Detector technologies

A brief overview

Image courtesy of CERN

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

jory.sonneveld@cern.ch

Nikhef

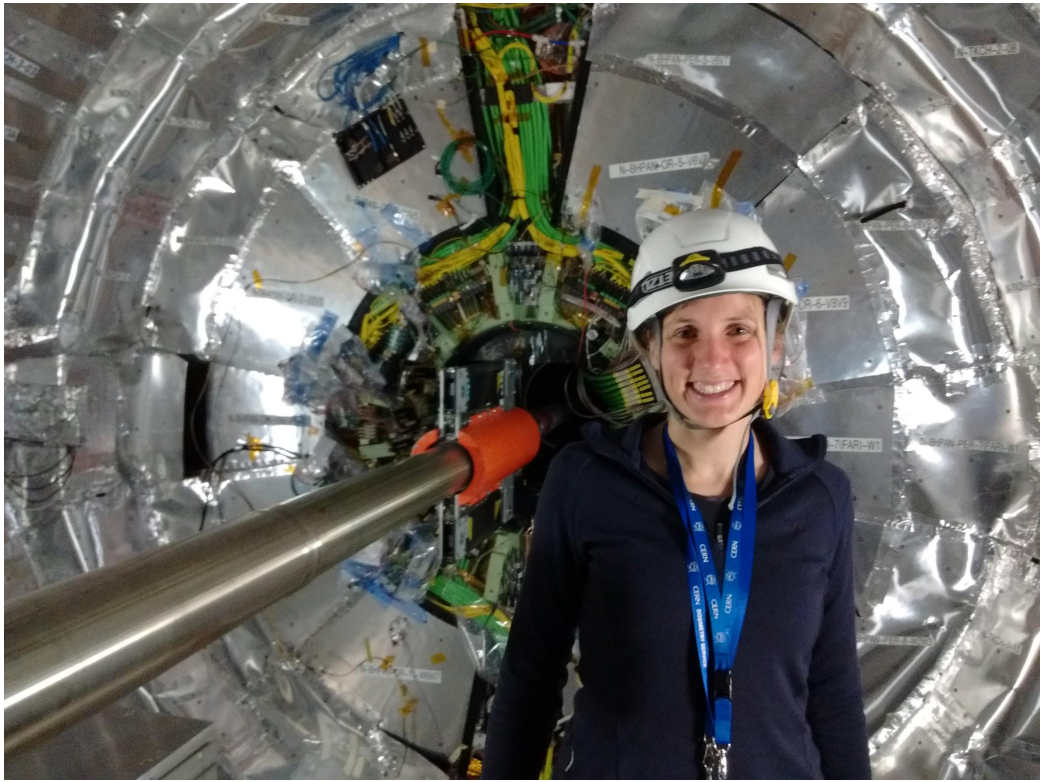
University of Amsterdam

Ik ben onderzoeker in natuurkunde

Ik werk aan de universiteit van Amsterdam en ontwikkel detectoren in de Nikhef detector R&D groep.

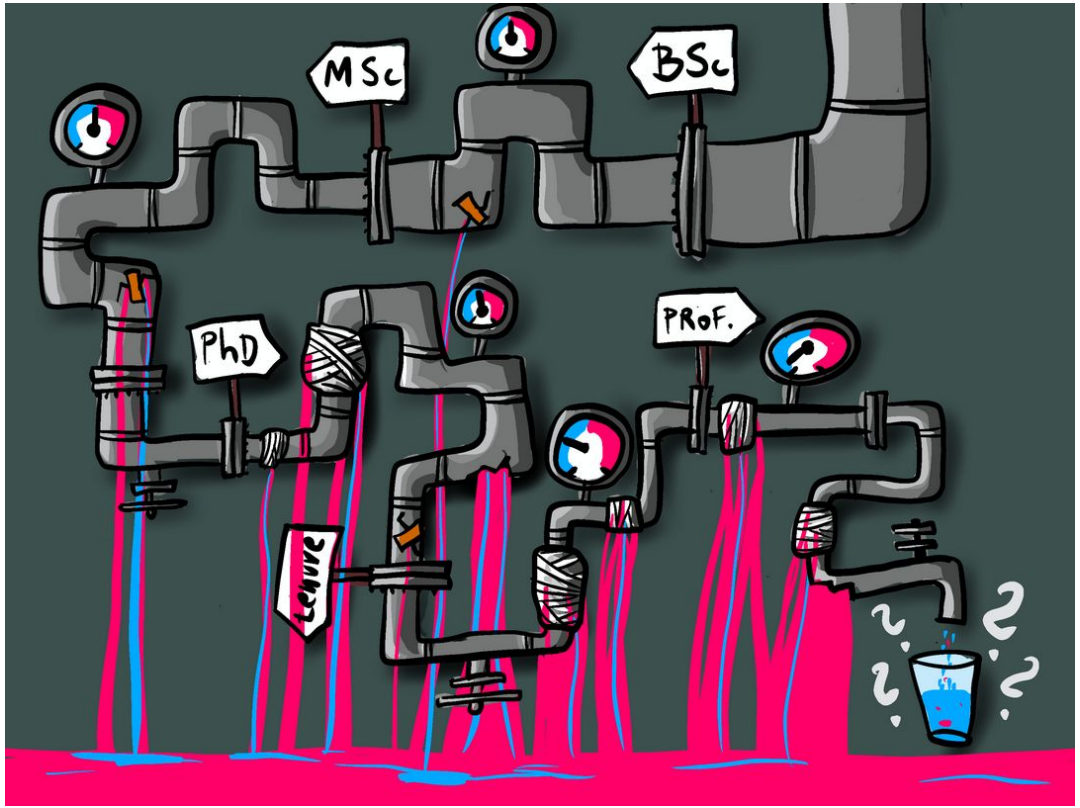
Ik heb ook detectoren bediend en data geanalyseerd: sta ik voor een deeltjesdetector waaraan gewerkt heb op CERN.

Door de buis gaan hele kleine deeltjes met bijna de lichtsnelheid!



Diversiteit

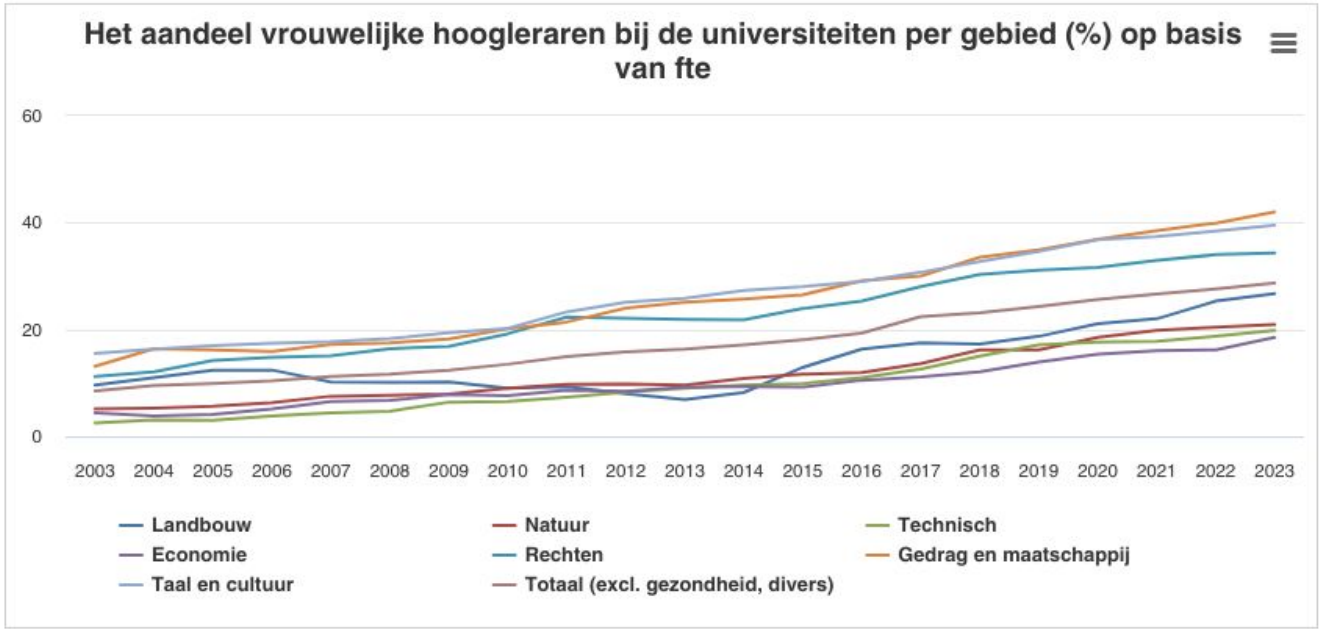
Onderweg naar de carrière gaat veel talent verloren



Onze bachelorinstroom is maar 25% vrouw

https://iop.uva.nl/people/d-i-council/posters/leaky-pipeline.html

Voorbeelden zijn er weinig



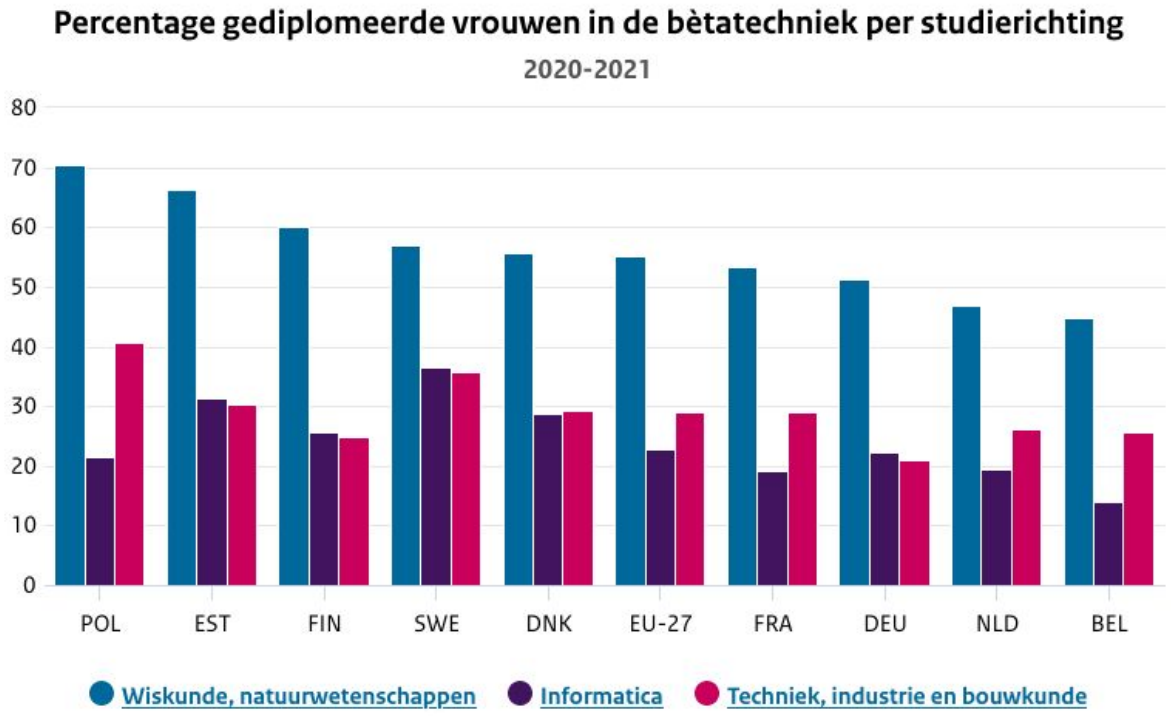
Gegevens: Download als CSV bestand

Bron: UNL/ WOPI

Notities: Exclusief Gezondheid en hoogleraren bij de universitair medische centra. Het percentage vrouwelijke hoogleraren aan de universitair medische centra is toegenomen van 17,3% in 2012 tot 25,7% in 2020. (Zie 'Extra toelichting WOPI').

Van het Rathenau instituut

Weinig vrouwen in techniek in Nederland



Van ocwincijfers.nl

Diversiteit

Image: kcl.ac.uk

Young girls become interested in STEM subjects around the age of 11 and then quickly lose interest when they are 15
Study from 2017 commissioned by Microsoft.

Causes
Social pressure
Lack of mentors
Lack of access to hands-on-learning

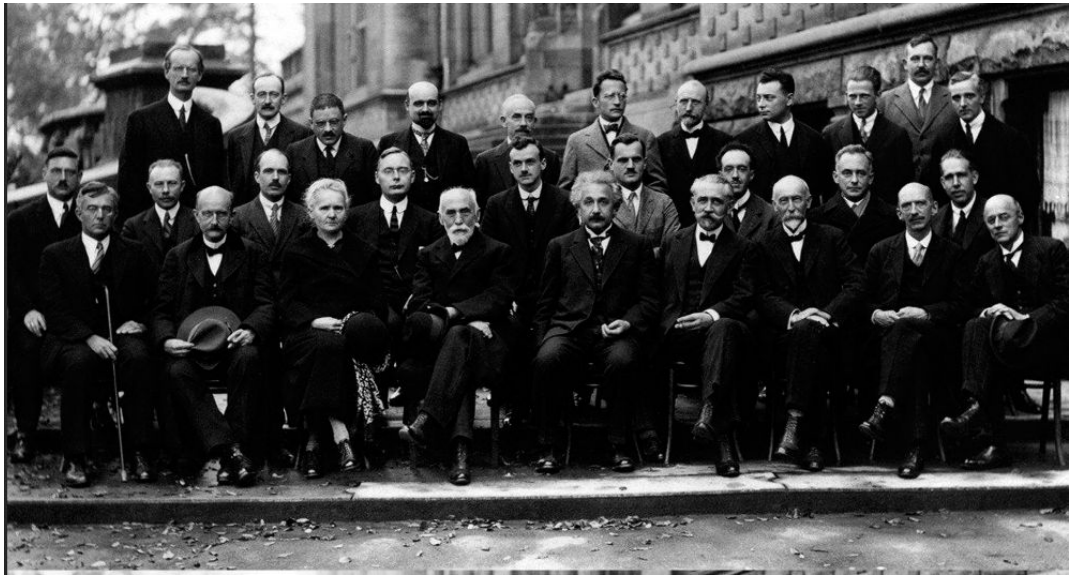
Girls' confidence declines dramatically during puberty, even when they outperform boys in school.

A study published in 2018 asked 1,300 pupils:

- Similar confidence up to age 12
- 30% lower confidence in girls after

Van Kiara Nirghin in de Economist

Diversiteit: waar is iedereen?



Niet-Nederlandse komaf kiest:

- economische opleiding
- universitaire rechtenstudie
- Niet ‘Cultuur en maatschappij’: te "soft"
- Niet ‘natuur en techniek’: te zwaar (!)

Van wikipedia

Vaak hebben allochtone studenten ook een grote ‘drive’ om te willen slagen binnen hun schoolloopbaan, omdat ze het **gevoel hebben dat ze zich meer moeten bewijzen dan autochtone studenten**.

You can make a difference

Affirm girls' achievements and identities, especially between ages 8 and 14:

"The praise I received from my favourite teachers when I was in middle school has stayed with me throughout college. [...] Sometimes all it takes is one teacher affirming you—especially when your cultural identities are not being affirmed anywhere else."

Van Tigidankay Saccoh in de Economist

What can you do?
Emphasize importance of trial-and-error
Affirm achievements

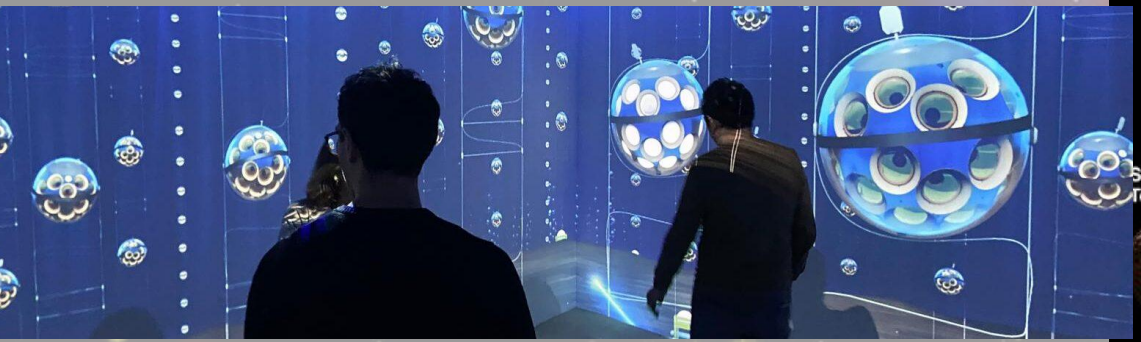
Deeltjes: waar komen ze vandaan?

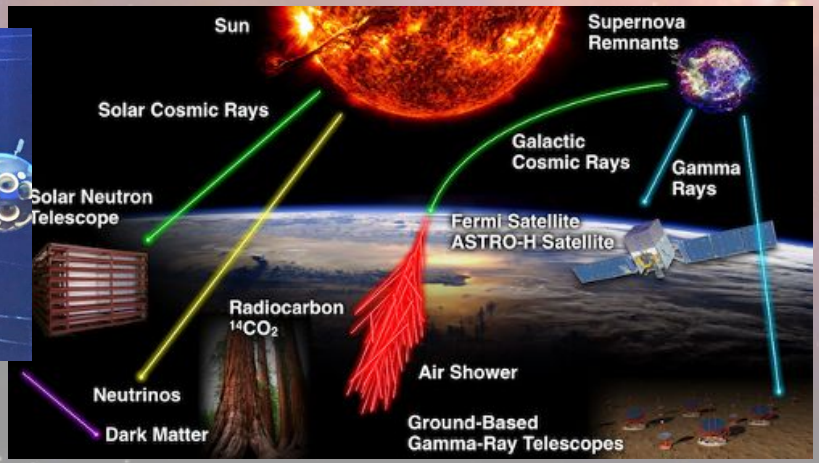
Deeltjes vanuit de ruimte

10000 keer per seconde gaan er deeltjes uit kosmische stralen door jou heen

Wat zijn die deeltjes en hoe gedragen ze zich?
Waarvan zijn wij en het universum gemaakt?

From https://www.km3net.org/





KM3net: cubic kilometer neutrino telescope
in Mediterranean Sea, can detect photons
kan gamma stralen detecteren

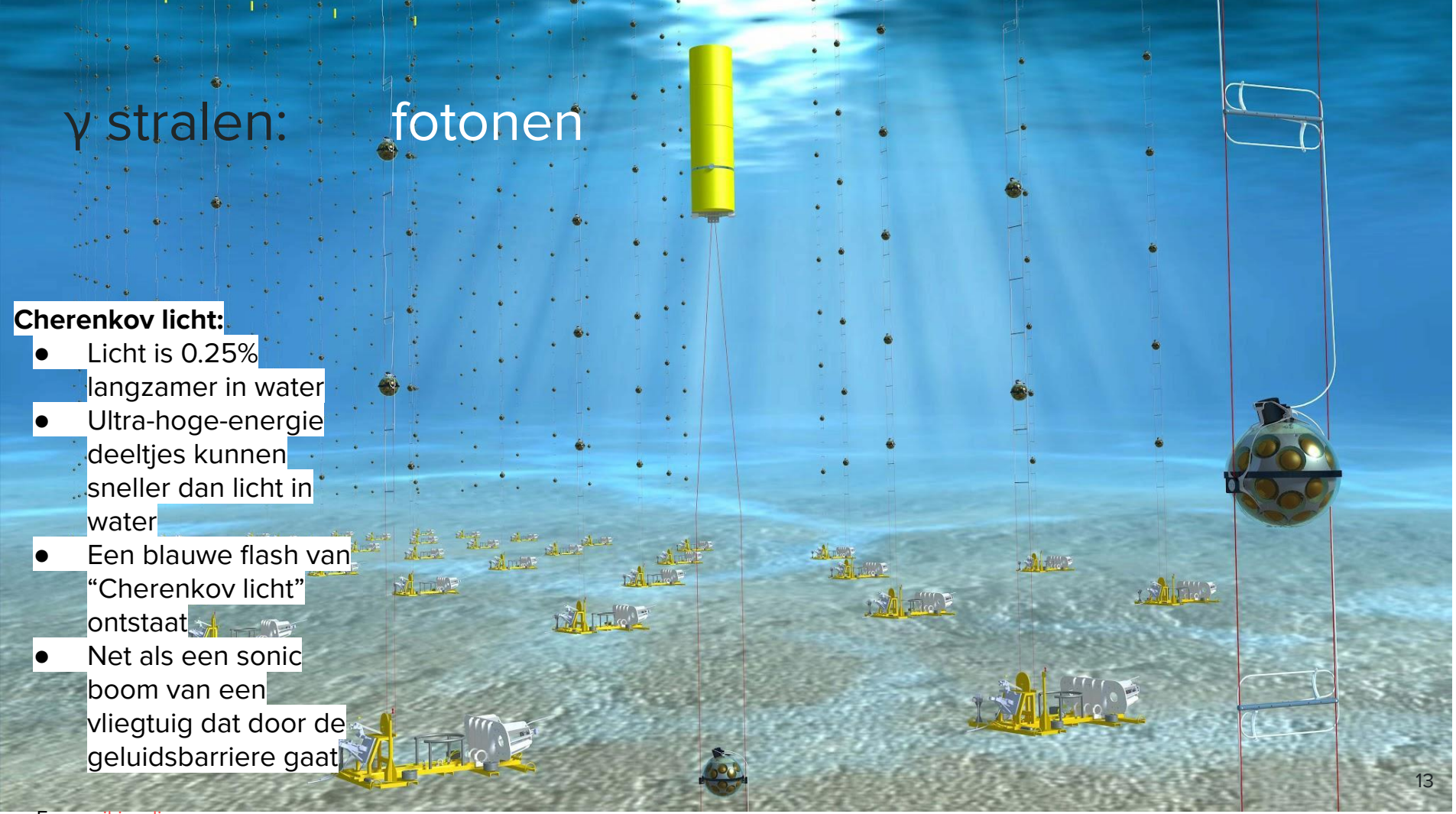
http://www.isee.nagoya-u.ac.jp/en/assets_c/2016/03/study01_1-thumb-500xauto-153.png

Hoe kunnen we zo’n deeltje detecteren?

γ stralen: fotonen

Cherenkov licht:

- Licht is 0.25% langzamer in water
- Ultra-hoge-energie deeltjes kunnen sneller dan licht in water
- Een blauwe flash van “Cherenkov licht” ontstaat
- Net als een sonic boom van een vliegtuig dat door de geluidsbarriere gaat



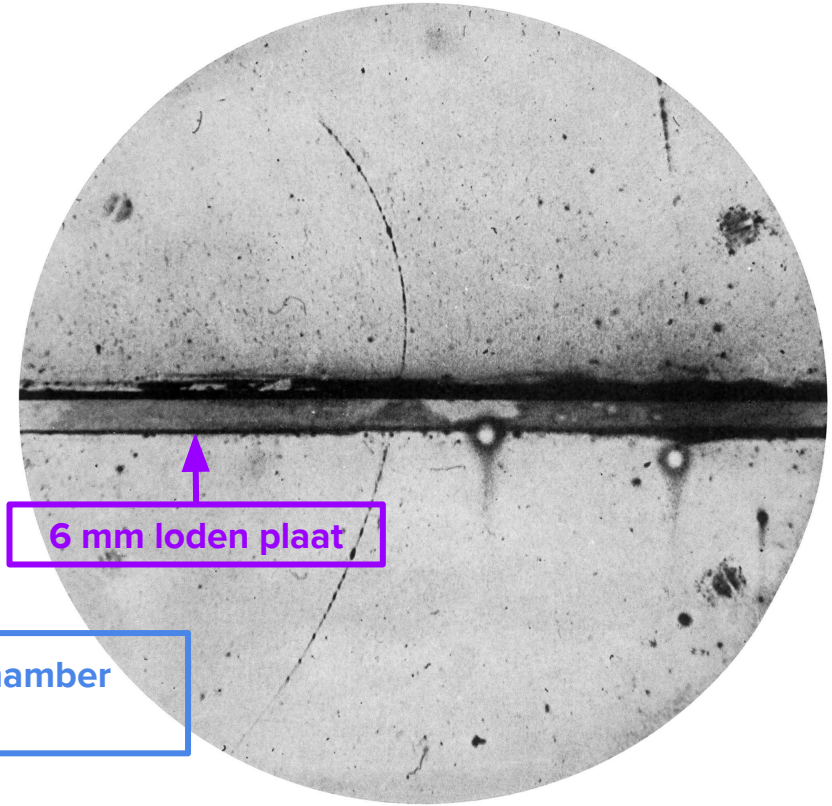
From wikipedia

Ontdekking van antimaterie

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

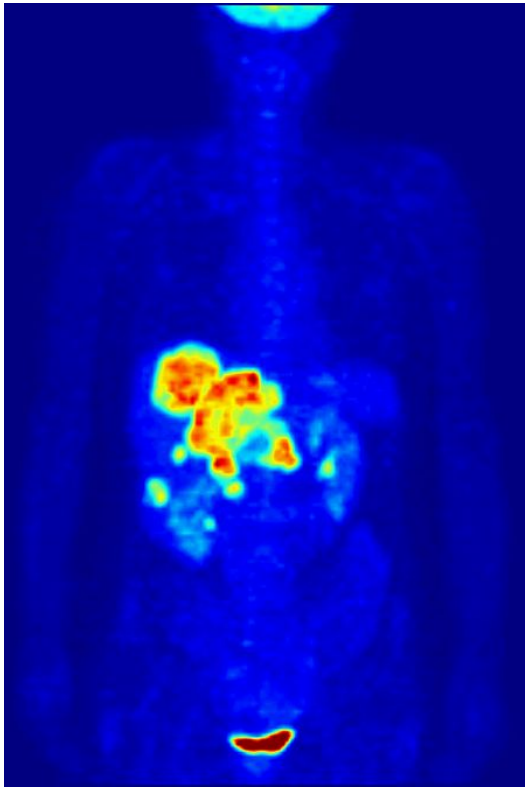
Het eerste positron ooit geobserveerd!

Nevelkamer: gasmengsel van superverzadigd water of alcohol. Een energetisch deeltje ioniseert het gas en ionen vormen condensatiecentra die zichtbaar worden als wolk.



15000 Gauss = 1.5T magnetisch veld Wilson cloud chamber (nevelkamer) voor detectie van kosmische straling

Meer deeltjesdetectoren



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

(b)

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

Positron emission tomography

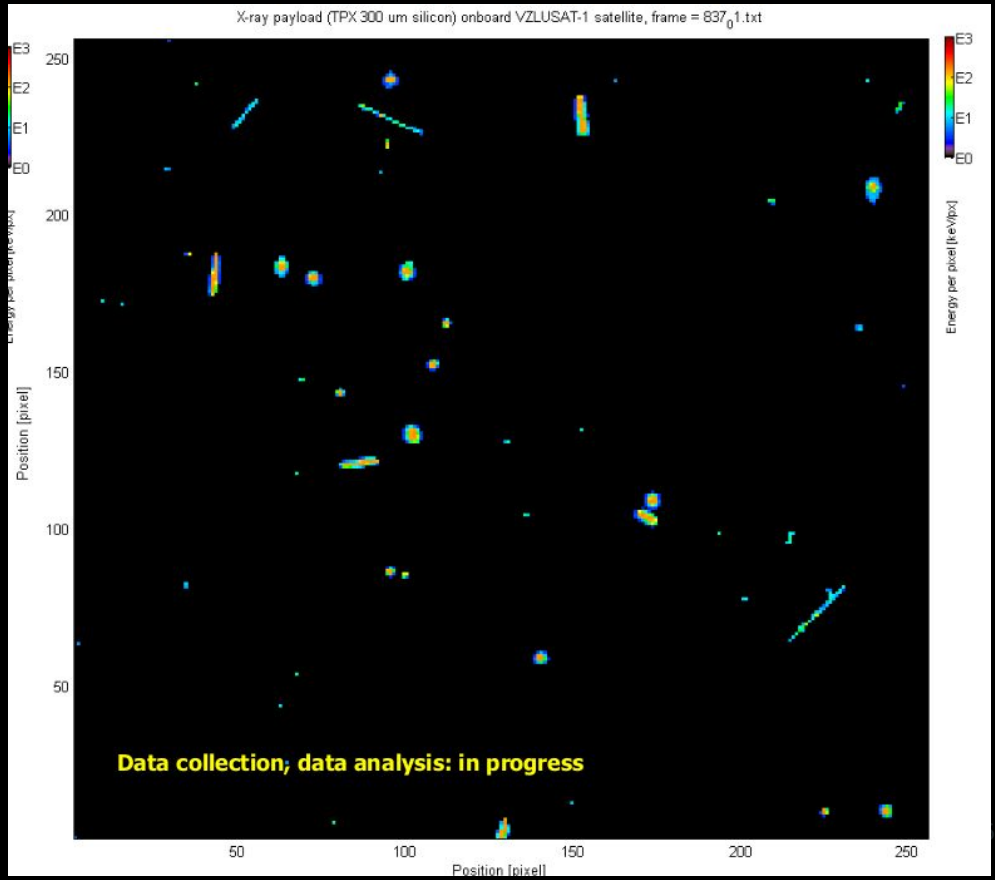
https://upload.wikimedia.org/wikipedia/commons/thumb/d/d9/Smoke_detector.JPG/1920px-Smoke_detector.JPG

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

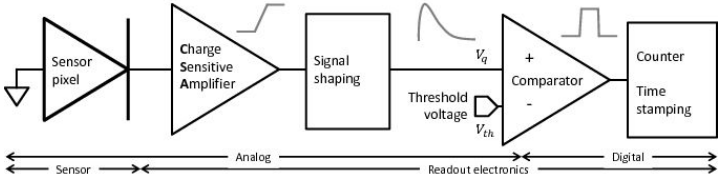
Detectie van deeltjes

Deeltjes laten sporen achter!

See also
https://advacam.com/camera/edu-kit/
or no need for the whole package:
https://advacam.com/camera/minipix-edu/

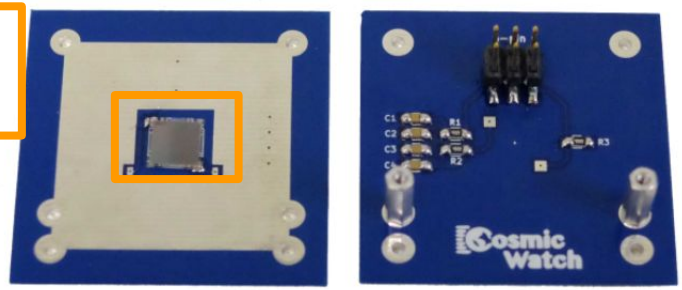


Build your own muon detector



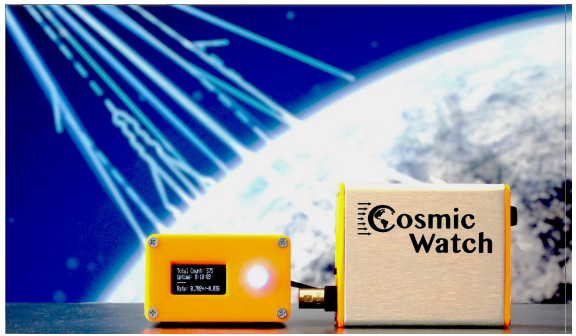
Readout: arduino

Silicon photomultiplier



scintillator

With a scintillator (plastic) and a silicon photomultiplier you can build your own muon detector!



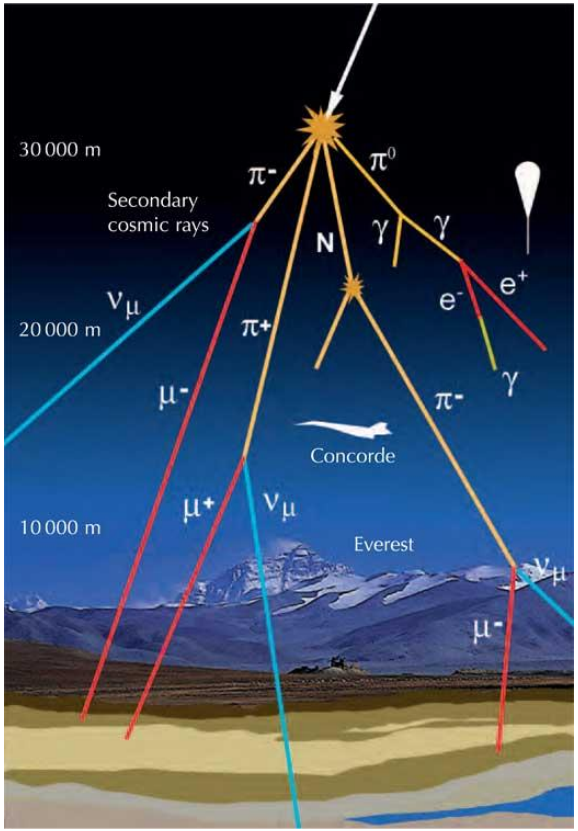
[Cosmic Watch Detector]

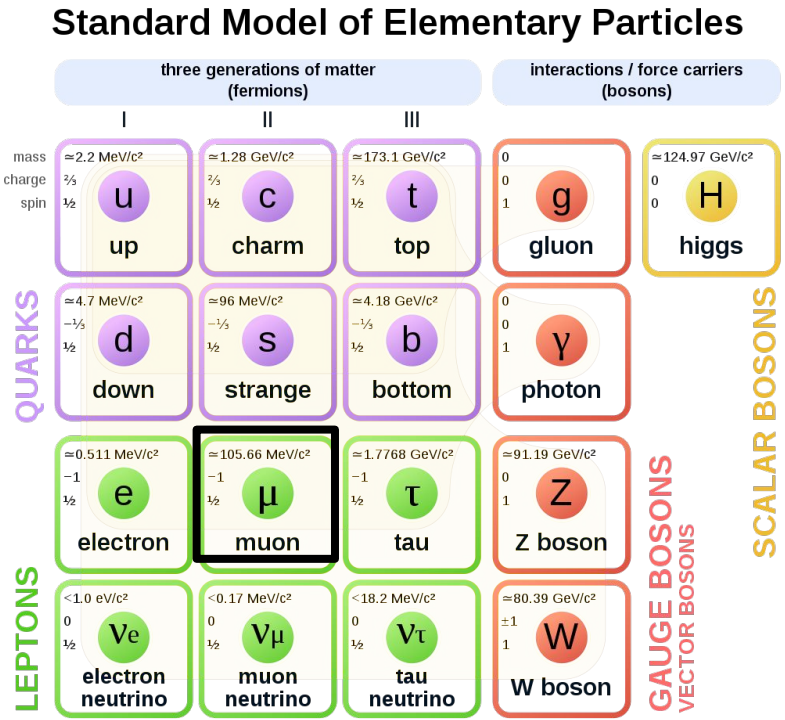
Figures from [here] and [here]

Wat voor deeltjes?

Vele verschillende deeltjes!

Waar is het proton?

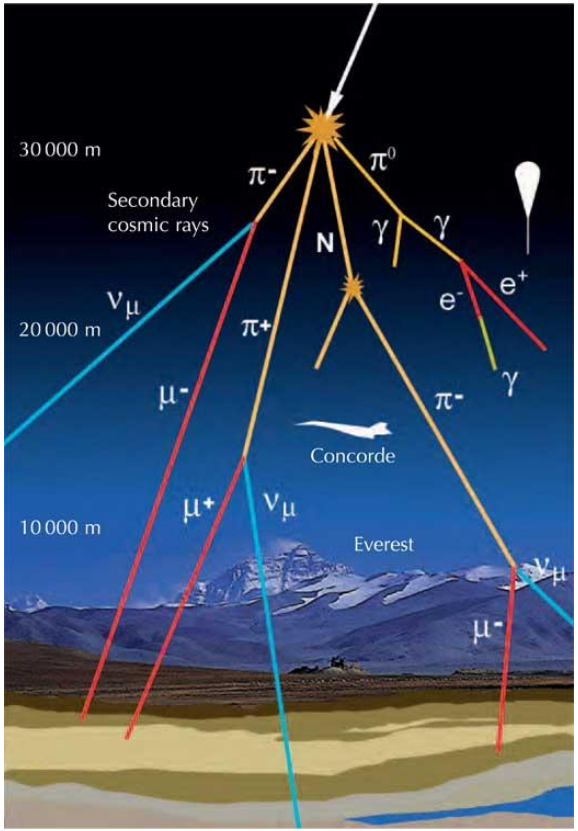


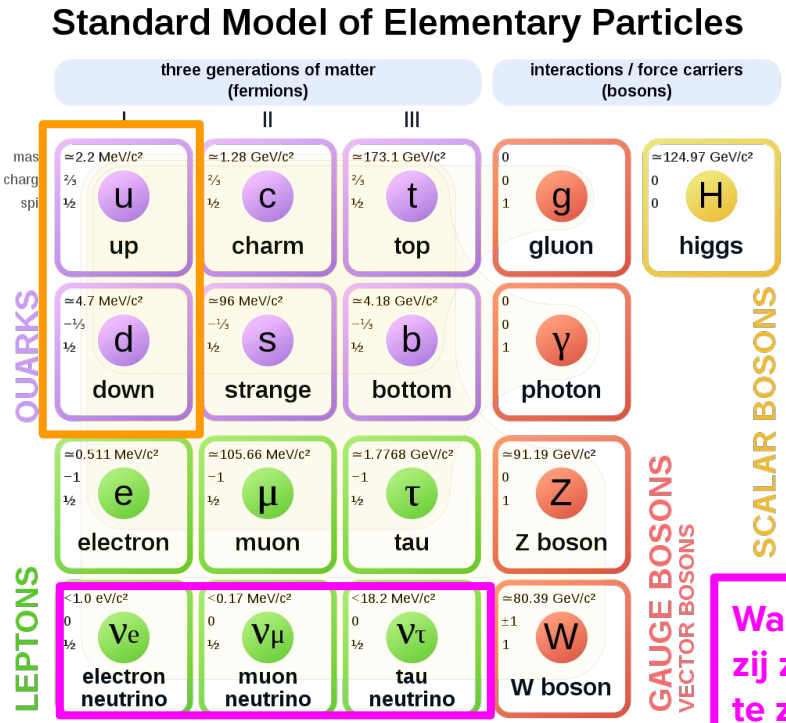


leder deeltje gedraagt zich anders, afhankelijk van massa, lading. Op aarde zien we veel **muonen.**

Vele verschillende deeltjes!

Proton = u+u+d
3 quarks! Samengehouden door gluonen.





Waarom zijn zij zo moeilijk te zien?

leder deeltje gedraagt zich anders, afhankelijk van massa, lading. Op aarde zien we veel **muonen.**

Hoe detecteer je zo’n deeltje op CERN?

Large Hadron Collider

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

6.8 tera-electronvolt (**TeV**) per proton beam
Largest and most powerful collider in the world!

protons

Two beampipes!

p

p

https://cdn.mescience.com/wp-content/uploads/2015/05/cern-lhc-aerial.jpg
H t tp://s ites.uci.edu/energyobserver/files/2012/08/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

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

2x2800 bunches of protons 25 ns apart

protons

LHCb

ATLAS

CERN Meyrin

CERN Prevessin

7 km

SUISSE

FRANCE

CMS

ALIC

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

MeV = 10^6 eV

GeV = 10^9 eV

TeV = 10^{12} eV

PeV = 10^{15} eV

Two beampipes!

p

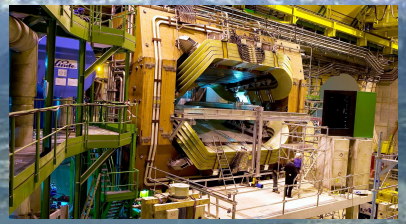
p

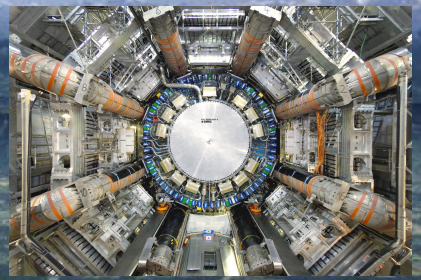
LHC 27 km

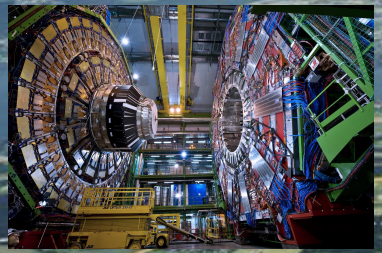
https://cdn.mescience.com/wp-content/uploads/2015/05/cern-lhc-aerial.jpg
H t tp://s ites.uci.edu/energyobserver/files/2012/08/lhc-aerial.jpg
https://upload.wikimedia.org/wikipedia/commons/6/62/CERN_LHC_Proton_Source.JPG

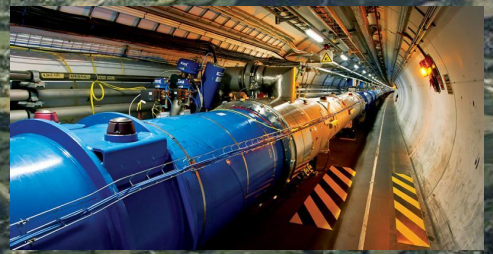
https://www.youtube.com/watch?v=NhXMXiXOWAA
https://home.cern/sites/home.web.cern.ch/files/image/inline-images/old/lhc_long_1.jpg

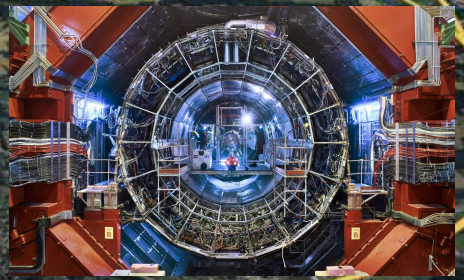
Large Hadron Collider











https://cdn.zmescience.com/wp-content/uploads/2015/05/cern-lhc-aerial.jpg
H.t. tp://s..ites.uci.edu/energyobserver/files/2012/01/lhc-aerial.jpg
https://upload.wikimedia.org/wikipedia/commons/6/62/CERN_LHC_Proton_Source.JPG
https://home.cern/sites/home.web.cern.ch/files/image/inline-images/old/lhc_long_1.jpg

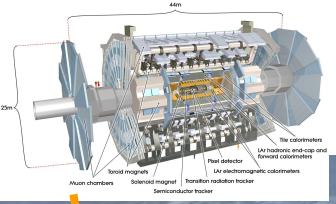
LHC magneten: Kouder dan het universum!

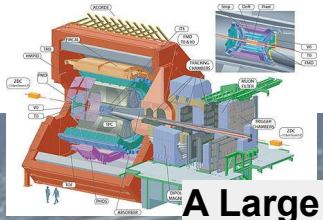
Naar 1.8 K zodat de magneten (in het blauwe omhulsel) supergeleidend worden

Het universum is warmer: 2.73 kelvin!

van cern.ch

Detectors at the LHC





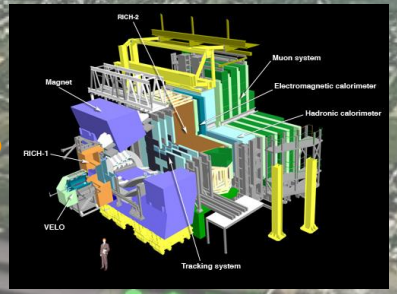
ALICE

ATLAS

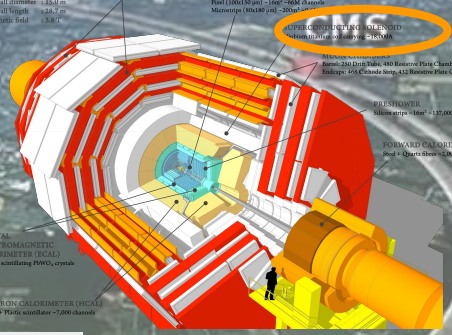
LHCb

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

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



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
Why a second multipurpose detector?



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

Other detectors: MoEDAL, TOTEM, LHCforward, Faser, SND

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

Wat detecteren we?

Niet alle bekende elementaire deeltjes!

Directly detect:

Vervalsproducten **jets**

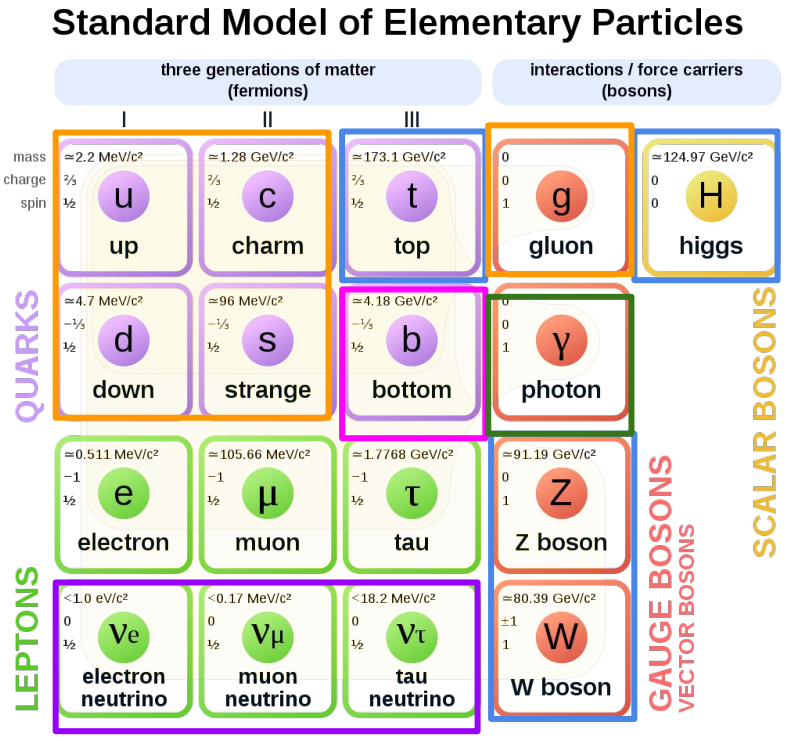
Indirectly detect:

Missing energy

Secondary vertex + jets

Neutral particles

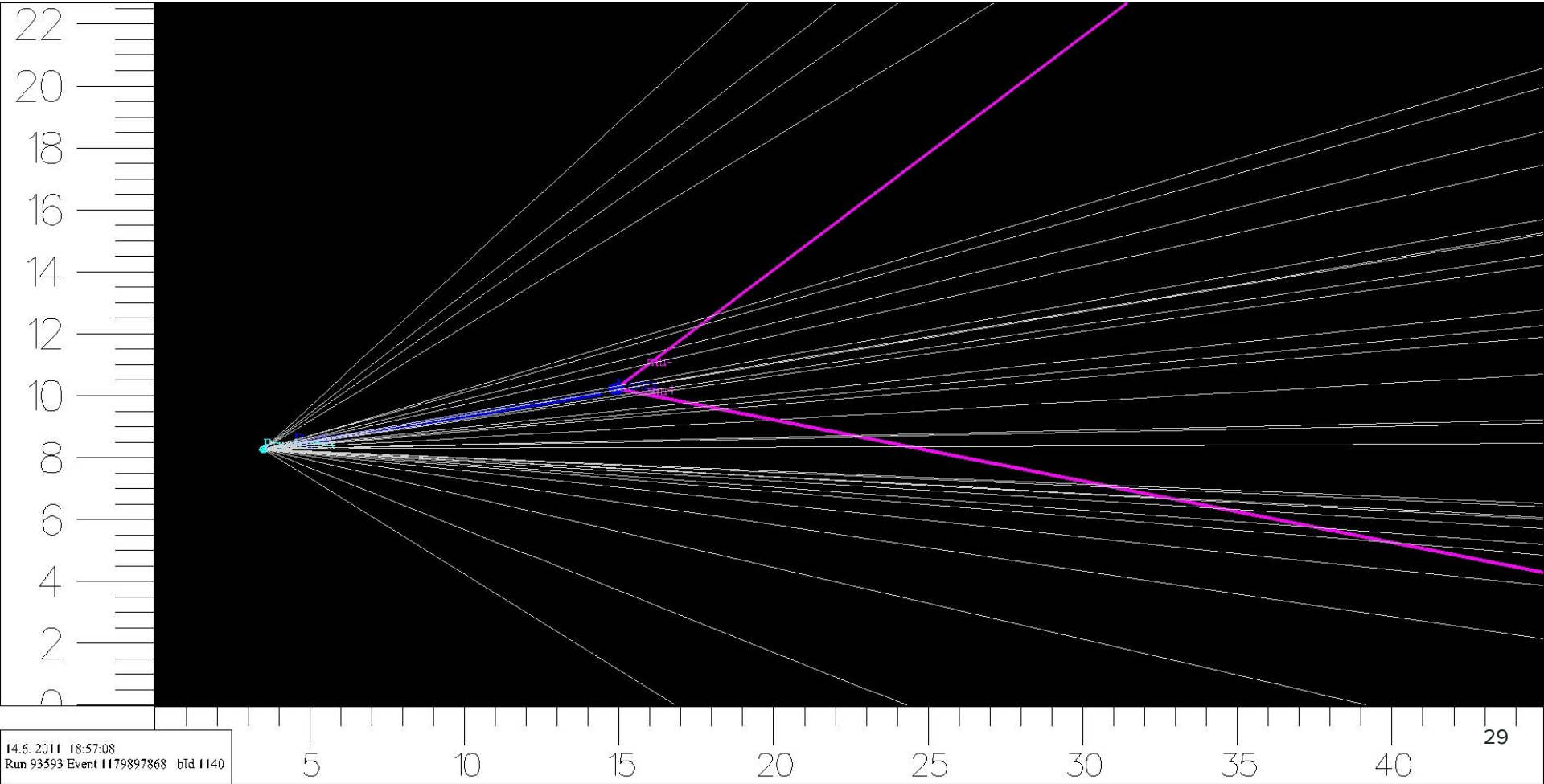
Should be able to detect and identify:
$e^{\pm}$, $\mu^{\pm}$, γ, $\pi^{\pm}$, $K^{\pm}$, $p^{\pm}$, K^{0}, n
using mass, charge, interaction



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

LHCb $B_s \rightarrow \mu^+\mu^-$

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



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

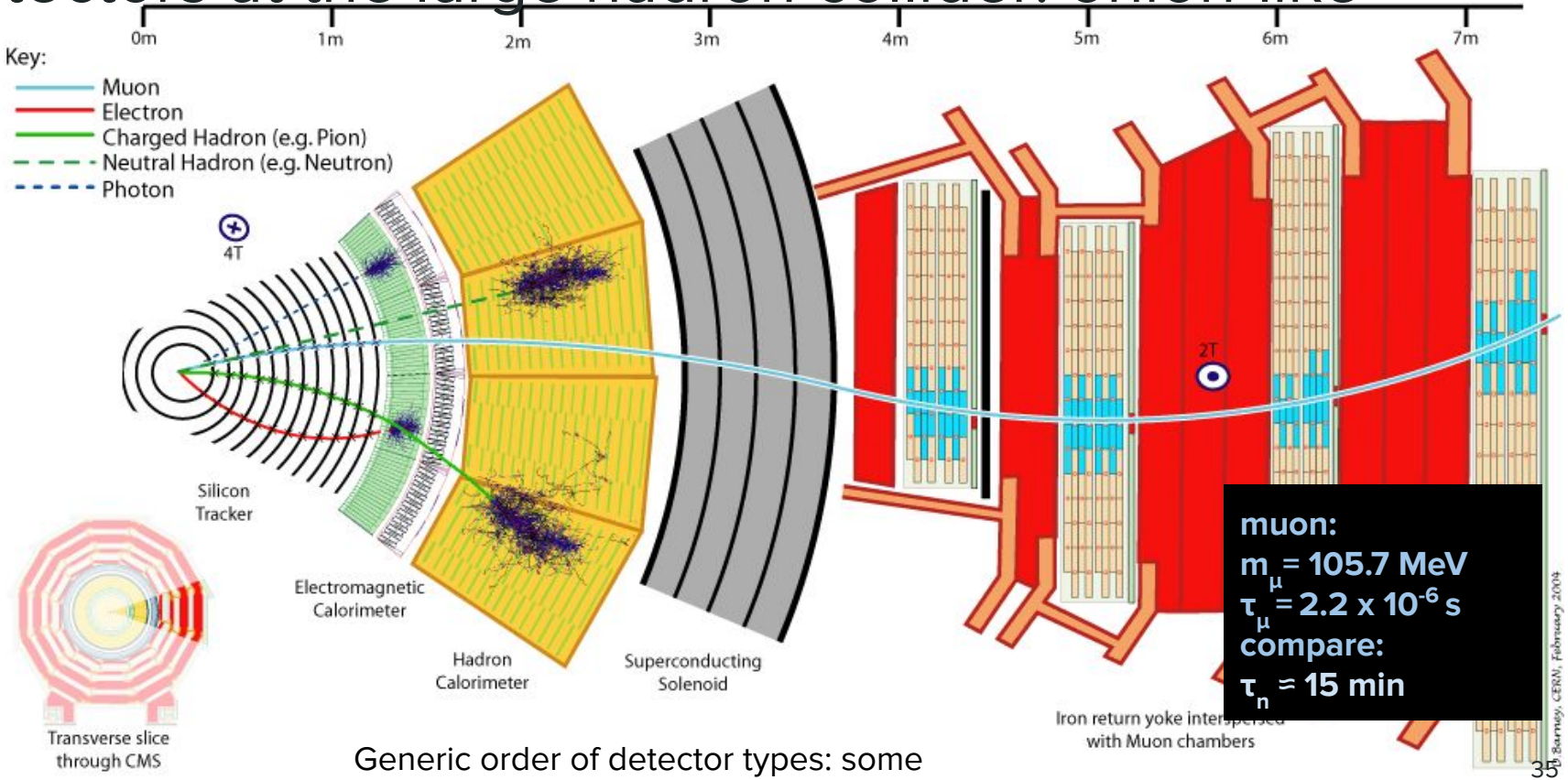
Hoe detecteren we?

100 meter onder de grond is een holte voor experimentatie, van de grootte van een kathedraal, die 1 van de twee experimenten herbergt die het Higgs boson heeft gevonden: CMS, een detector van 14000 ton !

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

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

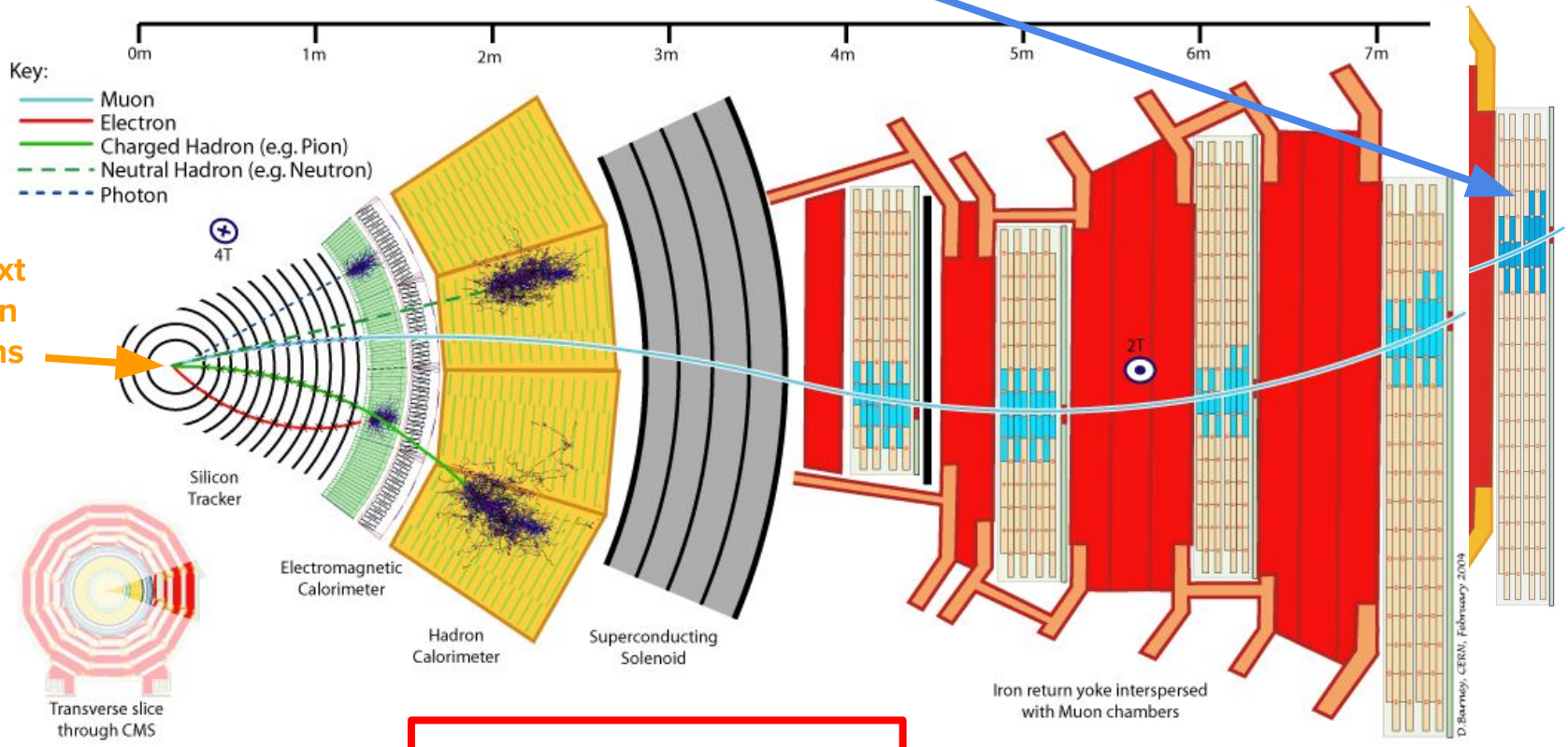
Detectors at the large hadron collider: onion-like



Generic order of detector types: some measurements destructive!

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

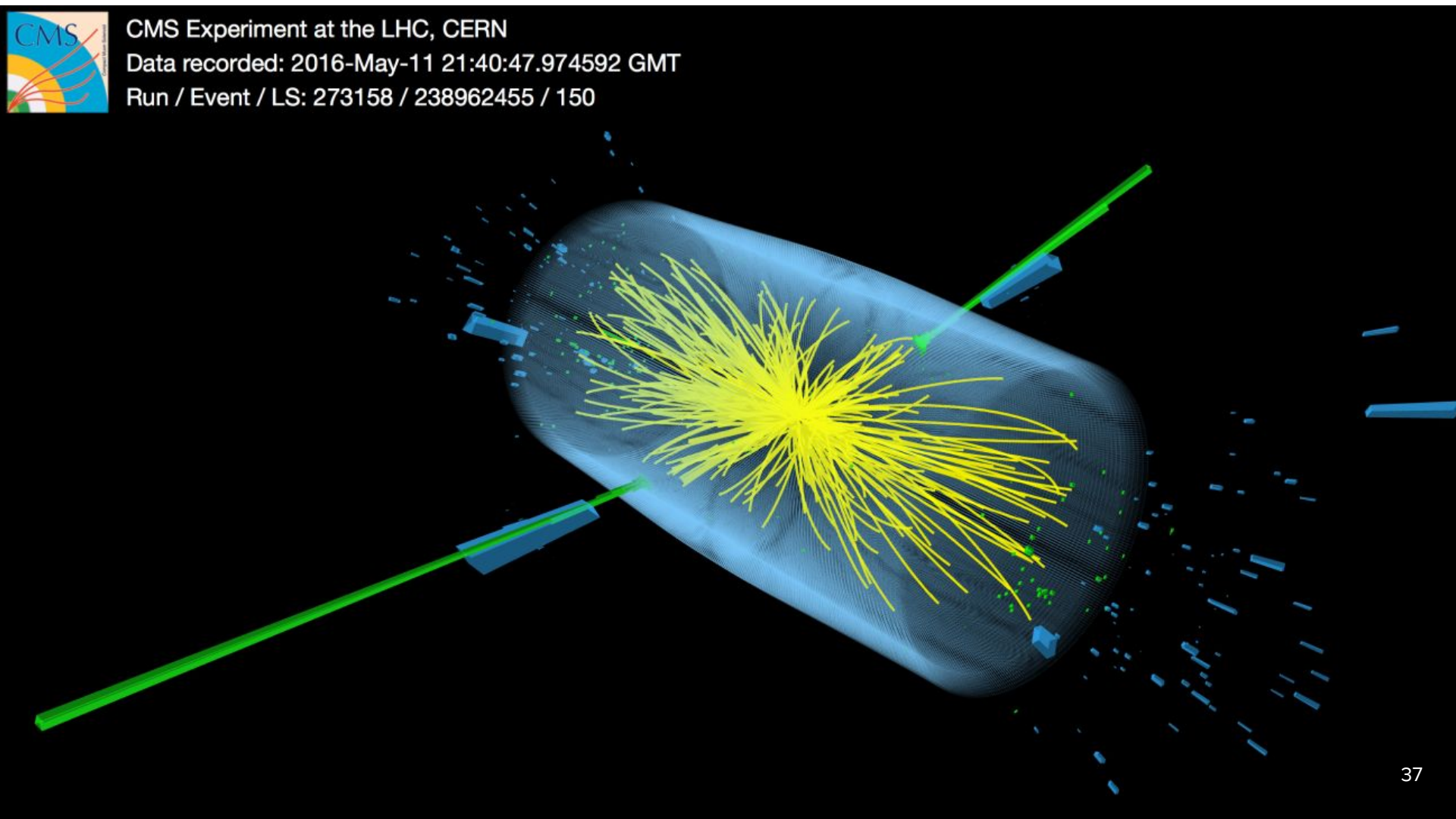
Note when the muon arrives here



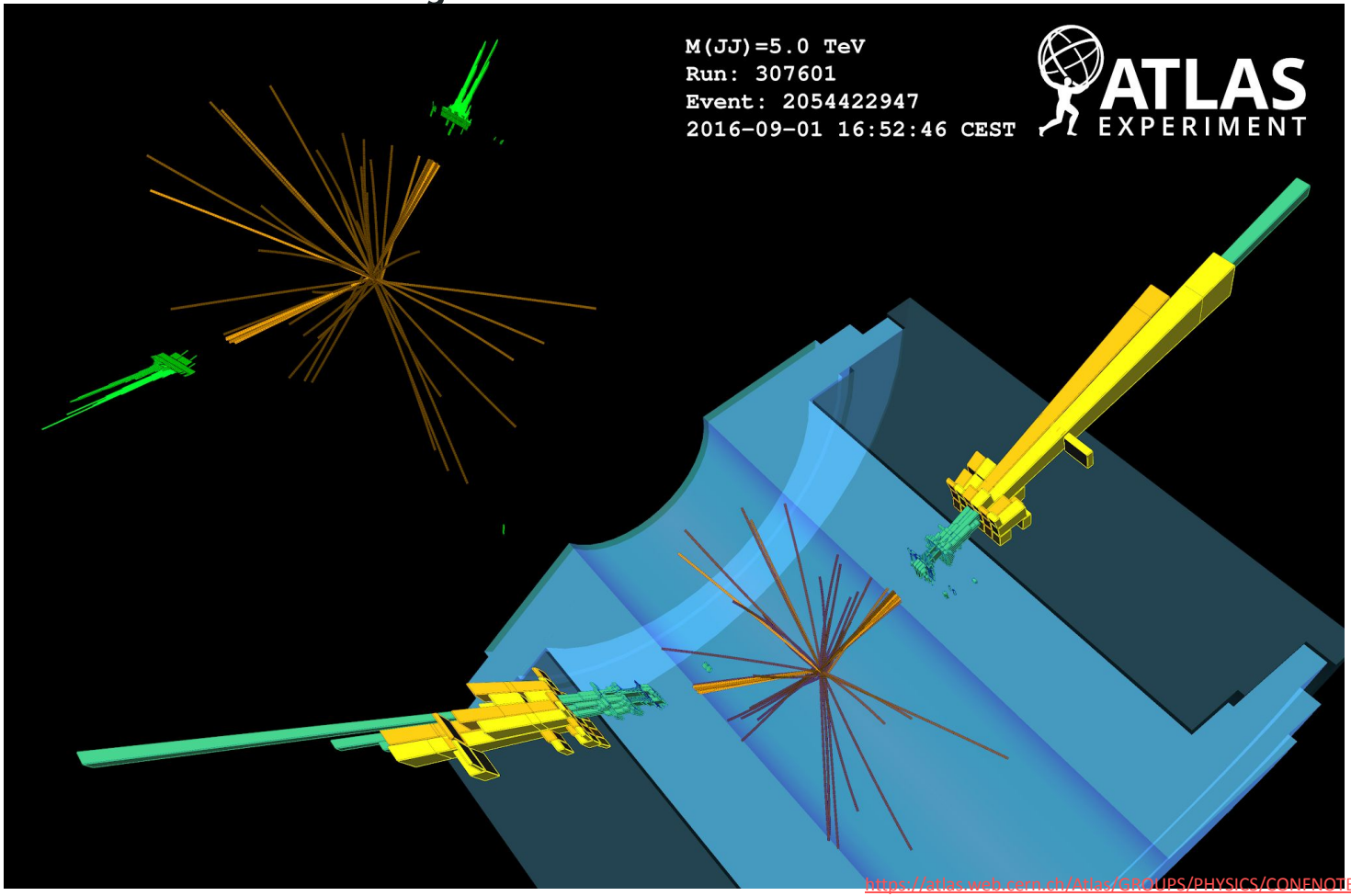
The next collision happens here:

25 ns • c ≅7.5m

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


CMS Experiment at the LHC, CERN
Data recorded: 2016-May-11 21:40:47.974592 GMT
Run / Event / LS: 273158 / 238962455 / 150

Diboson event: jets in the ATLAS detector



https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CONFNOTES/ATLAS-CONF-2018-016/fig_16.png

Zware ionen

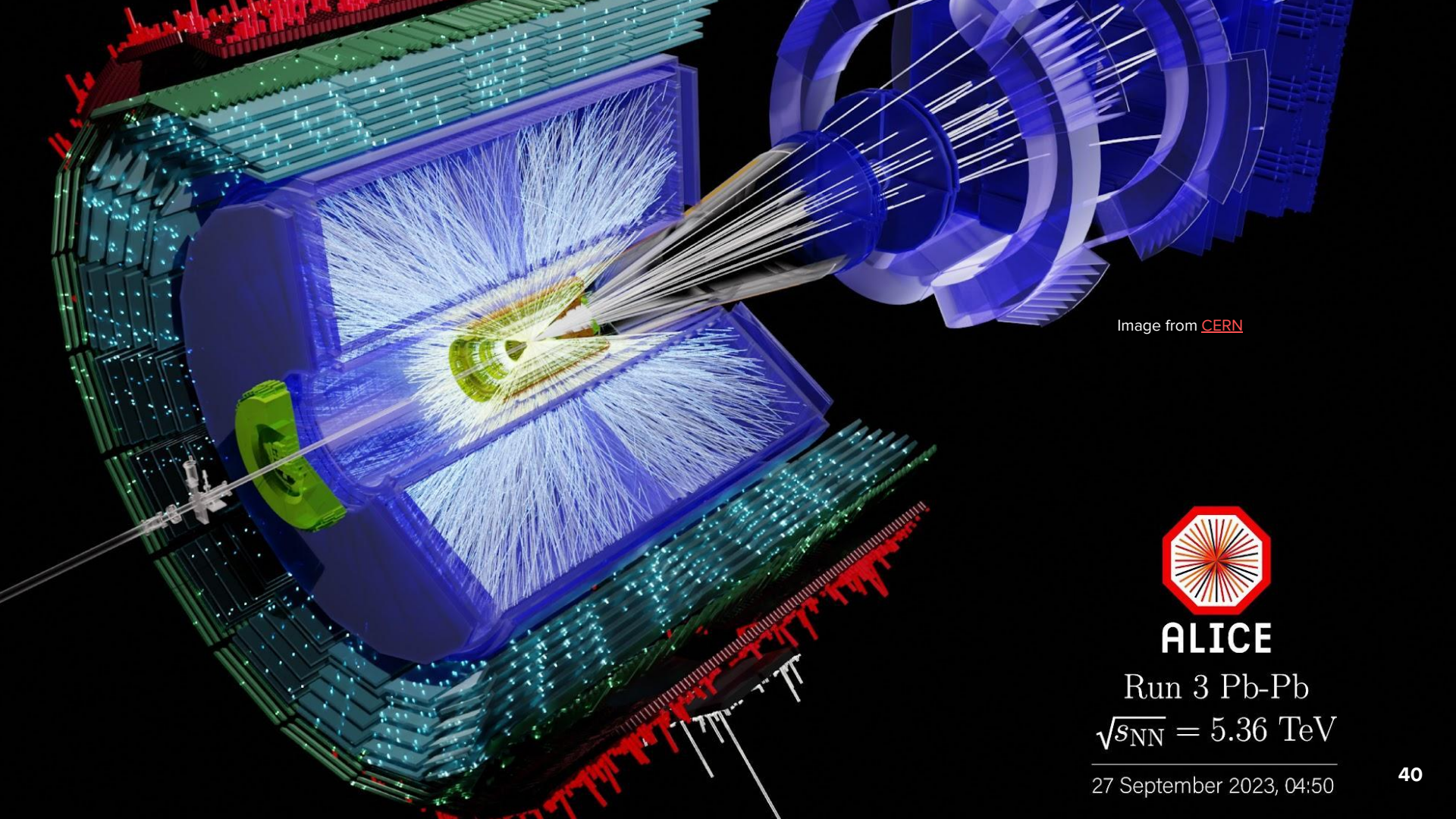
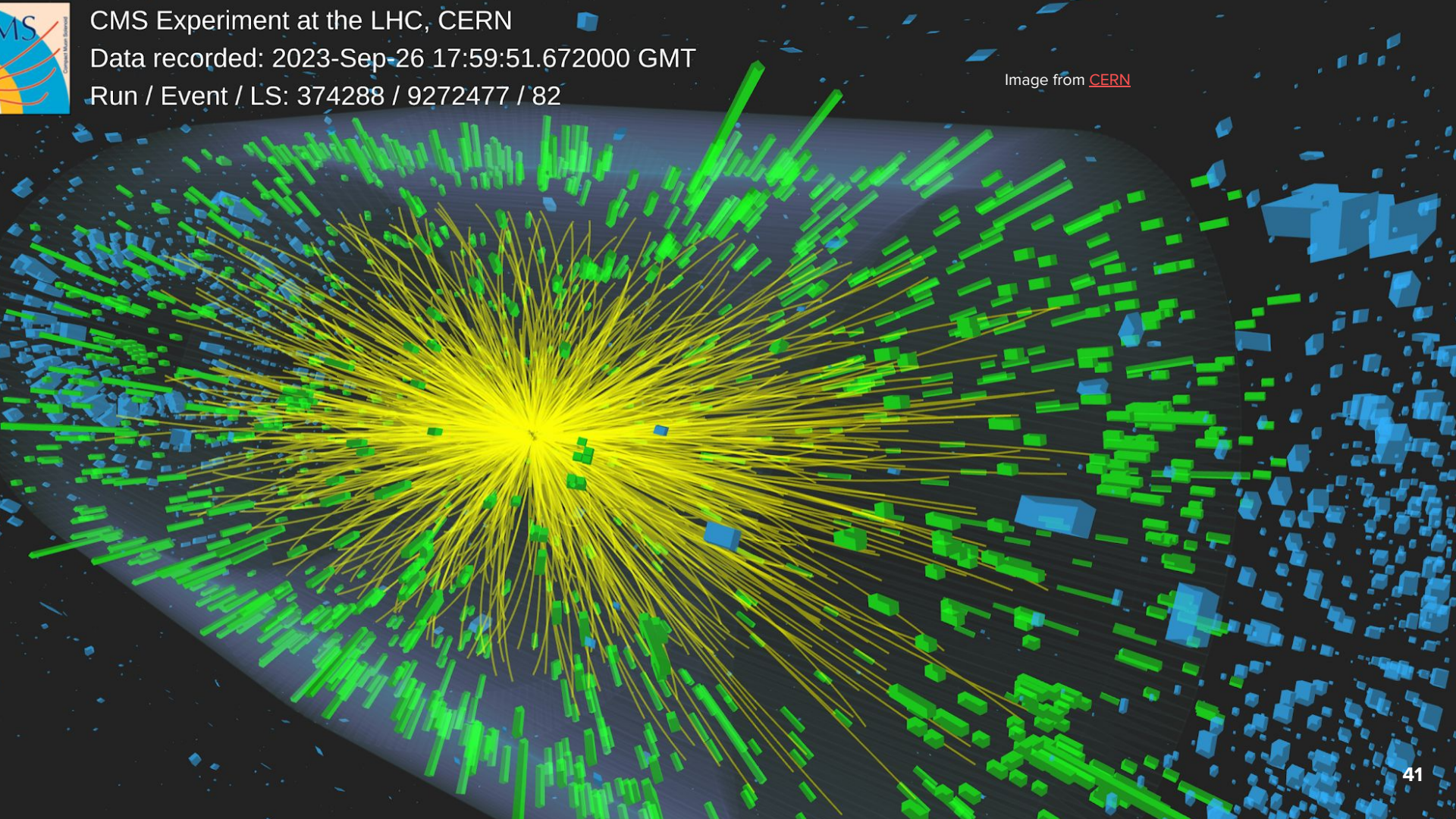
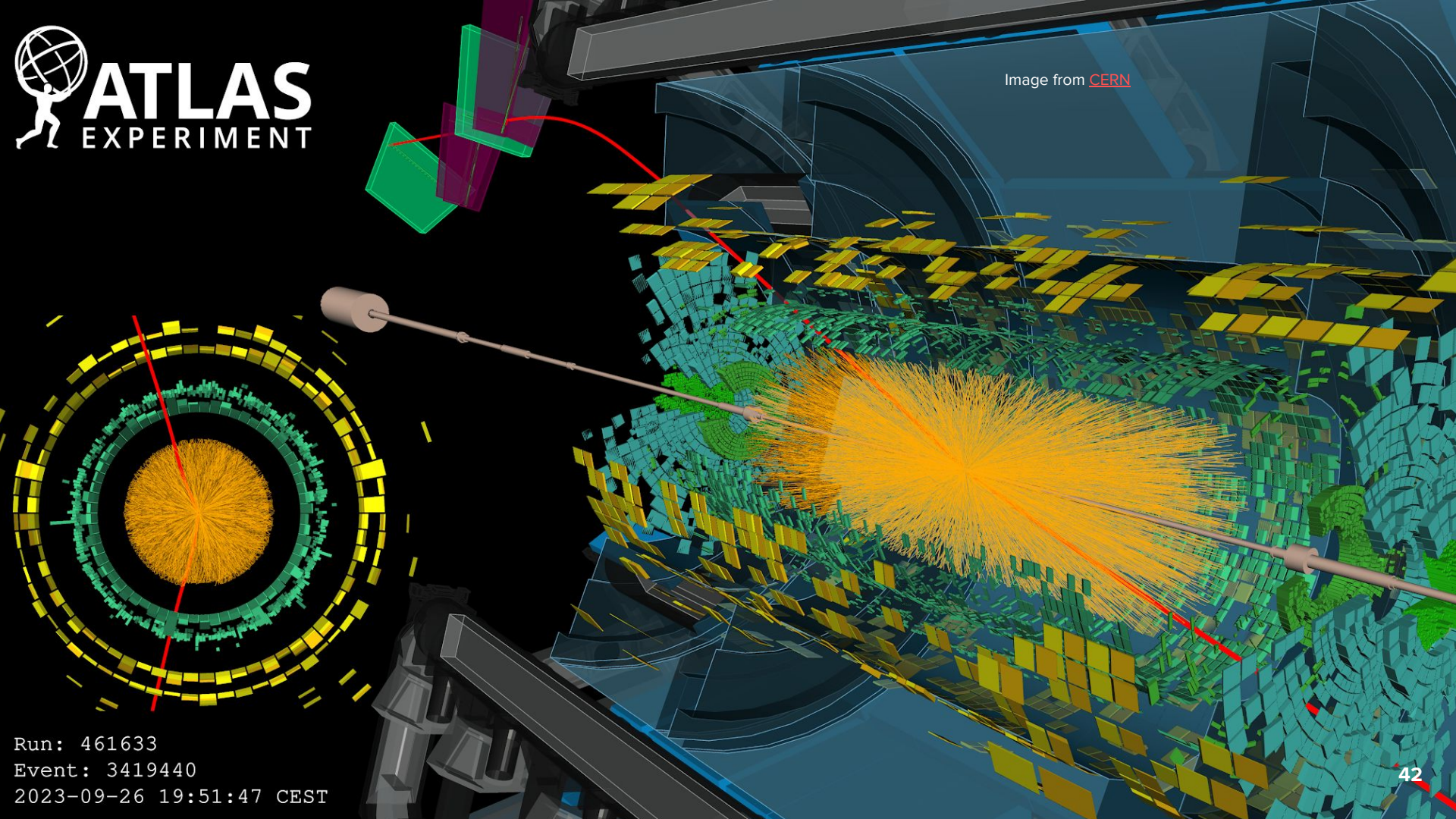


Image from CERN


CMS Experiment at the LHC, CERN
Data recorded: 2023-Sep-26 17:59:51.672000 GMT
Run / Event / LS: 374288 / 9272477 / 82
Image from CERN


ATLAS
EXPERIMENT
Image from CERN
Run: 461633
Event: 3419440
2023-09-26 19:51:47 CEST
42

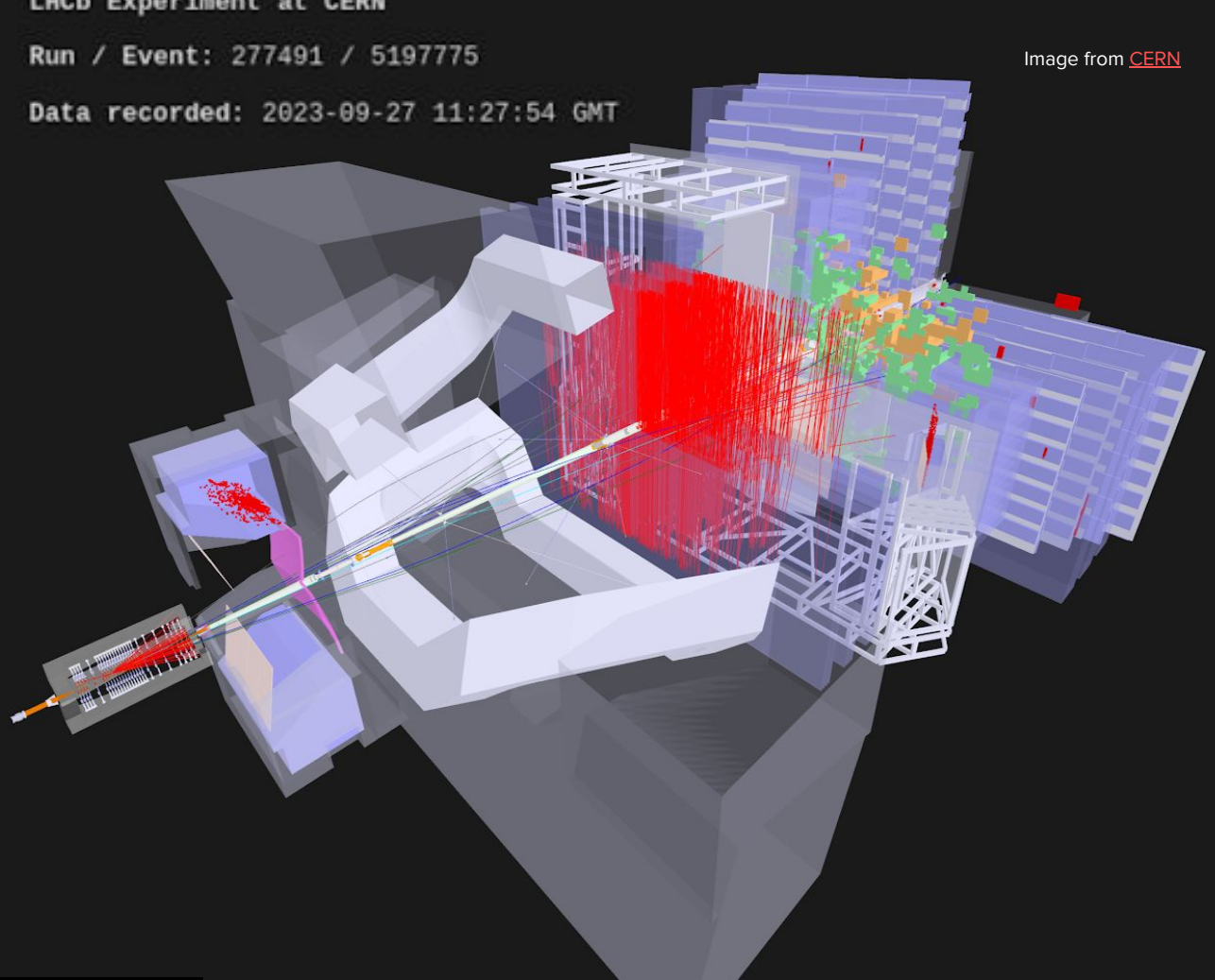


Image from CERN

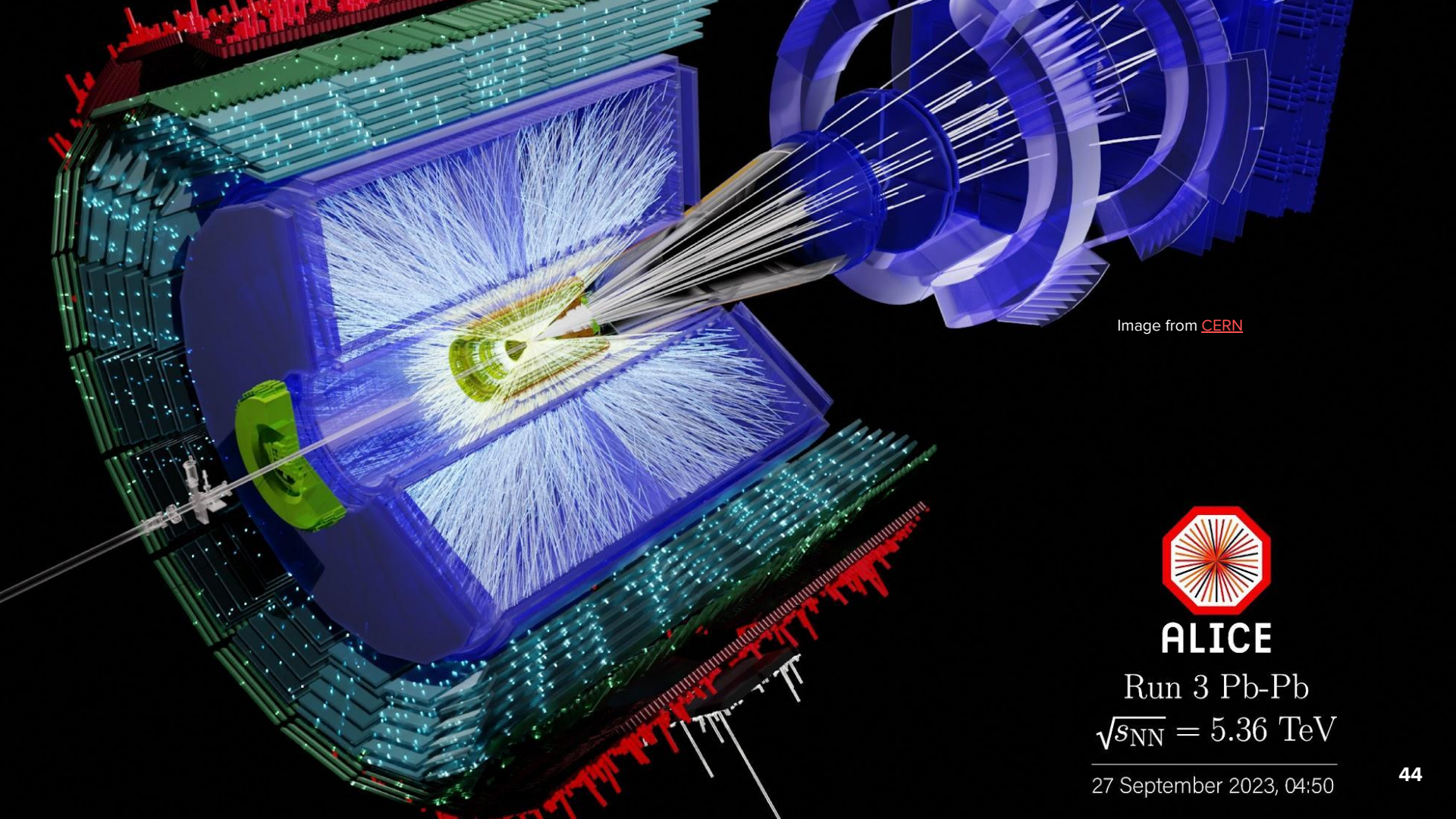
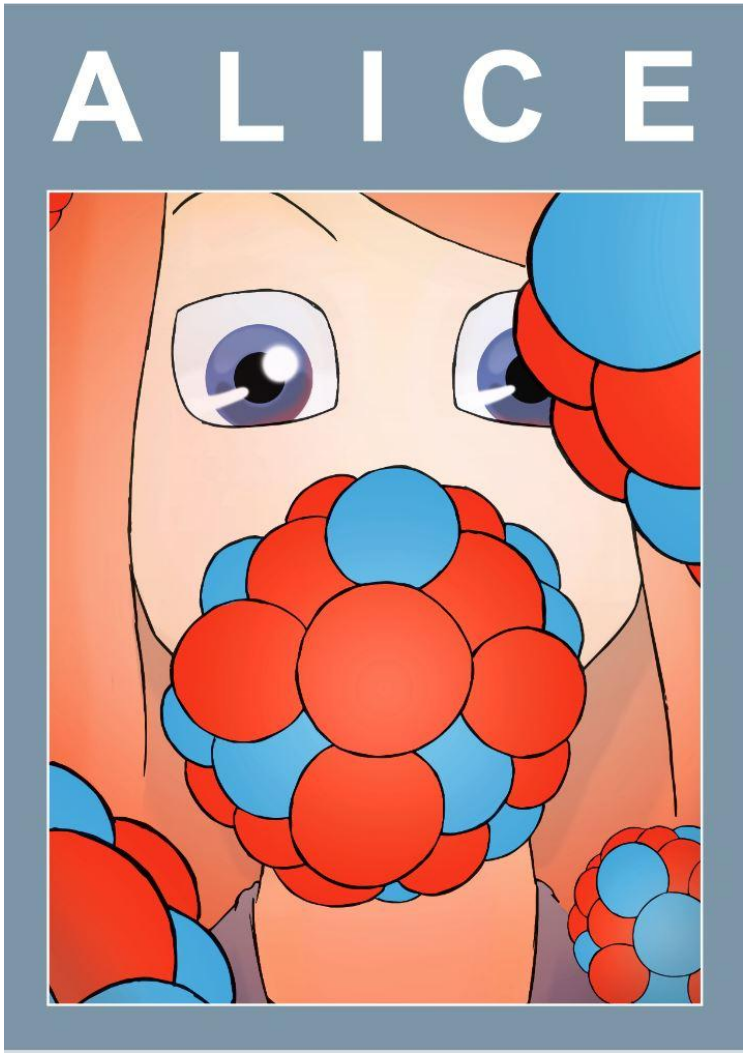
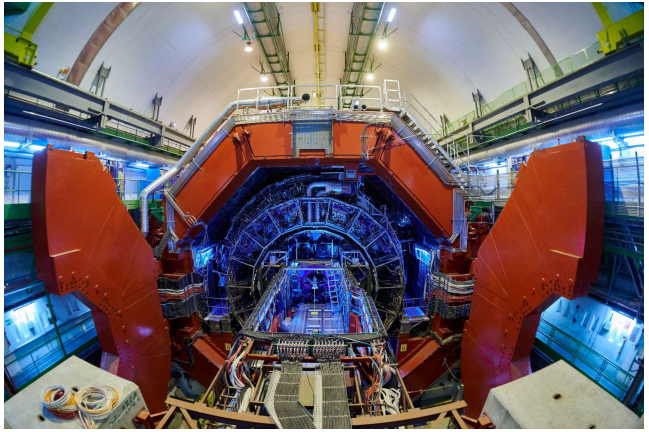


Image from CERN

Who is ALICE?

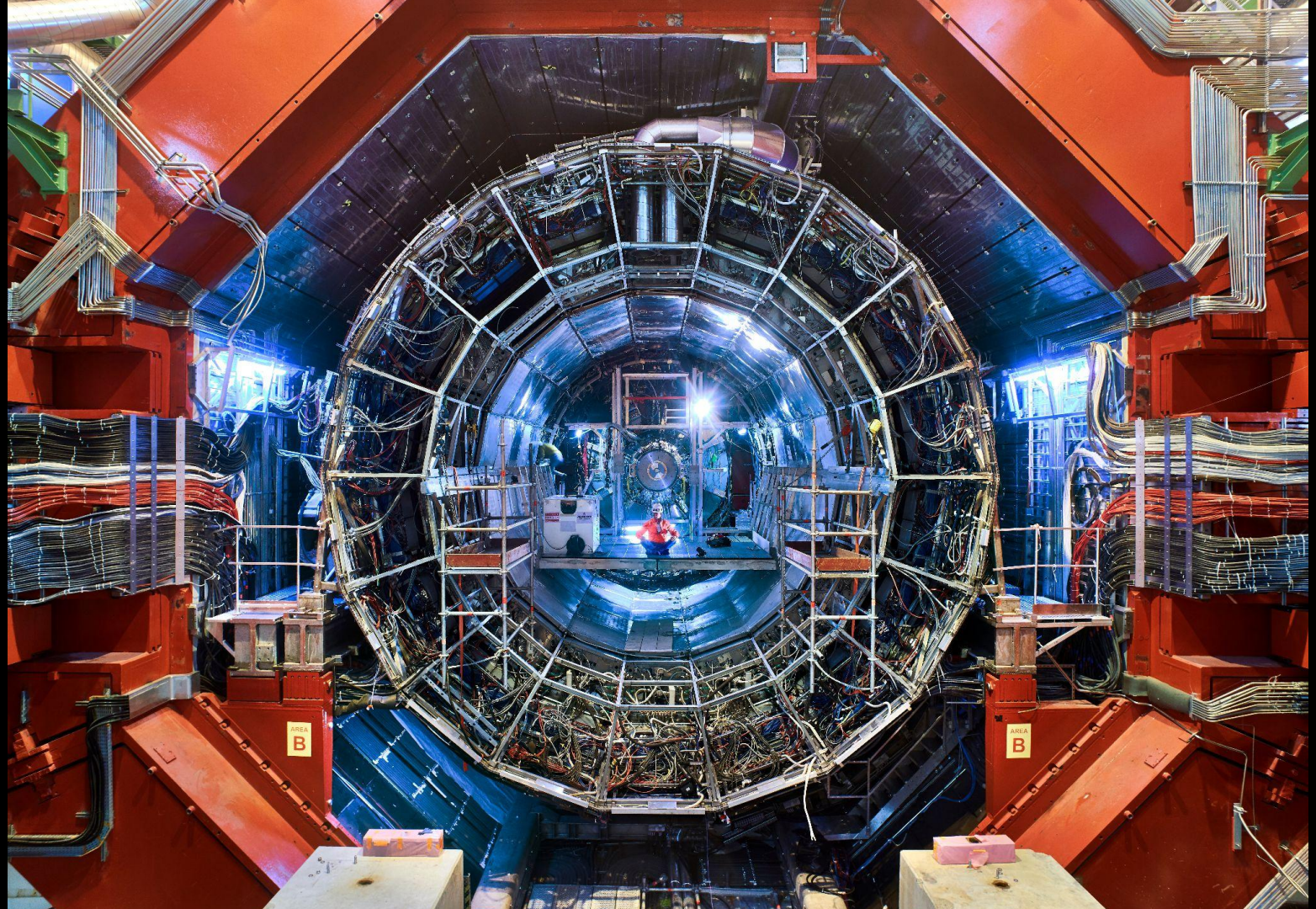


The ALICE detector: heavy ions



From
https://alice.cern/brochures
https://cds.cern.ch/record/2809617

From https://cds.cern.ch/record/2665476

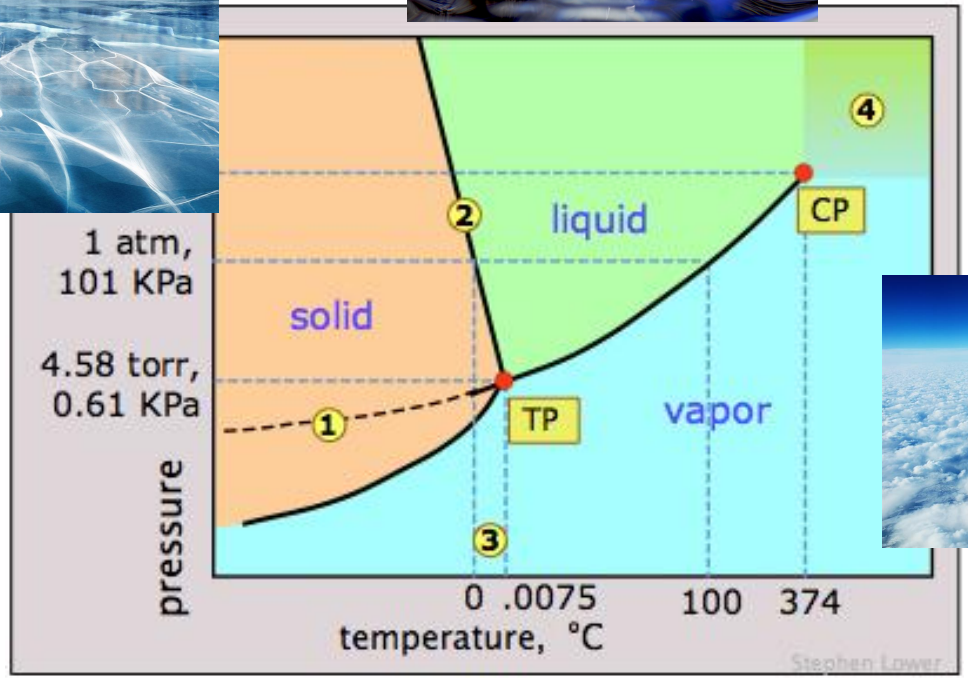


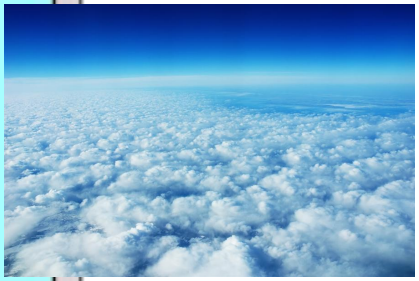
A familiar diagram

From https://en.wikipedia.org/wiki/Water

From https://www.metoffice.gov.uk/weather/learn-about/weather/types-of-weather/frost-and-ice/ice

Matter comes in many different phases

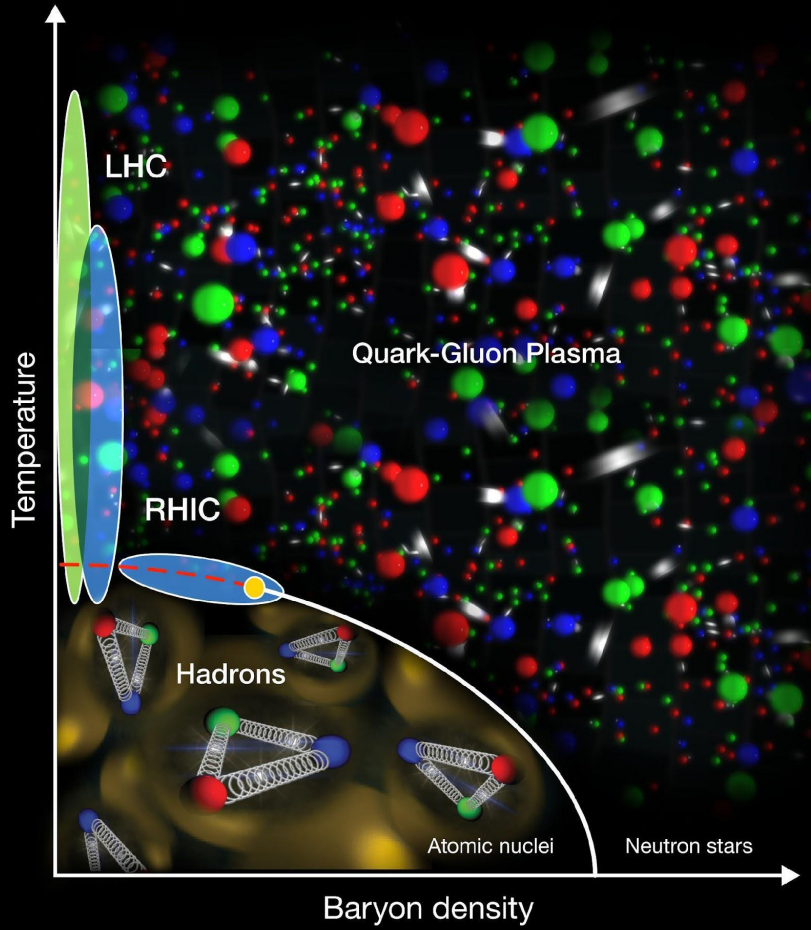




From https://research.noaa.gov/article/ArtMID/587/ArticleID/1299/Water-vapor-in-the-upper-atmosphere-amplifies-global-warming-says-new-study

Image from https://chem.libretexts.org/Bookshelves/General_Chemistry/Book%3A_Chem1_(Lower)/07%3A_Solids_and_Liquids/7.05%3A_Changes_of_State

Quantum chromodynamics Phase diagram



Quark gluon plasma: more than 500,000 times hotter than the core of the sun!

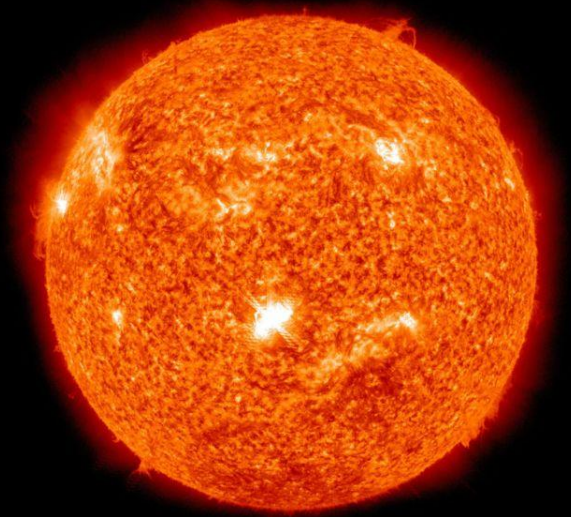
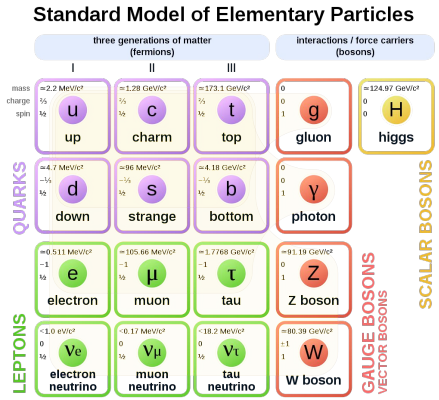


Image from https://education.nationalgeographic.org/resource/sun

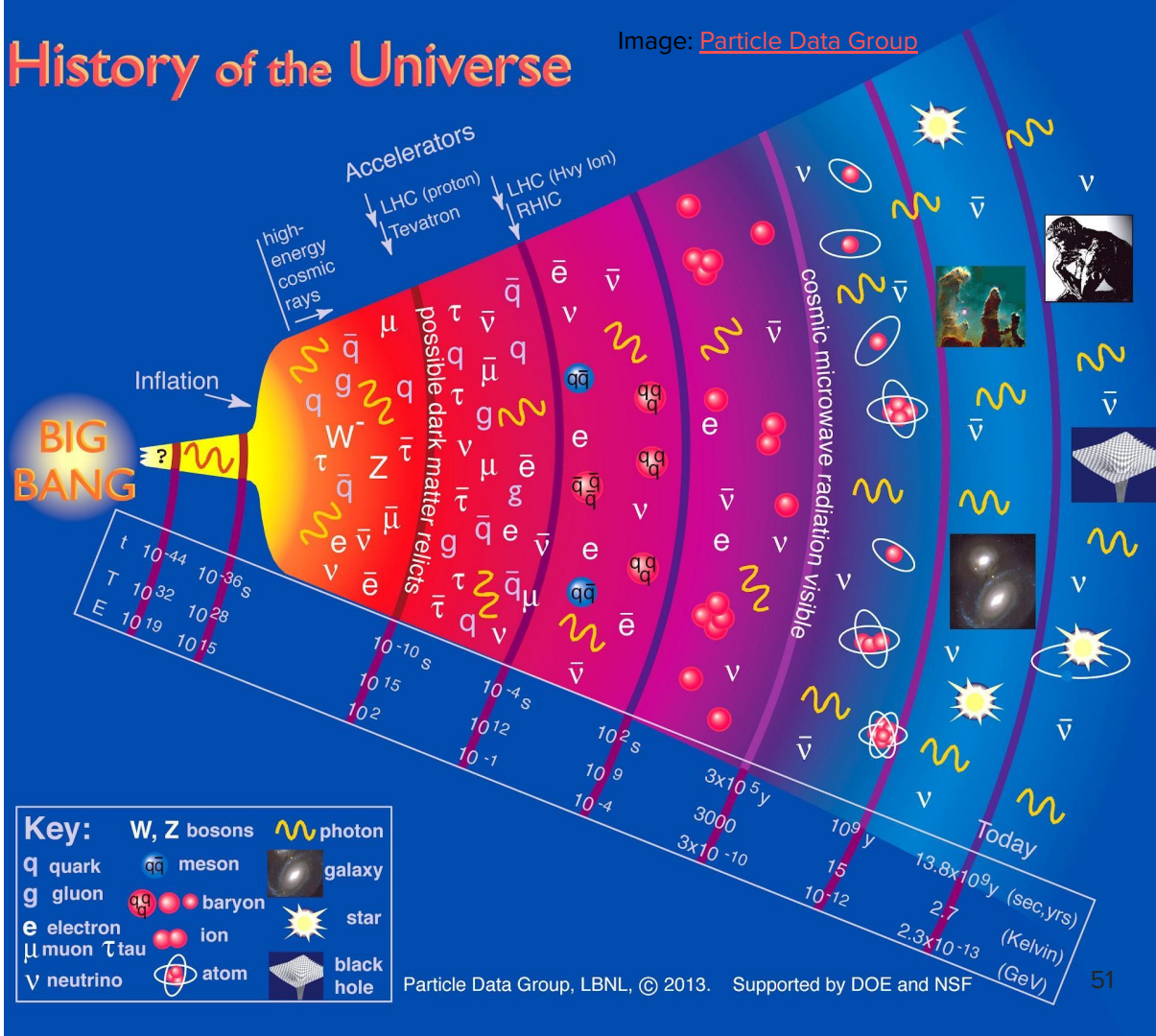
A glimpse into the start of the universe

Timeline

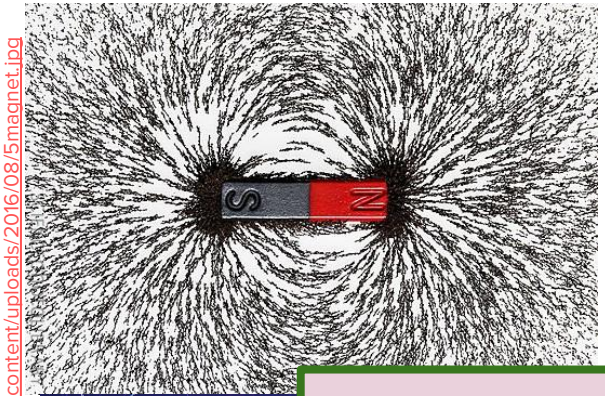
- $5.4 \cdot 10^{-44}$ s and **T > 10^{19} GeV** Planck time
- 10^{-43} s and **T ~ 10^{19} GeV** Grand Unification of the forces



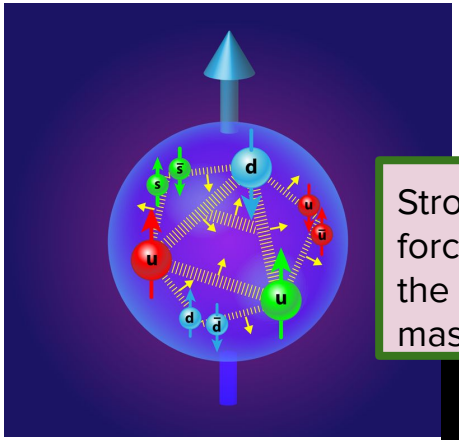
What are the four known forces in nature?



Interactions: four known forces

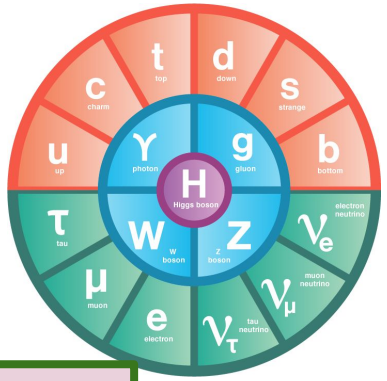


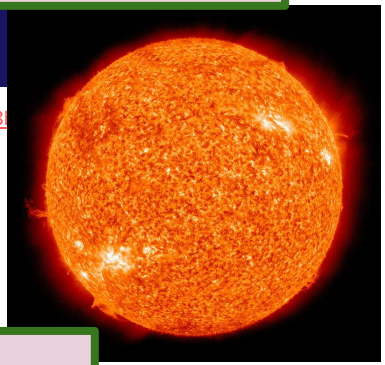
electromagnetism



Strong nuclear force: how does the proton get its mass?

https://physics.aps.org/assets/89b4f0e0-b8
b70d-d90f744d1790/e23_2.png





Weak nuclear force

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

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

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

https://upload.wikimedia.org/wikipedia/commons/thumb/3/33/Lightning_0257.jpg/1200px-Lightning_0257.jpg

Hypothetical unification into a theory of everything

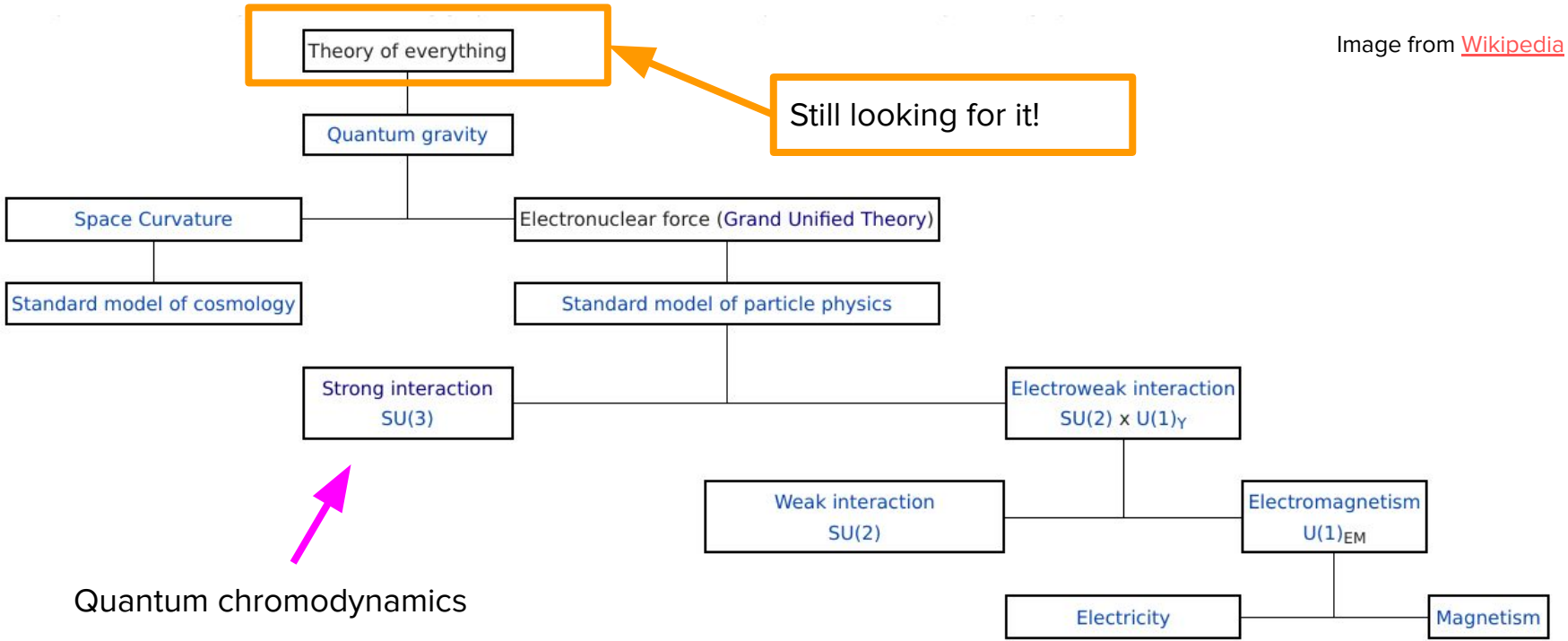


Image from Wikipedia

Timeline

- $5.4 \cdot 10^{-44}$ s and **T > 10^{19} GeV** Planck time
- 10^{-43} s and **T ~ 10^{19} GeV** Grand Unification
- 10^{-36} s and **T ~ 10^{15} GeV** Inflation
- 10^{-11} s and **T ~ 200 MeV** Quark Gluon Plasma

QGP: a state where quarks and gluons are free: main ALICE goal.

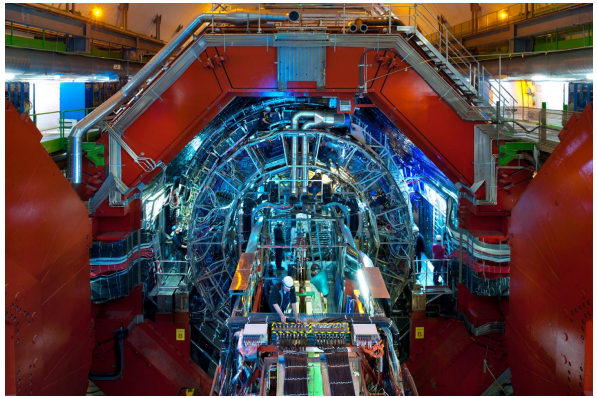
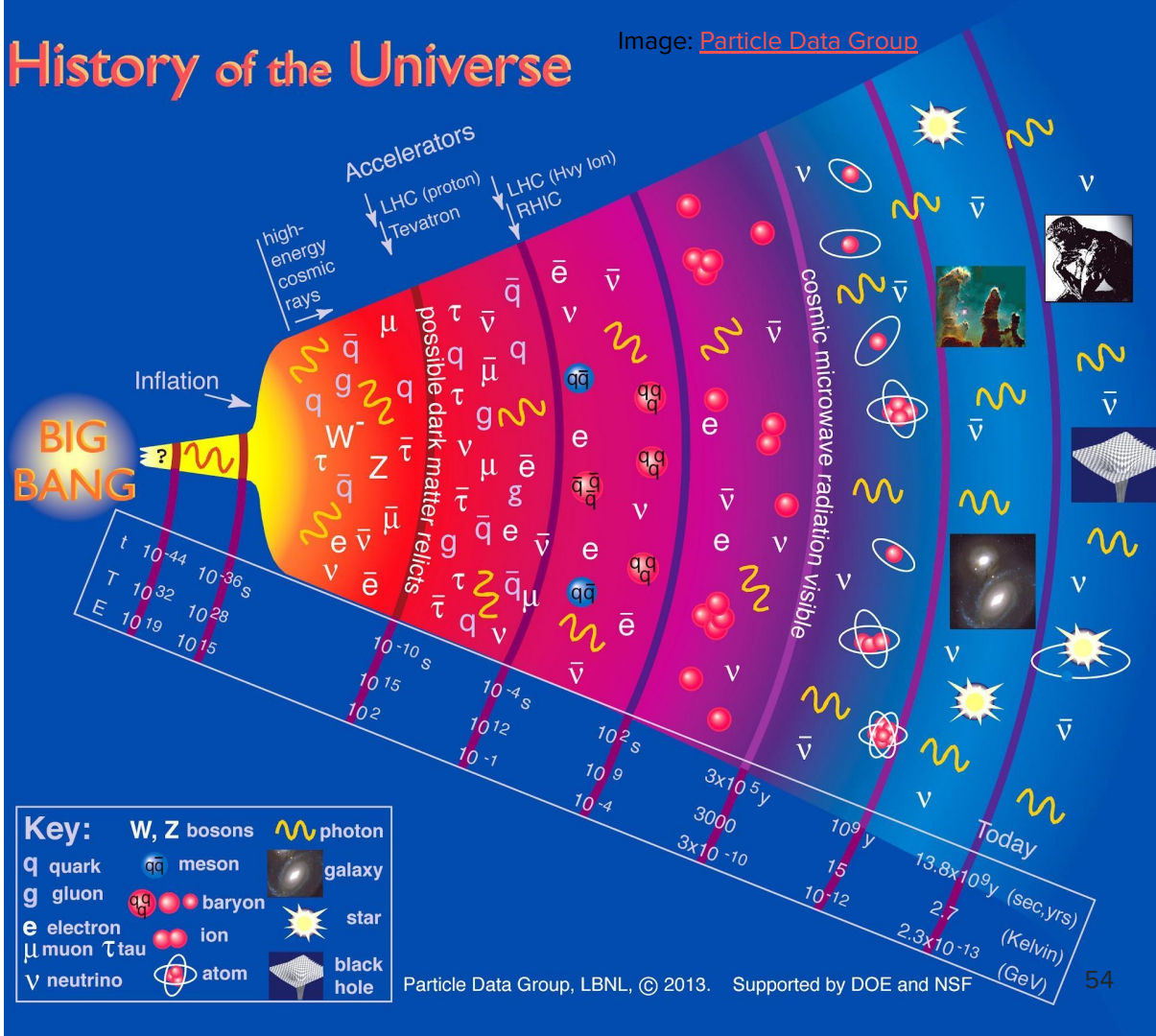


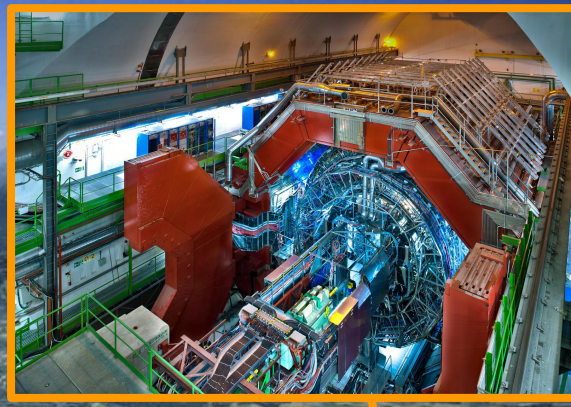
Image: Wikipedia

Image: Particle Data Group



Large Hadron Collider

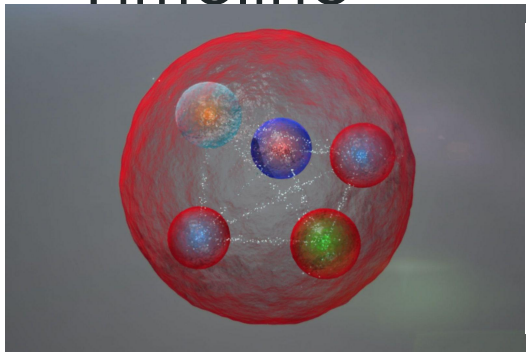
Image from CERN



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

Timeline

Images: wired.com



Penta quark

- 10^{-5} s and **T ~ 200 MeV** Hadronization and Baryogenesis

Meson and Baryon

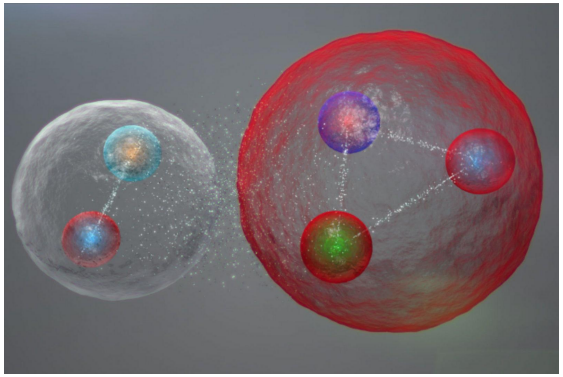
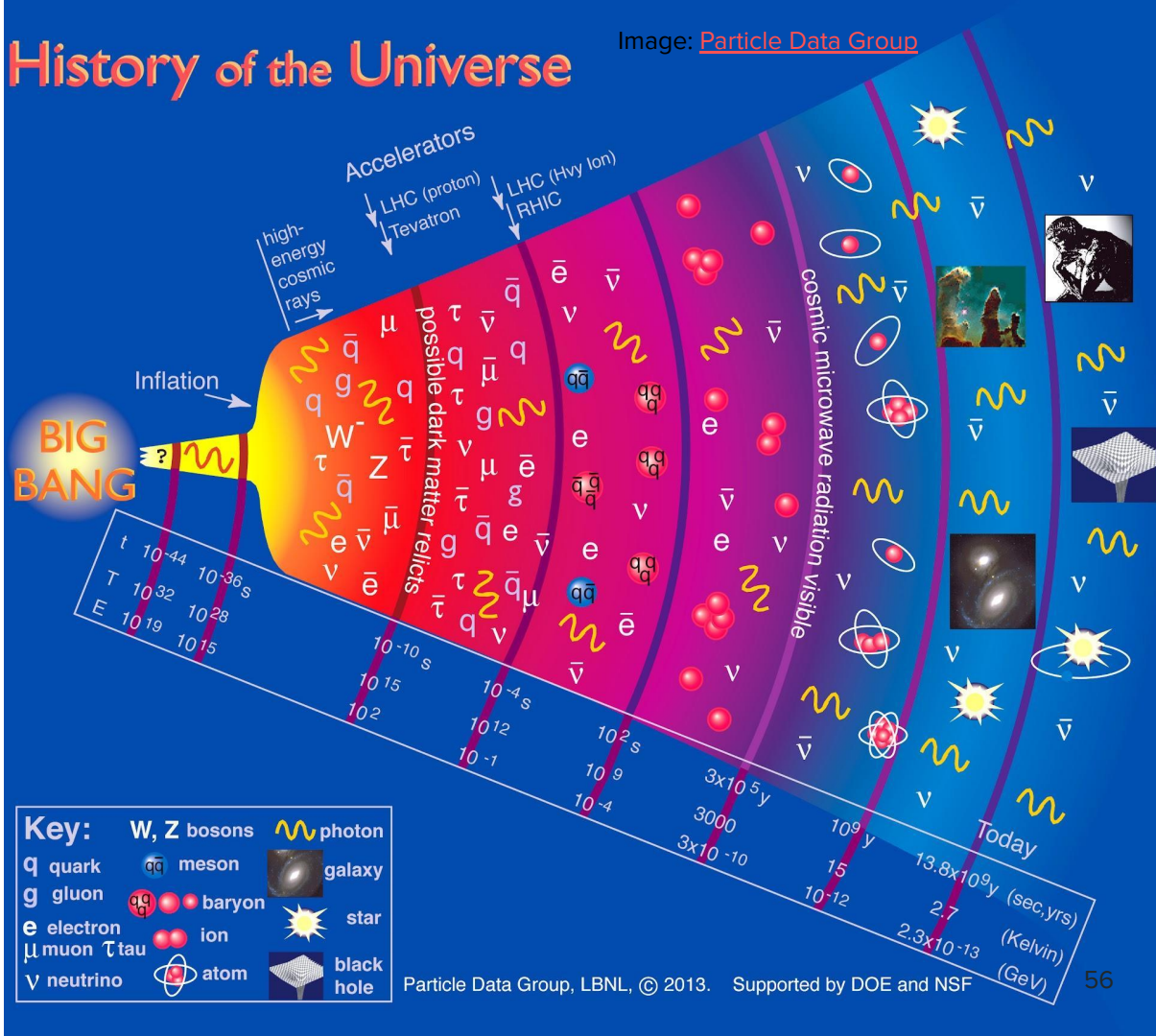
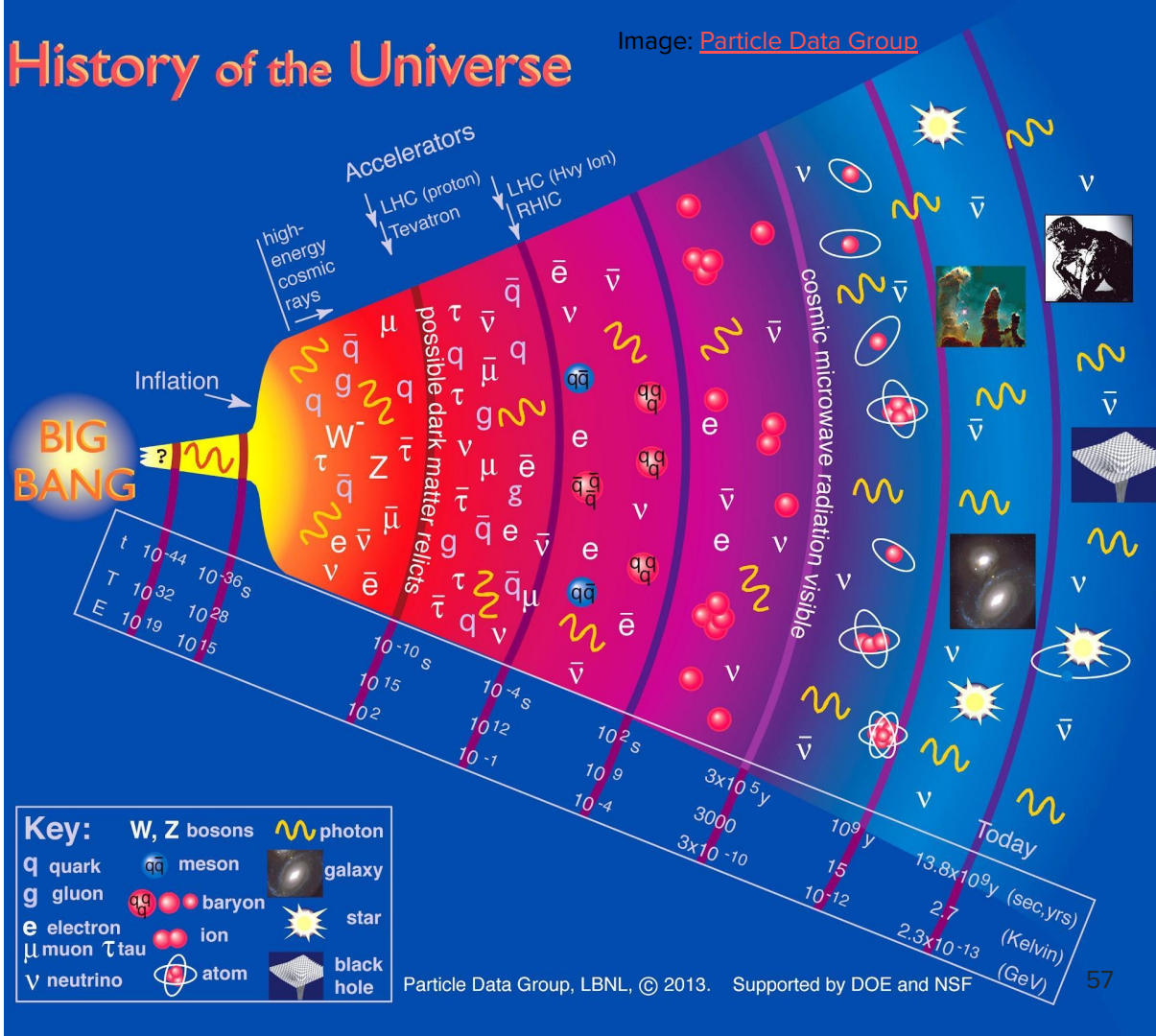


Image: Particle Data Group



Timeline

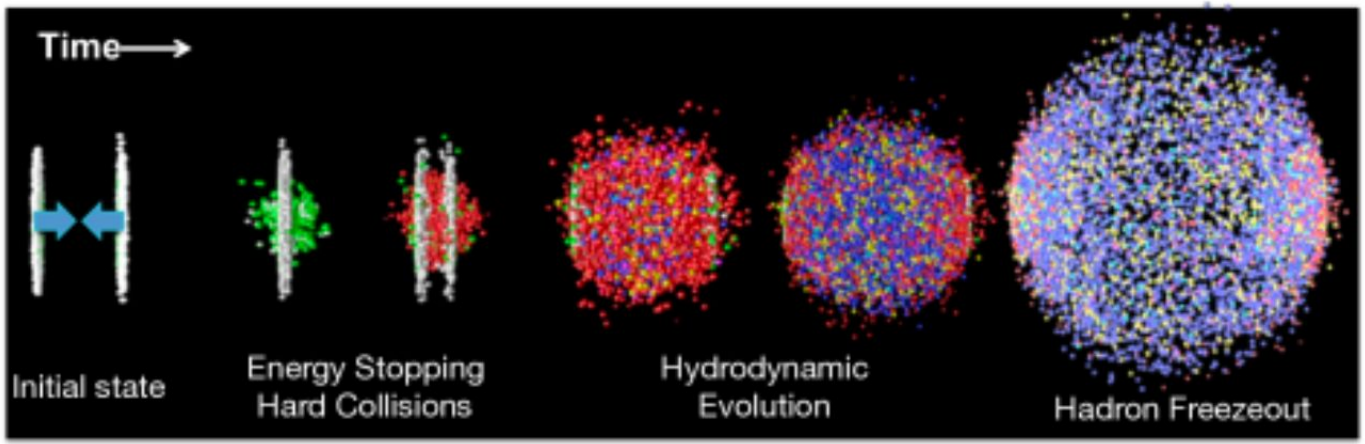
- $5.4 \cdot 10^{-44}$ s and **T > 10^{19} GeV** Planck time
- 10^{-43} s and **T ~ 10^{19} GeV** Grand Unification
- 10^{-36} s and **T ~ 10^{15} GeV** Inflation
- **T ~ 10^{1} – 10^{3} GeV** dark matter freeze-out
- 10^{-11} s and **T ~ 100 GeV** Quark Gluon Plasma
- 10^{-5} s and **T ~ 200 MeV** Hadronization and Baryogenesis
- 1 s or **T ~ 1 MeV** neutron freeze-out
- 1 s or **T ~ 1 MeV** neutrino freeze-out
- 3 min and **T ~ 100 keV** nucleosynthesis: D, ^{3}He, ^{4}He, Li
- **T ~ 1 eV** structure formation
- **T ~ 0.4 eV** photon decoupling → CMB
- **T = 2.7 K ~ 10^{-4} eV** today



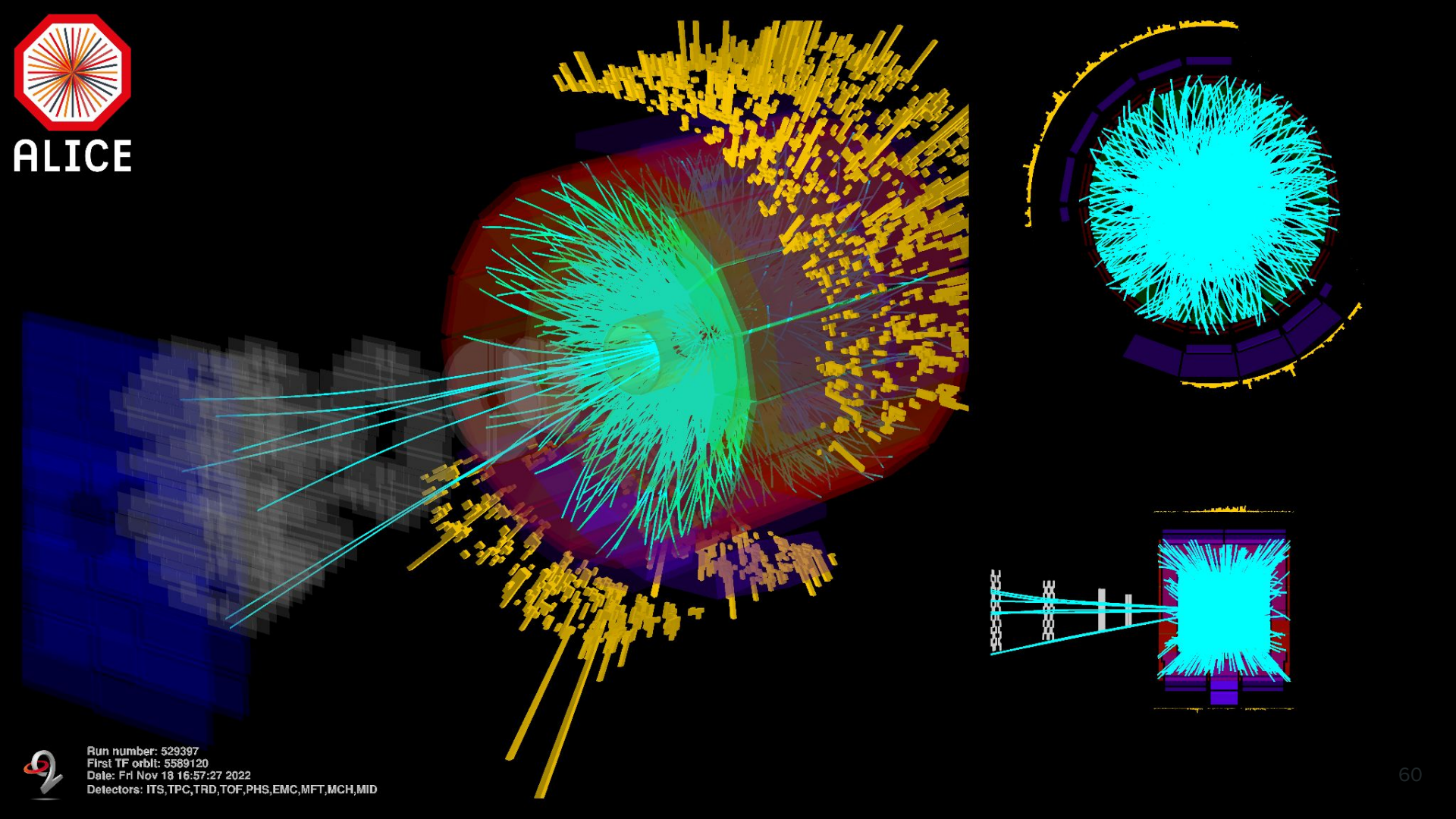
Heavy ions for quark gluon plasma

Quark gluon plasma in the laboratory

- We collide heavy-ions, like lead on lead at speeds close to *c*, the speed of light (~0.9998 c)



- The energy density in the collision is large enough to produce QGP in the laboratory


ALICE
Run number: 529397
First TF orbit: 5589120
Date: Fri Nov 18 16:57:27 2022
Detectors: ITS,TPC,TRD,TOF,PHS,EMC,MFT,MCH,MID

First ion collisions after long shutdown of several years!

See also
https://home.cern/news/news/experiments/first-lead-ion-collisions-lhc-record-energy
https://alice.cern/node/169

What is the LHC doing right now?

Check out https://op-webtools.web.cern.ch/vistar/vistars.php?usr=LHC1 or google “vistars LHC page 1”

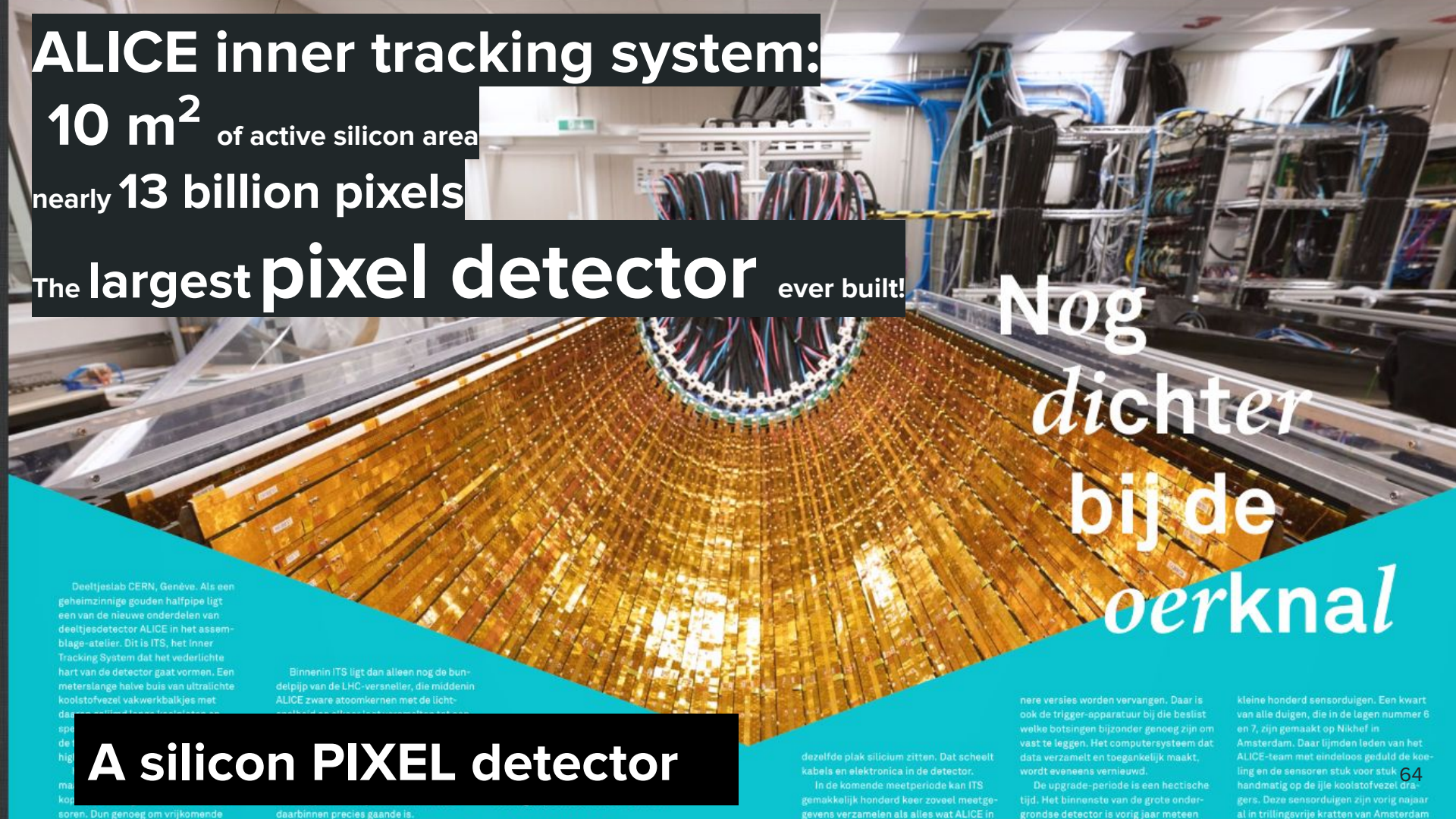
Hoe detecteren we zo’n deeltje?

ALICE inner tracking system:

10 m^2 of active silicon area

nearly **13 billion pixels**

The **largest pixel detector** ever built!



Nog *dichter* bij de *oerknal*

A silicon PIXEL detector

Deeltjeslab CERN, Genève. Als een geheimzinnige gouden halfpipe ligt een van de nieuwe onderdelen van deeltjesdetector ALICE in het assemblage-atelier. Dit is ITS, het Inner Tracking System dat het vederlichte hart van de detector gaat vormen. Een meterslange halve buis van ultralichte koolstofvezel vakwerkbalkjes met daa... spe... de t... hig... ma... kop... soren. Dun genoeg om vrijkomende

Binnenin ITS ligt dan alleen nog de bundelpijp van de LHC-versneller, die middenin ALICE zware atoomkernen met de licht-

daarbinnen precies gaande is.

dezelfde plak silicium zitten. Dat scheelt kabels en elektronica in de detector.

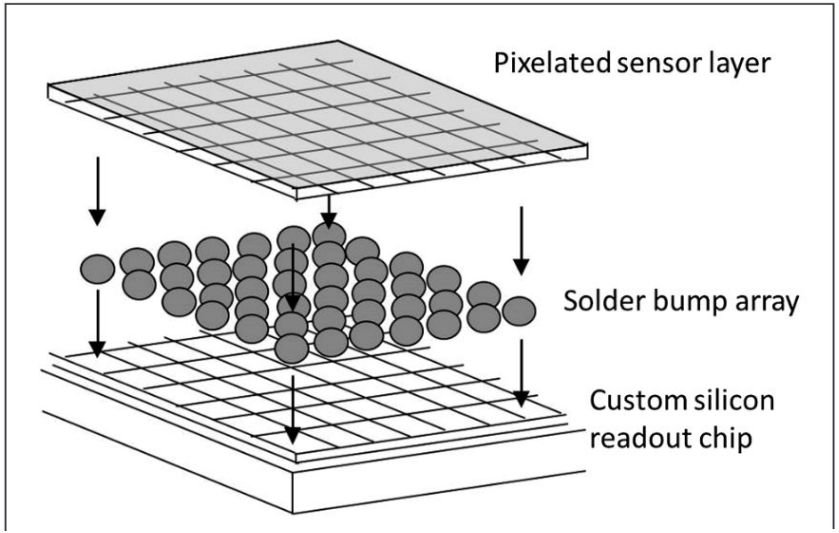
In de komende meetperiode kan ITS gemakkelijk honderd keer zoveel meetgegevens verzamelen als alles wat ALICE in

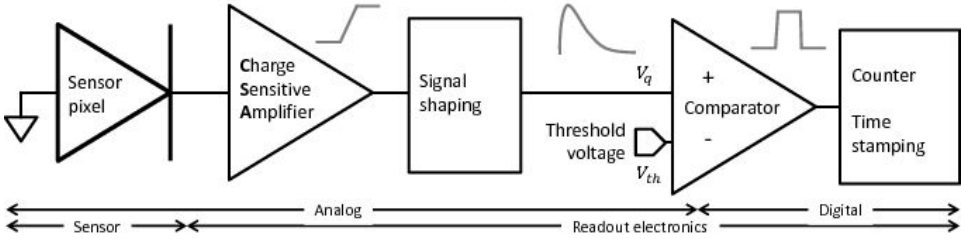
nere versies worden vervangen. Daar is ook de trigger-apparatuur bij die beslist welke botsingen bijzonder genoeg zijn om vast te leggen. Het computersysteem dat data verzamelt en toegankelijk maakt, wordt eveneens vernieuwd.

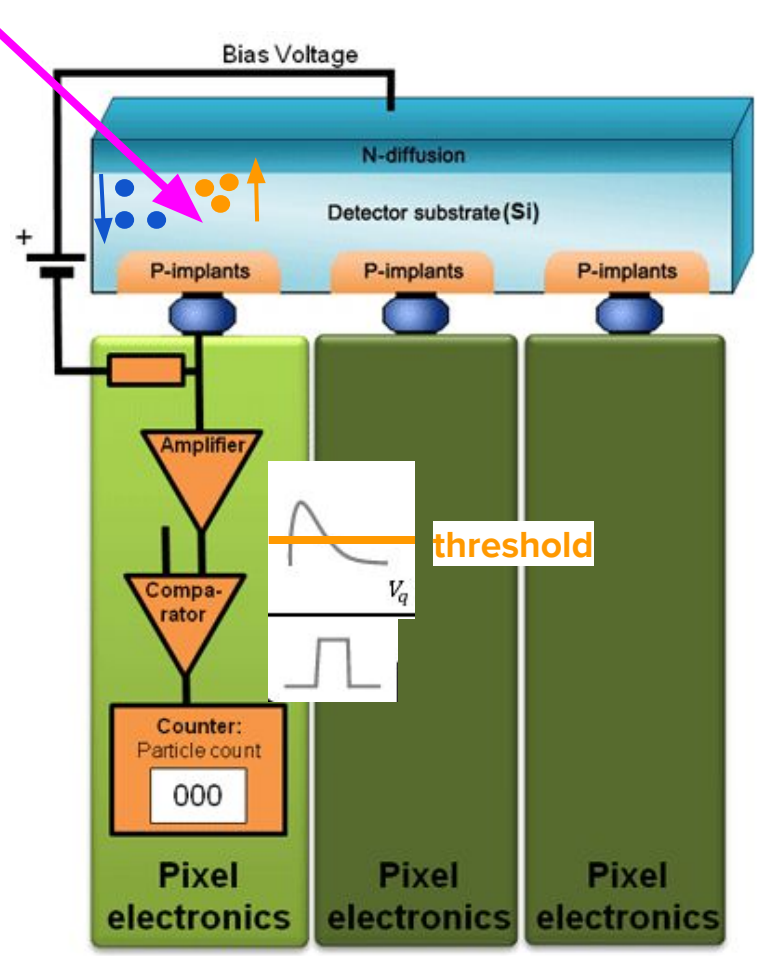
De upgrade-periode is een hectische tijd. Het binnenste van de grote ondergrondse detector is vorig jaar meteen

kleine honderd sensorduigen. Een kwart van alle duigen, die in de lagen nummer 6 en 7, zijn gemaakt op Nikhef in Amsterdam. Daar lijmden leden van het ALICE-team met eindeloos geduld de koeling en de sensoren stuk voor stuk handmatig op de ijle koolstofvezel dragers. Deze sensorduigen zijn vorig najaar al in trillingsvrije kratten van Amsterdam

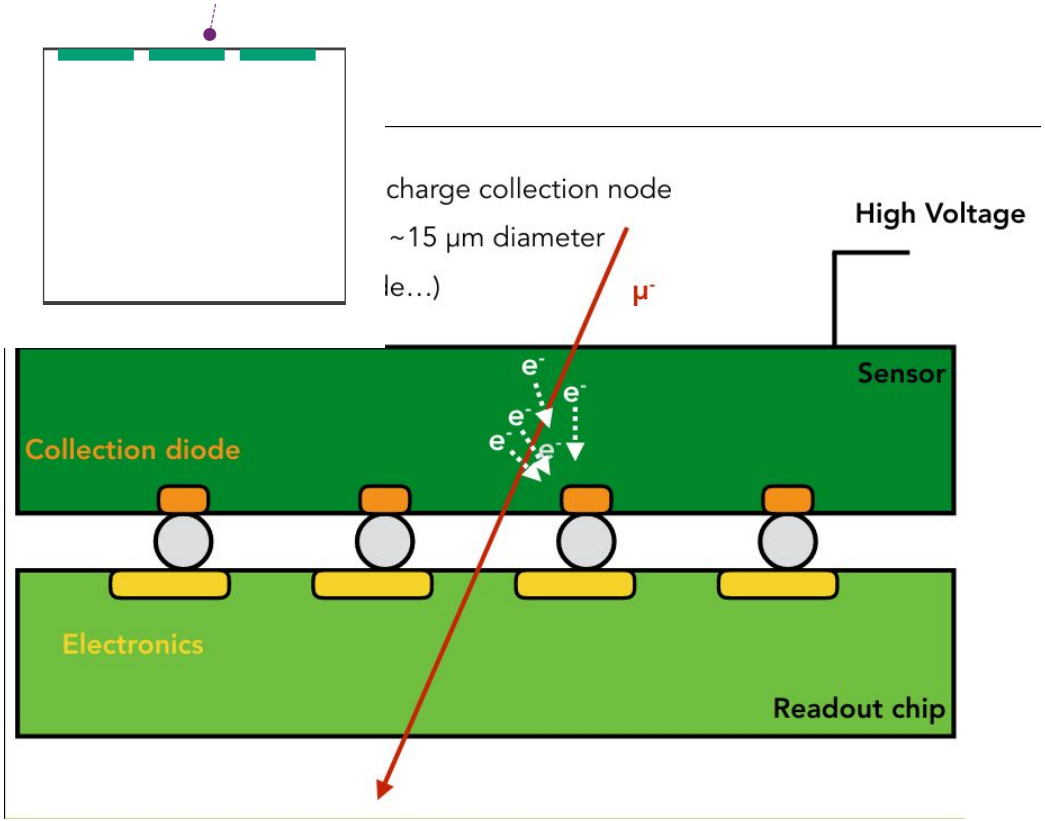
A hybrid pixel detector



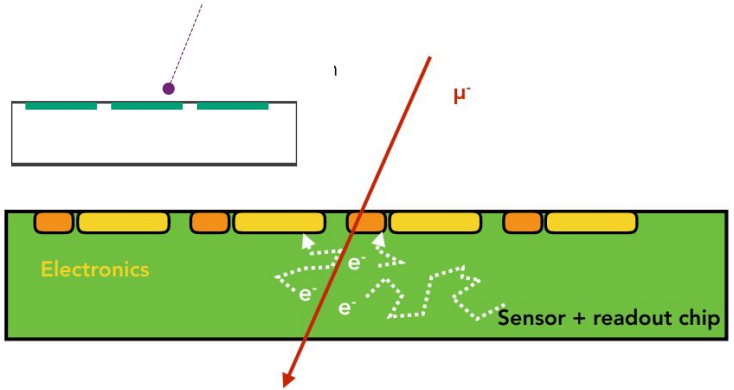




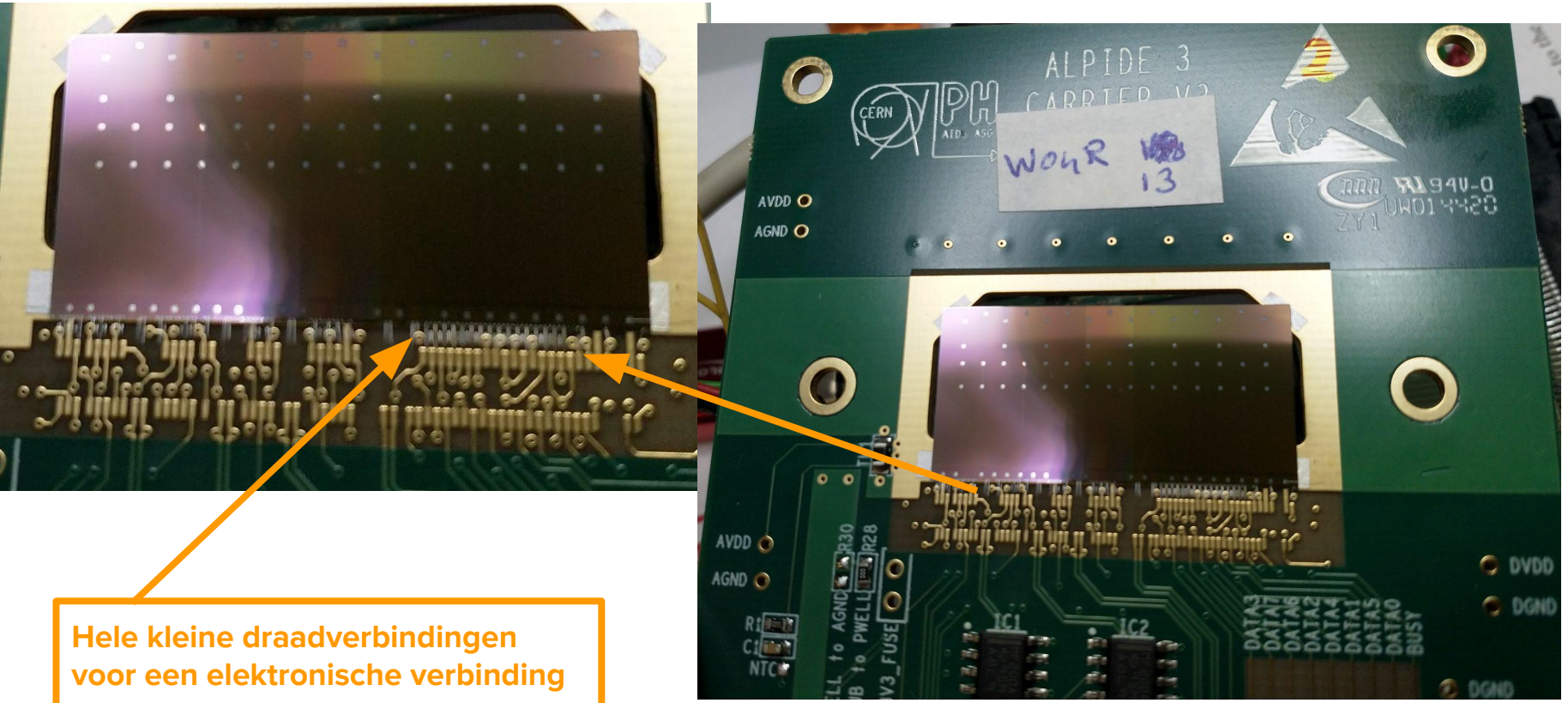
Deeltjes maken lading los in een sensor: *ionisatie*



Ionisatie: atoom of molecuul raakt een elektron kwijt of krijgt er één bij.



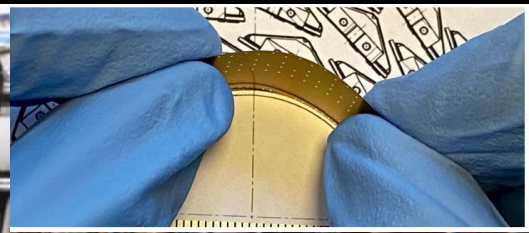
Een silicium pixeldetector



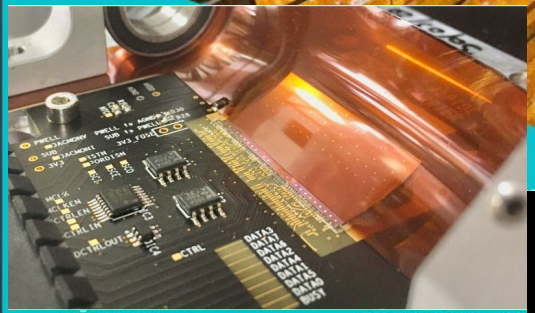
Hele kleine draadverbindingen
voor een elektronische verbinding

Mijn passie: pixeldetectoren van silicium -- ook in je telefoon!

Zo dun, we kunnen ze buigen!



Nog *dichter* bij de *oerknal*



Ik werk aan hele snelle pixel detectoren: we gaan voor 10 ps = 0.00000000001 seconde!

Het goud is overigens geen goud, maar polyimide-folie met ragdunne koperen voedingskabels voor de sensoren. Dun genoeg om vrijkomende

zijn ontstaan. ITS moet de d
betrappen die uit die zieden
ontsnappen en de fysici vertellen wat er
daarbinnen precies gaande is.

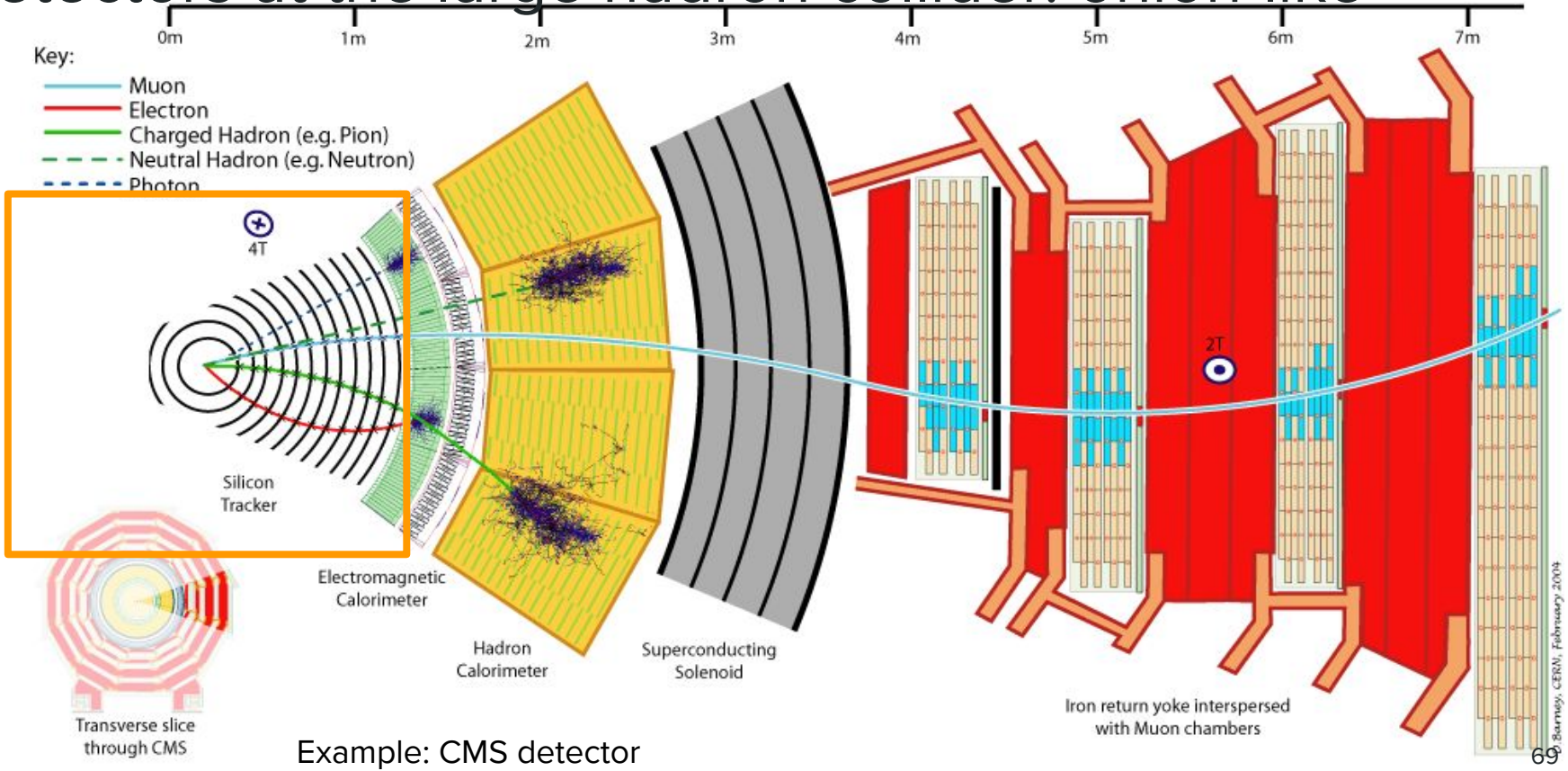
botsingen preciezer worden bekeken.

gemakkelijk honderd keer zoveel meetgegevens verzamelen als alles wat ALICE in

tijd. Het binnenste van de grote onderzoekt deze detector is vorig jaar meteen

gers. Deze sensordulgen zijn vorig najaar
al in trillingsvrije kratten van Amsterdam

Detectors at the large hadron collider: onion-like



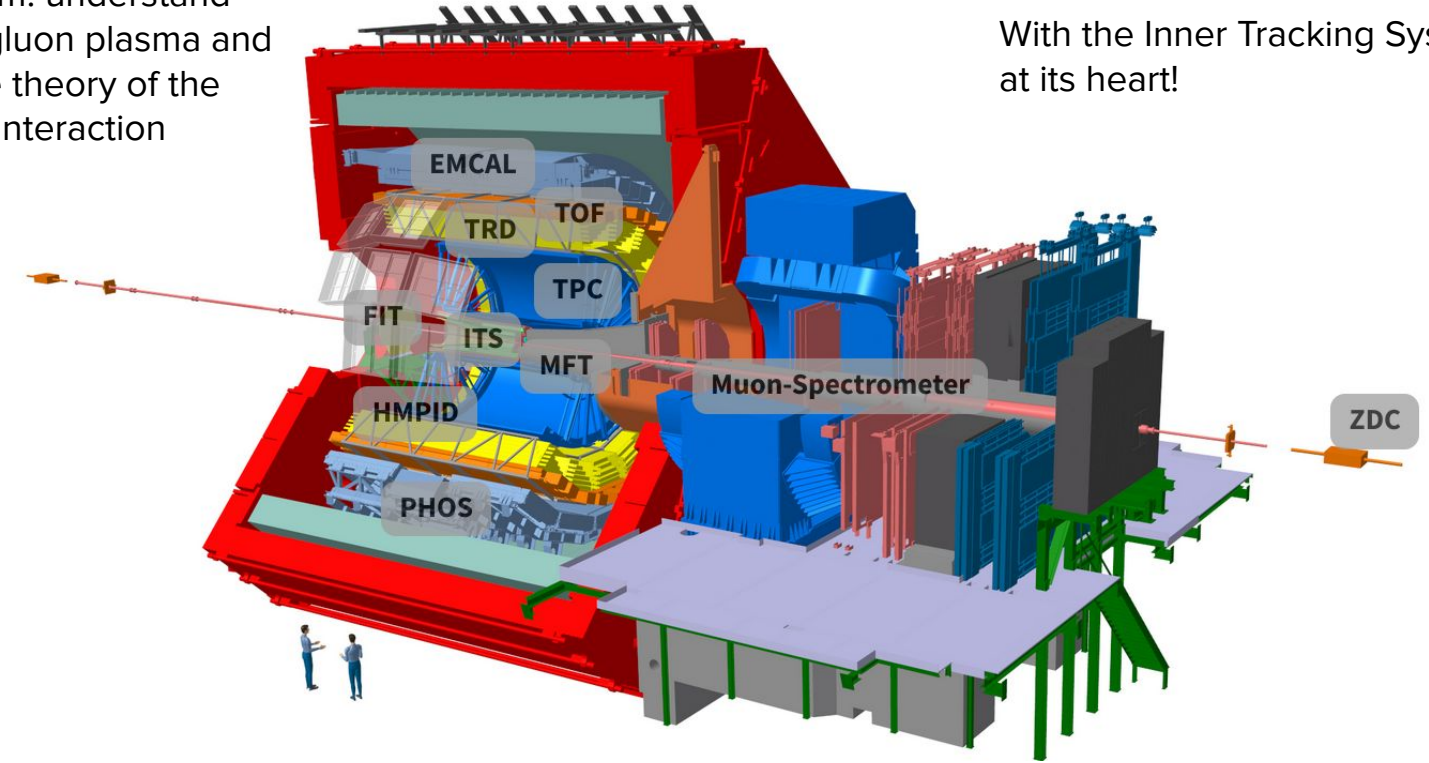
Example: CMS detector

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

The ALICE detector: onion-like

Main aim: understand quark gluon plasma and test the theory of the strong interaction

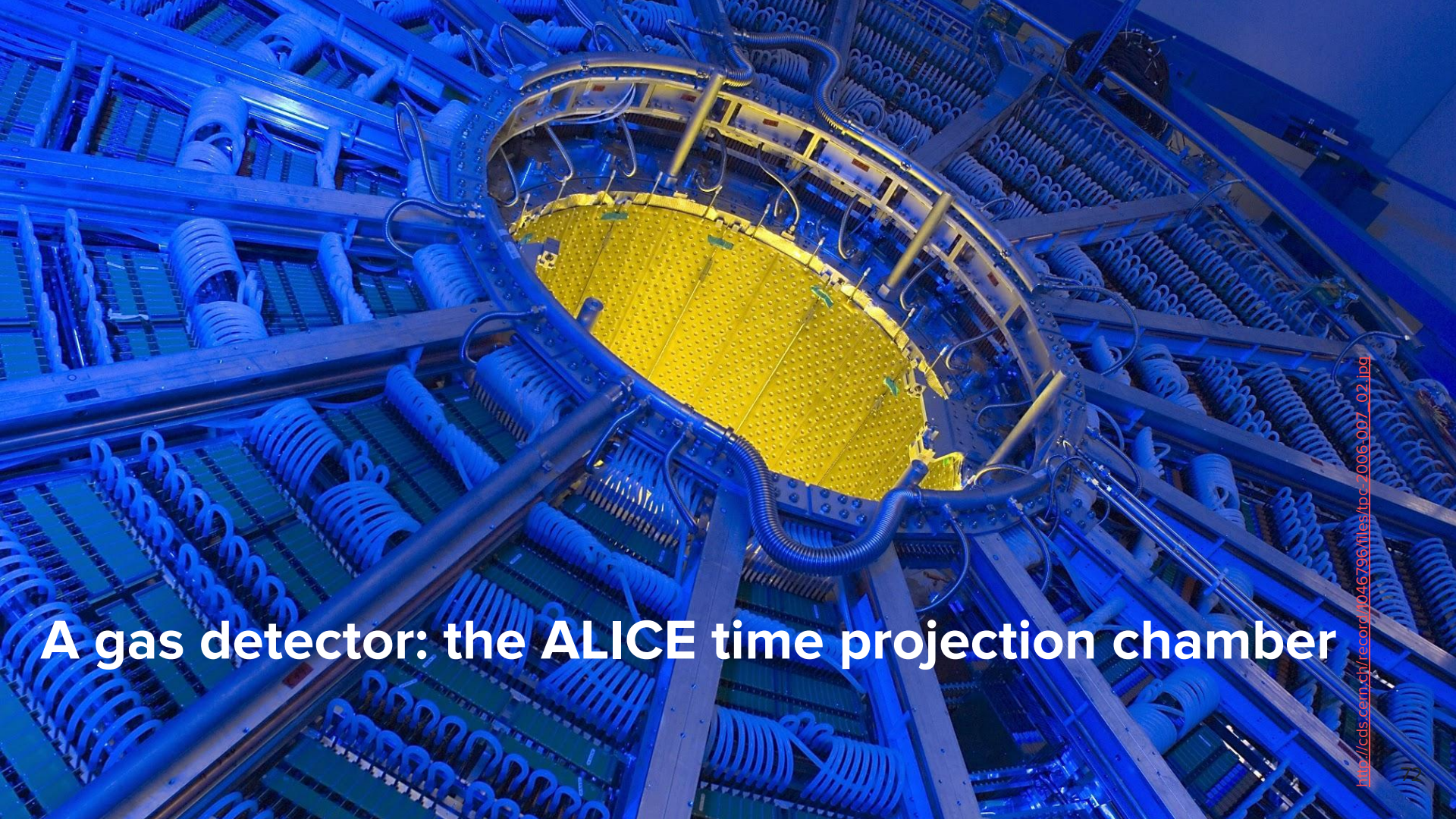
With the Inner Tracking System at its heart!



From https://alice.cern/experiment

ALICE Time Projection Chamber

Een gas detector

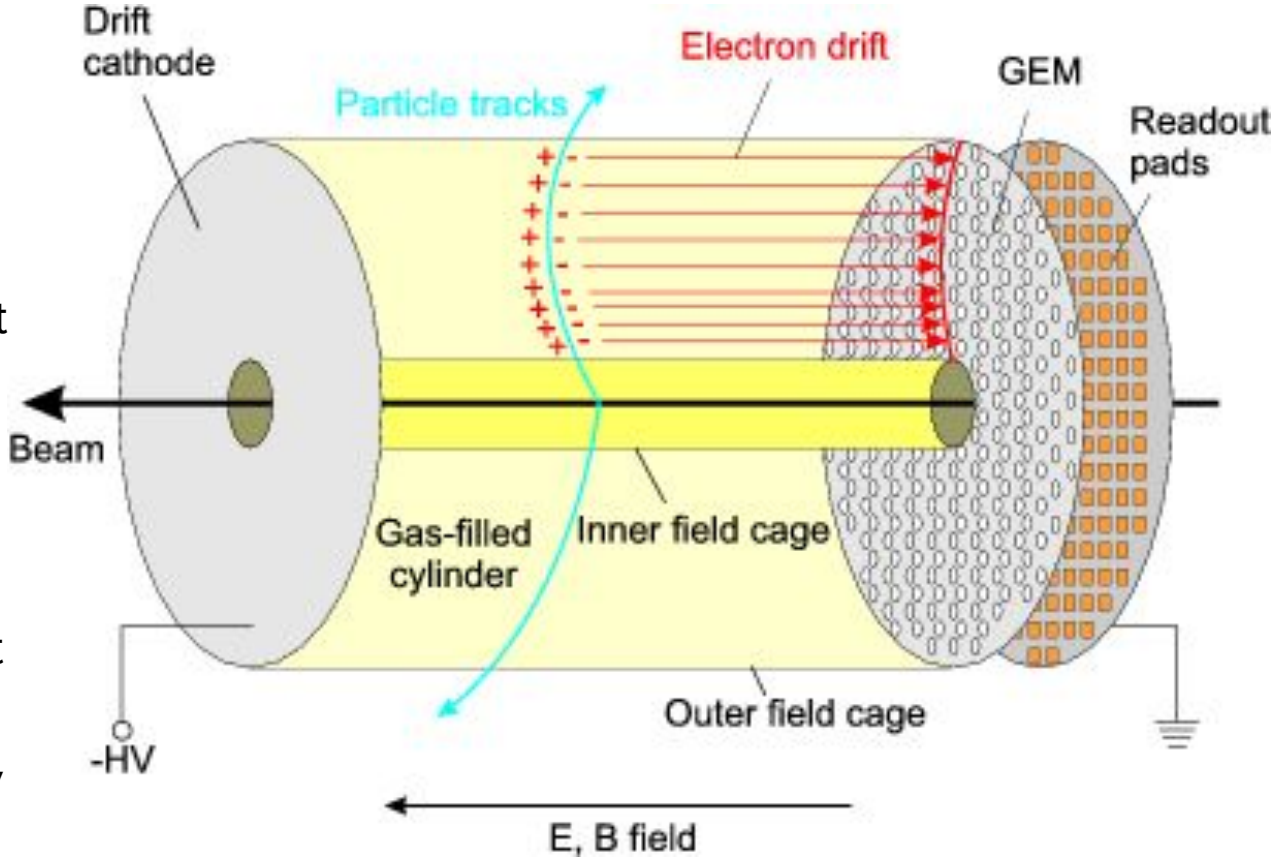


A gas detector: the ALICE time projection chamber

http://cds.cern.ch/record/1046796/files/tpc_2006-007_02.jpg

TPC

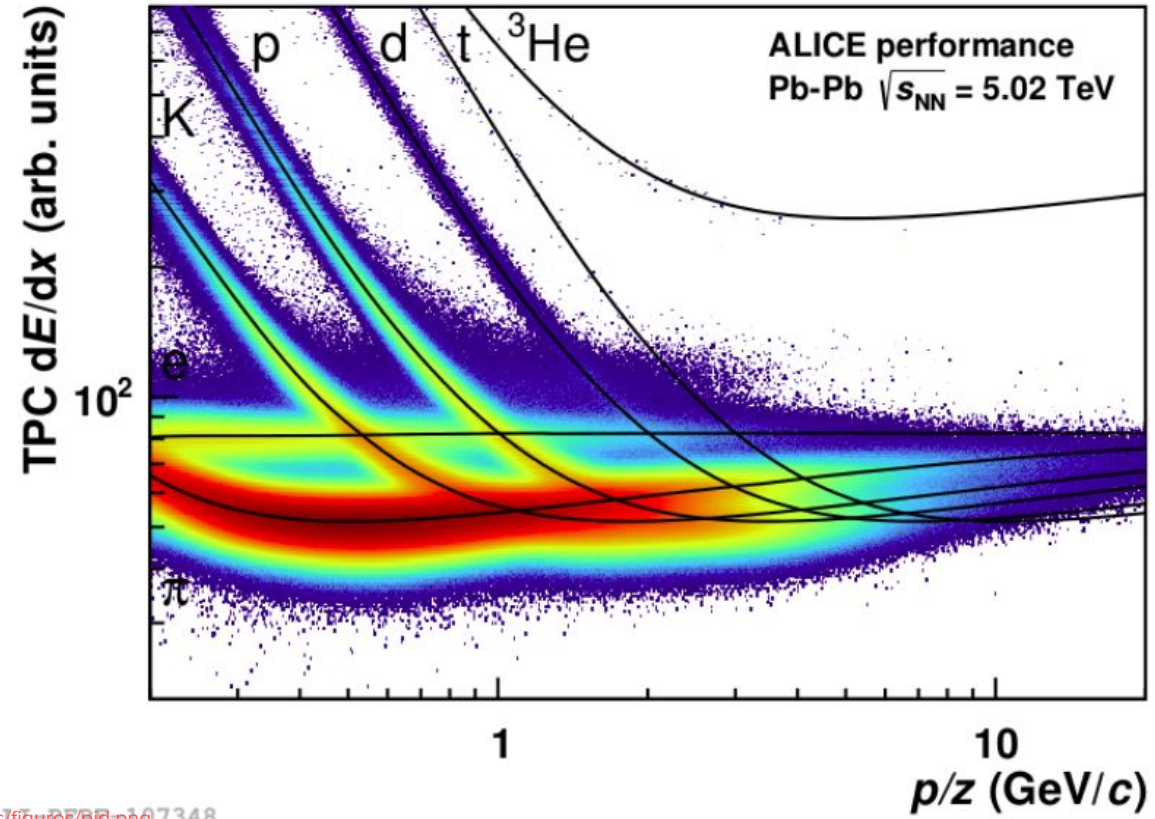
1. Ionization of gas in **chamber** with electric field causes electron drift
2. Signal gets amplified, in this case by gas electron multipliers ➔ electron avalanche
3. Readout pads can detect signal that can be **projected** onto trajectory
4. z (along beam) information from **timing**



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

ALICE time projection chamber: particle identification

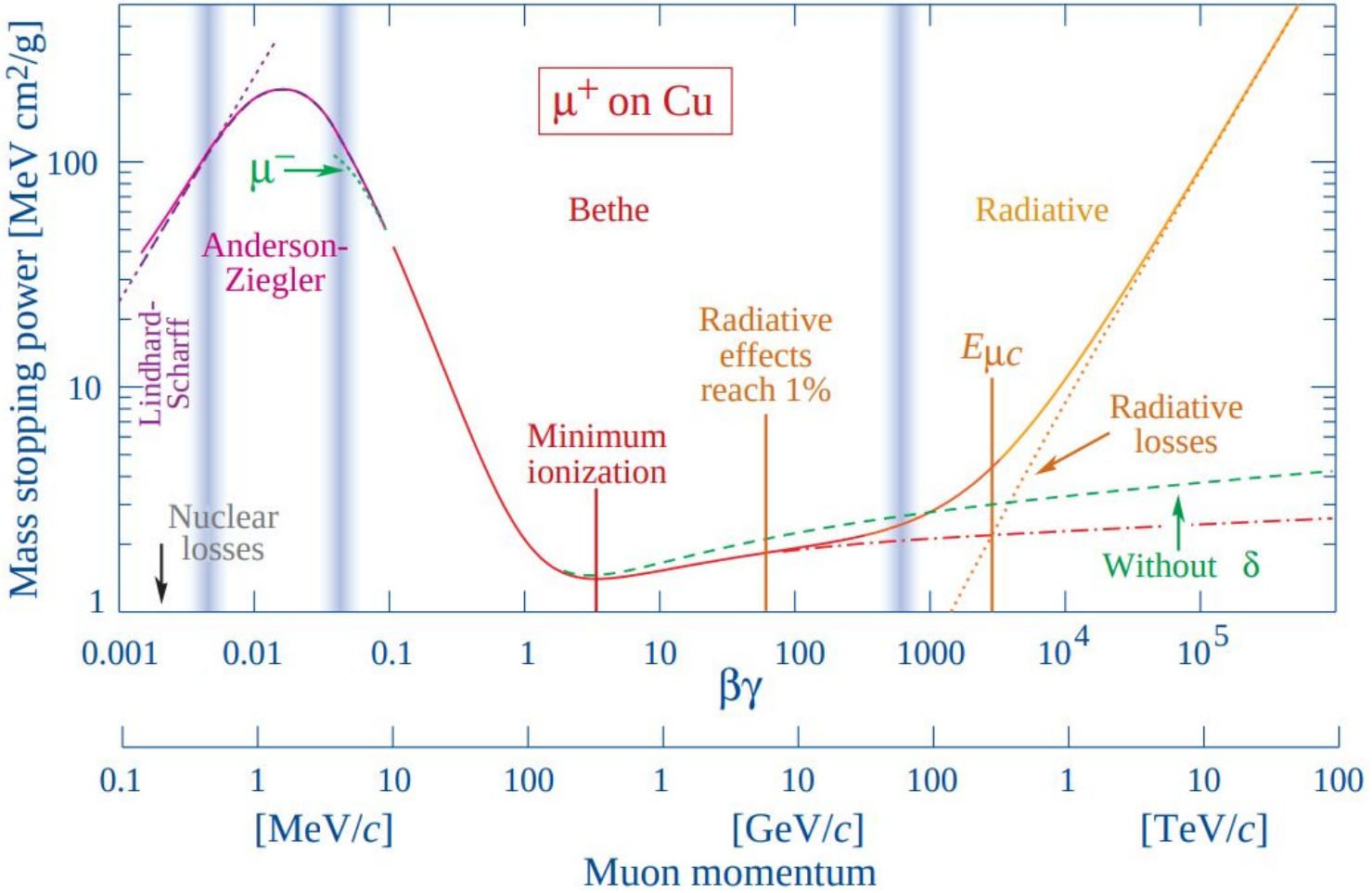
- Every point is one measurement!
- Can identify particles for low momenta
- For higher momenta, all particles behave like a minimum ionizing particle (MIP)



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

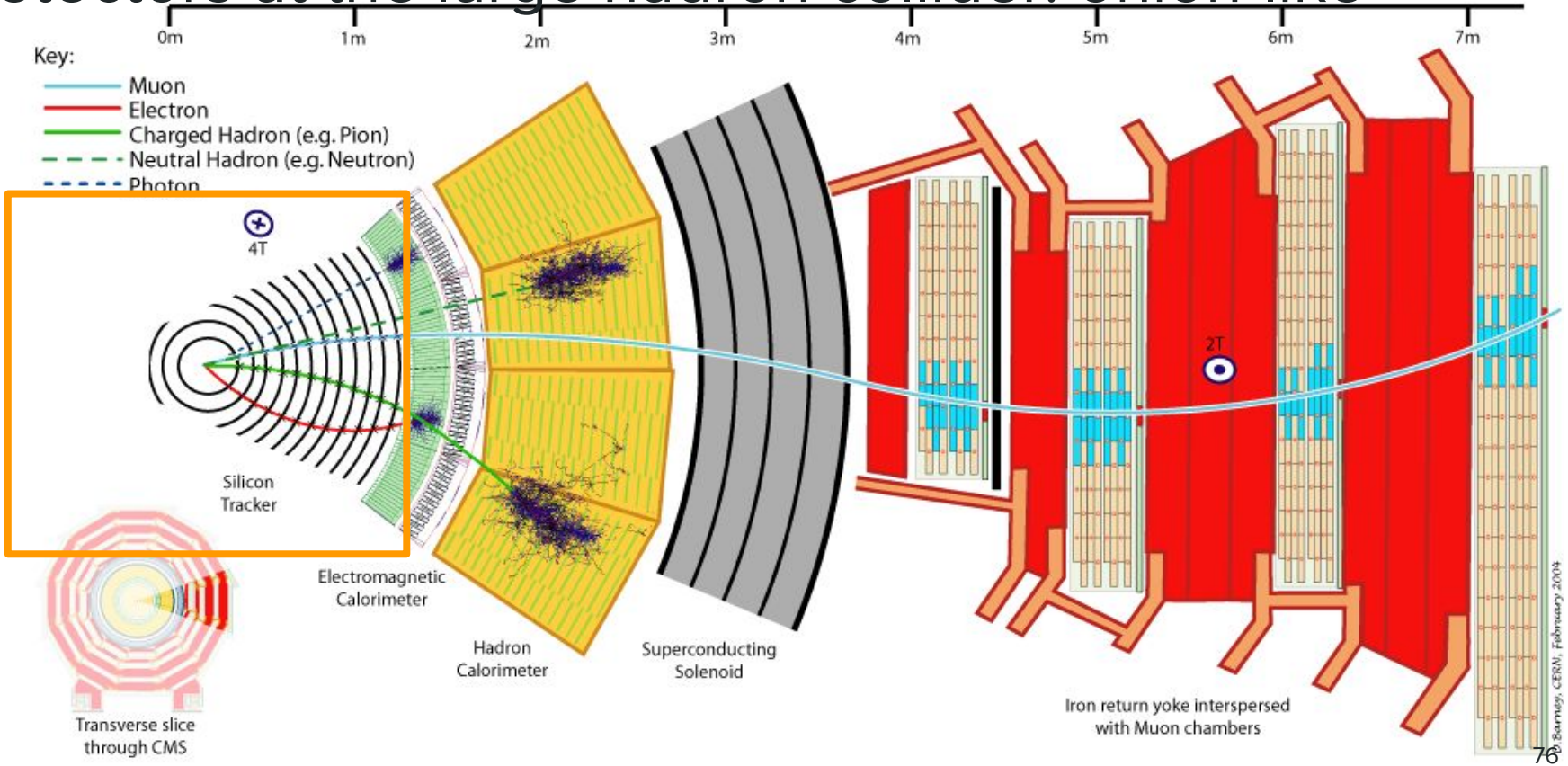
https://alice-doc.github.io/alice-analysis-tutorial/analysis/figures/pid.png

Ionization loss



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

Detectors at the large hadron collider: onion-like



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

How to measure neutrinos?

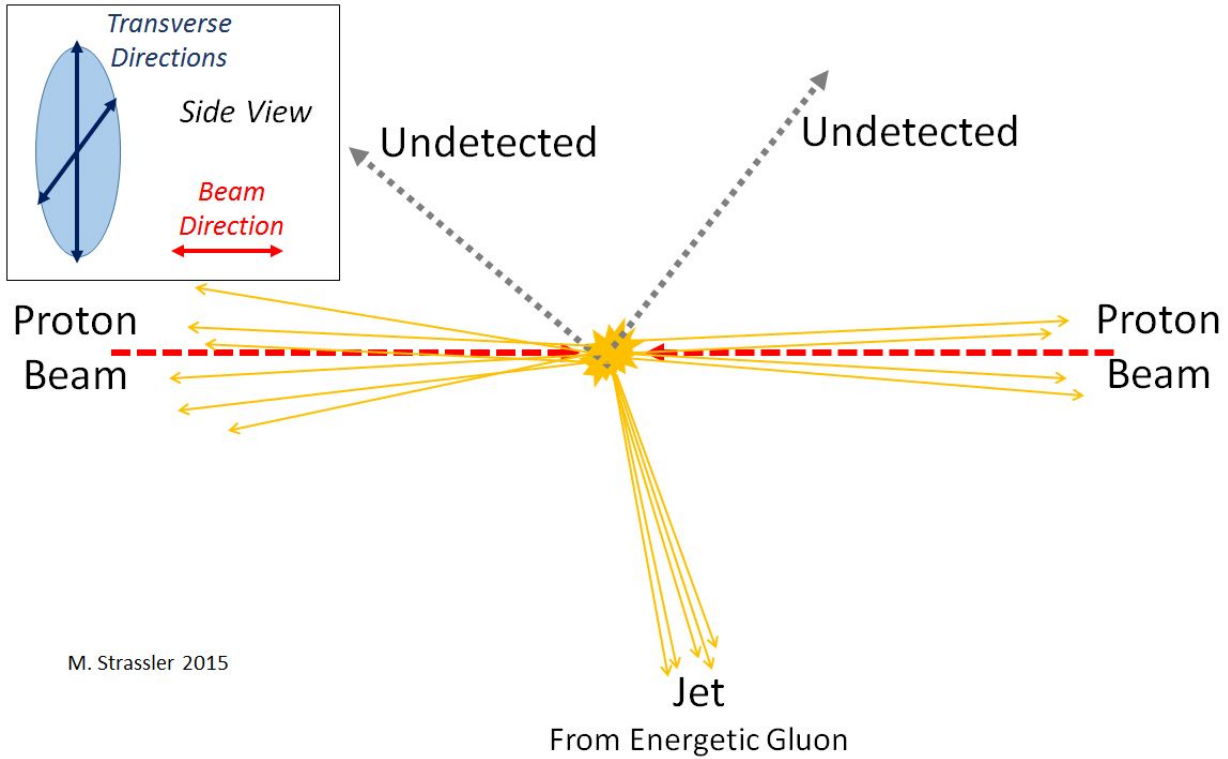
Missing transverse momentum

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
- De meeste van de zon en uit de atmosfeer
- Zeldzame gebeurtenissen van zwarte gaten, supernovae…

KM3NeT: cubic kilometer neutrino telescope

- **Tussen 2 en 4 km diep in middelandse zee (FR-IT-GR)**
- **12000 digital optical modules (DOMs) aan 600 draden**
- **Cherenkov detectie met fotobuizen**
- **GeV, TeV, and PeV neutrinos**

Nederland speelt een grote rol in de constructie!

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

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

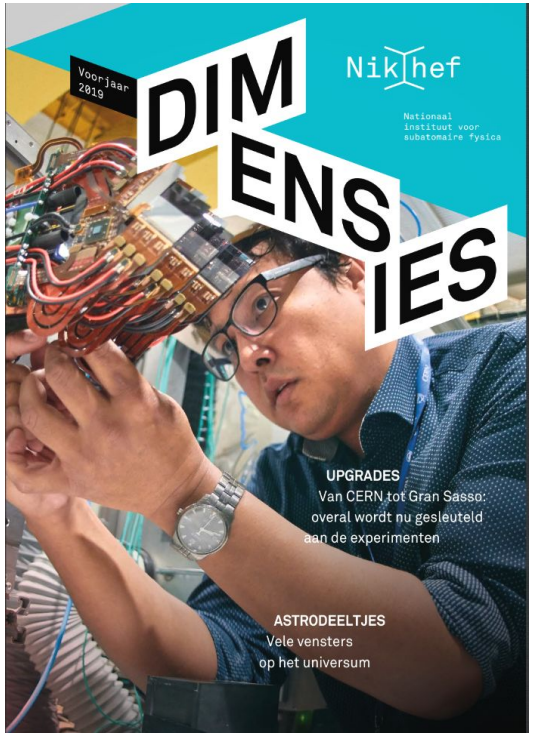
- 10^9 neutrinos / cm^2/s
- Most from sun and atmosphere
- Rare events from black holes, supernovae…

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

Nieuwe detectoren op Nikhef en CERN

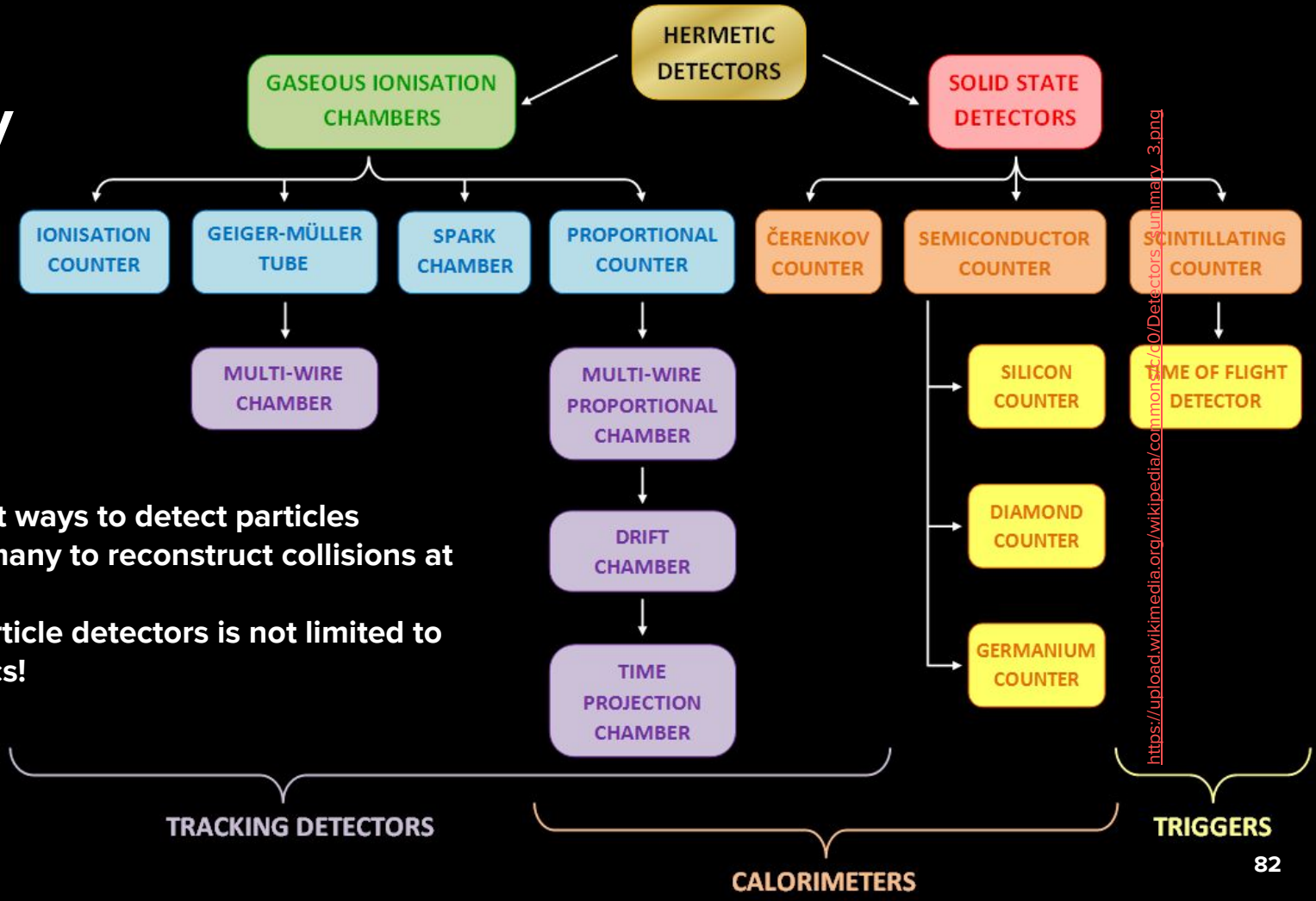
Nikhef wetenschapsdag
En hier
Zaterdag 5 oktober 12:00-17:00
Wetenschapsdag Amsterdam Science Park

Op Nikhef werken we mee aan detectoren die op CERN bij de LHC worden geïnstalleerd!



Summary

- Many different ways to detect particles
- We combine many to reconstruct collisions at the LHC
- The use of particle detectors is not limited to collider physics!

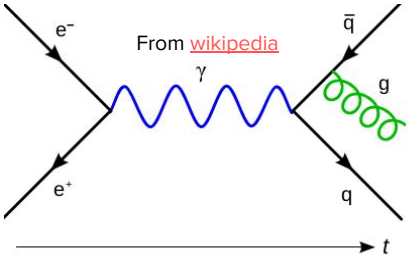


Extra materiaal

Credits

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

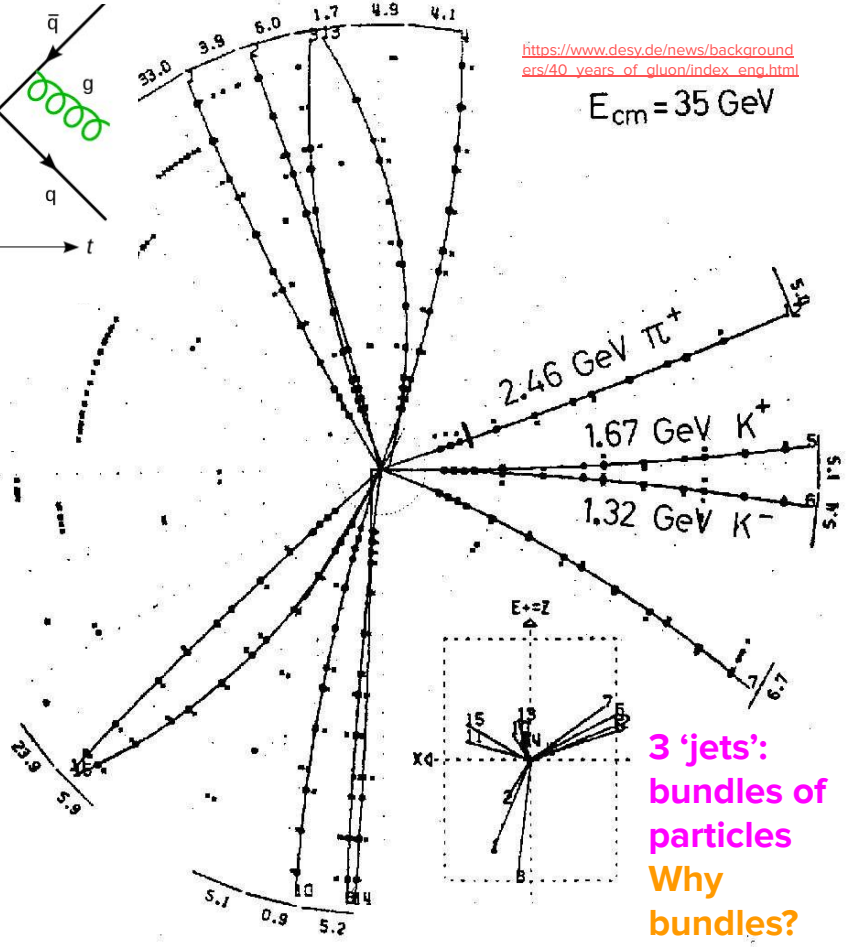
Gluon discovery



From wikipedia

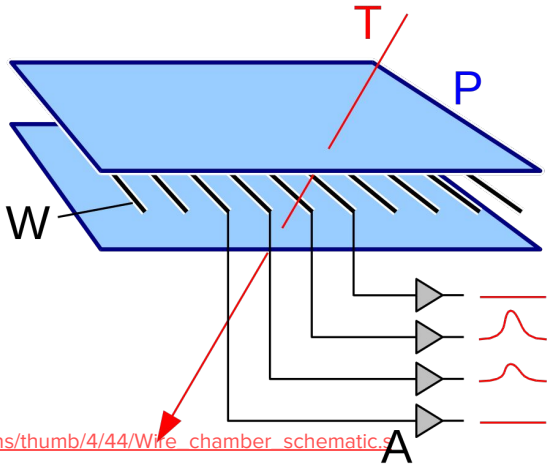
Event in *drift chamber* of JADE experiment at PETRA collider at DESY.

Such events were used to prove the existence of gluons: e+e− ➔ qq¯g .



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

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.

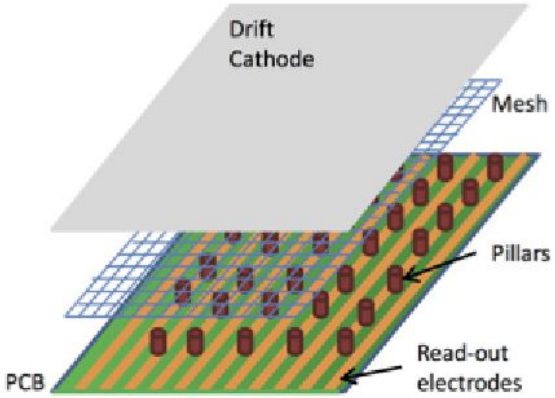


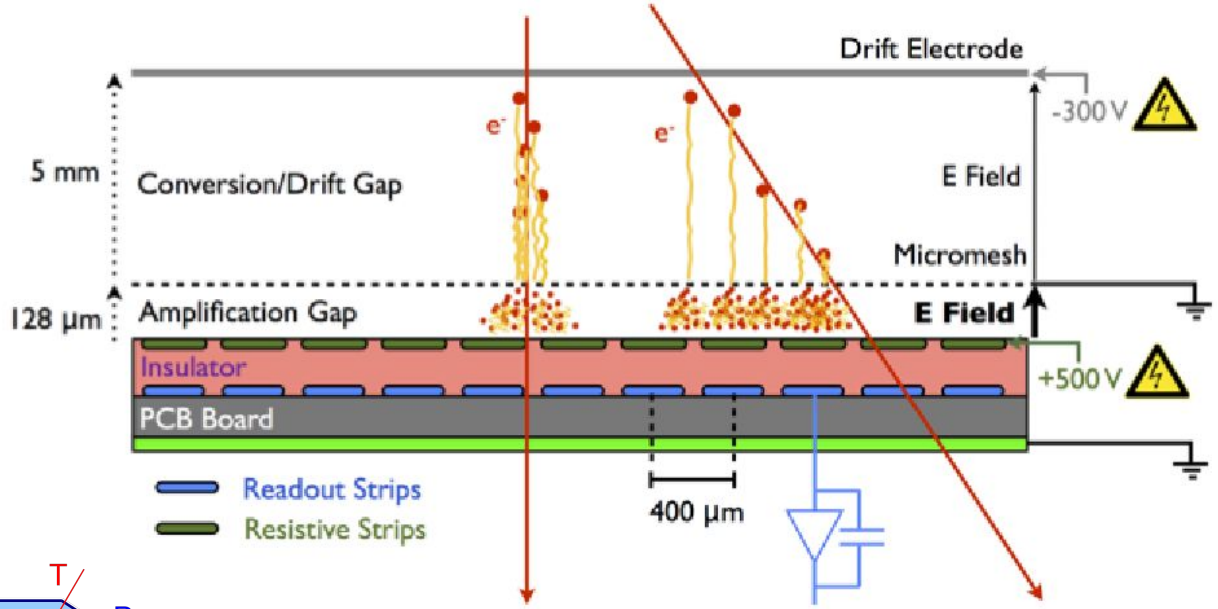
https://upload.wikimedia.org/wikipedia/commons/thumb/4/44/Wire_chamber_schematic.svg/1024px-Wire_chamber_schematic.svg.png

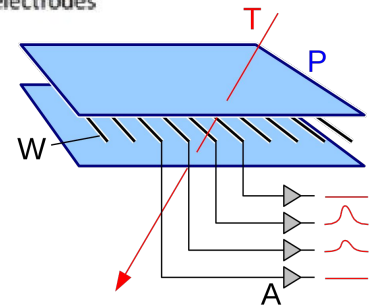
22.9.80

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

Micromesh Gaseous Structure: Micromegas





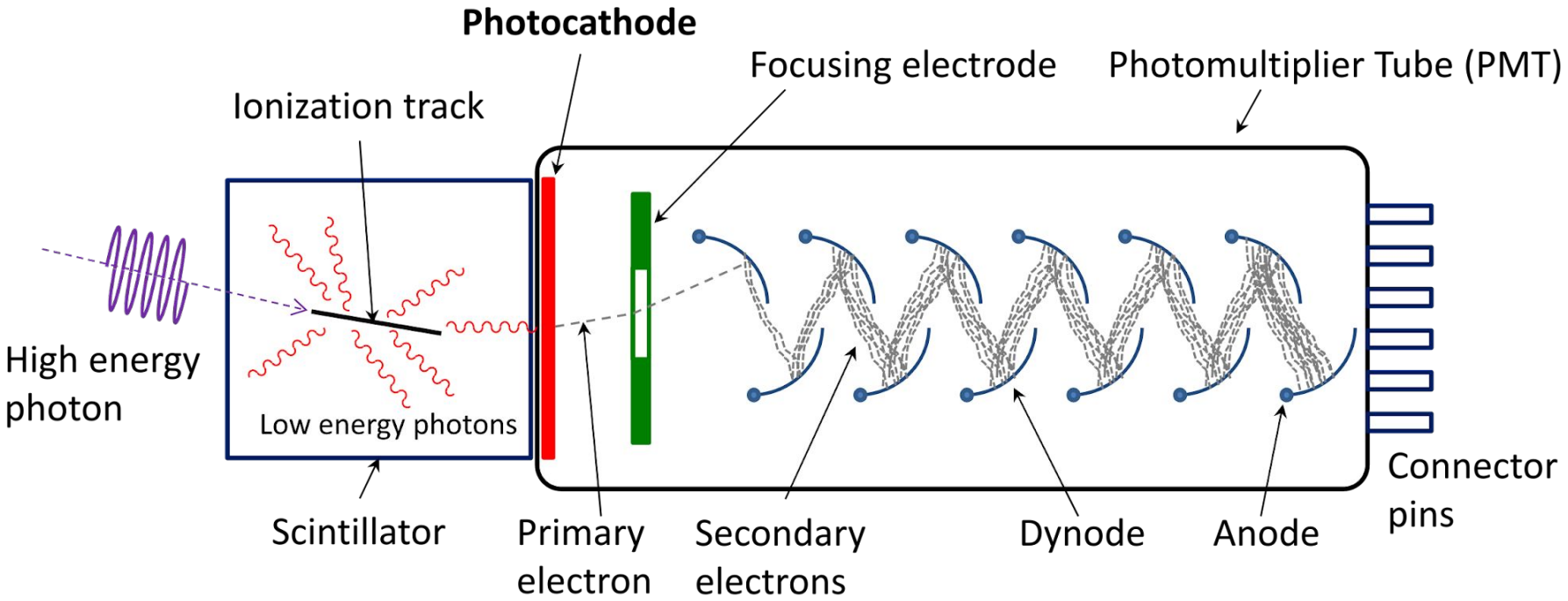


In addition to drift layer also an amplification layer

Figure from M. Iodice

Photomultiplier tube

Image from Wikipedia



KATRIN: neutrino mass measurement

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

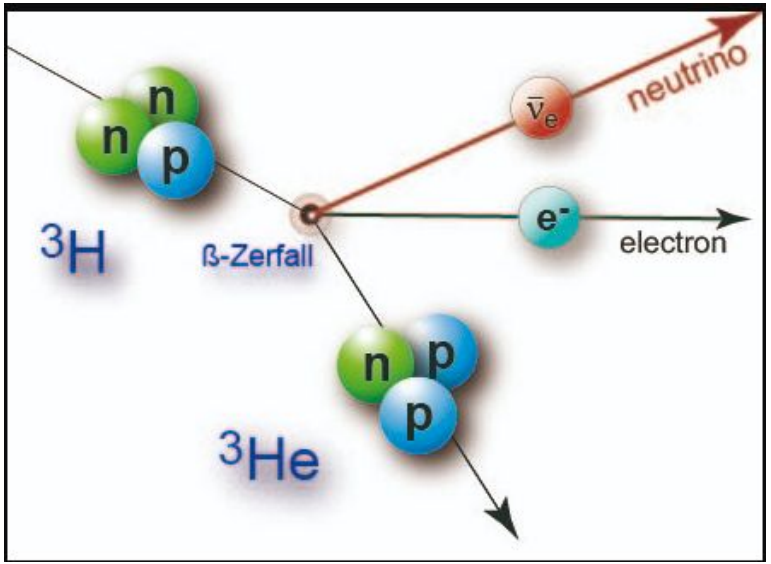
https://upload.wikimedia.org/wikipedia/commons/c/c6/Ortsdurchfahrt-Leopoldshafen.jpg

$m_\nu < 0.8$ eV: most precise measurement of neutrino mass!

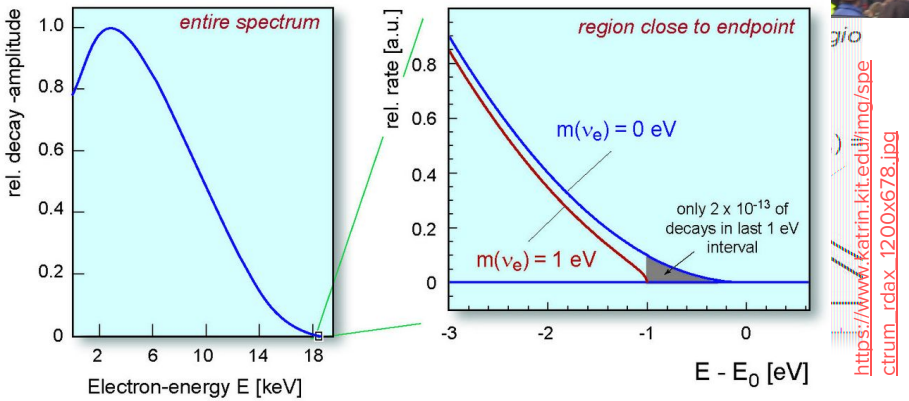
Recently published! https://arxiv.org/abs/1909.06048

KATRIN: neutrino mass measurement

Karlsruhe tritium neutrino experiment



$m_\nu < 1.1$ eV (90% confidence level)



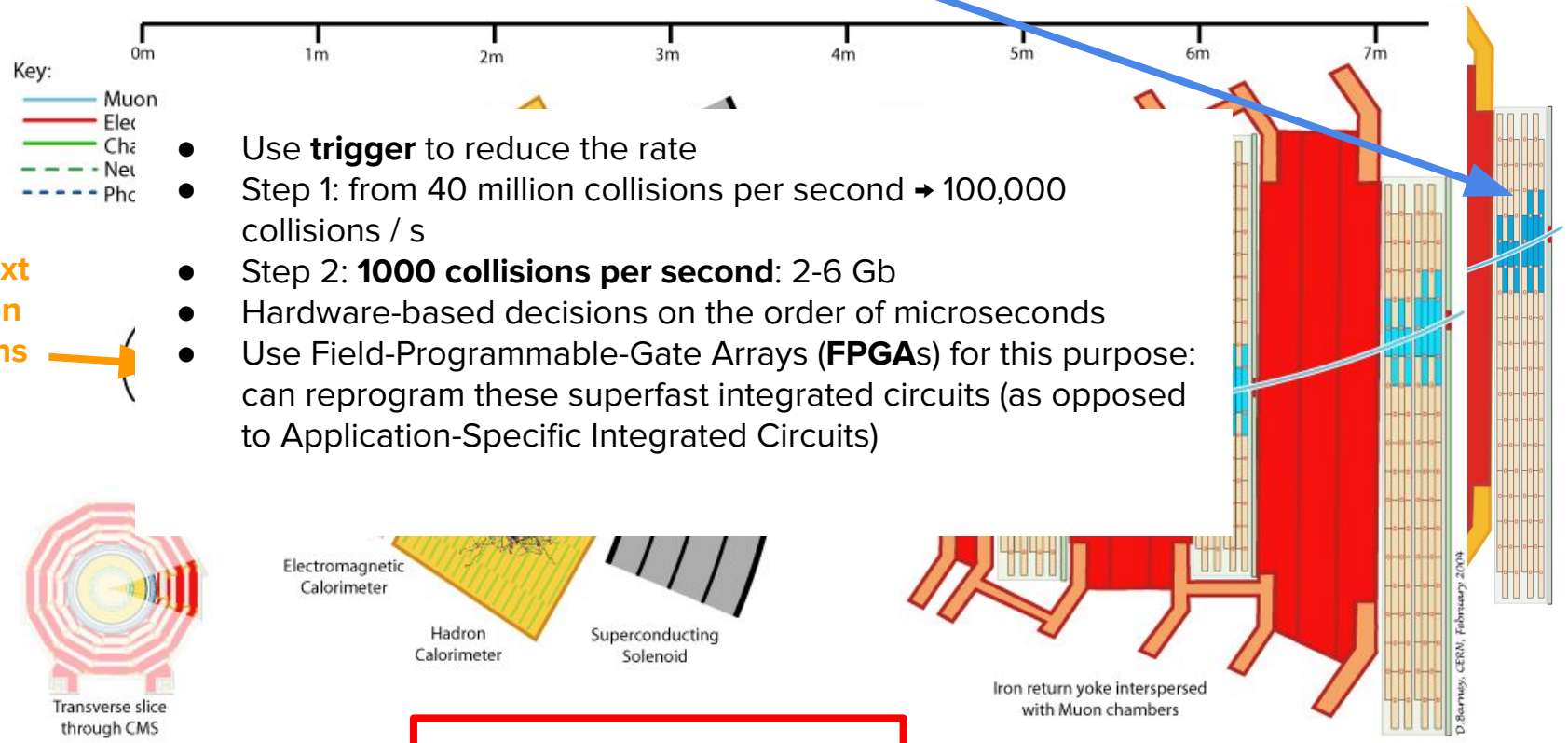
Derive neutrino mass information from electron energy

First experiment with sub-eV neutrino mass constraints: https://www.nature.com/articles/s41567-021-01463-1

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

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

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)

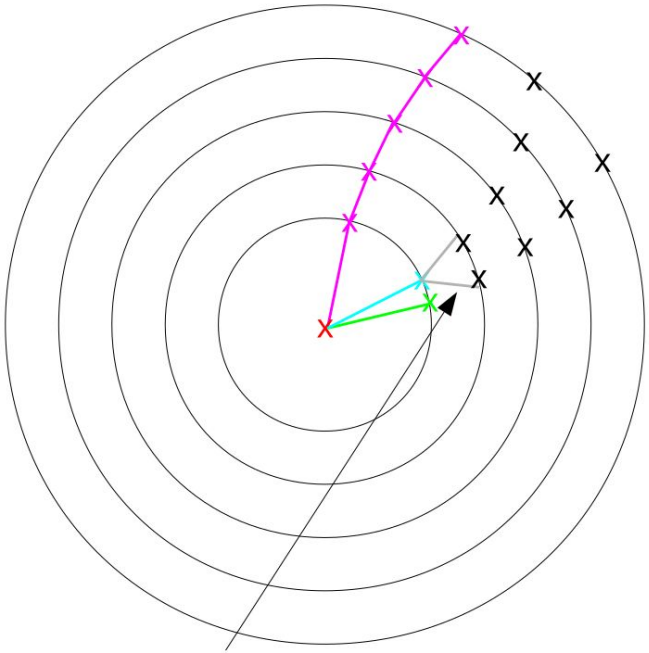
The next collision happens here:

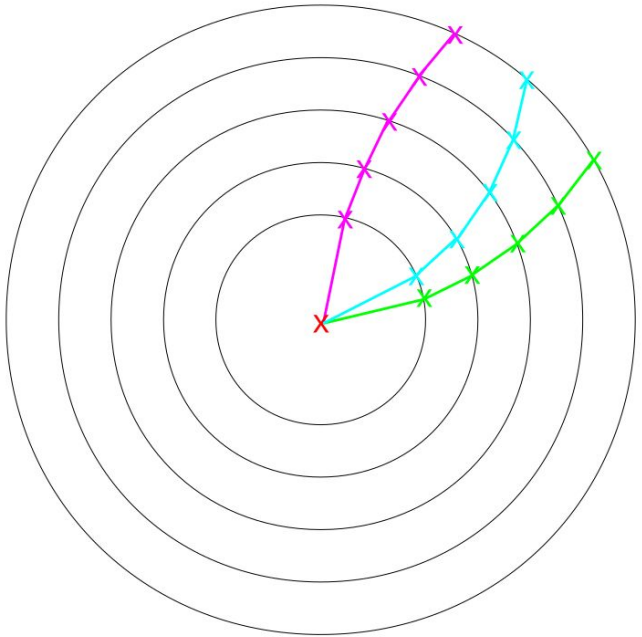
25 ns • c ≅7.5m

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

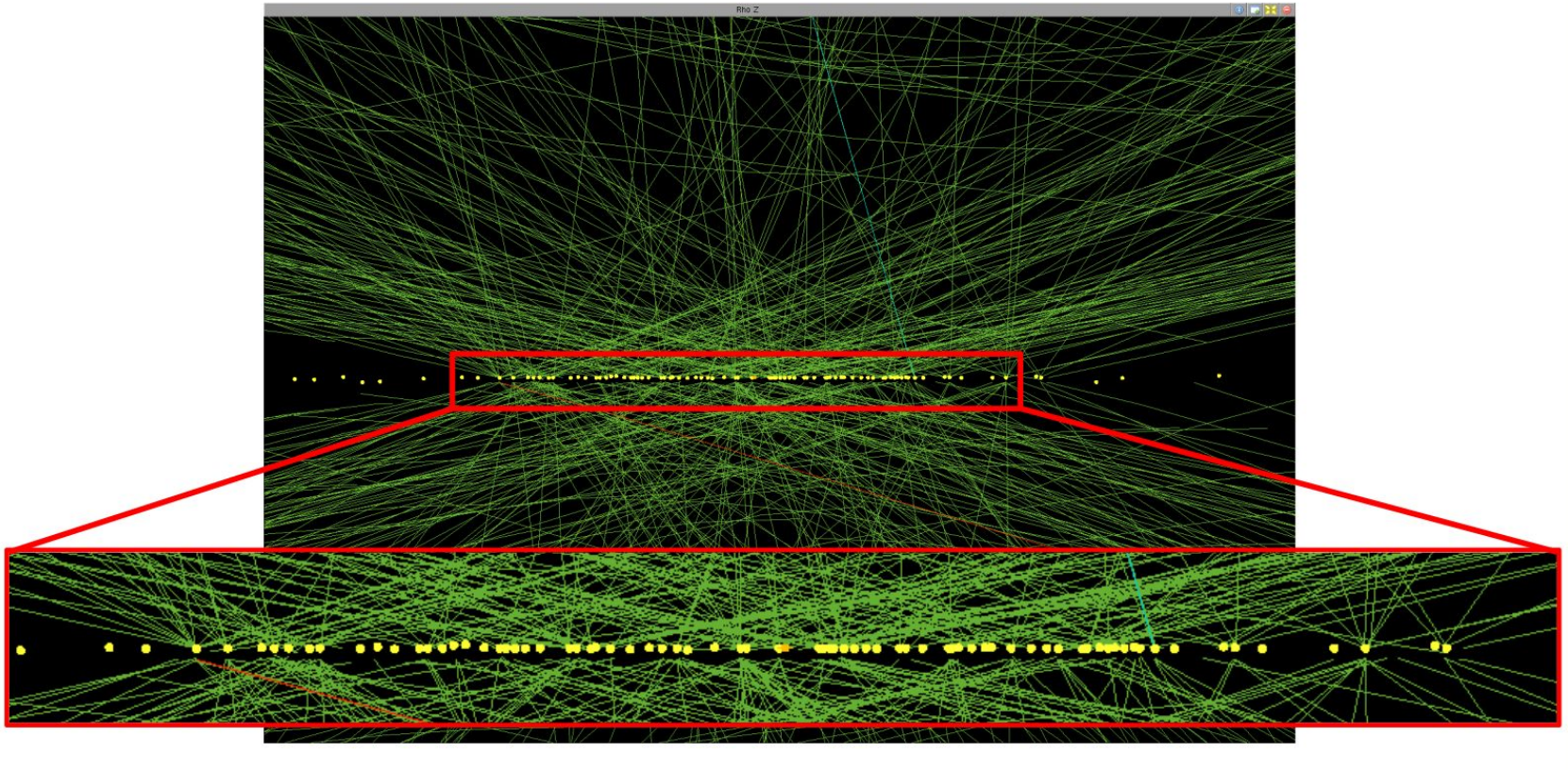
Track reconstruction

Track reconstruction: find hits that belong to track



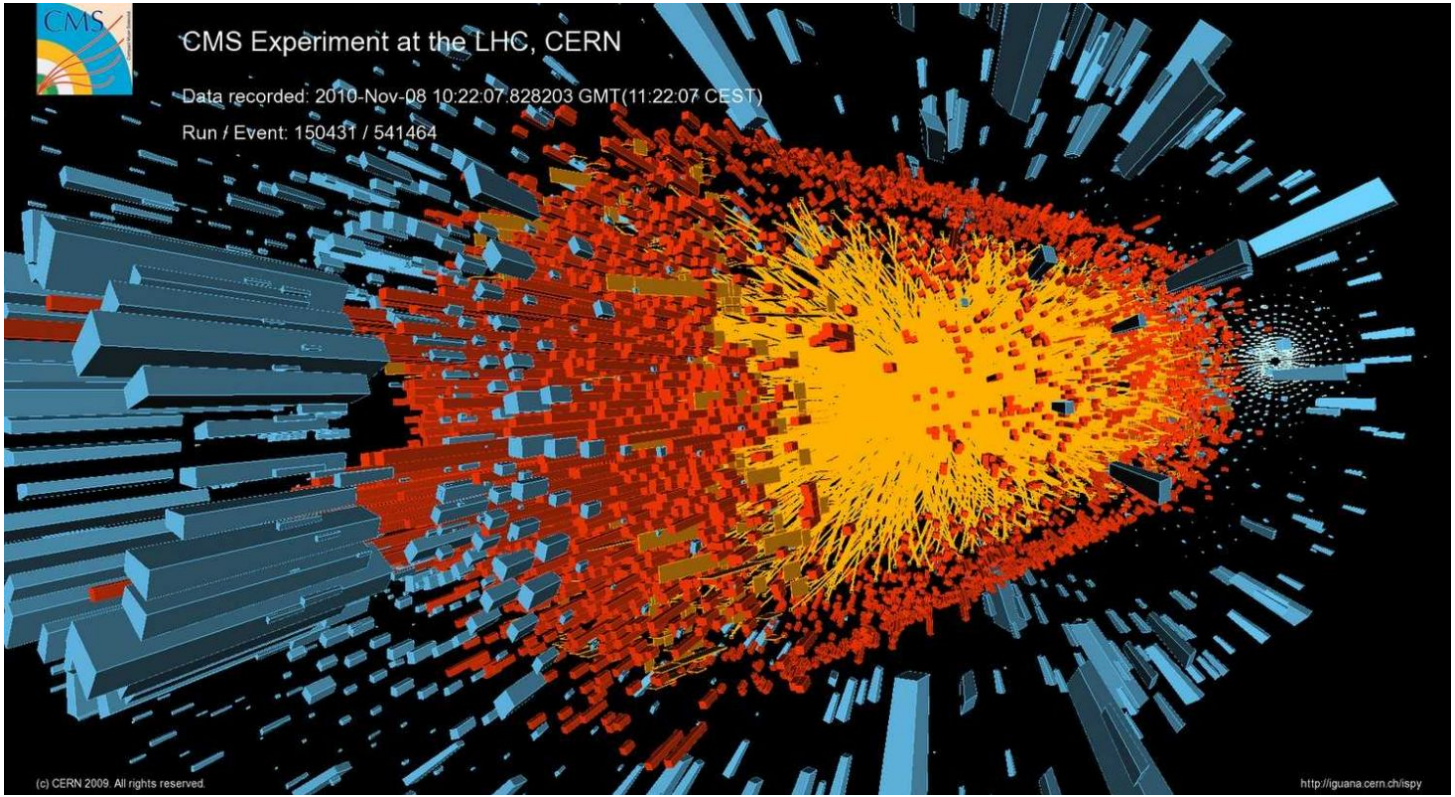


What if 78 interactions happen simultaneously?

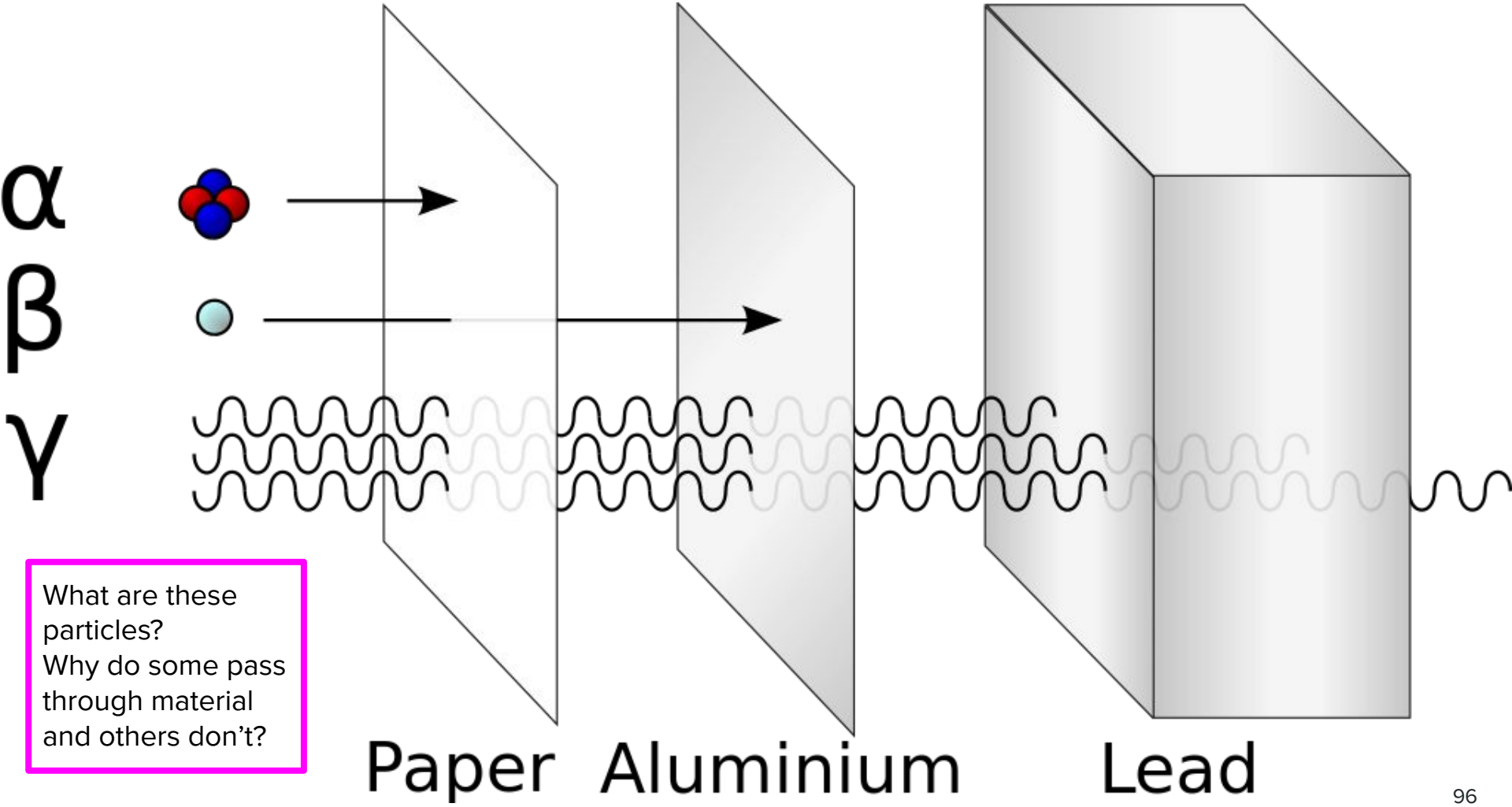


Or a collision of 2 lead nuclei?

10000 charged tracks!

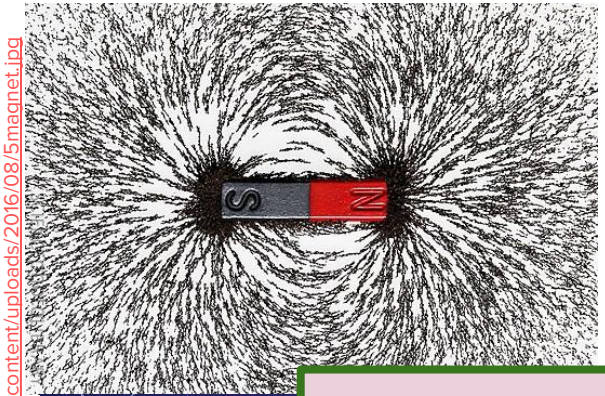


Calorimeters



What are these particles?
Why do some pass through material and others don't?

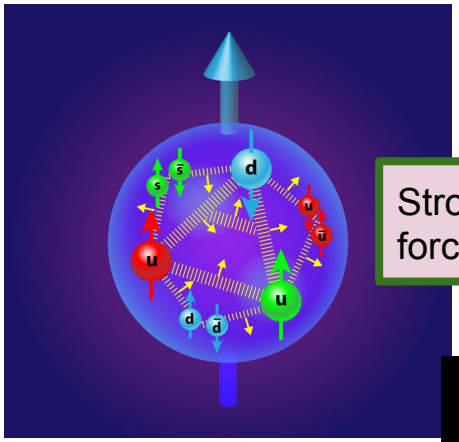
Interactions: four known forces



electromagnetism

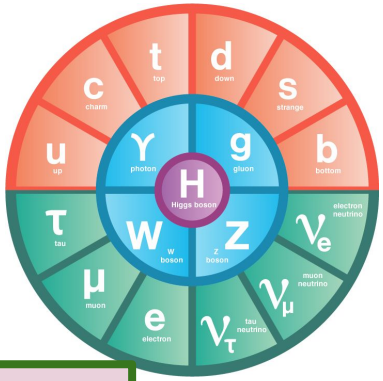
http://blog.science4you.es/wp-content/uploads/2016/08/5magnet.jpg

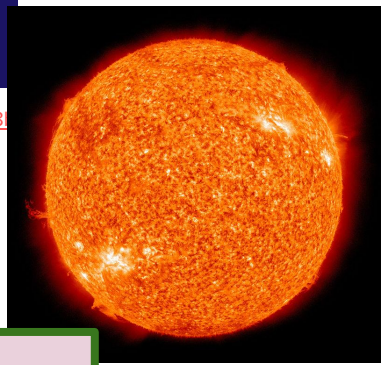
https://upload.wikimedia.org/wikipedia/commons/thumb/3/33/Lightning_0257.jpg/1200px-Lightning_0257.jpg



Strong nuclear force

https://physics.aps.org/assets/89b4f0e0-b8
b70d-d90f744d1790/e23_2.png

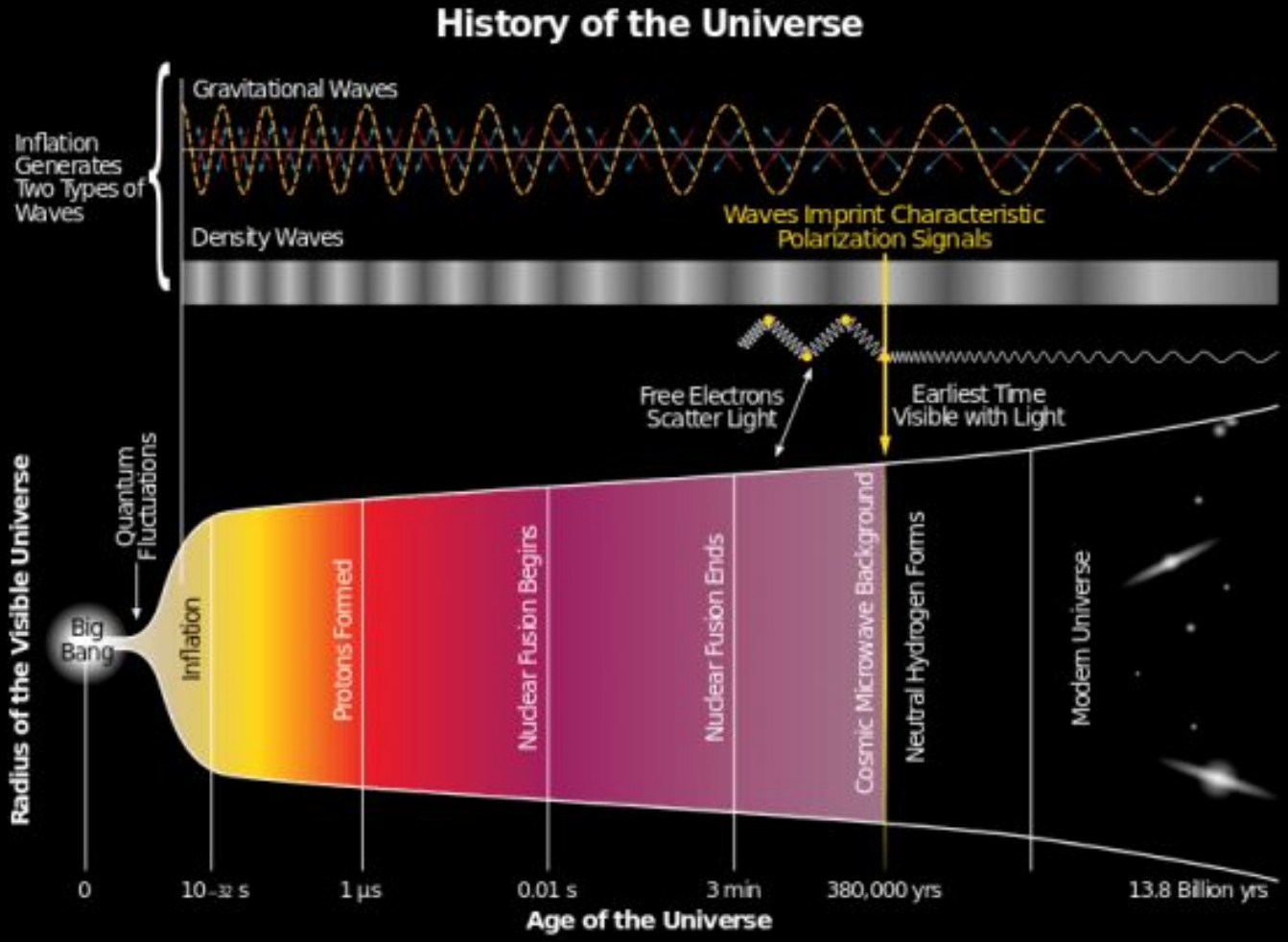




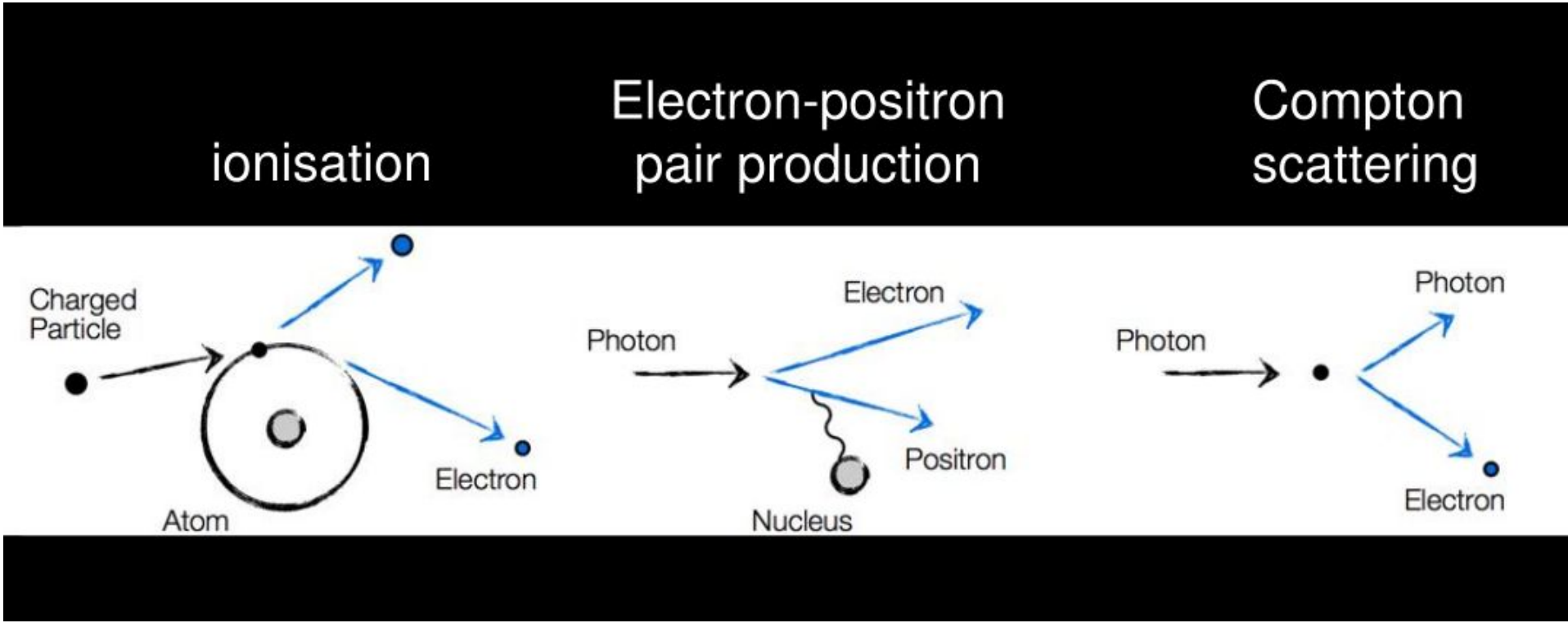
https://upload.wikimedia.org/wikipedia/commons/thumb/b/b4/The_Sun_by_the_Atmospheric_Imaging_Assembly_of_NASA%27s_Solar_Dynamics_Observatory_-_20100819.jpg/800px-The_Sun_by_the_Atmospheric_Imaging_Assembly_of_NASA%27s_Solar_Dynamics_Observatory_-_20100819.jpg

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

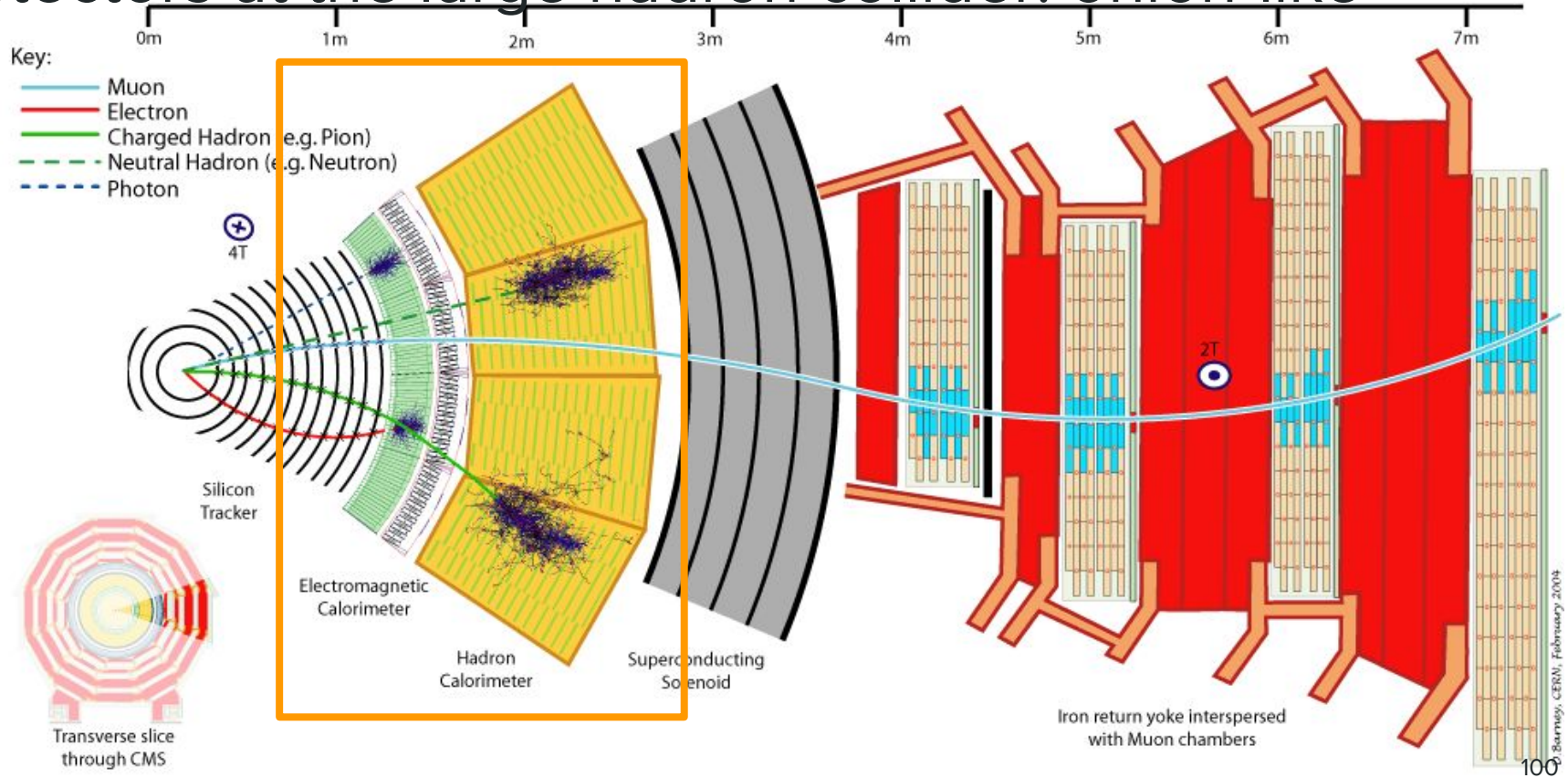
Weak nuclear force


History of the Universe
Gravitational Waves
Inflation Generates Two Types of Waves
Density Waves
Waves Imprint Characteristic Polarization Signals
Free Electrons Scatter Light
Earliest Time Visible with Light
Radius of the Visible Universe
Quantum Fluctuations
Big Bang
Inflation
Protons Formed
Nuclear Fusion Begins
Nuclear Fusion Ends
Cosmic Microwave Background
Neutral Hydrogen Forms
Modern Universe
0
10−32 s
1 µs
0.01 s
3 min
380,000 yrs
13.8 Billion yrs
Age of the Universe

Interaction with matter: destructive measurement



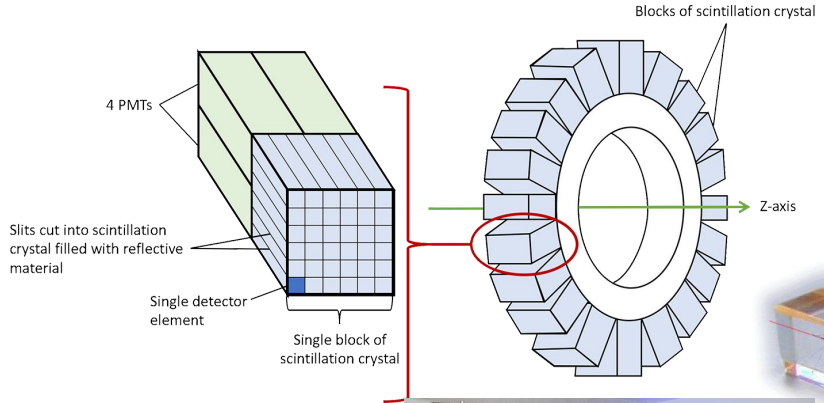
Detectors at the large hadron collider: onion-like



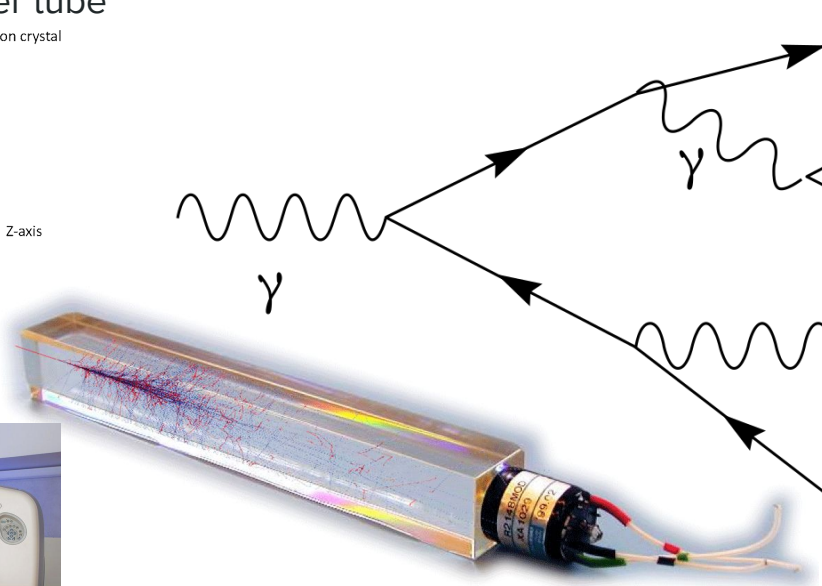
http://inspirehep.net/record/826852/files/EPS_CMS_Slice.png

Electromagnetic calorimeter

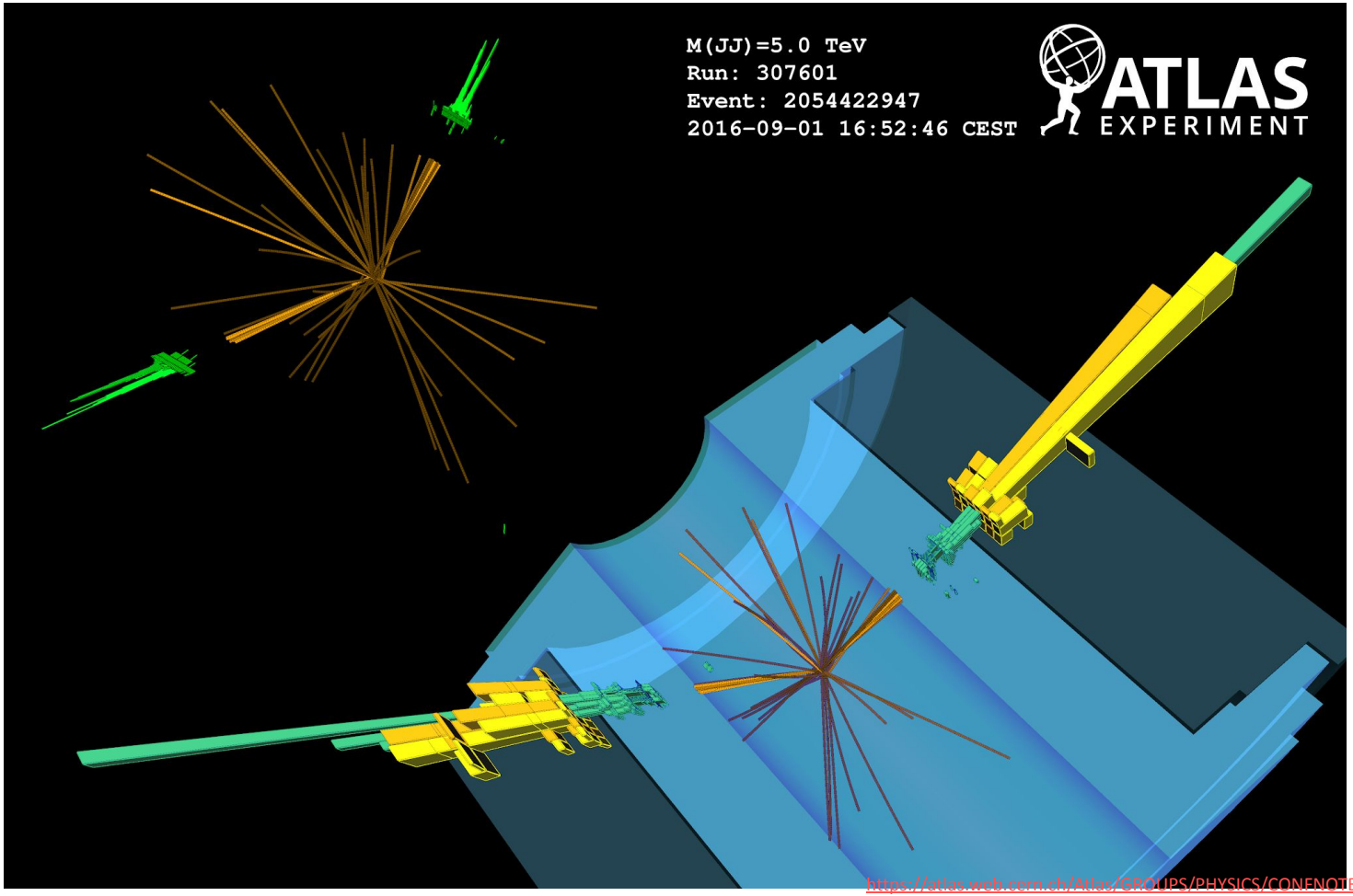
- Electromagnetic shower by interaction with material
- CMS uses scintillating lead tungstate crystals of 1.5 kg that can take 2 days to grow!
- Light detected with a photomultiplier tube



Same crystals used in PET scanners



Diboson event: jets in the ATLAS detector

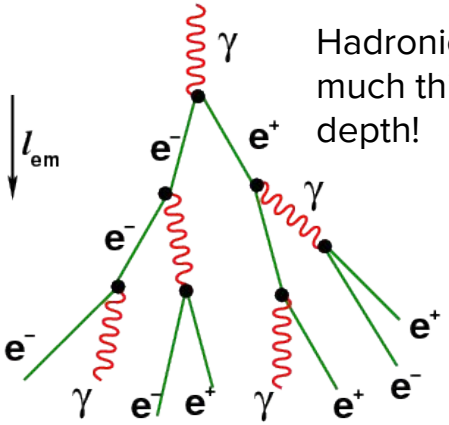


https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CONFNOTES/ATLAS-CONF-2018-016/fig_16.png

Hadronic calorimeter

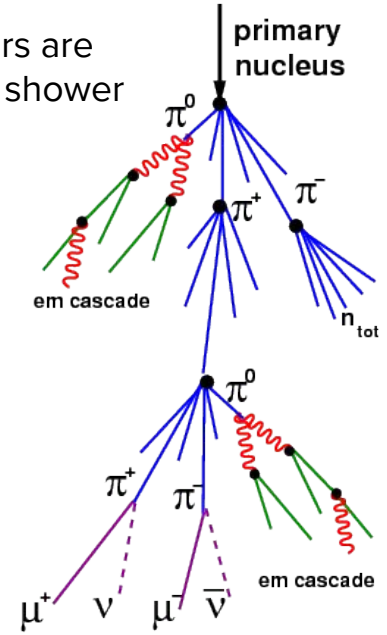
	λ_{int} [cm]	X_0 [cm]
Szint.	79.4	42.2
LAr	83.7	14.0
Fe	16.8	1.76
Pb	17.1	0.56
U	10.5	0.32
C	38.1	18.8

em cascade

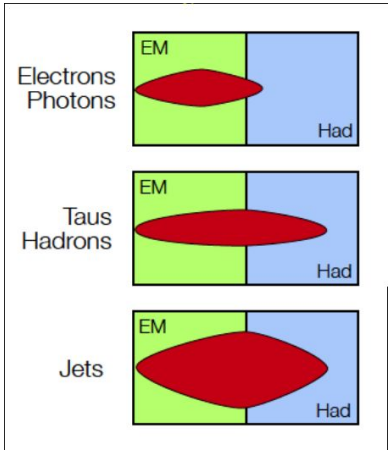


Hadronic calorimeters are much thicker: larger shower depth!

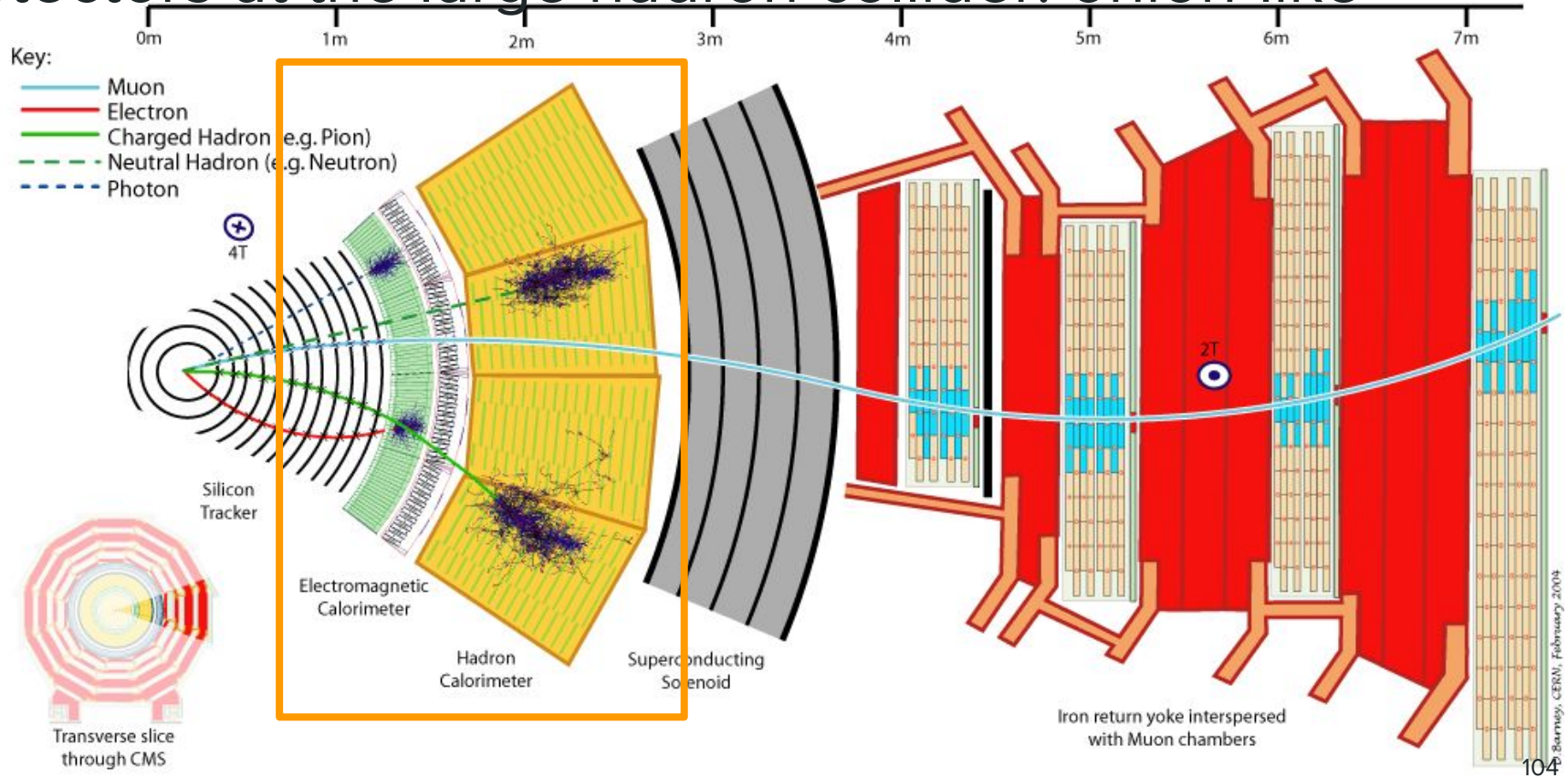
hadronic cascade



Need to consider fractions of energy in each calorimeter



Detectors at the large hadron collider: onion-like



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

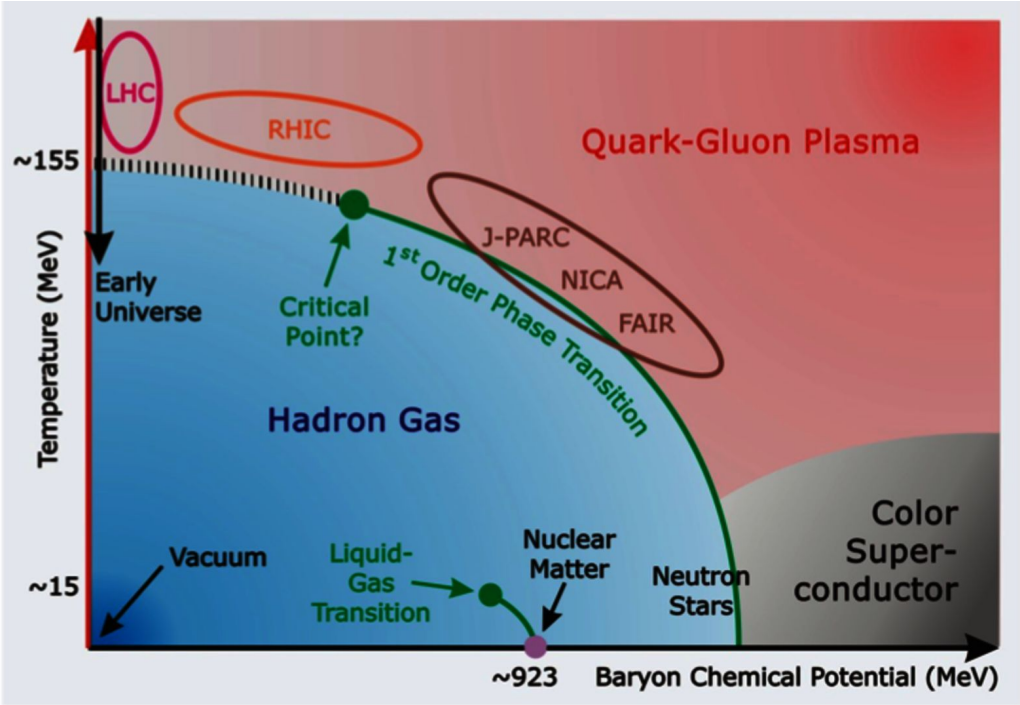
CMS = compact muon solenoid

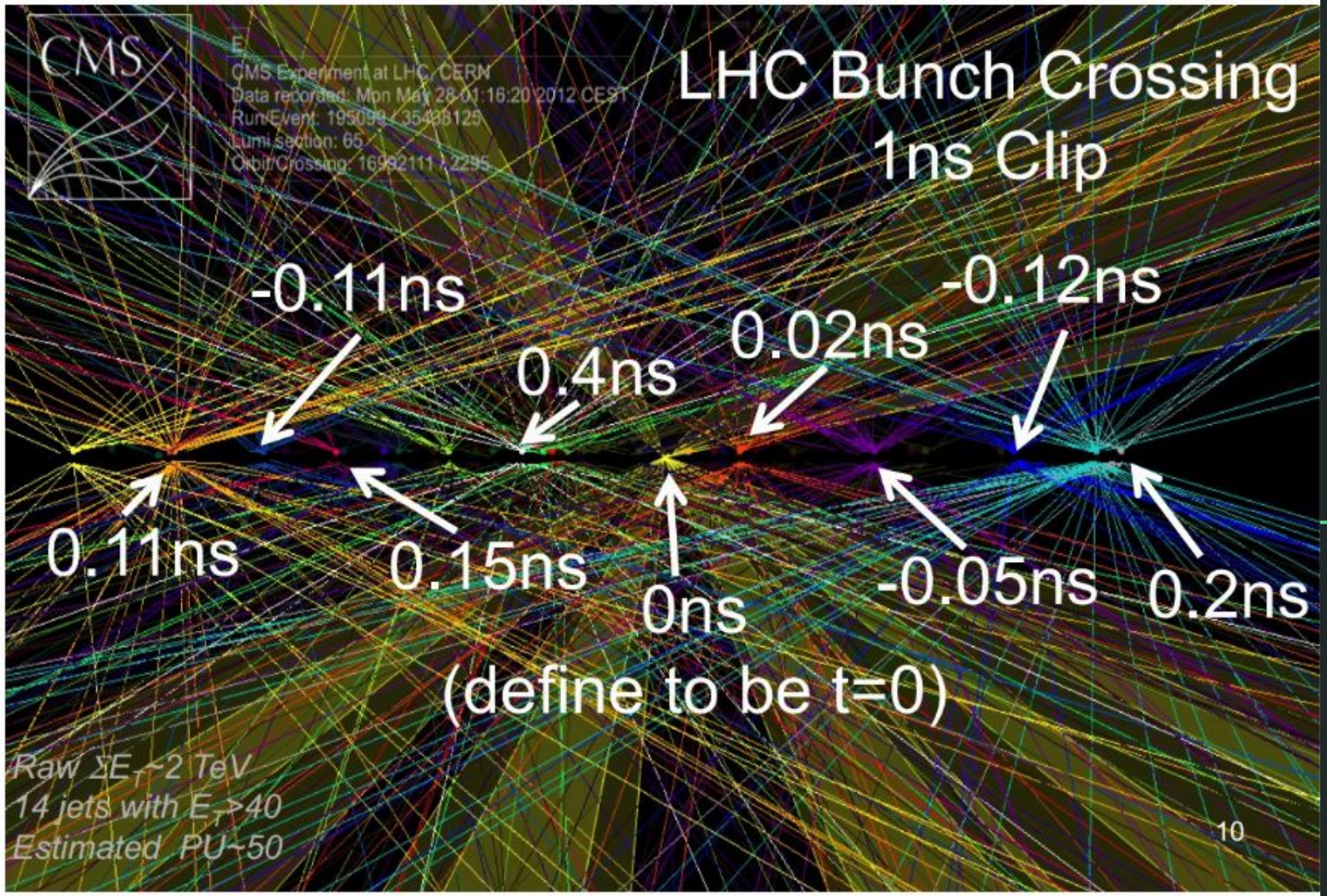
De CMS solenoid:

- Is de grootste supergeleidende magneet ooit gemaakt
- Weegt 12000 ton
- Is gekoeld tot 4.65 K, 2 graden warmer dan in de ruimte
- Is 100,000 keer sterker dan het magneetveld op aarde
- Heeft genoeg energie om 18 ton goud te smelten
- Heeft bijna twee keer zoveel ijzer als de Eiffeltoren

Waarom zware ionen bestuderen?

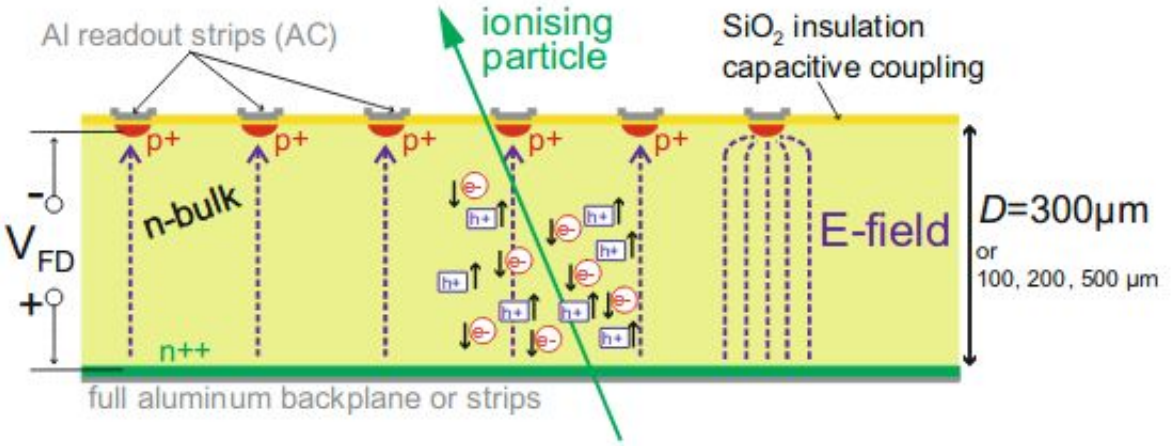
From gsi.de




CMS
CMS Experiment at LHC, CERN
Data recorded: Mon May 28 01:16:20 2012 CEST
Run/Event: 195099 / 35488125
Lumi section: 65
Orbit/Crossing: 16992111 / 2295
LHC Bunch Crossing
1ns Clip
-0.11ns
0.4ns
0.02ns
-0.12ns
0.11ns
0.15ns
0ns
-0.05ns
0.2ns
(define to be t=0)
Raw ΣE_T~2 TeV
14 jets with E_T>40
Estimated PU~50
10

Ideal signal detection with silicon sensors

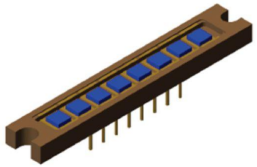
- A minimum ionizing particle (MIP) traveling through a fully depleted region (V_{FD}) creates electron hole pairs
- The charges drift to opposite directions under the electric field
- Within nanoseconds, charges are collected at the readout

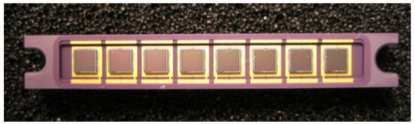


p-in-n silicon sensor

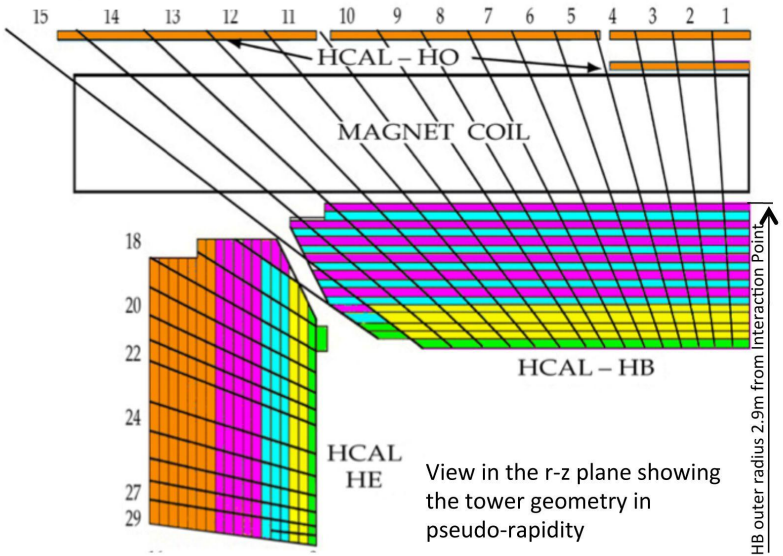
From Frank Hartmann

Photomultipliers ➜ silicon photomultipliers





SiPM array in ceramic holder



View in the r-z plane showing the tower geometry in pseudo-rapidity

CMS upgraded their hadronic calorimeter:
From hit information for 4 cells (1 tower) ➜ hit information per cell