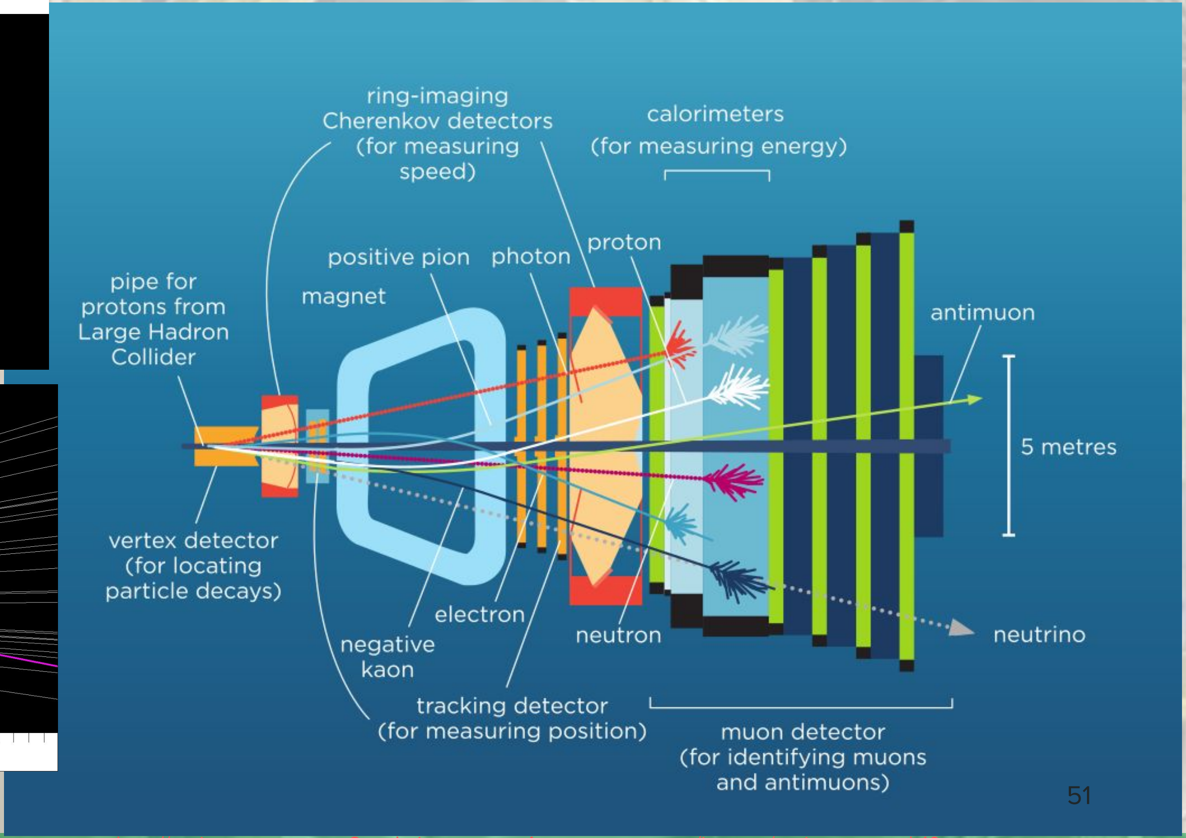
Cerenkov radiation like in HESS

http://lhcb-public.web.cern.ch/lhcb-public/Images2014/Images_2011/BsMuMUPt_b.jpg



http://lhcb-public.web.cern.ch/lhcb-public/Images2014/Images_2011/BsMuMu_xz_b.jpg

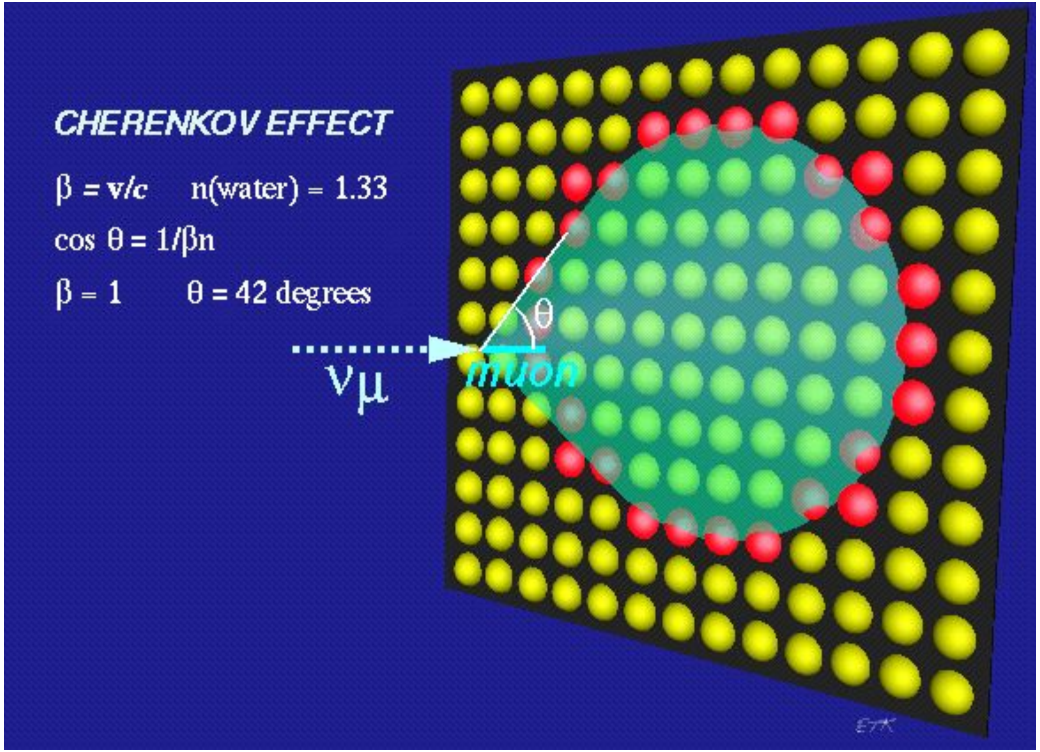


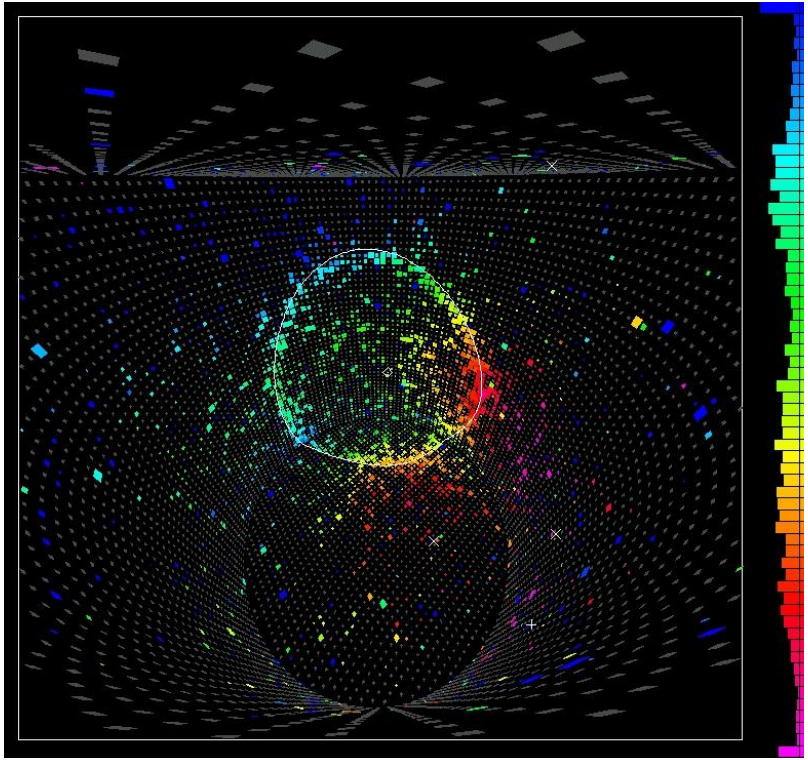


http://lhcb-public.web.cern.ch/lhcb-public/Welcome_270811.html

http://antimattermatters.s3-website-eu-west-1.amazonaws.com/images/antimatter_web10.png

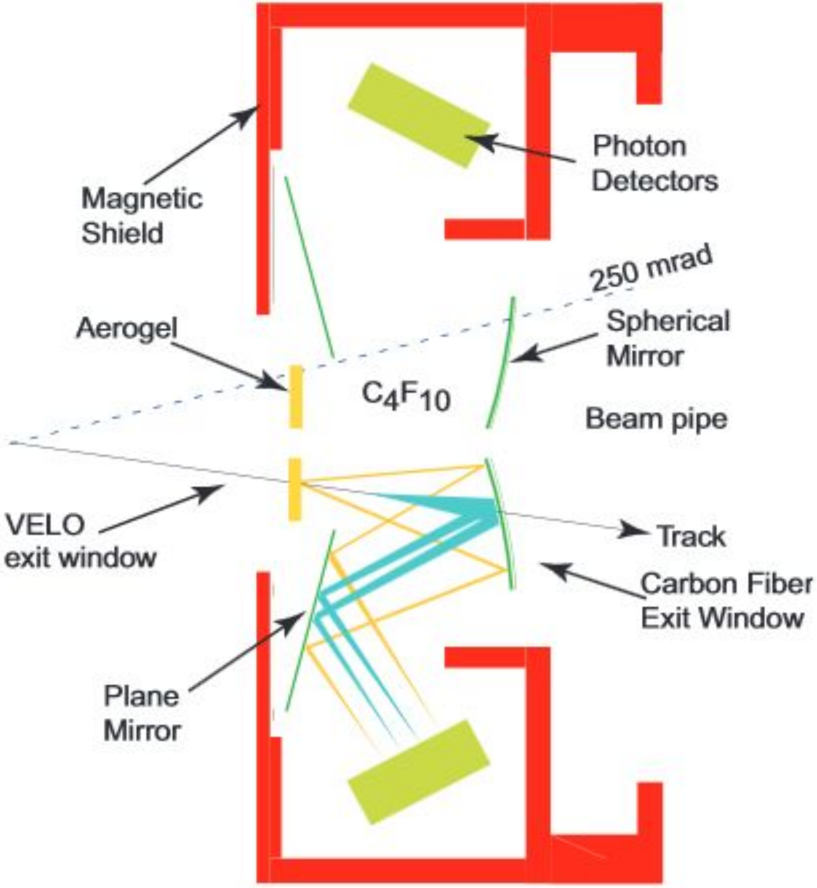
Ring imaging Cherenkov detector





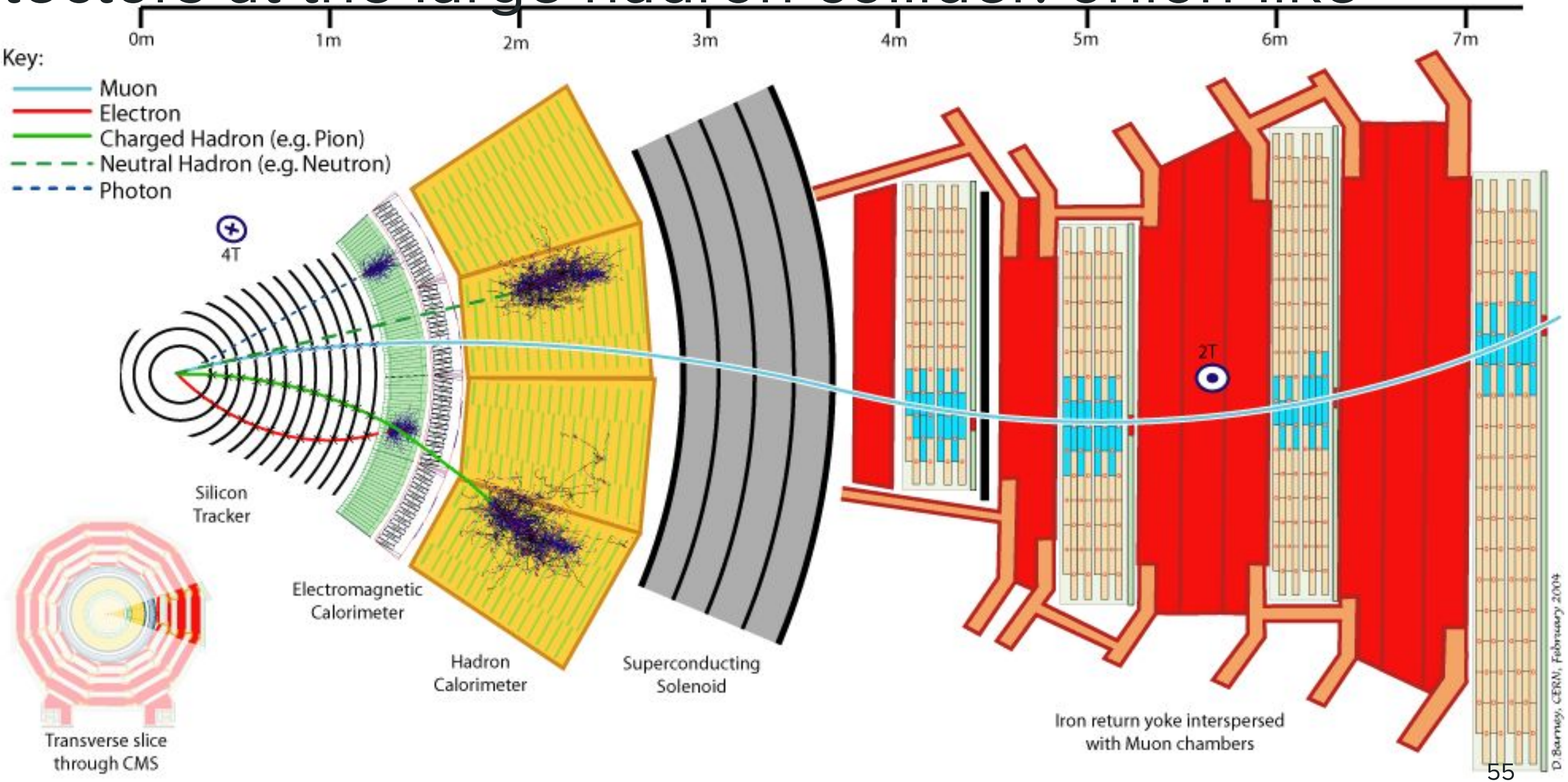
Cherenkov ring from a charged particle from a neutrino interaction in Kamiokande

LHCb RICH


Magnetic Shield
Photon Detectors
250 mrad
Aerogel
Spherical Mirror
C_4F_{10}
Beam pipe
VELO exit window
Track
Carbon Fiber Exit Window
Plane Mirror

How to identify a particle?

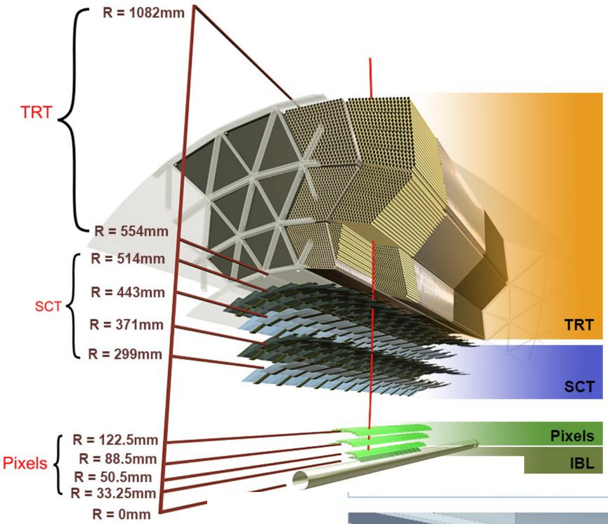
Detectors at the large hadron collider: onion-like



http://inspirehep.net/record/826852/files/EPS_CMS_Slice.png

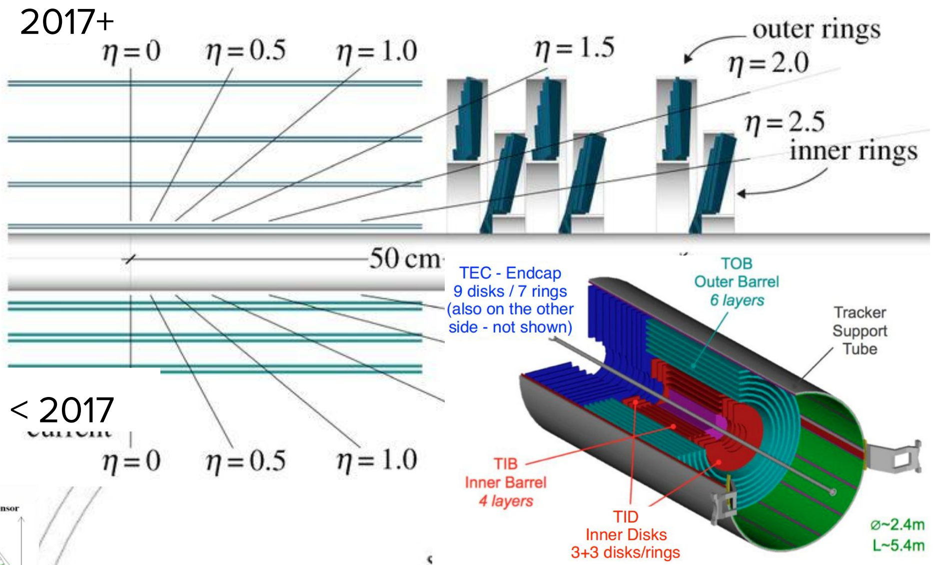
Future detectors

Plan for the LHC

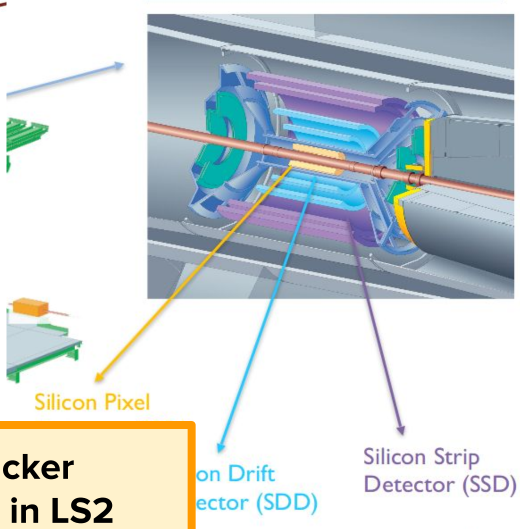


ATLAS: 3.325 cm from beam line

LHC Run 2: inner detector systems December 2018

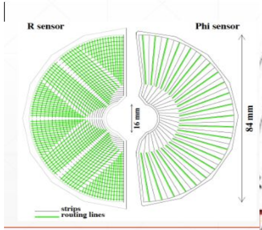


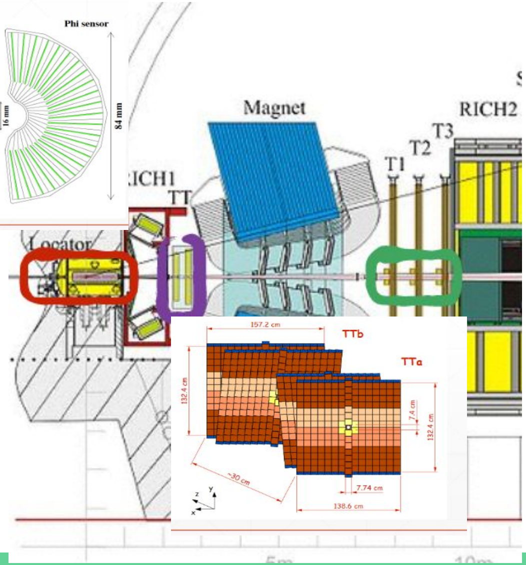
CMS: 2.9 cm from beam line

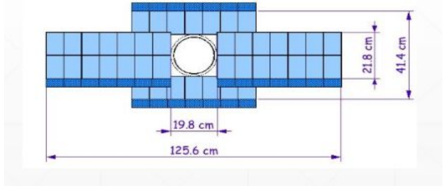


ALICE: 3.3 cm from beam line

Inner tracker upgrade in LS2

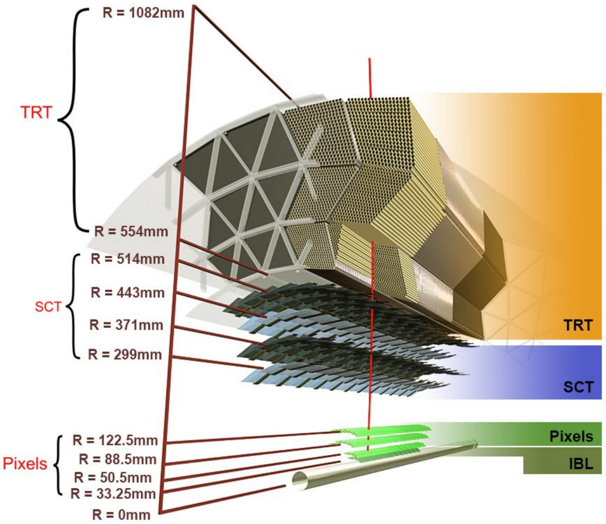






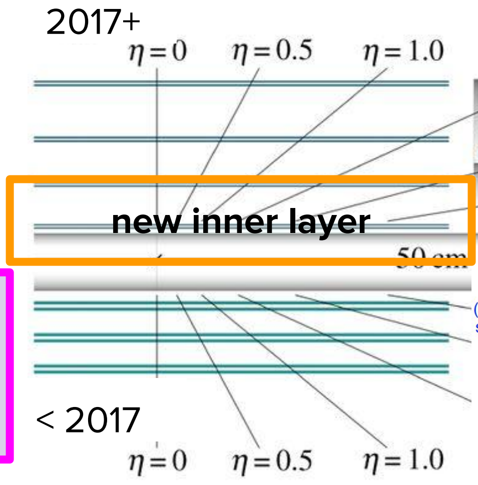
LHCb: 0.7 cm from beam line

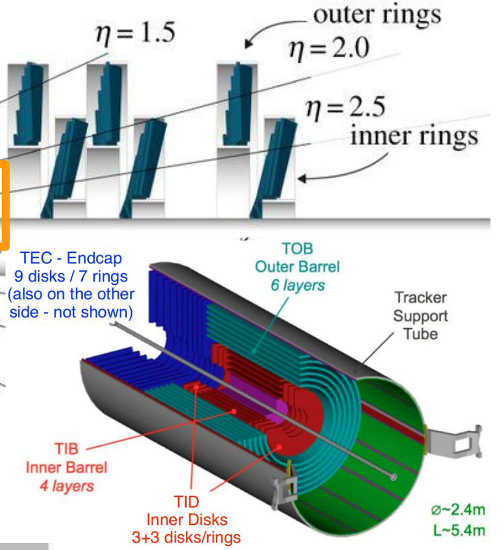
Velo upgrade in LS2



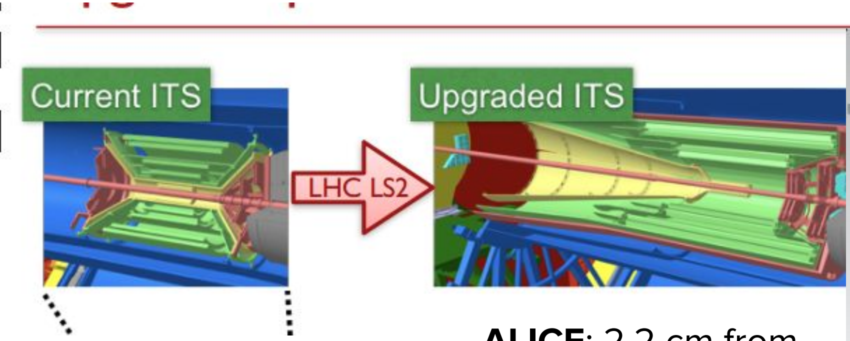
ATLAS: 3.325cm from beam line

LHC Run 2: inner detector systems early 2021



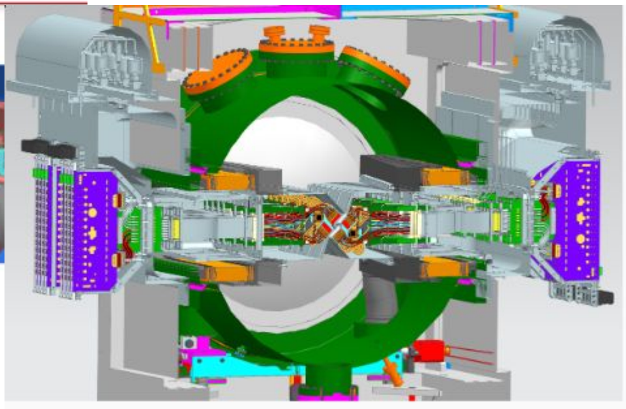


CMS: 2.9 cm from beam line



Inner tracker upgrade in LS2

ALICE: 2.2 cm from beam line, monolithic active pixel sensors 33 µm x 33 µm



LHCb: 0.51 cm from beam line, pixel sensors 55 µm x 55 µm in VELO

VELO and trackers upgrade in LS2

https://www.sciencemag.org/sites/default/files/styles/inline__699w__no_aspect/public/ca_0914NID_CMS_Detector_online.jpg?itok=EzPQHklv