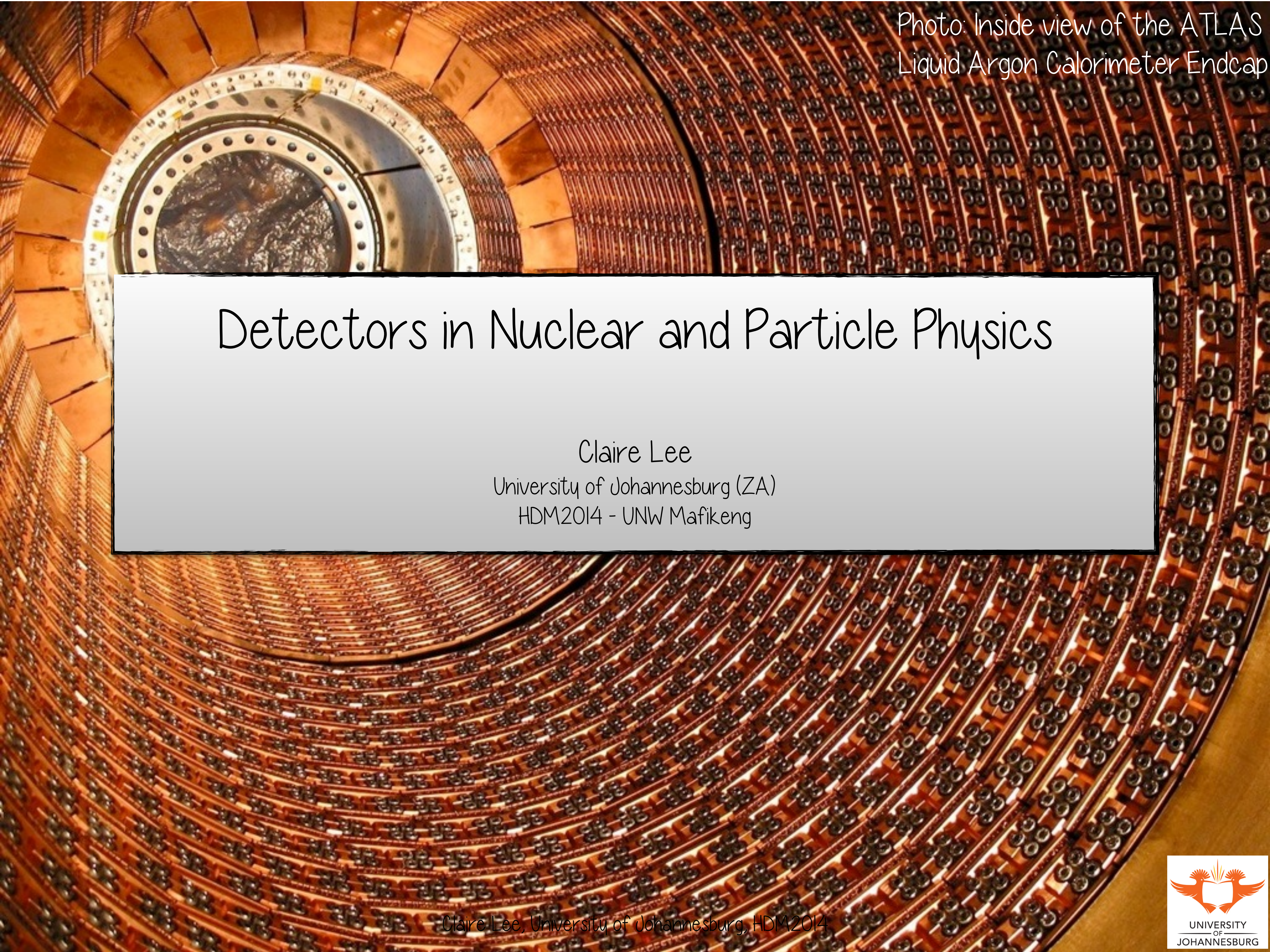


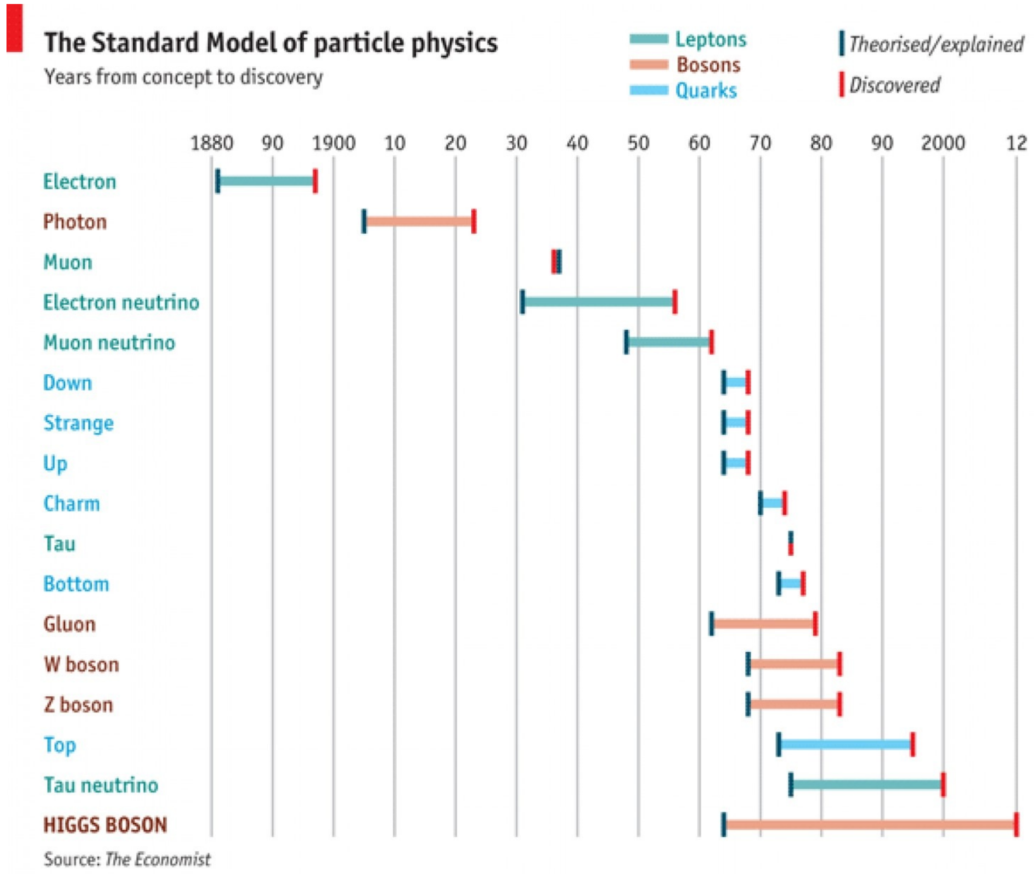
Photo: Inside view of the ATLAS Liquid Argon Calorimeter Endcap

Detectors in Nuclear and Particle Physics

Claire Lee
University of Johannesburg (ZA)
HDM2014 - UNW Mafikeng

Motivation

- To be able to study the universe & develop theories about the way it works we need to be able to measure it!
  - Our theories are only as good as how well they match to the data
  - But sometimes it takes technology time to develop before we can test the theories
- This course is just a brief overview of how we detect particles in experiments - personal choice.
- Who can guess the "first" fundamental particle detector?



The Standard Model of particle physics

Years from concept to discovery

Source: *The Economist*

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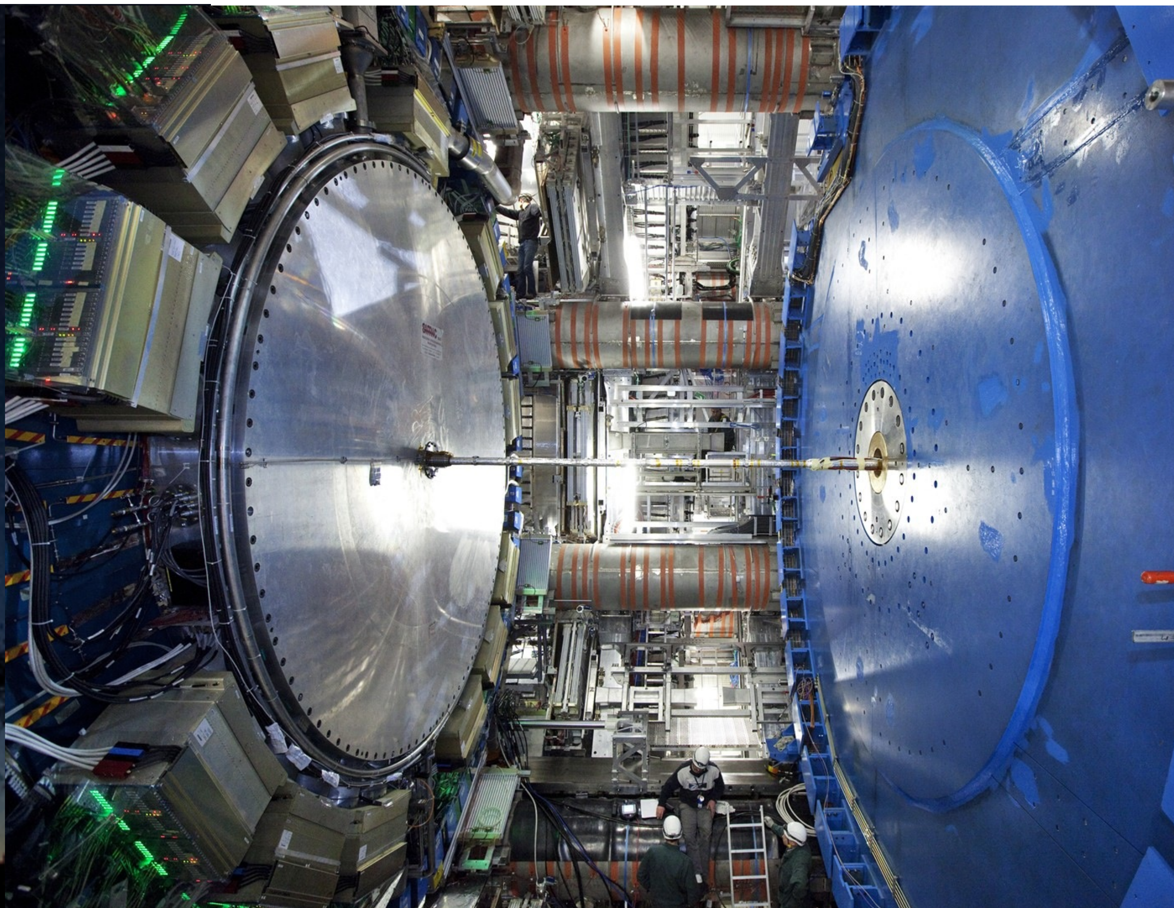
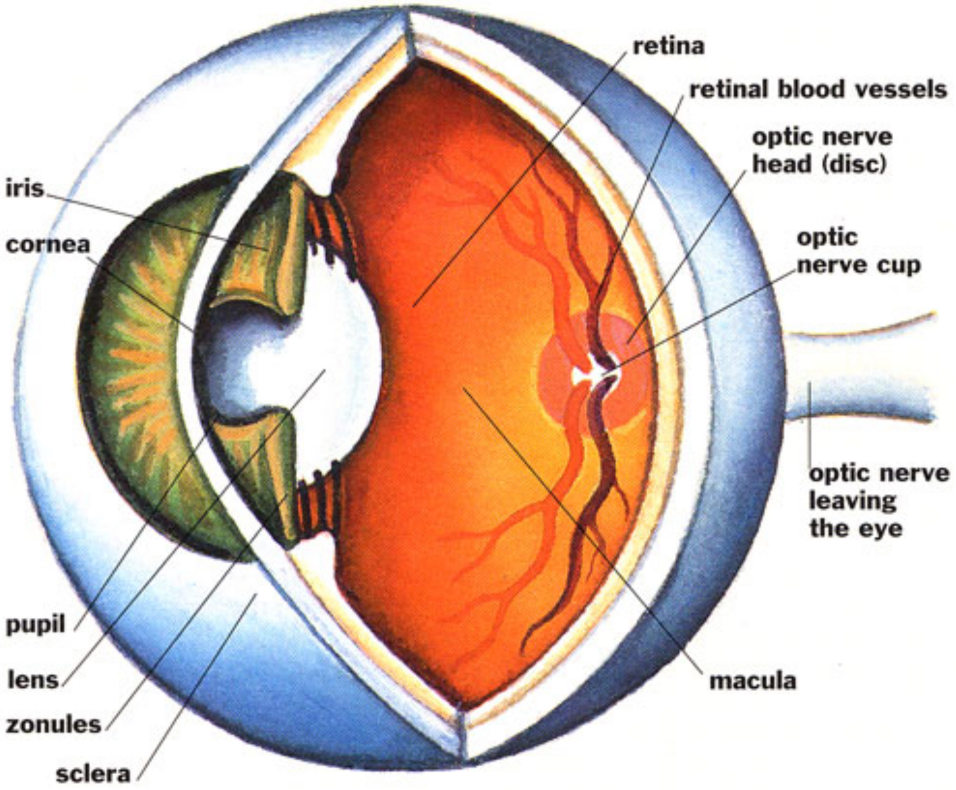


Most Common Particle Detector: Our Eye!

- How do we see?
  - Photons (particles of light) bounce off objects and enter your eye
  - The light gets focused onto the retina at the back of your eyeball
  - Chemical reactions happen in the special cells in the retina called rods and cones
  - These chemical reactions cause electrical impulses – they convert the light to an electrical signal
  - These electrical signals are carried to your brain and interpreted there.

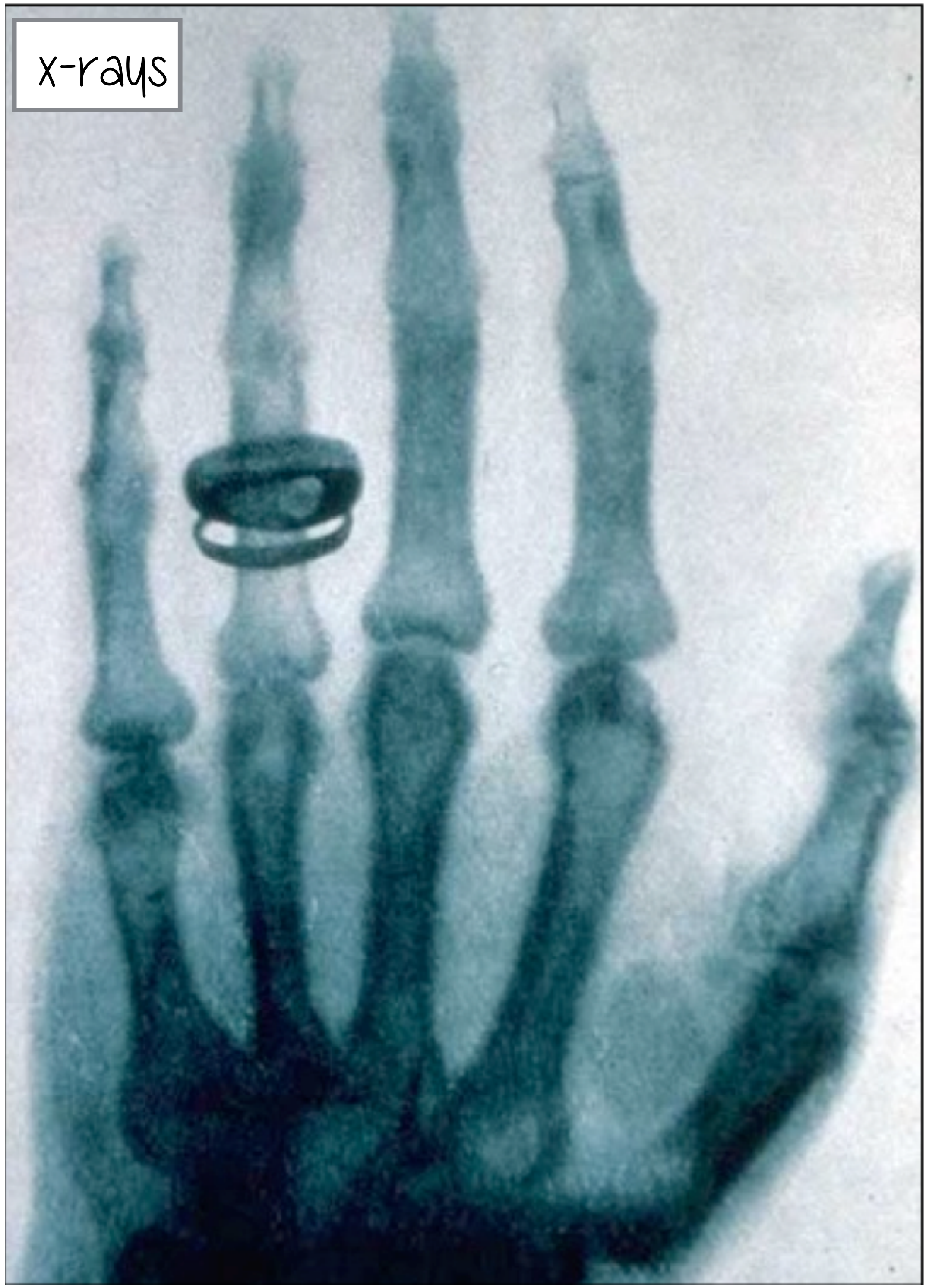
- So… we see because of the interactions between light and the matter of our eyes.

And it turns out that that's exactly how particle detectors work, too!



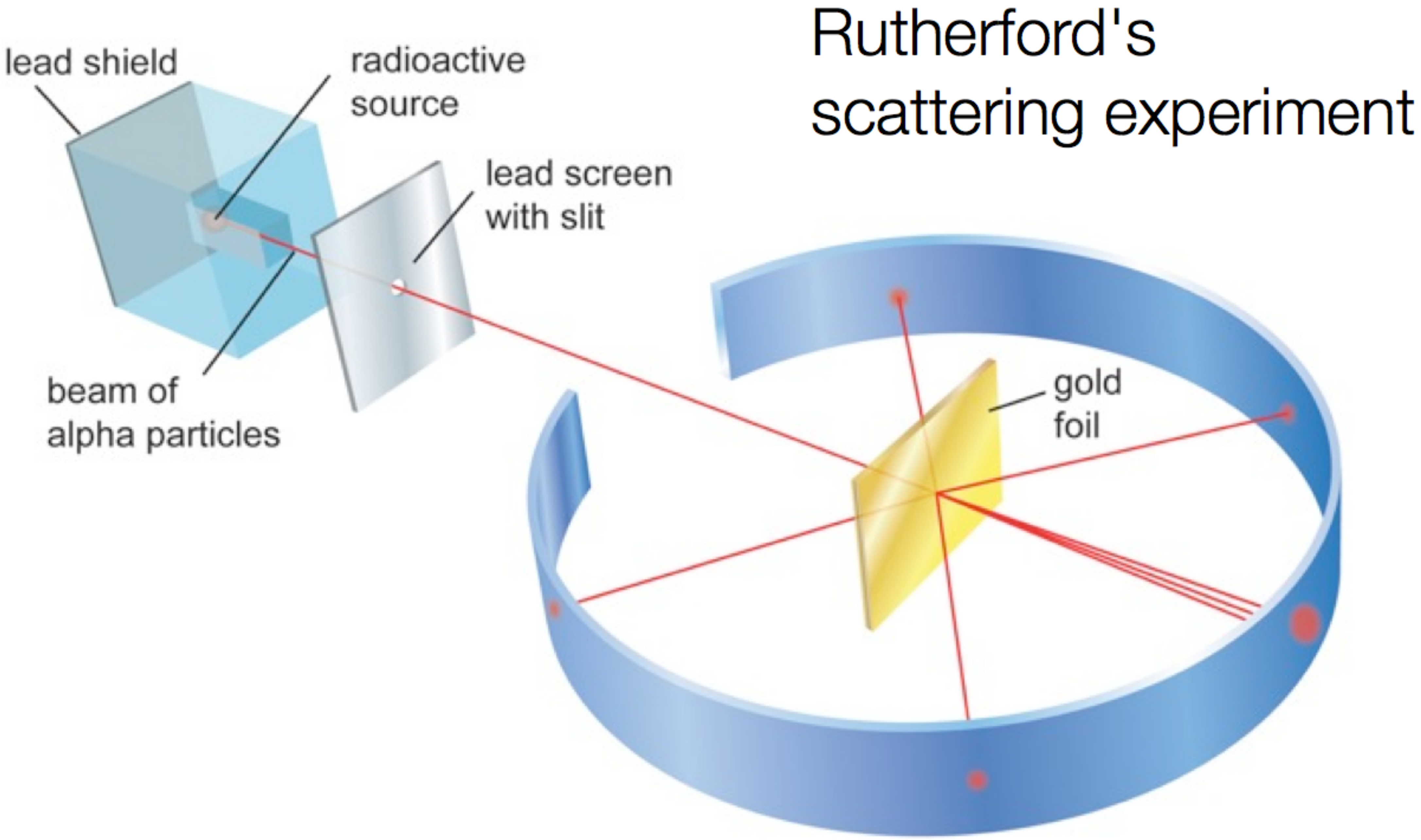
Some History

- 1896: An x-ray picture taken by Wilhelm Röntgen of Albert von Kölliker's hand at a public lecture on 23 January



Some History

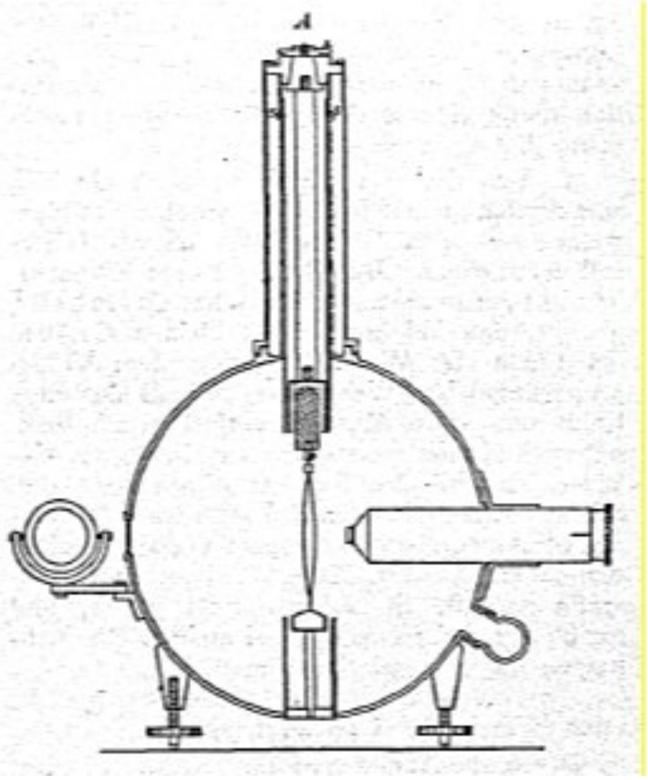
- 1911: Rutherford's scattering experiment & the structure of an atom

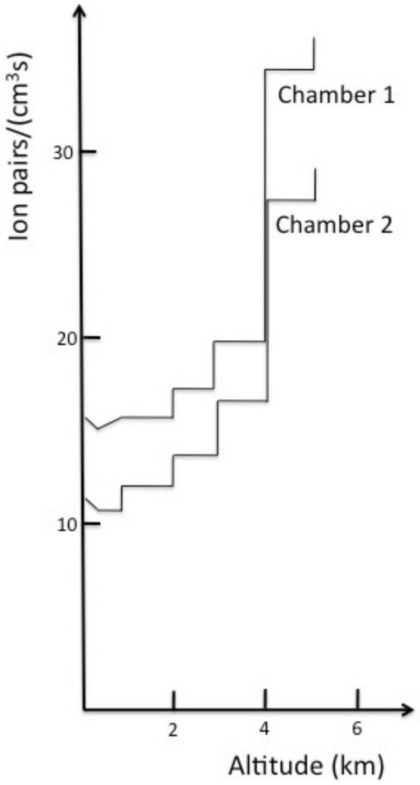


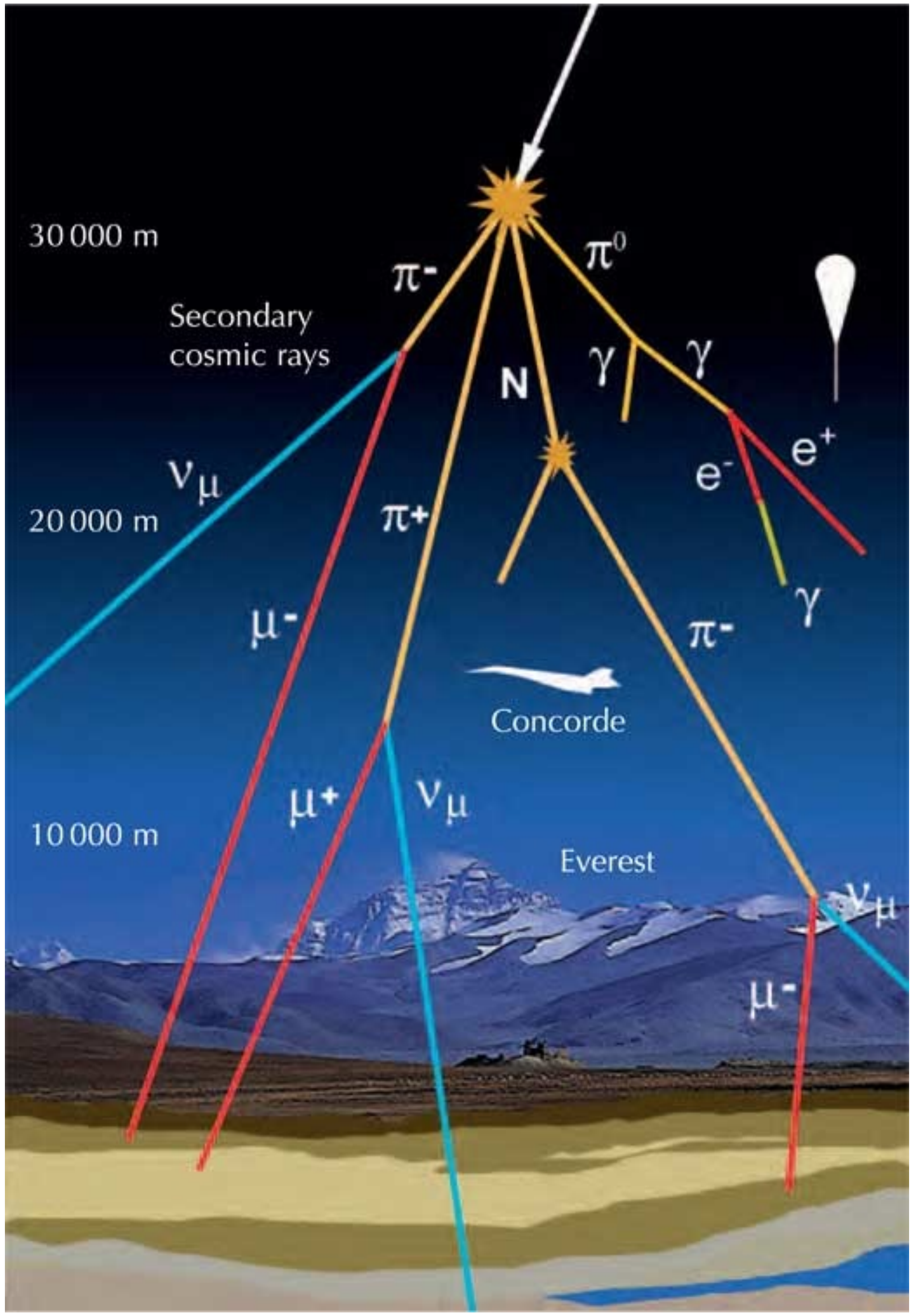
Schematic view of Rutherford experiment

Some History

- 1912: Hess's cosmic ray detection (Nobel prize 1936)

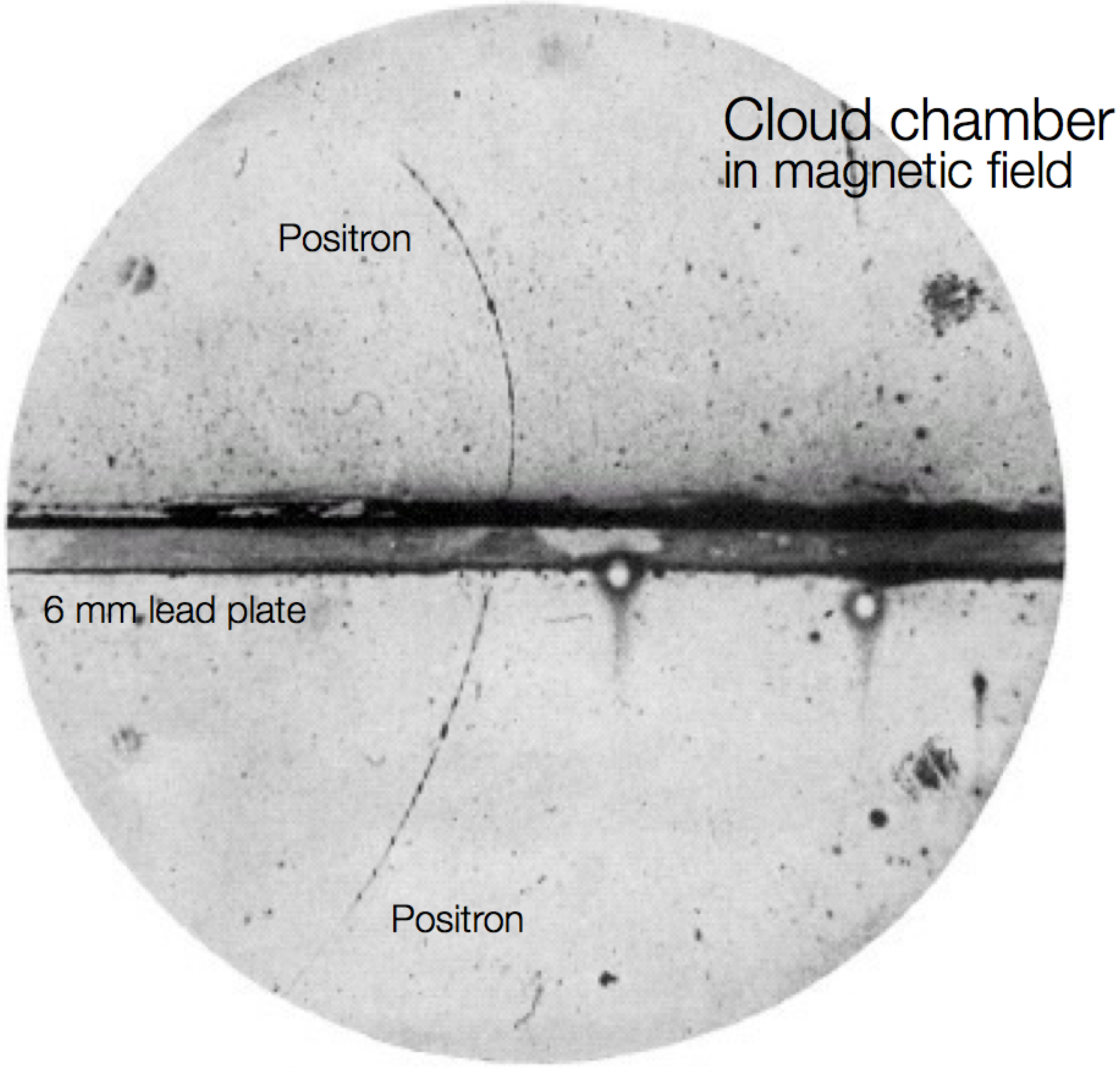






Some History

- 1932: Anderson's discovery of antimatter (Nobel Prize 1936)

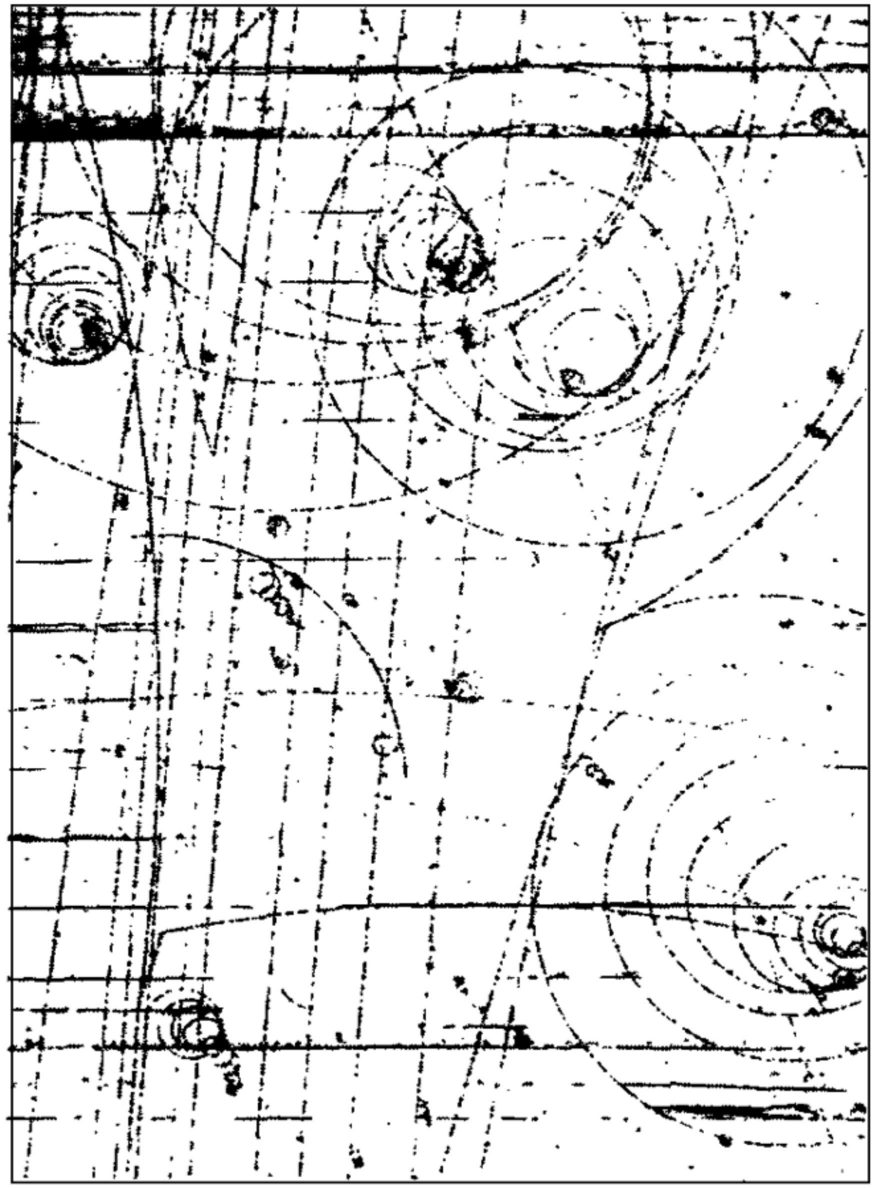


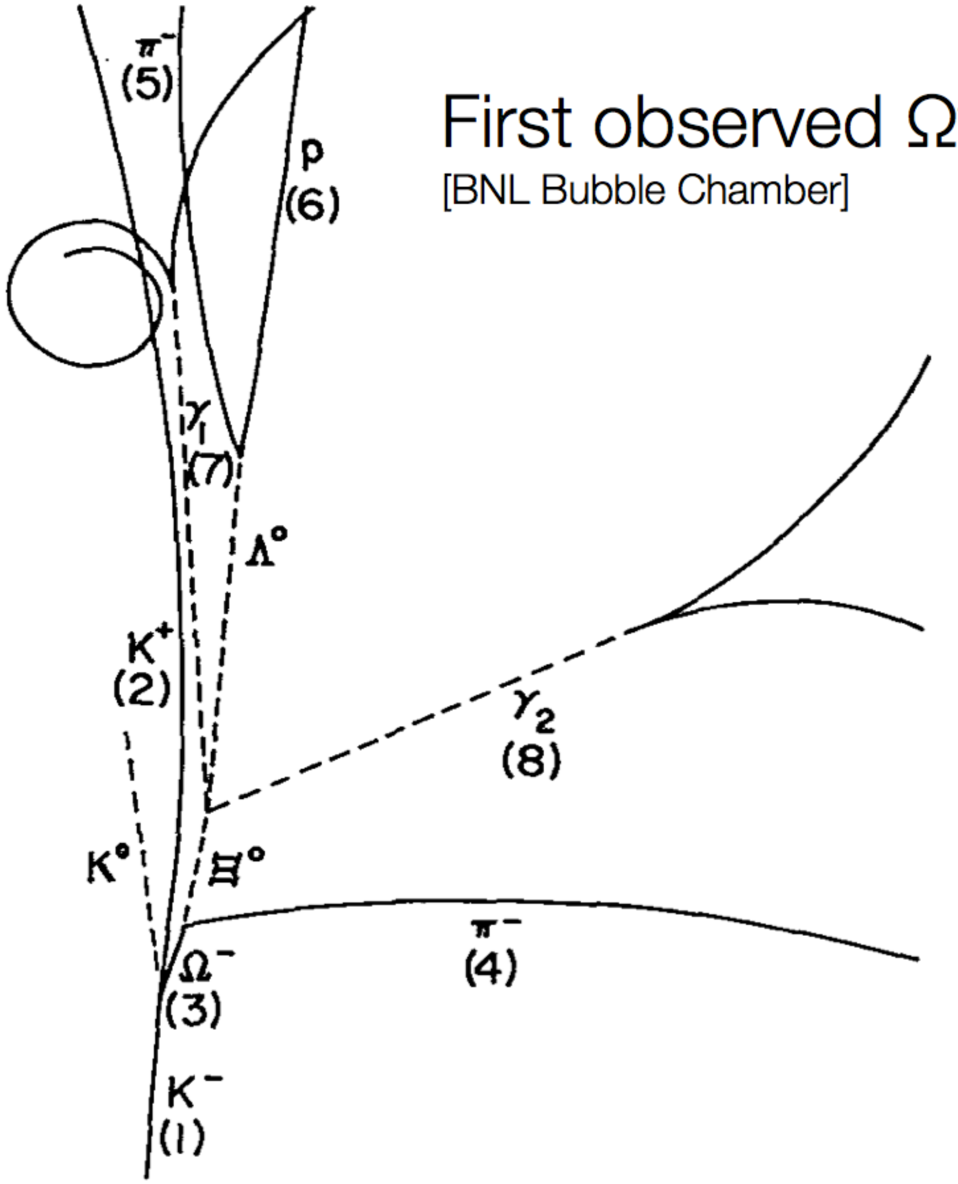
- 63 MeV positron passing through lead plate emerging as 23 MeV positron.

- The length of this latter pass is at least ten times greater than the possible length of a proton path of this curvature.

Some History

- 1947: Discovery of the **Ω^-**





First observed Ω^- event

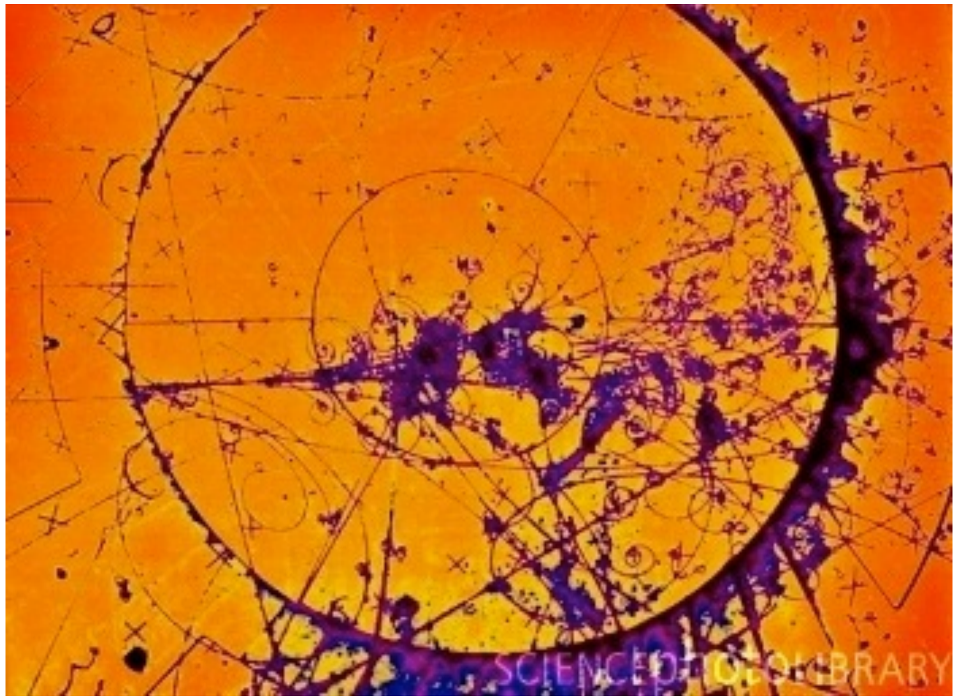
[BNL Bubble Chamber]

Some History

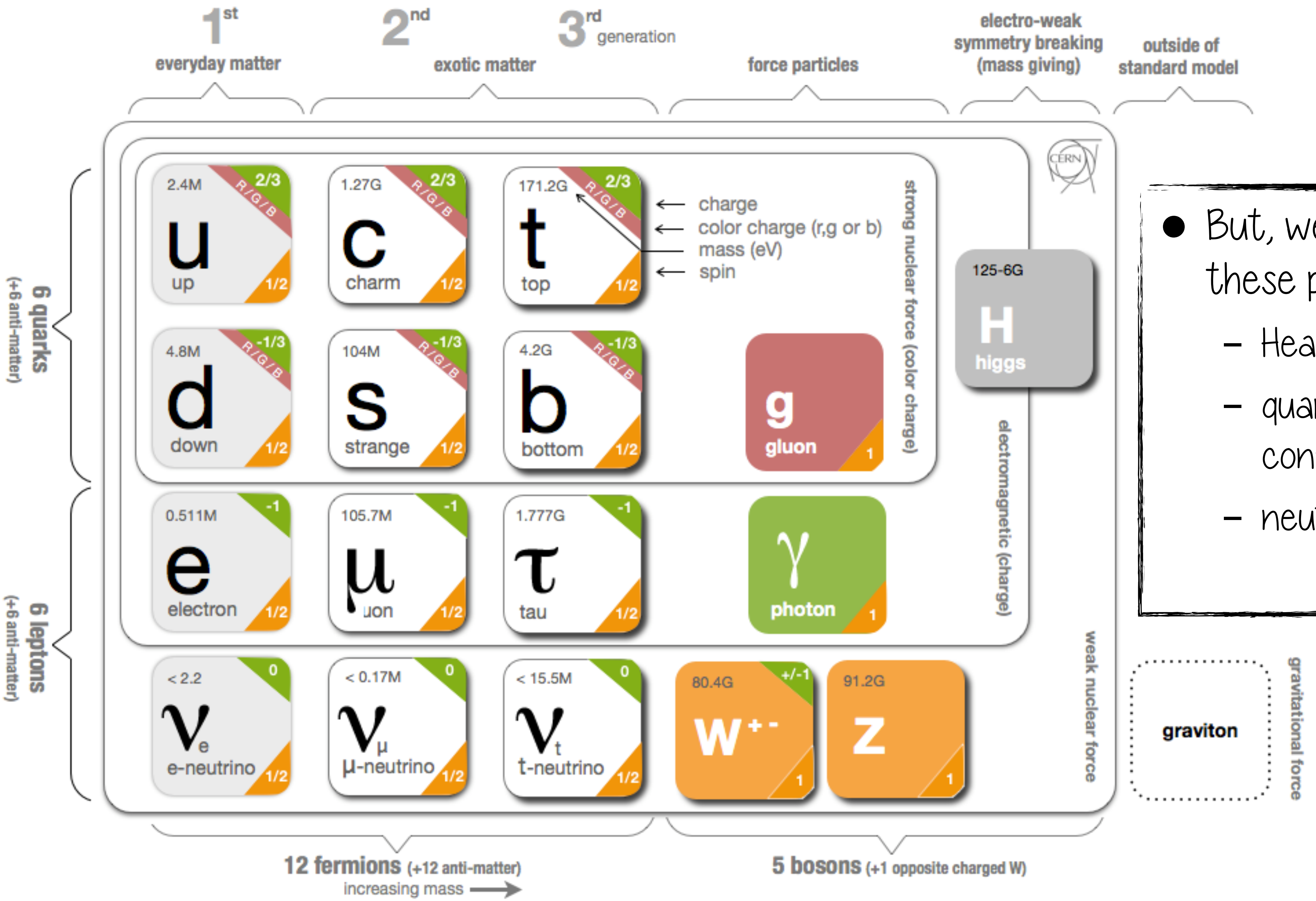
- As time goes on, the detectors have become more and more complex
  - Instead of using just one type of detector people started putting different types together to get more information

- Here, we will discover the basic techniques that allow particle detectors to work, and start to understand how to build them to get the information that we need.

- But first!
  - What did all of the discoveries have in common?
  - They were able to make their observations based on the way particles interacted with matter



Introduction to particle physics - The fundamental particles of the Standard Model



- But, we don't observe all of these particles in our daily life
  - Heavier particles decay
  - quarks&gluons combine due to confinement
  - neutrinos interact minimally

- Final state particles: electrons, photons, (muons), hadrons & their antiparticles

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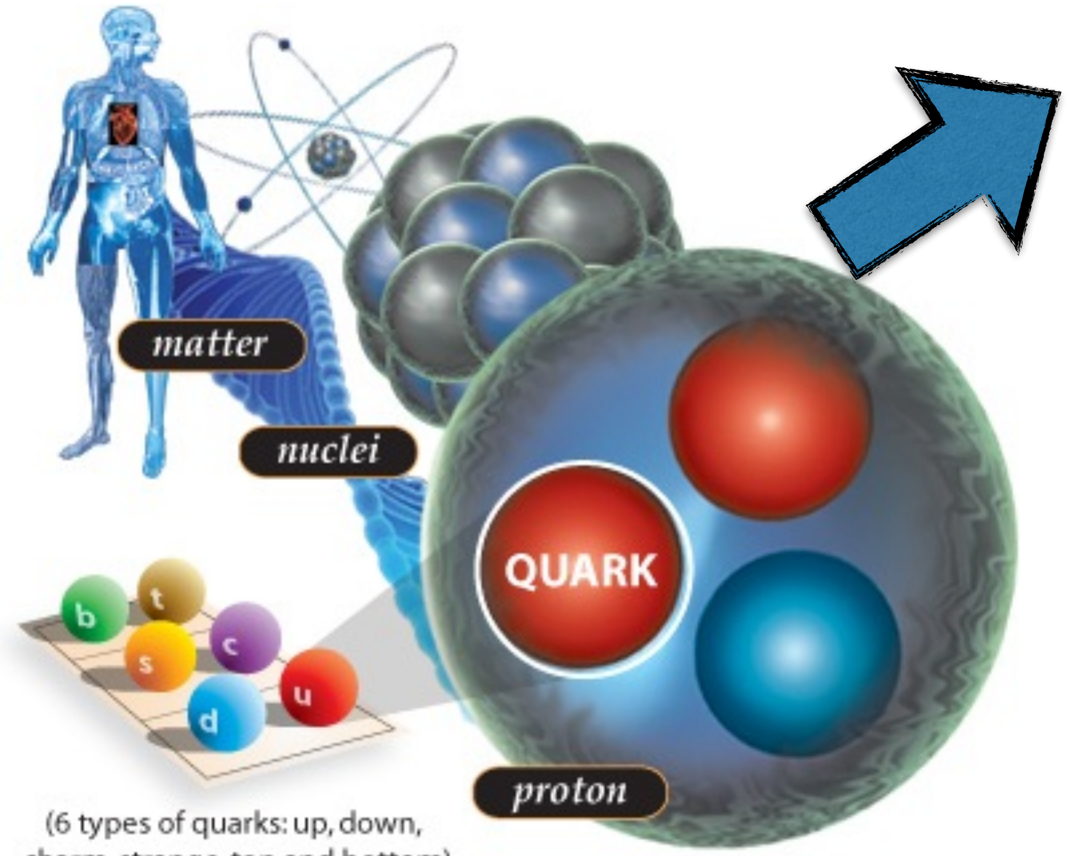
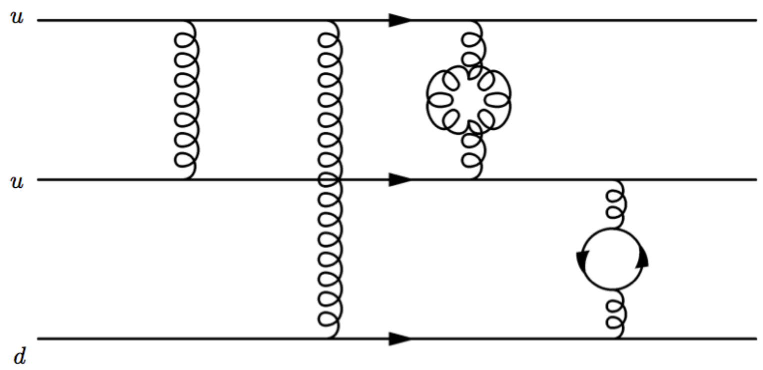
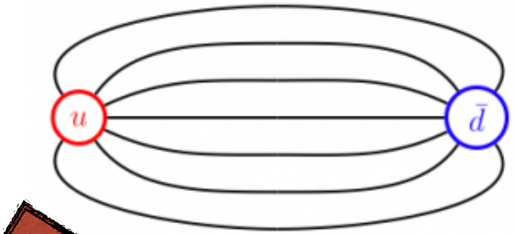
Aside: QCD & quark confinement



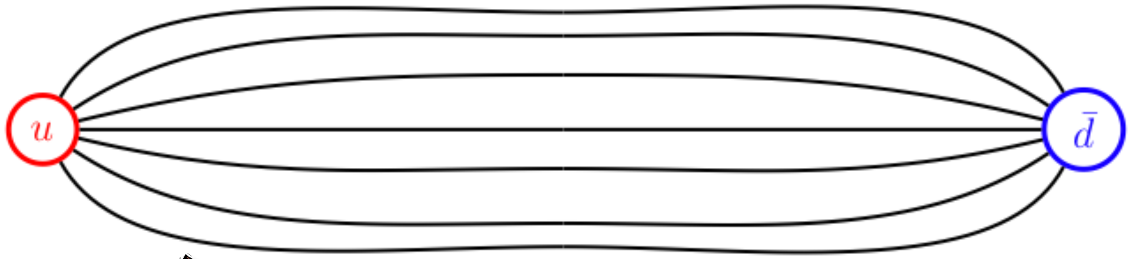
(6 types of quarks: up, down, charm, strange, top and bottom)



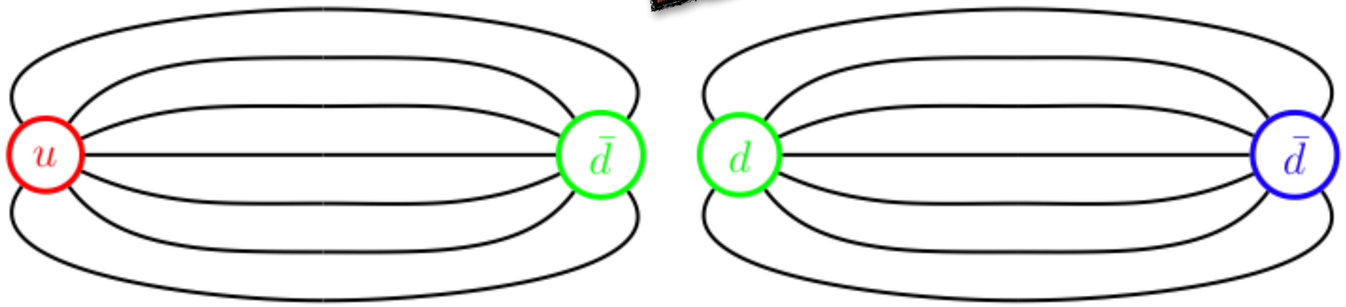
Confinement:
Quarks cannot exist on their own!



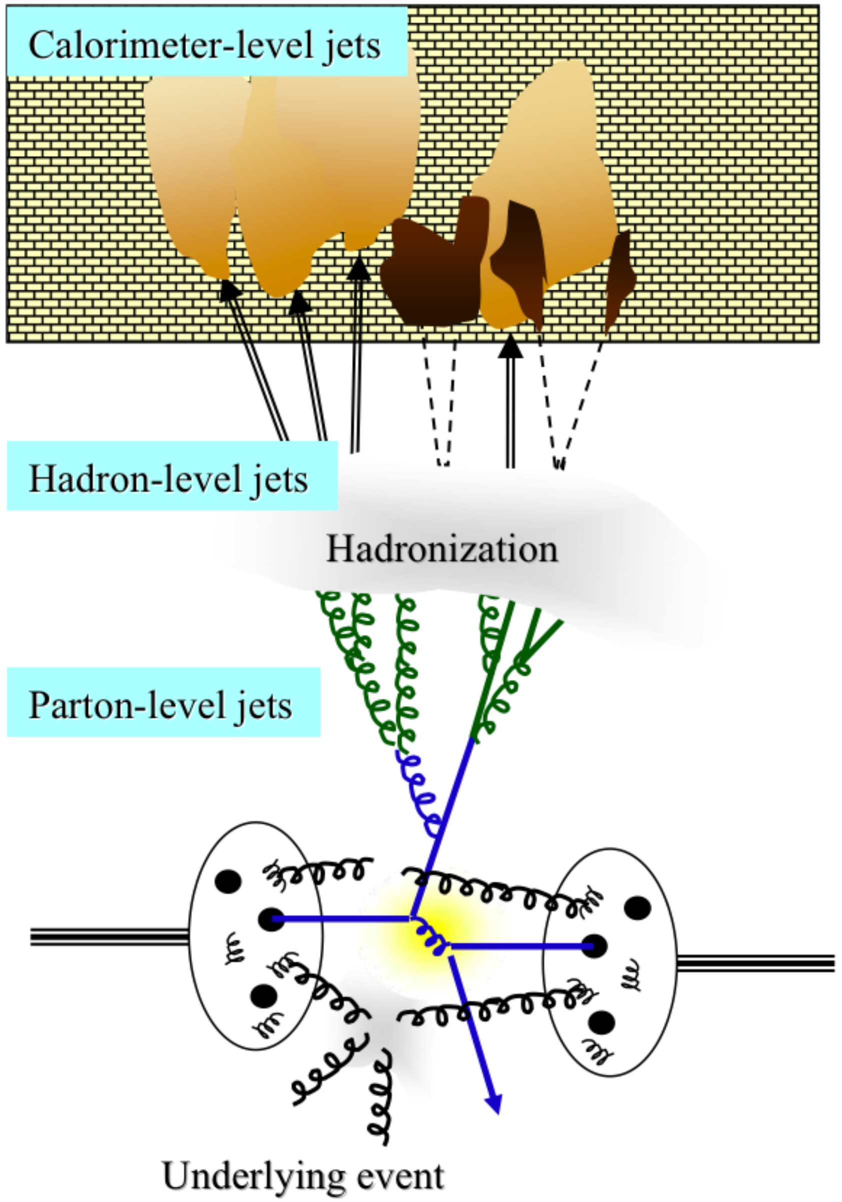
Pull apart!



Pull more!



POP! more particles!



Identifying Particles

- What are the quantities we need to measure to be able to distinguish between the different types of particles?

electrons (and positrons)
photons
muons (and antimuons)
charged hadrons (eg protons)
neutral hadrons (eg neutrons)

Identifying Particles

- What are the quantities we need to measure to be able to distinguish between the different types of particles?
  - Mass
  - Momentum
  - Energy
  - Charge
  - Lifetime*
  - Spin*
  - etc...

electrons (and positrons)
photons
muons (and antimuons)
charged hadrons (eg protons)
neutral hadrons (eg neutrons)

$$E^2 = \vec{p}\,^2 c^2 + m^2 c^4$$

$$\beta = \frac{v}{c}; \quad \gamma = \frac{1}{\sqrt{1-\beta}}$$

We can identify particles based on a combined measurement of:

$$(E, \vec{p}, Q)$$

$$(\vec{p}, \beta, Q)$$

$$(\vec{p}, m, Q)$$

eV = 1.6x10⁻19 J
c = 299 792 458 m/s
e = 1.602x10⁻19 C

Identifying Particles

- What are the quantities we need to measure to be able to distinguish between the different types of particles?
  - Mass
  - Momentum
  - Energy
  - Charge
  - Lifetime*
  - Spin*
  - etc...

electrons (and positrons)
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neutral hadrons (eg neutrons)

$$E^2 = \vec{p}\,^2 c^2 + m^2 c^4$$

$$\beta = \frac{v}{c}; \quad \gamma = \frac{1}{\sqrt{1-\beta}}$$

Okay! So, how do we make these measurements?

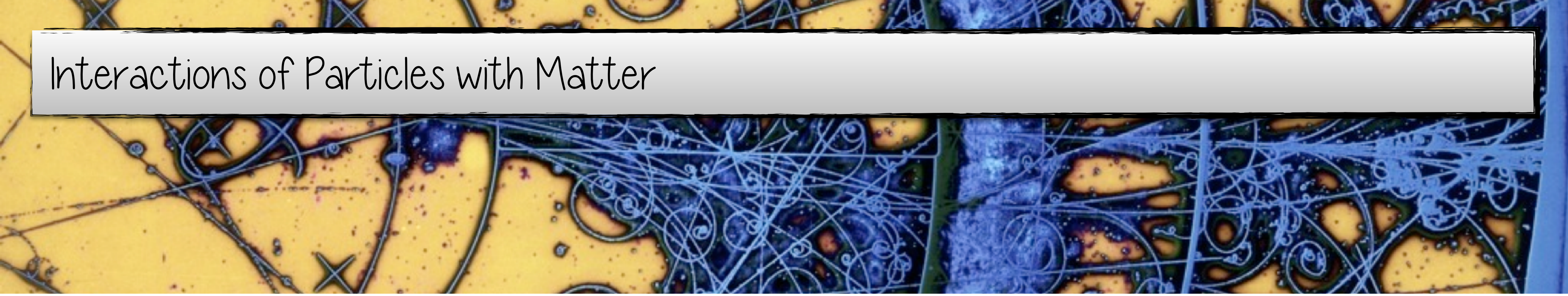
We can identify particles based on a combined measurement of:

$$(E, \vec{p}, Q)$$

$$(\vec{p}, \beta, Q)$$

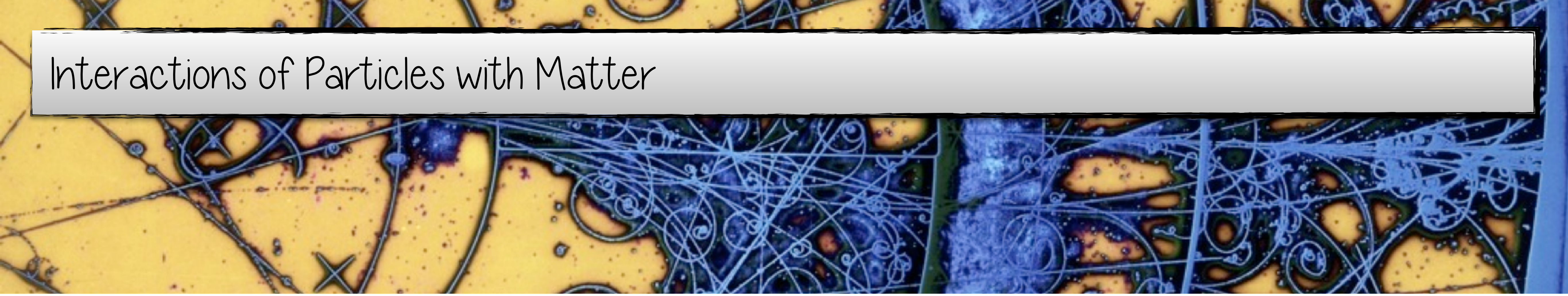
$$(\vec{p}, m, Q)$$

eV = 1.6x10⁻19 J
c = 299 792 458 m/s
e = 1.602x10⁻19 C



Interactions of Particles with Matter

- In order to detect a particle it must interact with the material of the detector.
- Some examples of the ways particles interact:

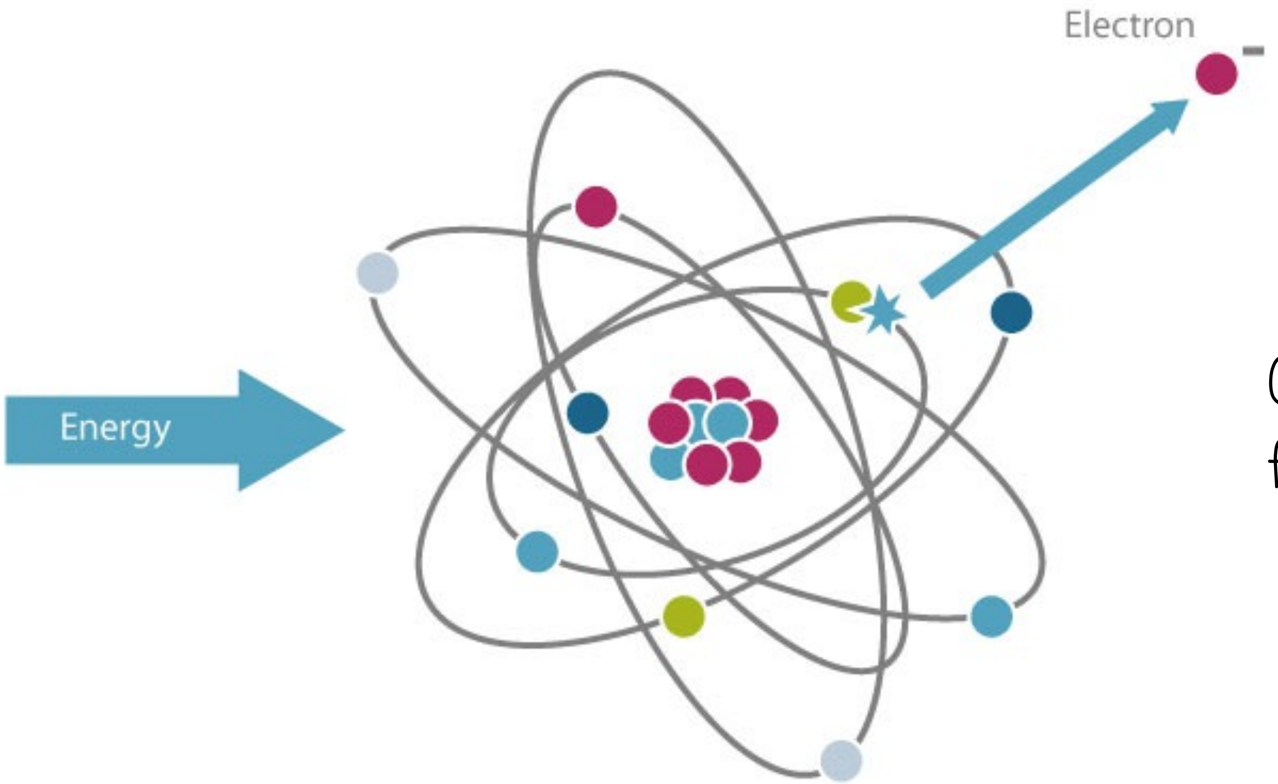


Interactions of Particles with Matter

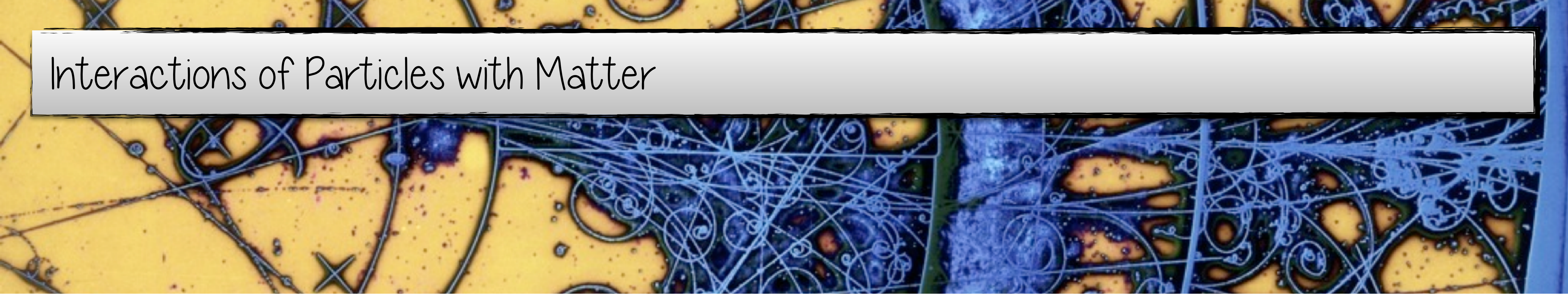
- In order to detect a particle it must interact with the material of the detector.

- Some examples of the ways particles interact:
  - Ionization

Gives off charge!



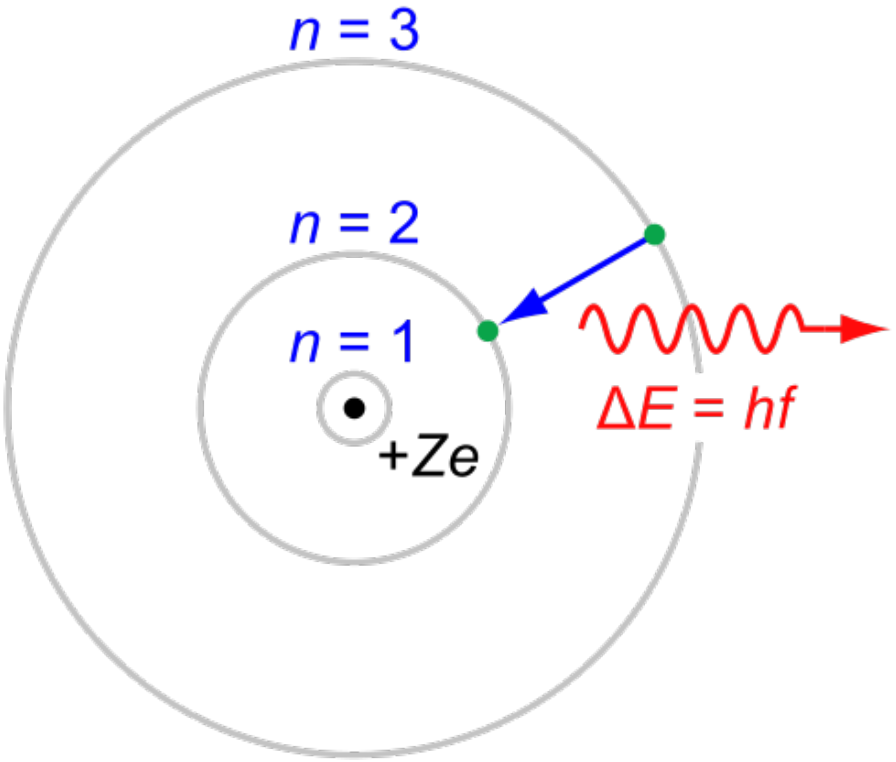
Charged particle "knocks" an electron free, leaving the atom ionised



Interactions of Particles with Matter

- In order to detect a particle it must interact with the material of the detector.
- Some examples of the ways particles interact
  - Photoemission

Gives off light!



An electron in an atom can gain energy from a particle and be excited into a higher orbit. When it returns to its ground state it emits a photon.

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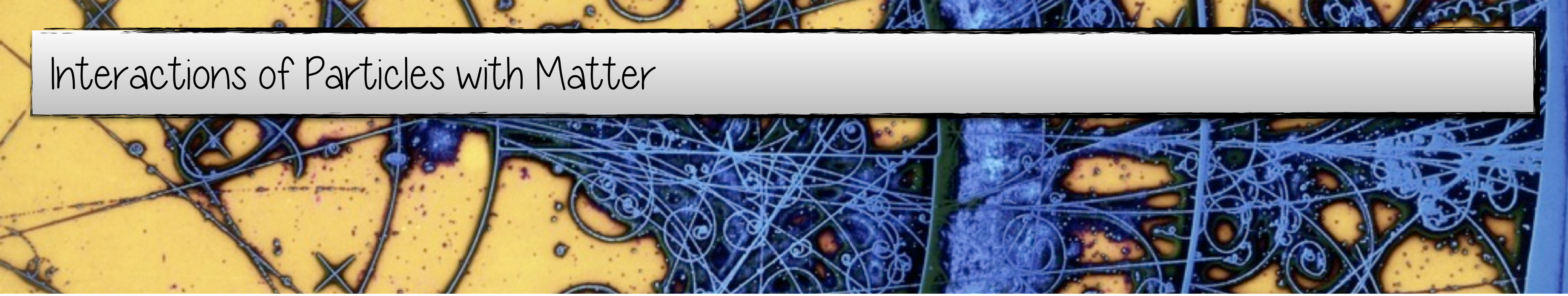
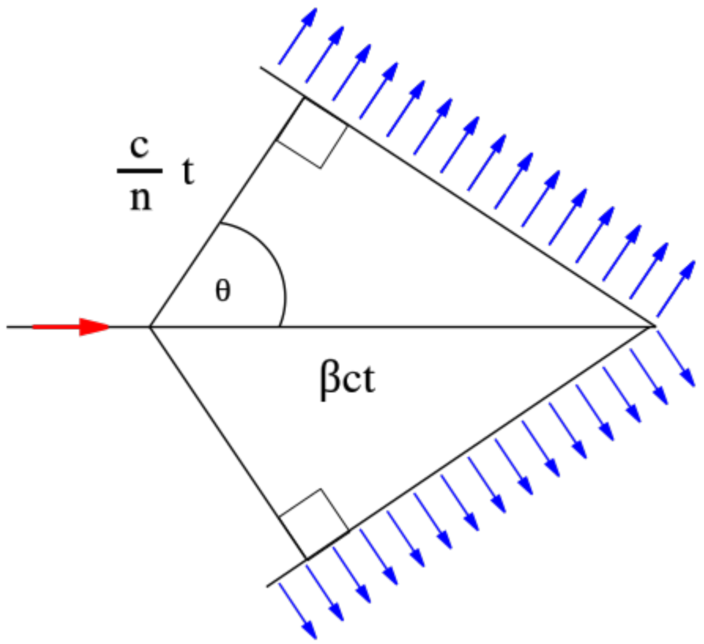
Interactions of Particles with Matter



- In order to detect a particle it must interact with the material of the detector.

Gives off light!

- Some examples of the ways particles interact
  - Cerenkov radiation



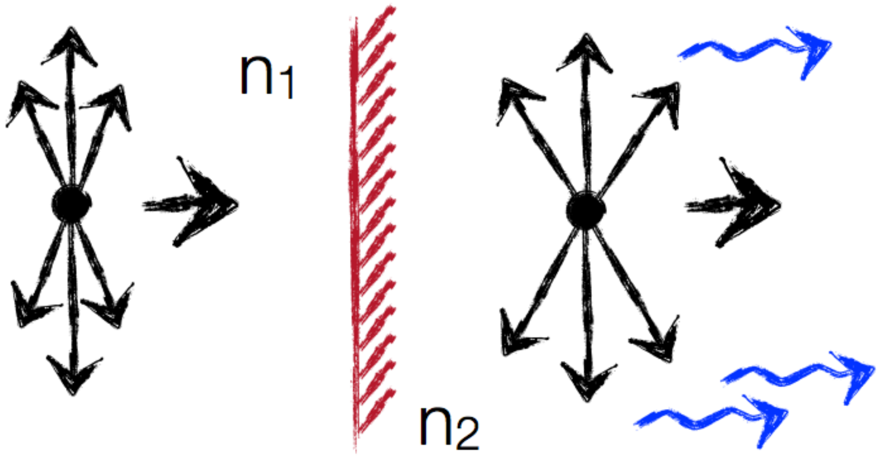
Light slows down in matter, depending on its refractive index. But a particle could move faster than the speed of light, in which case it will give off Cerenkov radiation (much like the sonic boom when breaking the sound barrier)

Interactions of Particles with Matter

- In order to detect a particle it must interact with the material of the detector.

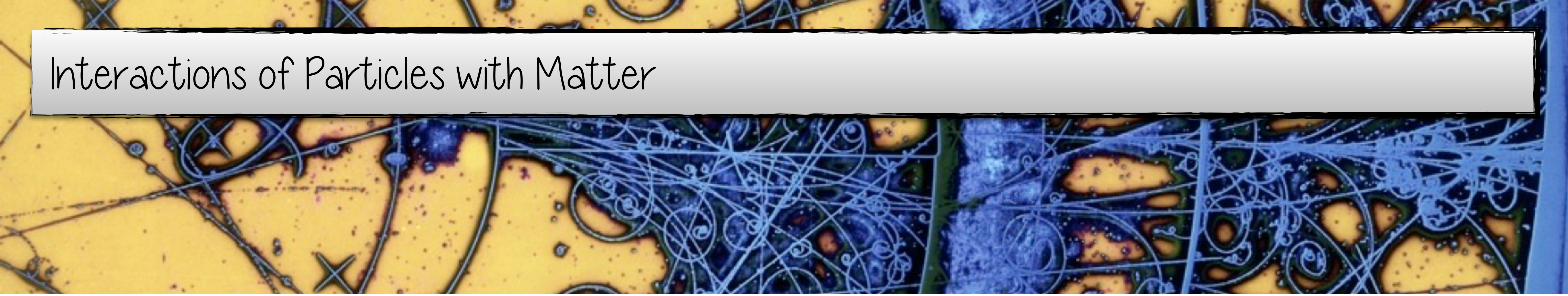
- Some examples of the ways particles interact:
  - Transition Radiation

Gives off light!



Transition radiation occurs if a relativistic particle passes the boundary between two media with different refraction indices

Interactions of Particles with Matter

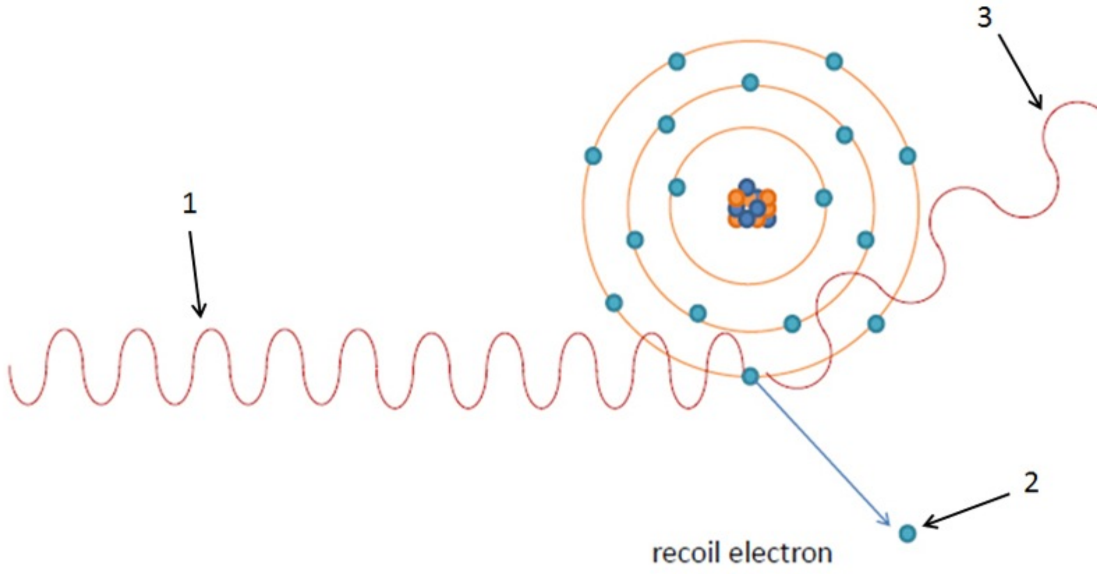


- In order to detect a particle it must interact with the material of the detector.

- Some examples of the ways particles interact:
  - Compton Scattering

Gives off charge!

Compton scattering



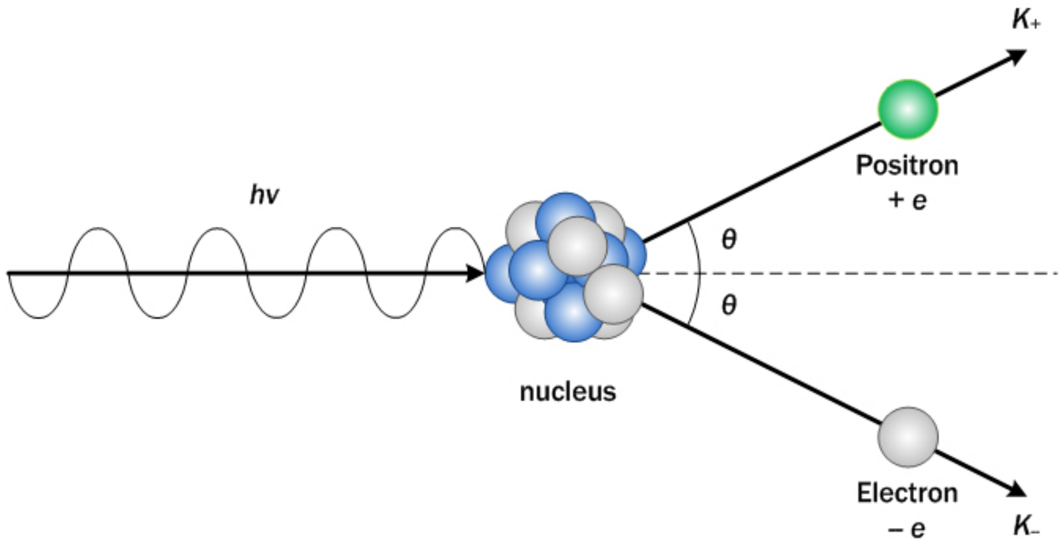
Photon ionises an atom by giving energy to an electron. Photon moves on with reduced energy

Interactions of Particles with Matter

- In order to detect a particle it must interact with the material of the detector.

- Some examples of the ways particles interact:
  - Pair production

Gives off charge!



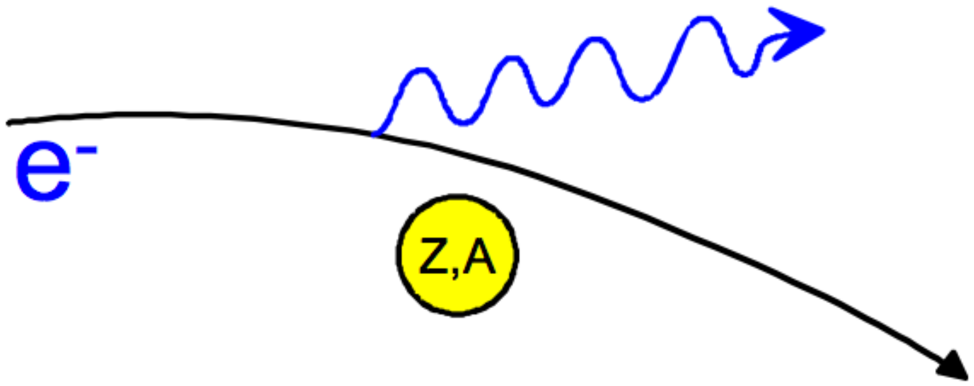
A photon interacting with a nucleus can convert into matter-antimatter pairs

Interactions of Particles with Matter

- In order to detect a particle it must interact with the material of the detector.

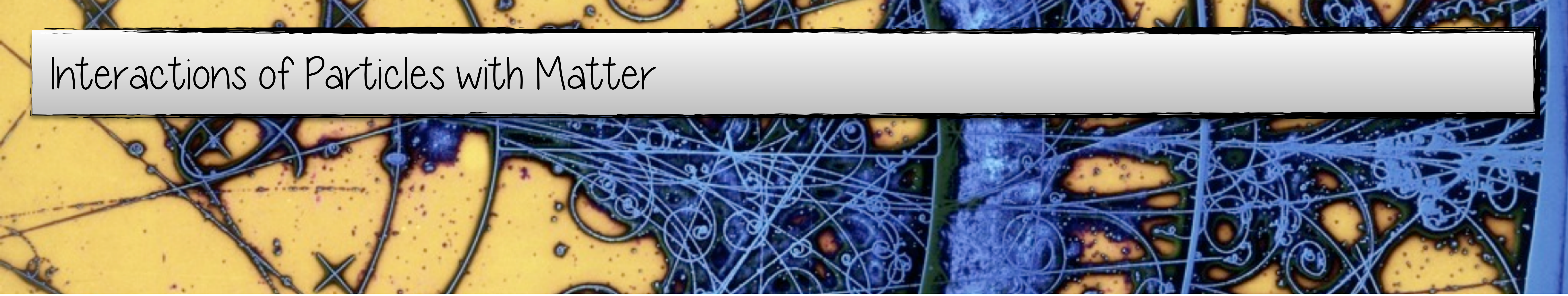
- Some examples of the ways particles interact:
  - Bremsstrahlung

Gives off light!



As an electron gets bent around a nucleus it emits a photon.

Interactions of Particles with Matter



- In order to detect a particle it must interact with the material of the detector.

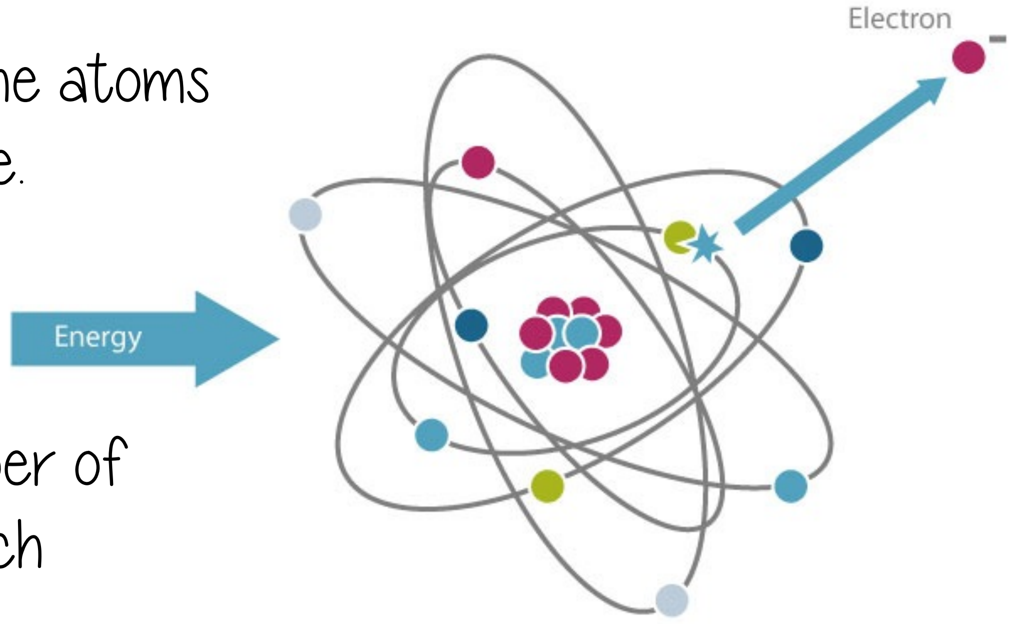
- Most particle detectors actually detect the light or electric charge the particle leaves behind.

- BUT: The properties of the particle may be different after we have detected it:
  - Lower Energy
  - Different Momentum
  - Completely Stopped

- We can tell what kind of particle it is by how it changes as it goes through the detector, and what it leaves behind (eg. light, electric charge).
  - We can also build our detectors in a particular way, "tuning" them to detect a particular type of particle while ignoring another

Energy Loss by Ionisation

- Charged (heavy) particles moving fast through matter ionises the atoms in the material, and leads to energy loss of the traveling particle.



- The energy loss per distance travelled is dominated by the number of collisions with electrons, and can be described by the Bethe-Bloch function:

Charge number of medium

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

Constant

Atomic mass of medium

Max. energy transfer in a single collision

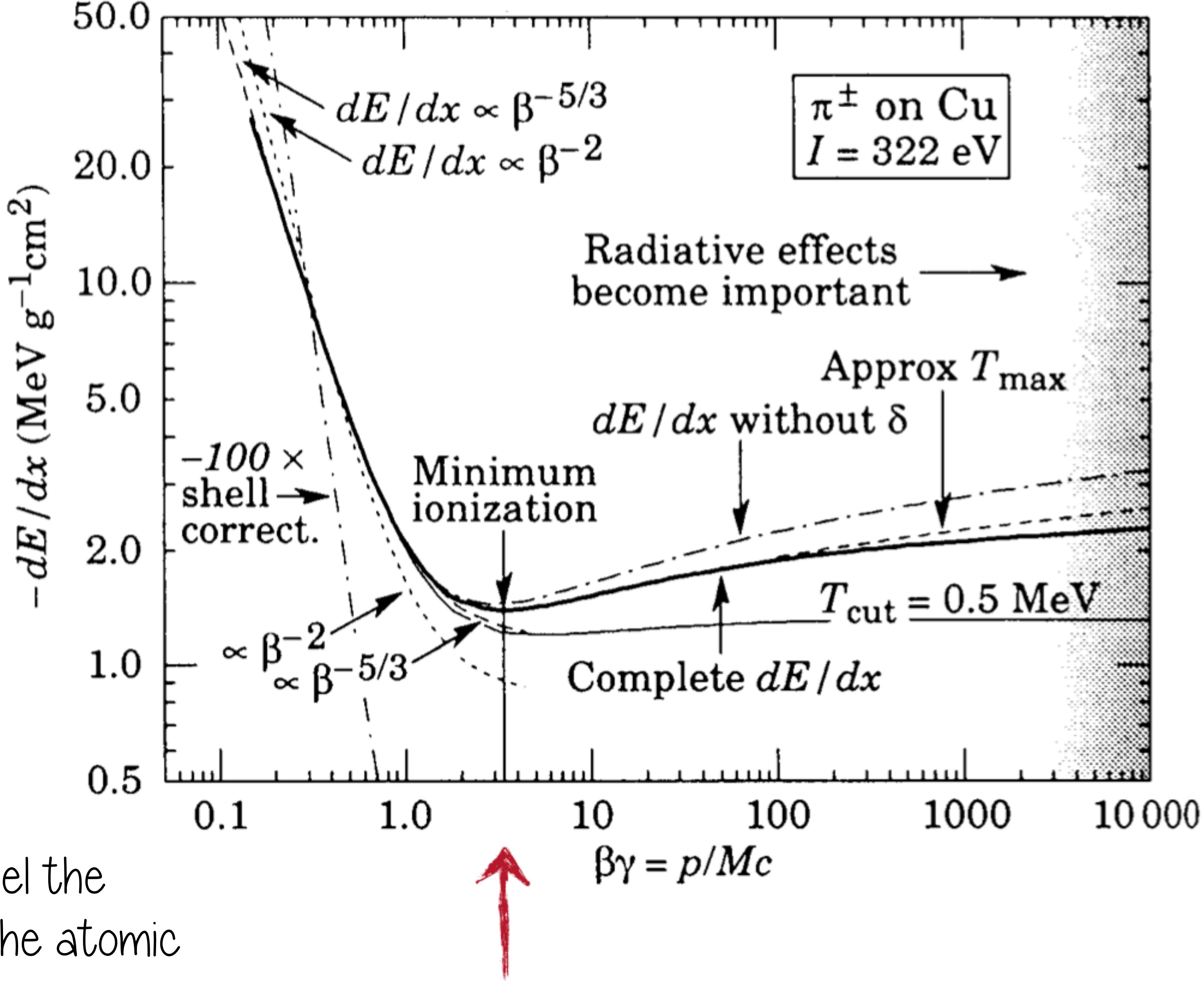
Charge of incident (incoming) particle

Understanding the Bethe-Bloch Function

- Energy loss of pions in Copper:

$$-\left\langle \frac{dE}{dx} \right\rangle = Kz^2 \frac{Z}{A} \frac{1}{\beta^2} \left[\frac{1}{2} \ln \frac{2m_e c^2 \beta^2 \gamma^2 T_{\max}}{I^2} - \beta^2 - \frac{\delta(\beta\gamma)}{2} \right]$$

At low incident particle energies the function has a $1/\boldsymbol{\beta}^2$ dependence



For high energy particles the function has a relativistic rise, as the interaction cross section increases (transverse E field increases due to Lorentz boost)

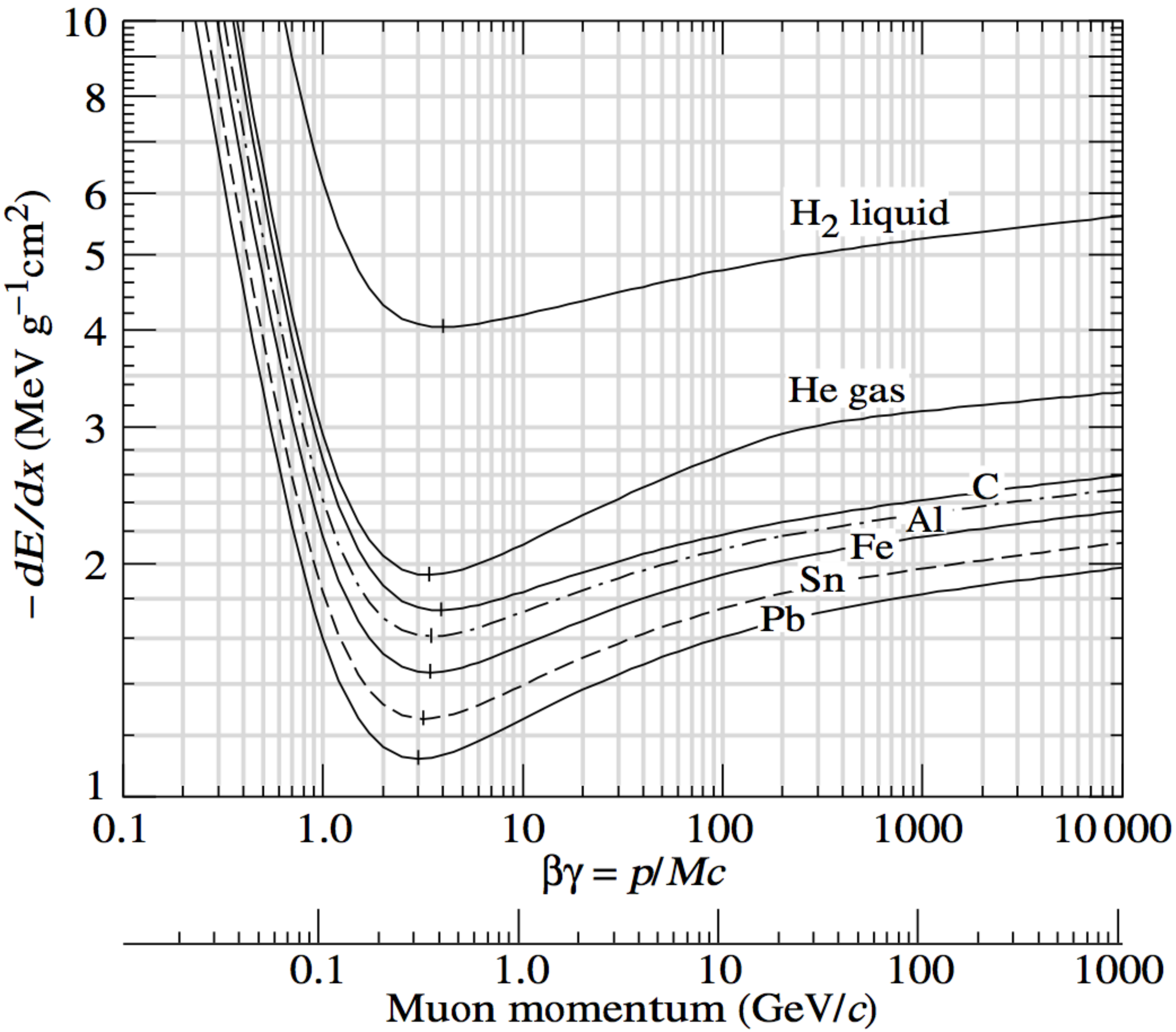
Slower particles feel the electric force of the atomic electron for a longer time, increasing the energy loss

$\beta\gamma$ = 3-4

Bethe-Bloch Function: dependence on medium

- Dependence on mass (A) and charge (Z) of target nucleus

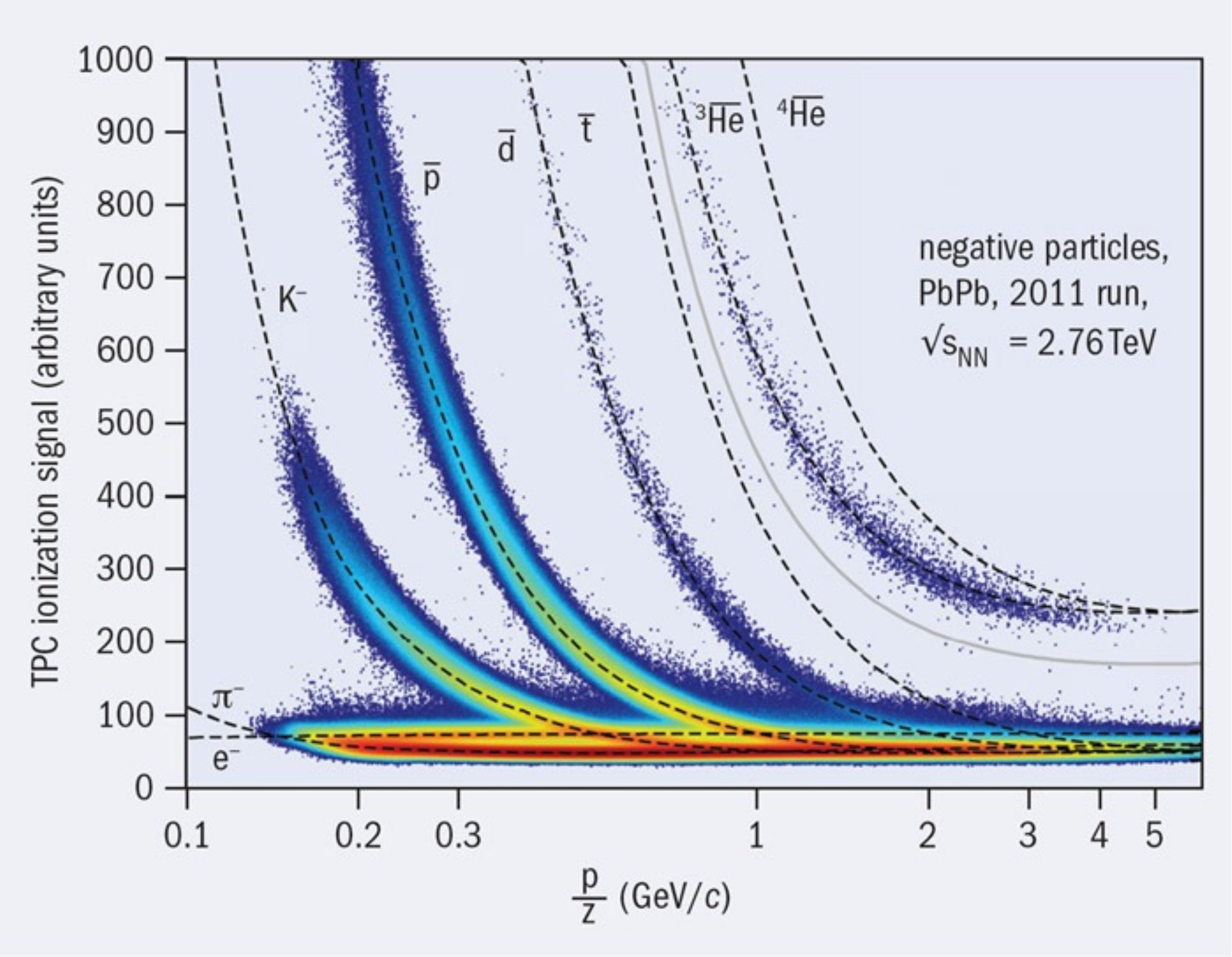
$$-\left\langle \frac{dE}{dx} \right\rangle = K z^2 \frac{Z}{A} \frac{1}{\beta^2} \left[\frac{1}{2} \ln \frac{2 m_e c^2 \beta^2 \gamma^2 T_{\max}}{I^2} - \beta^2 - \frac{\delta(\beta\gamma)}{2} \right]$$



Bethe-Bloch Function: dependence on particle type

$$-\left\langle \frac{dE}{dx} \right\rangle = Kz^2 \frac{Z}{A} \frac{1}{\beta^2} \left[\frac{1}{2} \ln \frac{2m_e c^2 \beta^2 \gamma^2 T_{\max}}{I^2} - \beta^2 - \frac{\delta(\beta\gamma)}{2} \right]$$

$T_{max} = 2m_e c^2 \beta^2 \gamma^2 / (1 + 2\gamma\, m_e/M + (m_e/M)^2)$

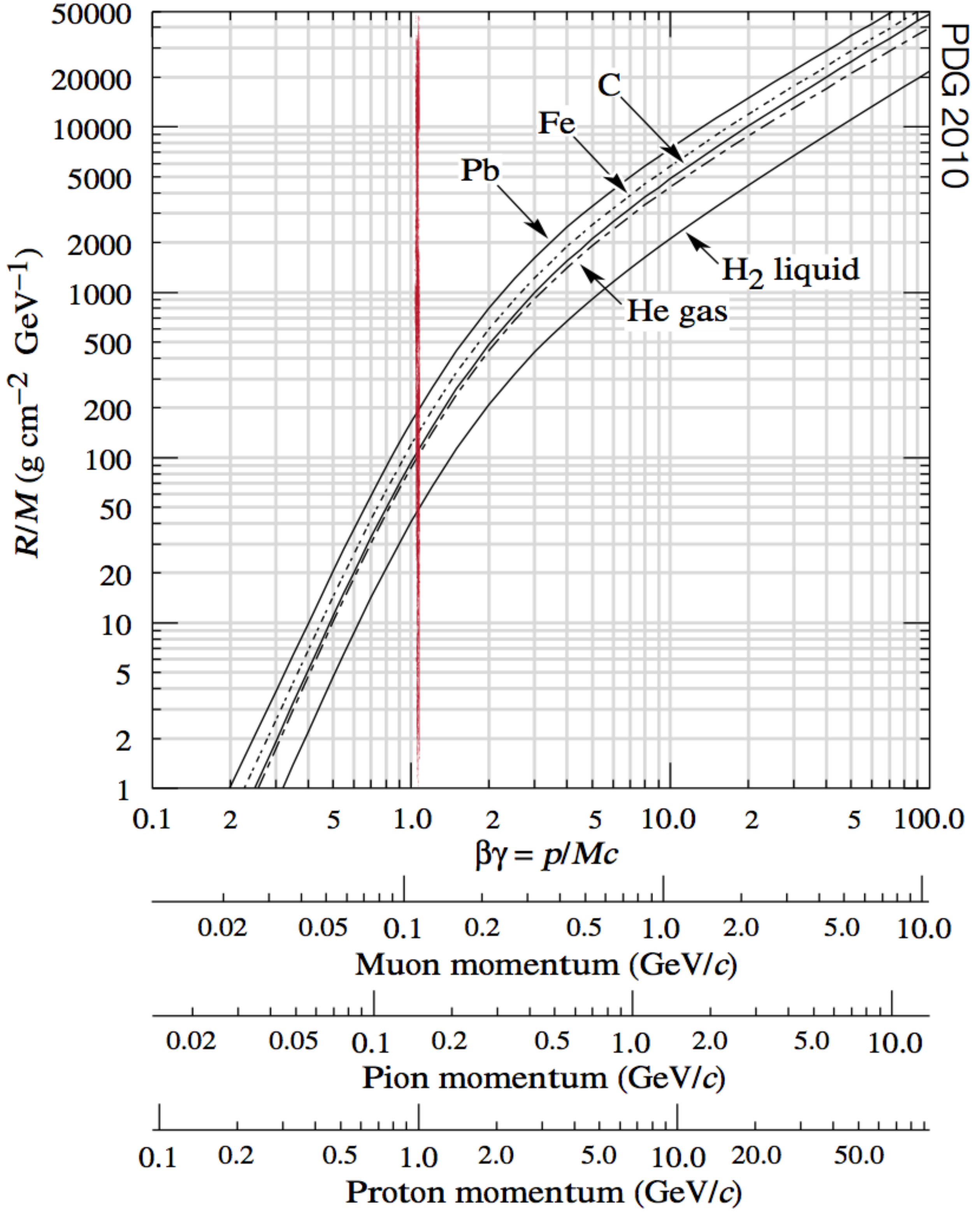


Mean Particle Range

- Since the particle is losing energy, eventually it will stop!

- The range R can be found by integrating over the energy loss from E down to zero:

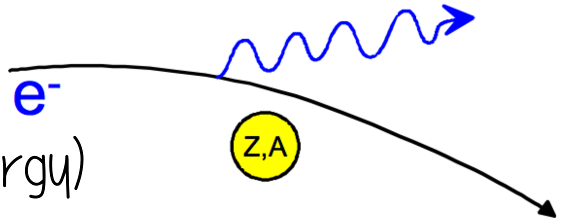
$$R = \int_E^0 \frac{dE}{dE/dx}$$



  - eg: 1 GeV proton on a lead target,
    - R ≈ 20 cm

Bethe-Bloch for Electrons

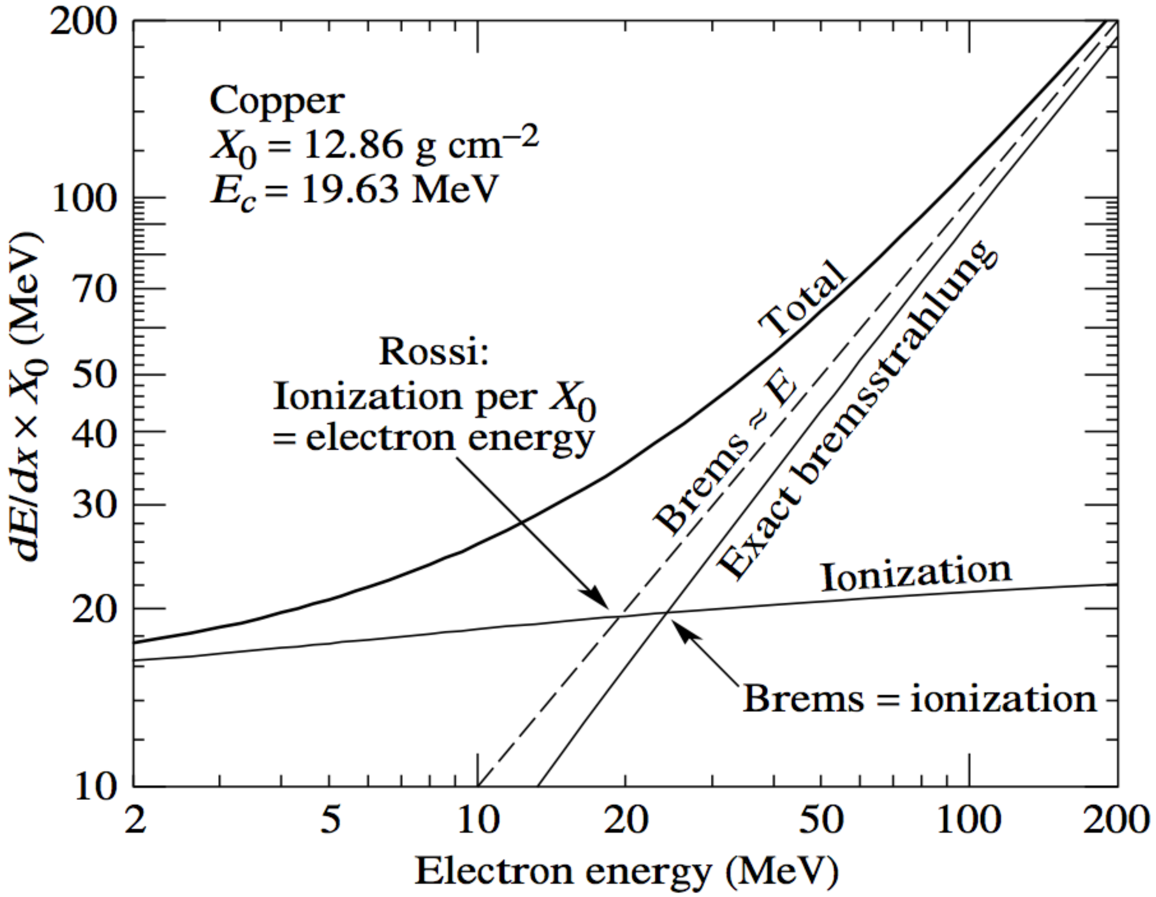
- The Bethe-Bloch function needs a correction for light particles such as electrons
  - Light particles are easily accelerated in the Coulomb field of a nucleus
  - Radiate photons due to conservation of momentum (and therefore lose extra energy)



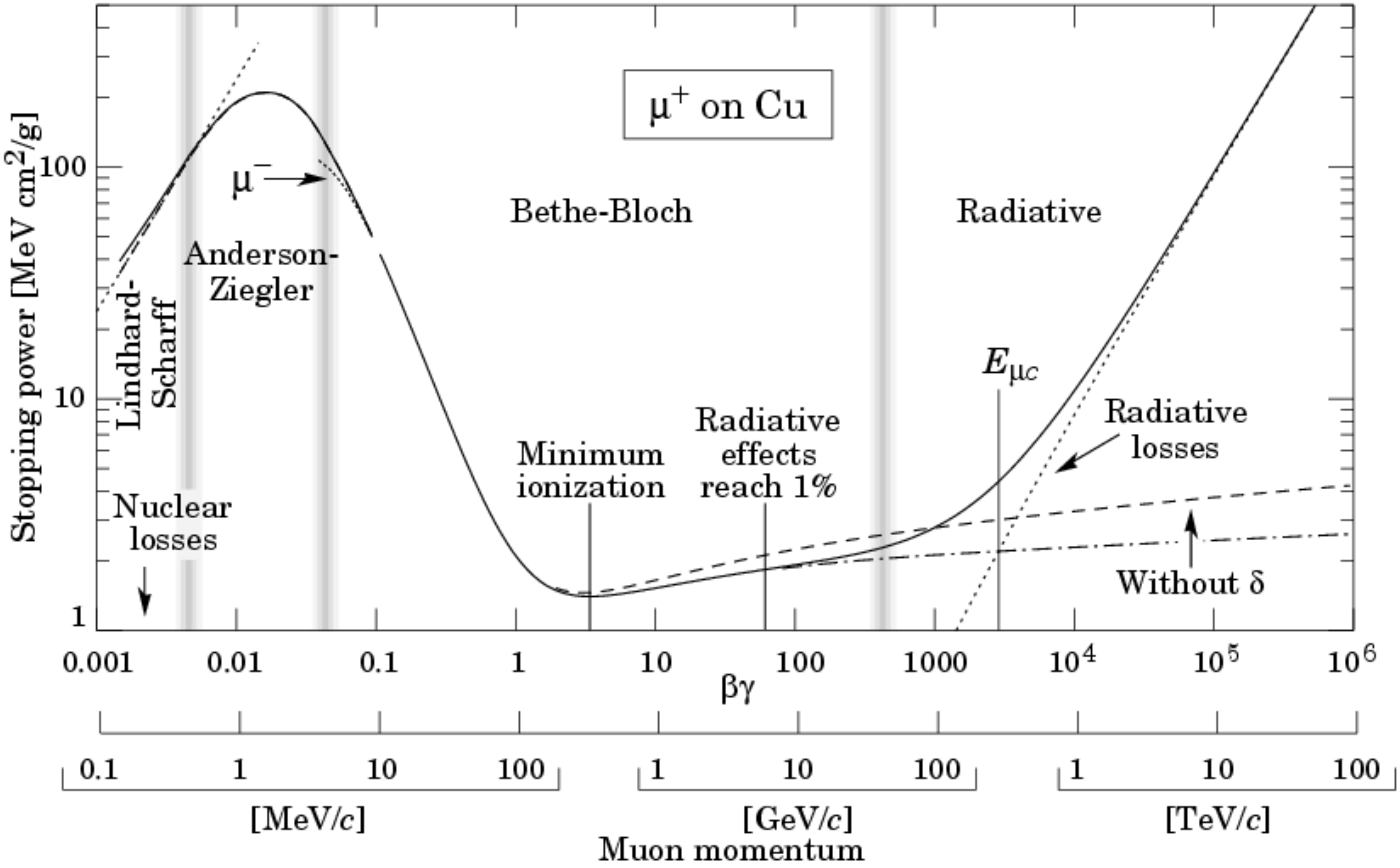
- The Critical Energy is the energy at which loss from Bremsstrahlung takes over from loss from Ionisation

$$\left.\frac{dE}{dx}(E_c)\right|_{\mathrm{Brems}} = \left.\frac{dE}{dx}(E_c)\right|_{\mathrm{Ion}}$$

$$\left(\frac{dE}{dx}\right)_{\mathrm{Tot}} = \left(\frac{dE}{dx}\right)_{\mathrm{Ion}} + \left(\frac{dE}{dx}\right)_{\mathrm{Brems}}$$

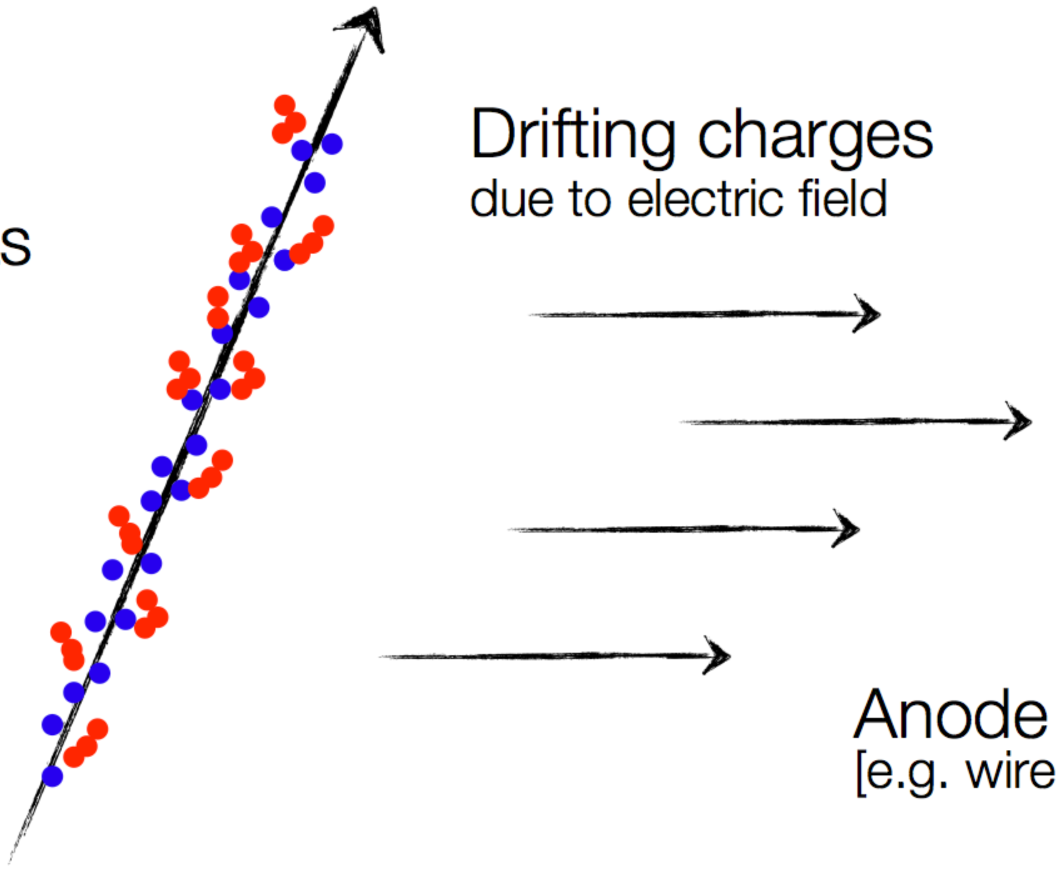


Energy Loss Summary (muons)



Let's Use Ionization to Build a Particle Detector!

Let's Use Ionization to Build a Particle Detector!



Schematic Principle
of gas detectors

Particle

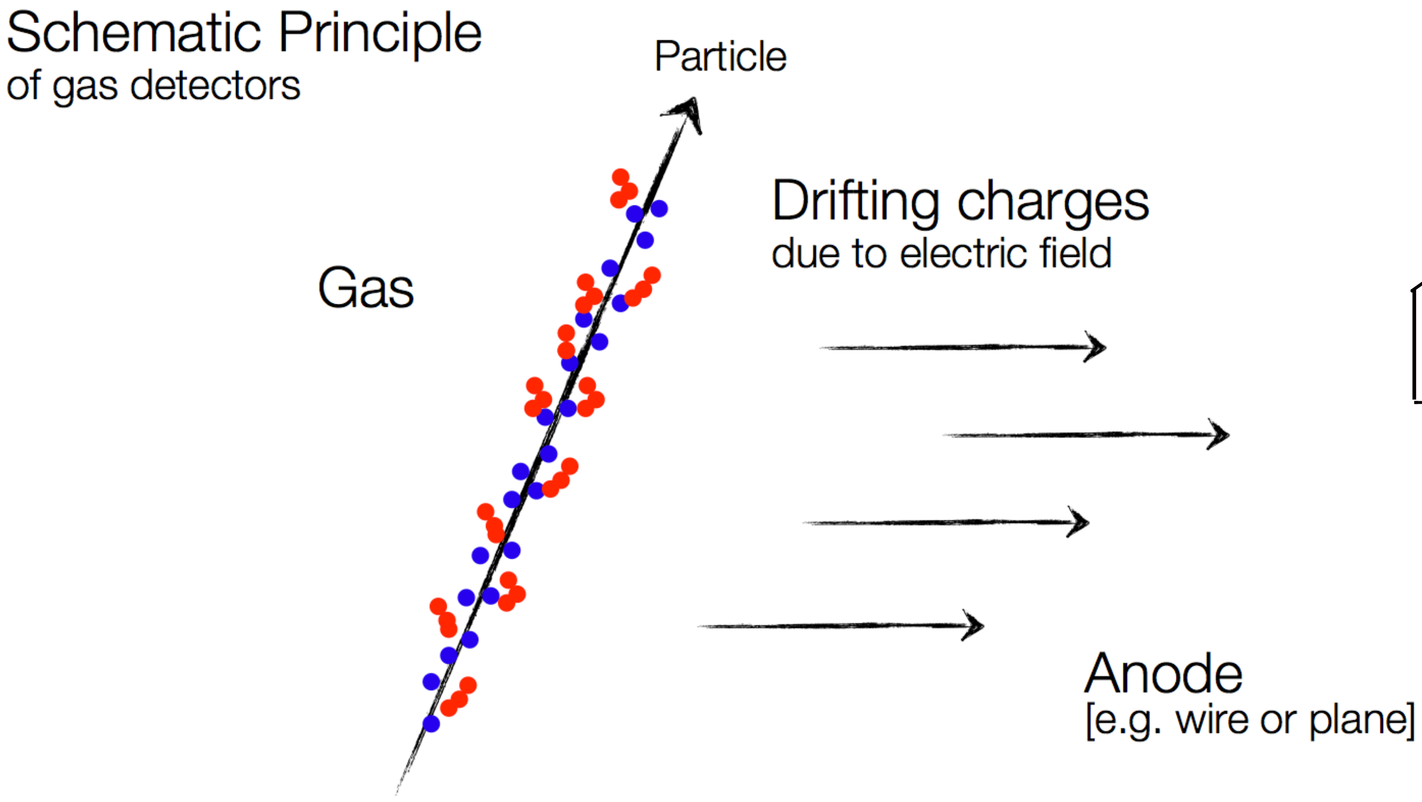
Gas

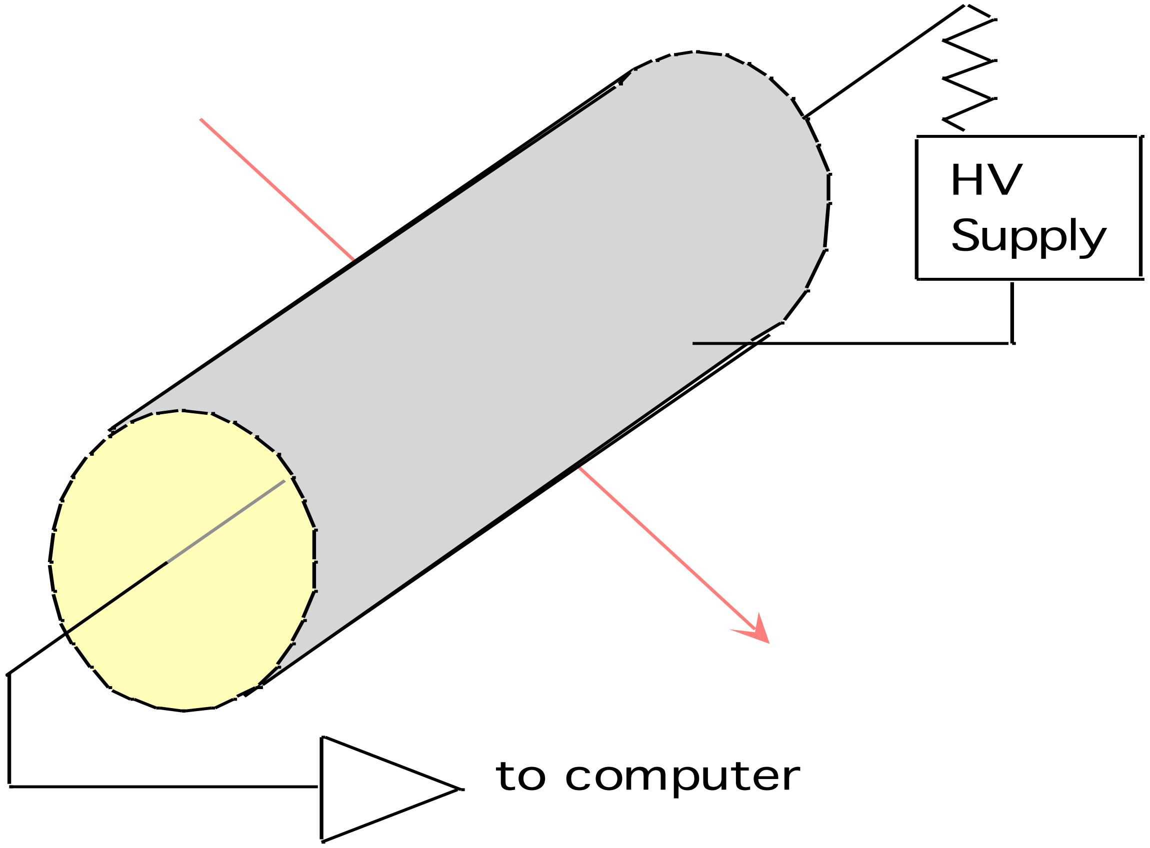
Drifting charges
due to electric field

Anode
[e.g. wire or plane]

Let's Use Ionization to Build a Particle Detector!

- Take a tube
- Fill it with a gas: (noble gases are more likely to ionize than others. Let's use Argon)
- Insert a conducting surface to make an intense electric field: The field at the surface of a small wire gets extremely high, so use tiny wires
- Attach electronics and apply high voltage
- And we're done!



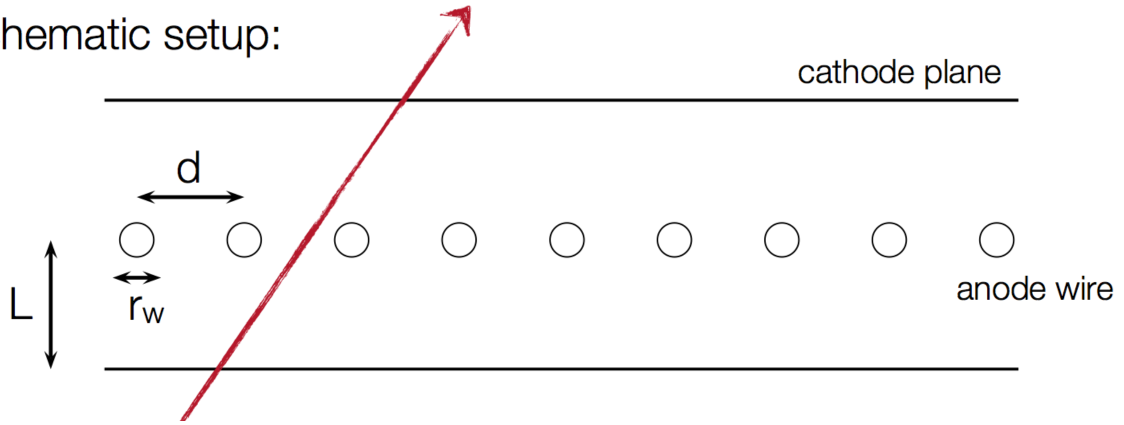


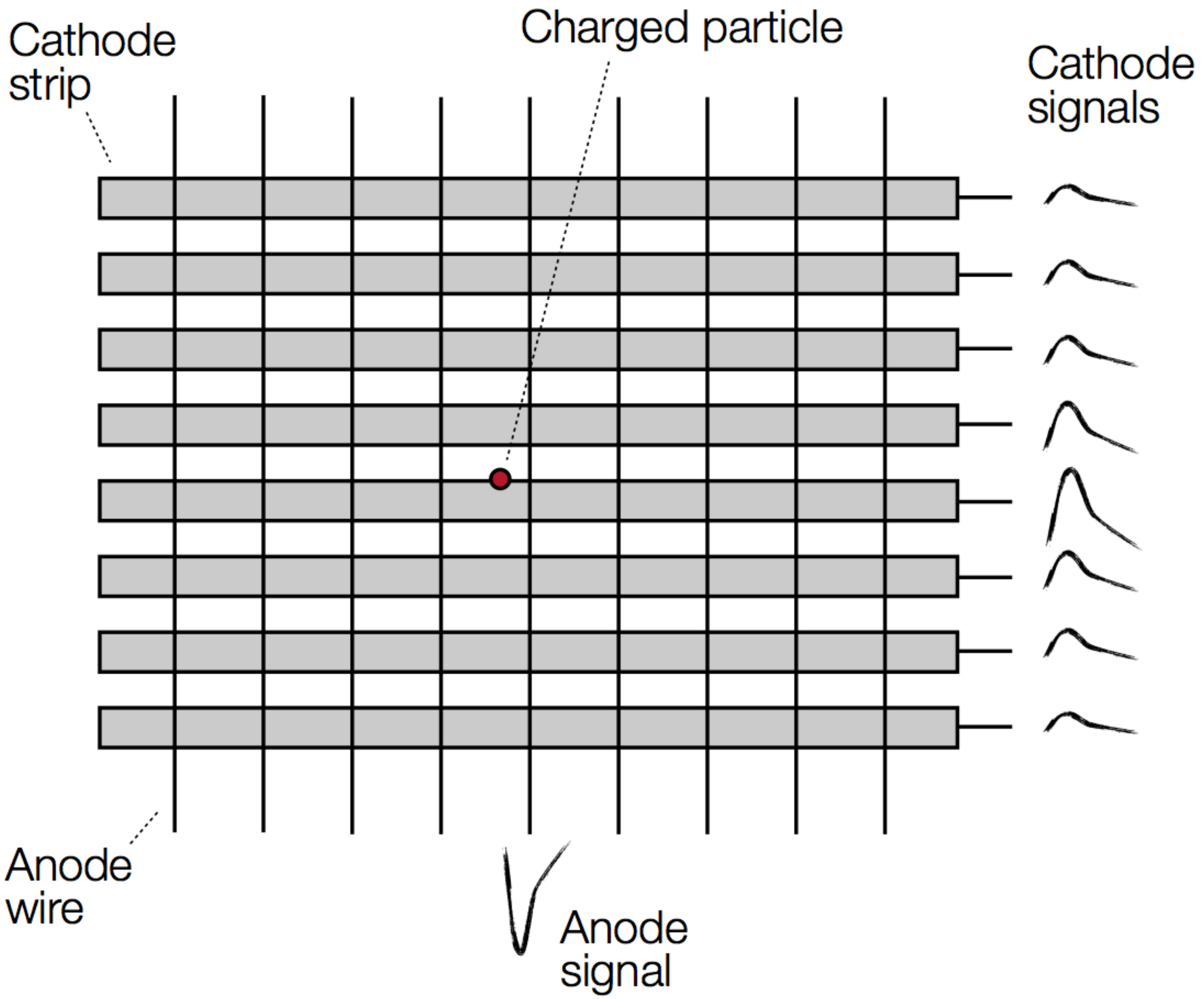
How can I make this more accurate?

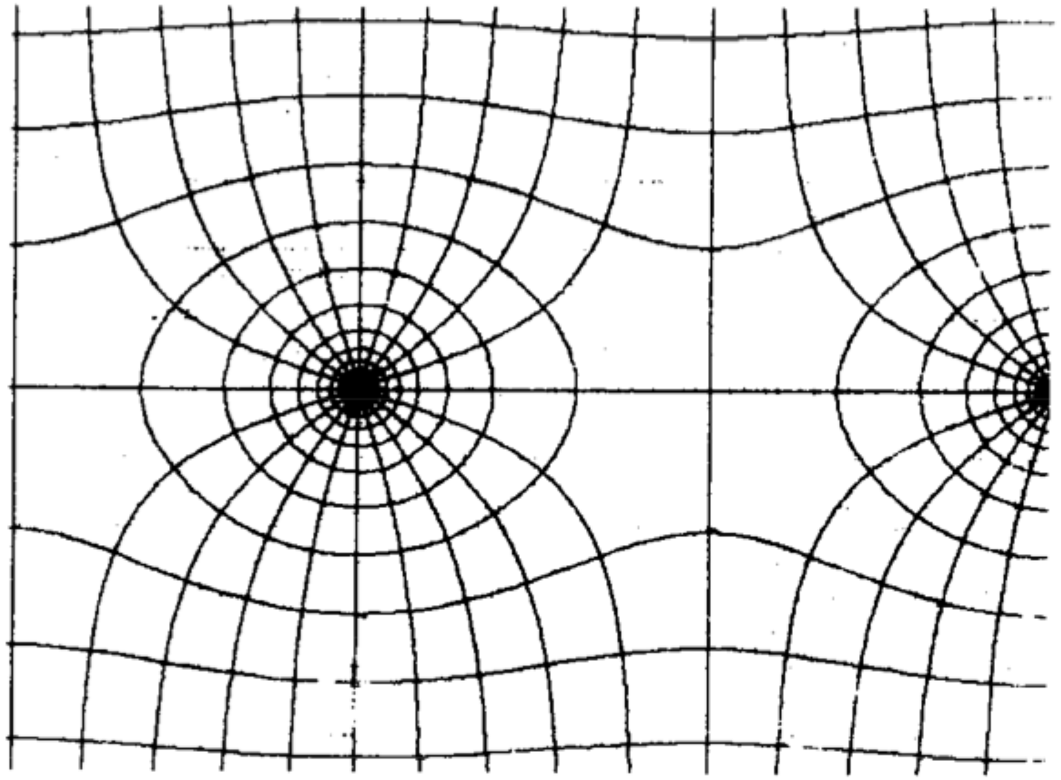
Multi Wire Chamber

- We can use many wires to get a more accurate position measurement

Schematic setup:





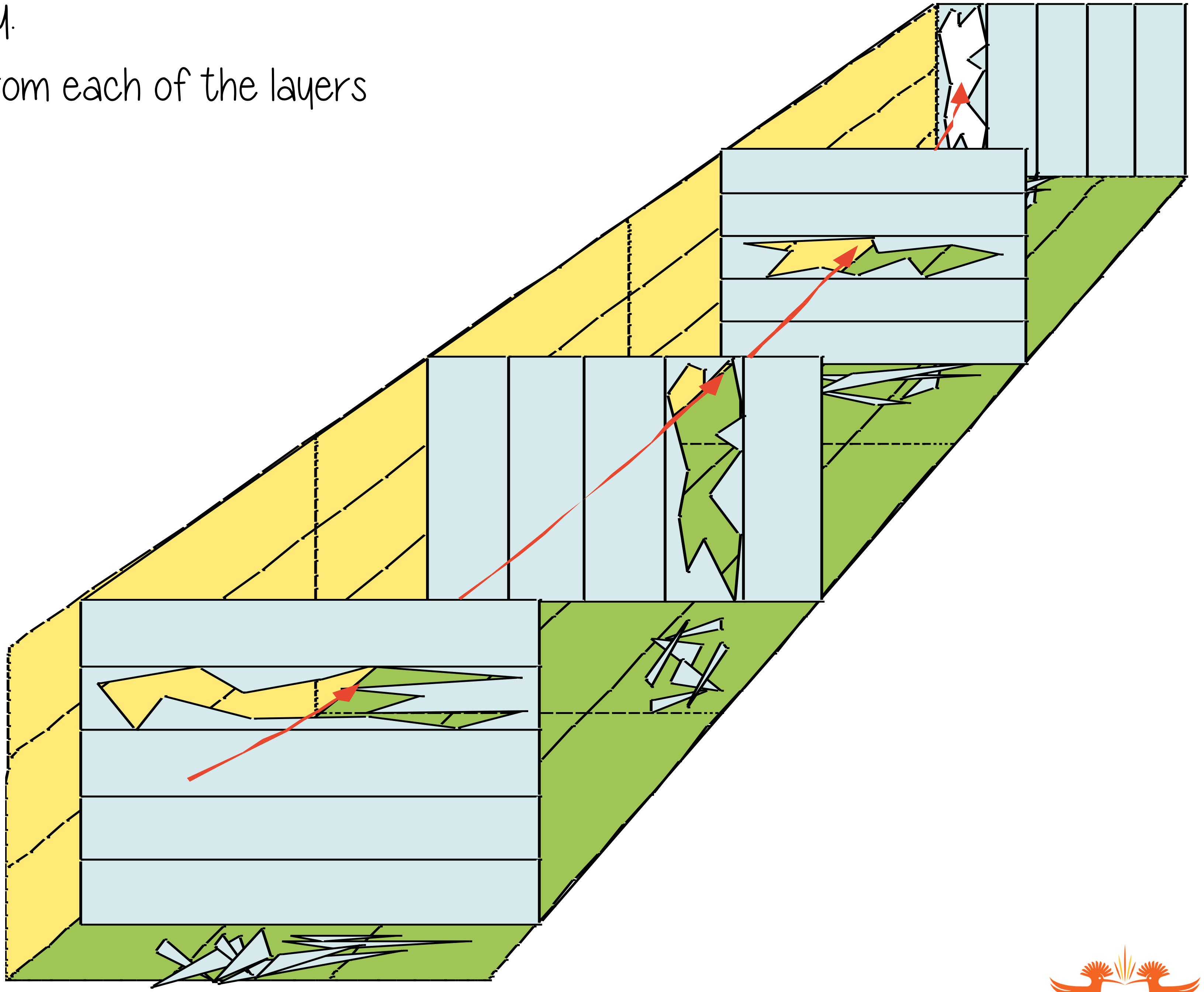


Multi Wire Chamber

- We can also layer the chambers longitudinally along the particle direction

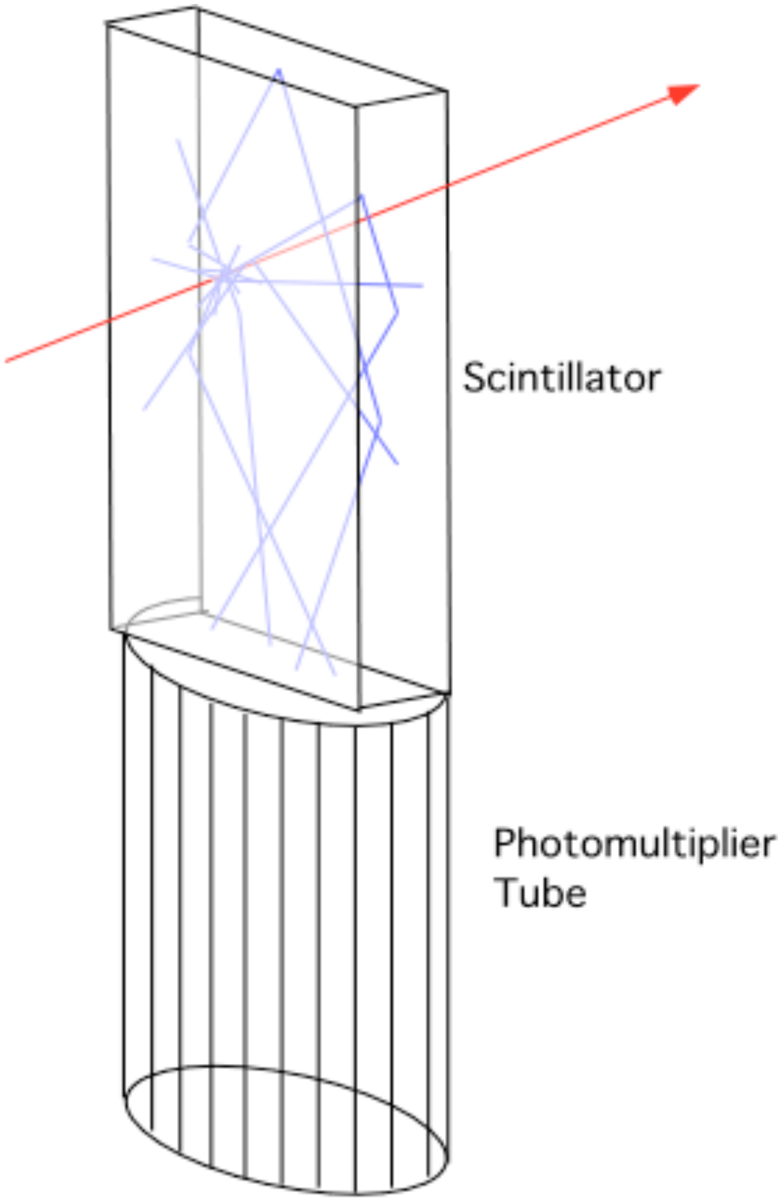
- If we make several measurements of track position along the length of the track, we can figure out the whole trajectory.
  - We can also time the signals coming from each of the layers

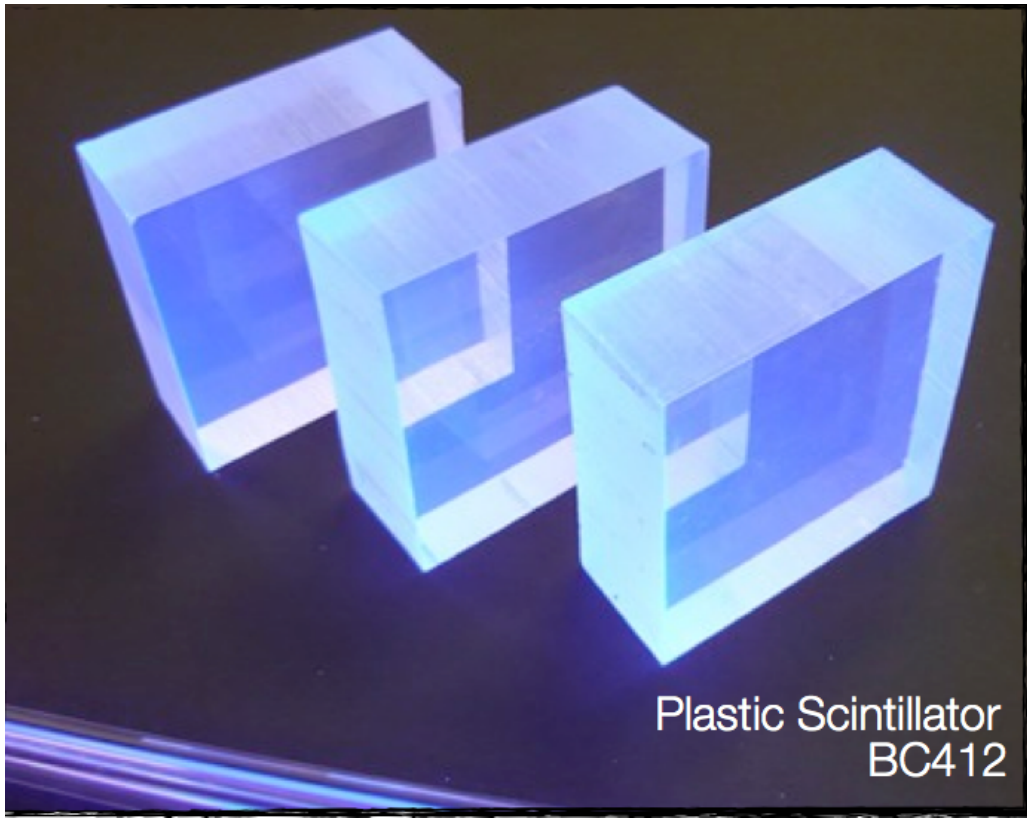
Mass
Momentum
Energy
Charge
Lifetime*
Spin*
etc...



What about using the produced light?

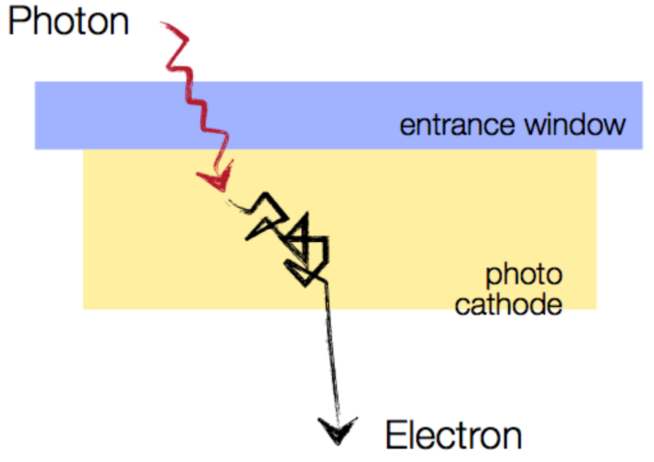
- Many materials radiate light, but most also absorb that light again so that it never gets out.
- However, a type of material called a scintillator produces light that does not get reabsorbed
- Scintillators have
  - Sensitivity to energy
  - Fast time response
  - Pulse shape discrimination

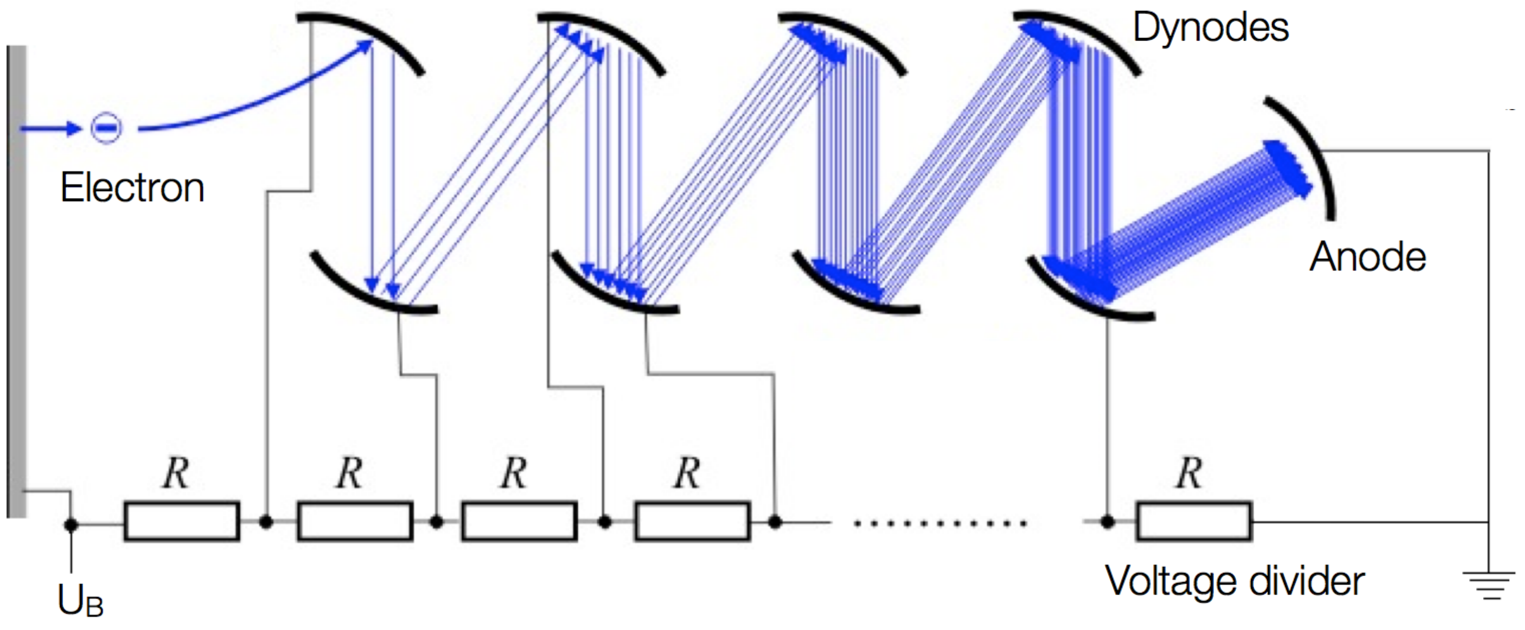


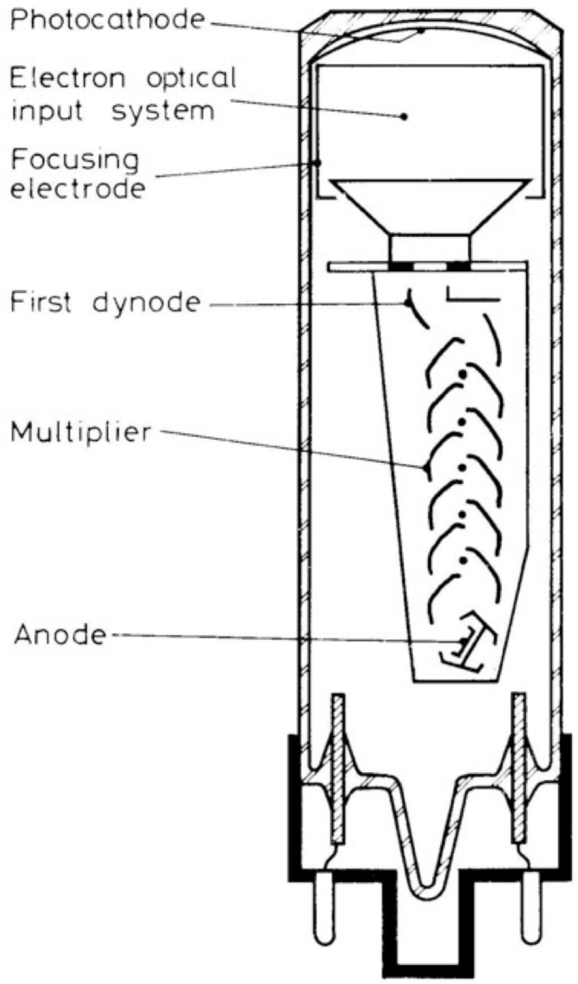


Aside: Photomultipliers

- Photomultipliers convert light into a detectable electronic signal
  - Use photo-electric effect to convert photons to photo-electrons (p.e.)
- Typical PMT Gain: > 10^6
  - PMT can "see" single photons!

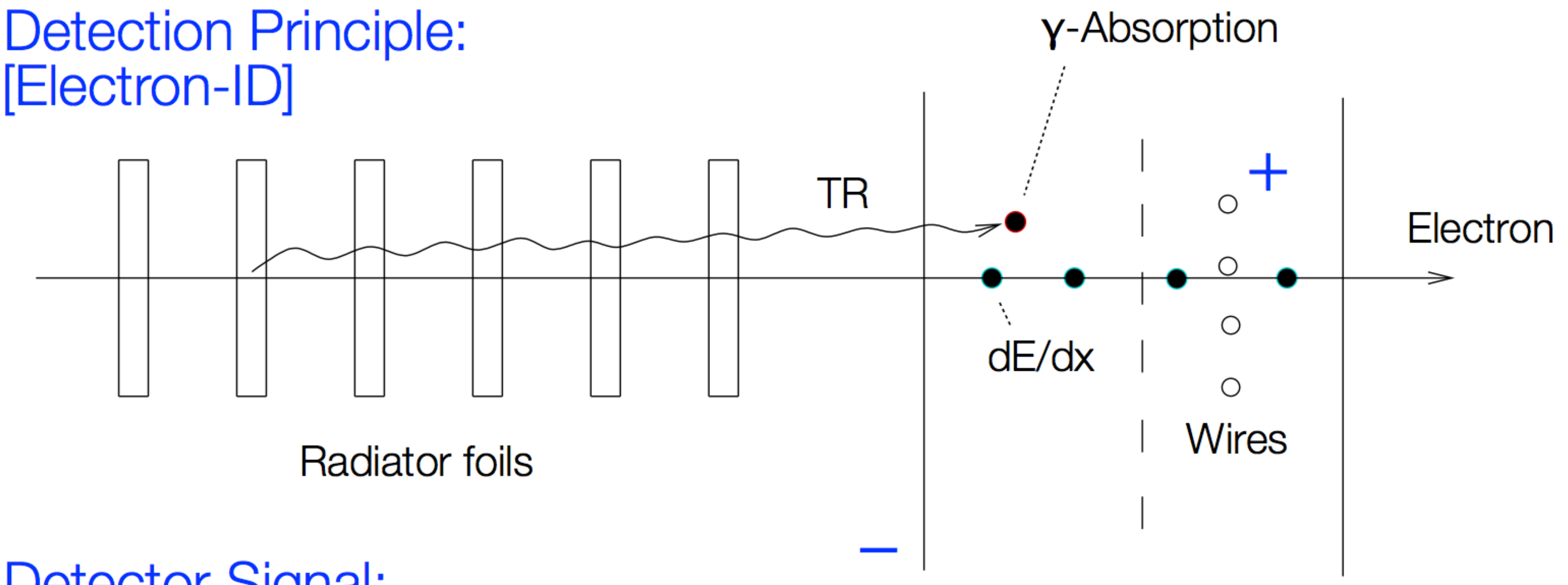




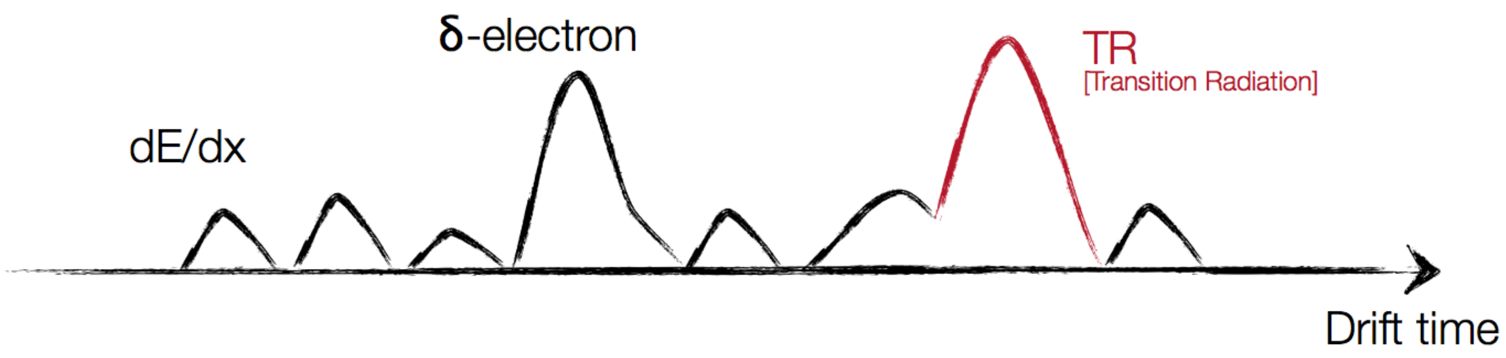


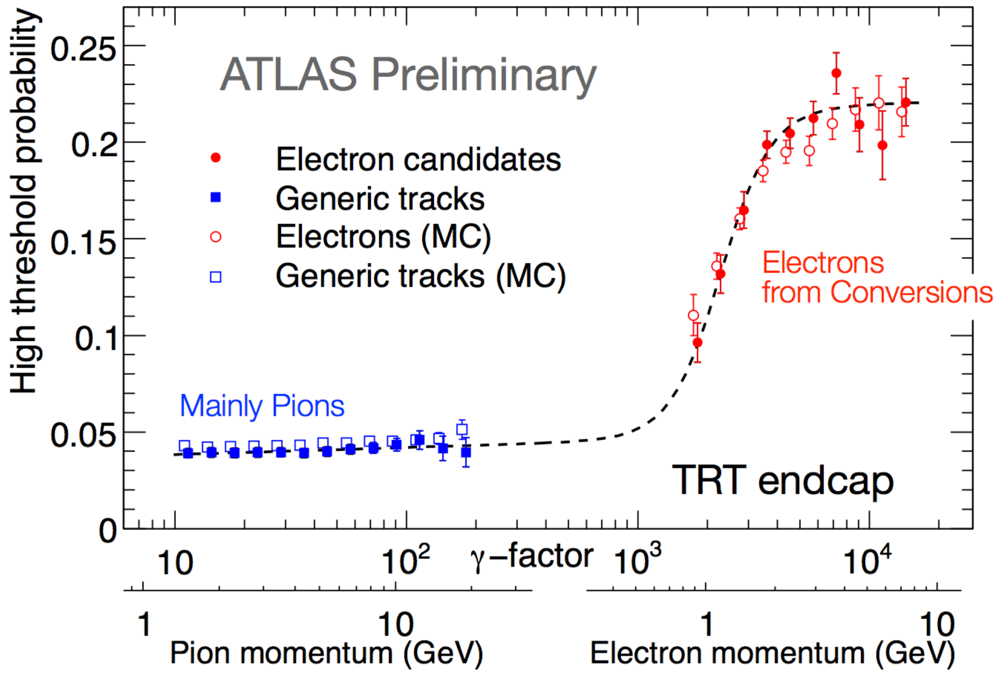
What about that Transition Radiation?

Detection Principle:
[Electron-ID]



Detector Signal:





Calorimetry

- If we completely stop a particle (eg in a scintillator) then all of its energy will be transferred into light
  - This is called a calorimeter

- Operating principle:
    - Incoming particle initiates particle shower …
      Shower Composition and shower dimensions depend on particle type and detector material …
  - Energy deposited in form of: heat, ionization, excitation of atoms, Cherenkov light …

- Calorimeters can measure the energy of both, charged and neutral particles, if they interact via either electromagnetic or strong forces
  - you would have a different EM or hadronic calorimeter

Summary I

- We detect particles from their interactions with matter
- Most interactions either give off light or electric charge
  - we build our detectors to exploit these in different ways

"Homework" (for tonight, not home!)

- Using the information you have learnt, how could you tell the difference between:
  - proton and neutron
  - electron and positron
  - electron and muon
  - positron and proton
  - A single proton and a jet

Recap

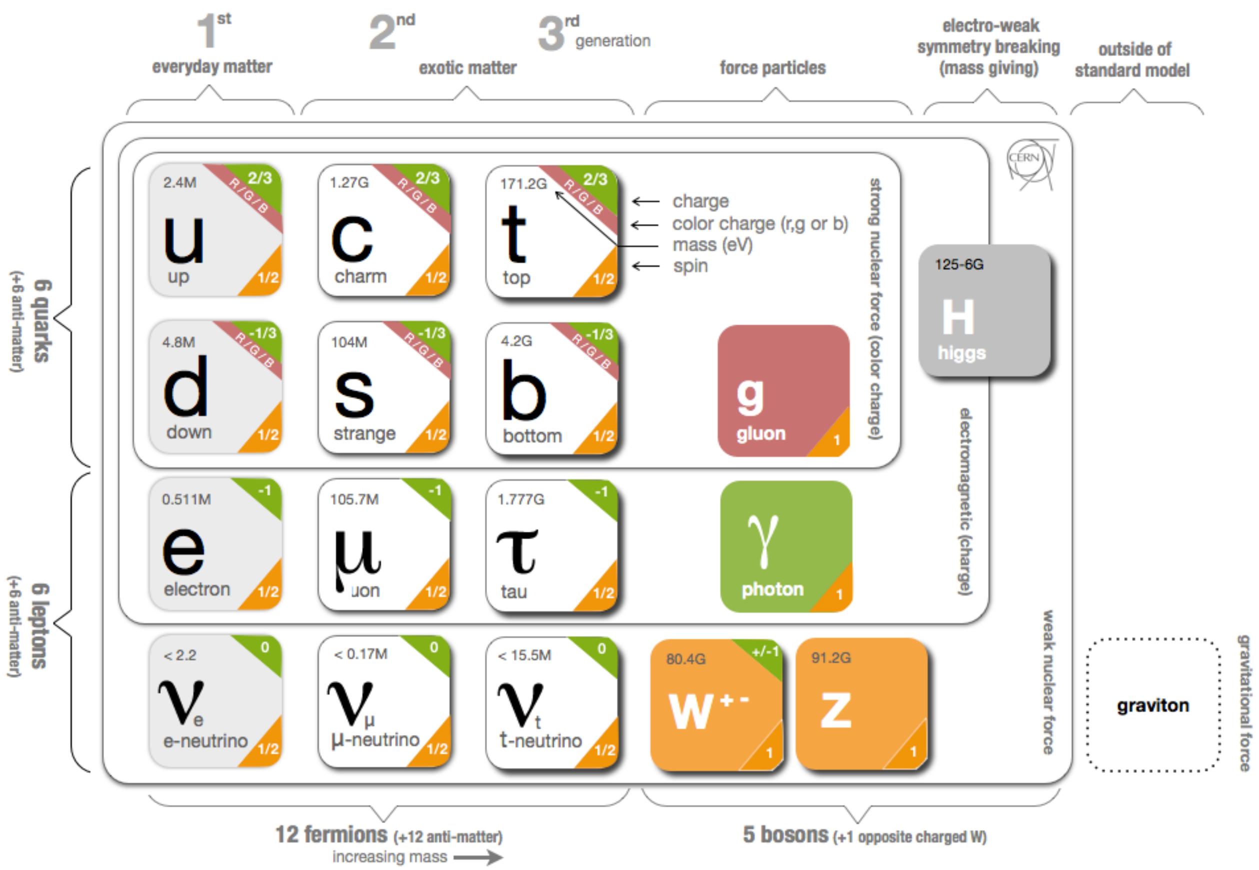
- We detect particles from their interactions with matter
- Most interactions either give off light or electric charge - we build our detectors to exploit these in different ways.

Tracking:
  - Drift/Multi wire chambers
  - Semiconductor detectors

Calorimetry:
  - Electromagnetic
  - Hadronic

Specialised:
  - Cerenkov
  - Transition radiation

(Magnets)



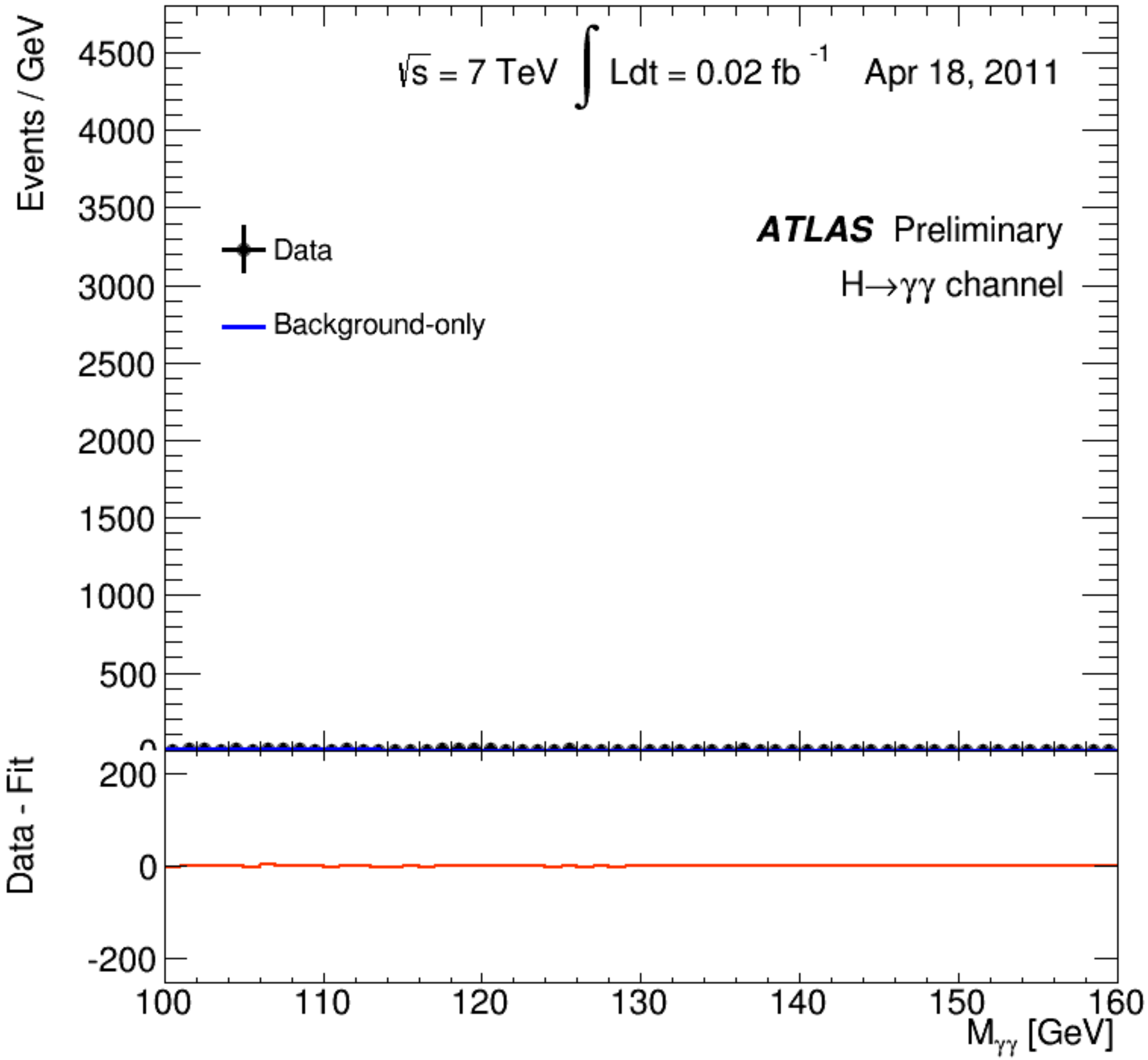
electrons (and positrons)
photons
muons (and antimuons)
charged hadrons (eg protons)
neutral hadrons (eg neutrons)

Mass
Momentum
Energy
Charge
Lifetime*
Spin*
etc...

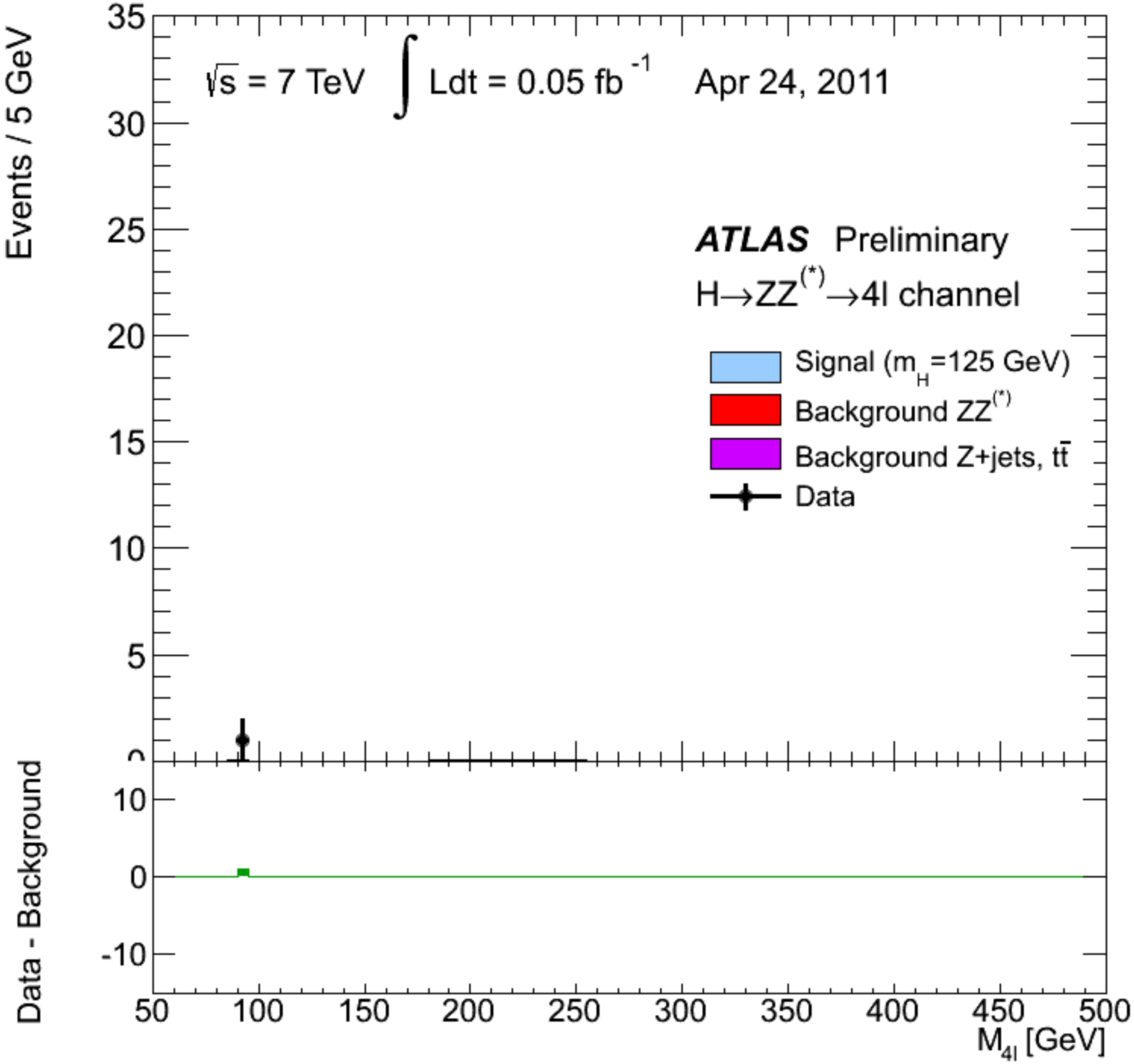
Homework

- Using the information you have learnt, how could you tell the difference between:
  - proton and neutron
    - Both would be stopped (shower) in a hadronic calorimeter. But protons would leave tracks in a tracking detector, whereas neutrons would leave no tracks.
  - electron and positron
    - Both leave tracks, both would shower in an EM calorimeter. But they would bend different ways in a magnetic field.
  - electron and muon
    - Both would leave tracks, but an electron would shower in a calorimeter, whereas a muon would go through.
  - positron and proton
    - Same charge. Positron would shower in an EM calorimeter, proton would shower in a hadronic calorimeter
  - A single proton and a jet
    - A jet is a cone of many charged and neutral hadrons, compared to a single proton.

Discovery of the Higgs boson (diphoton channel)



Discovery of the Higgs boson (4 lepton channel)



Build your own particle physics experiment!

- Now it's time for you to put it all together and build your own detector!

- Get into pairs/threes
- Each group take one of each type of shape (passing around)
- Give each shape a label for each detector type
- Build yourself a detector that would be able to identify the following events: (you don't need to use all shapes)
  - Draw the "signal" the particles would leave on the shapes

- Drift/Multi wire chambers
- Semiconductor trackers
- Electromagnetic calorimeter
- Hadronic calorimeter
- Cerenkov detector
- Transition radiation detector

Groups on the LEFT

A Higgs boson that decays to two Z bosons, each of which decay to electron or muon pairs

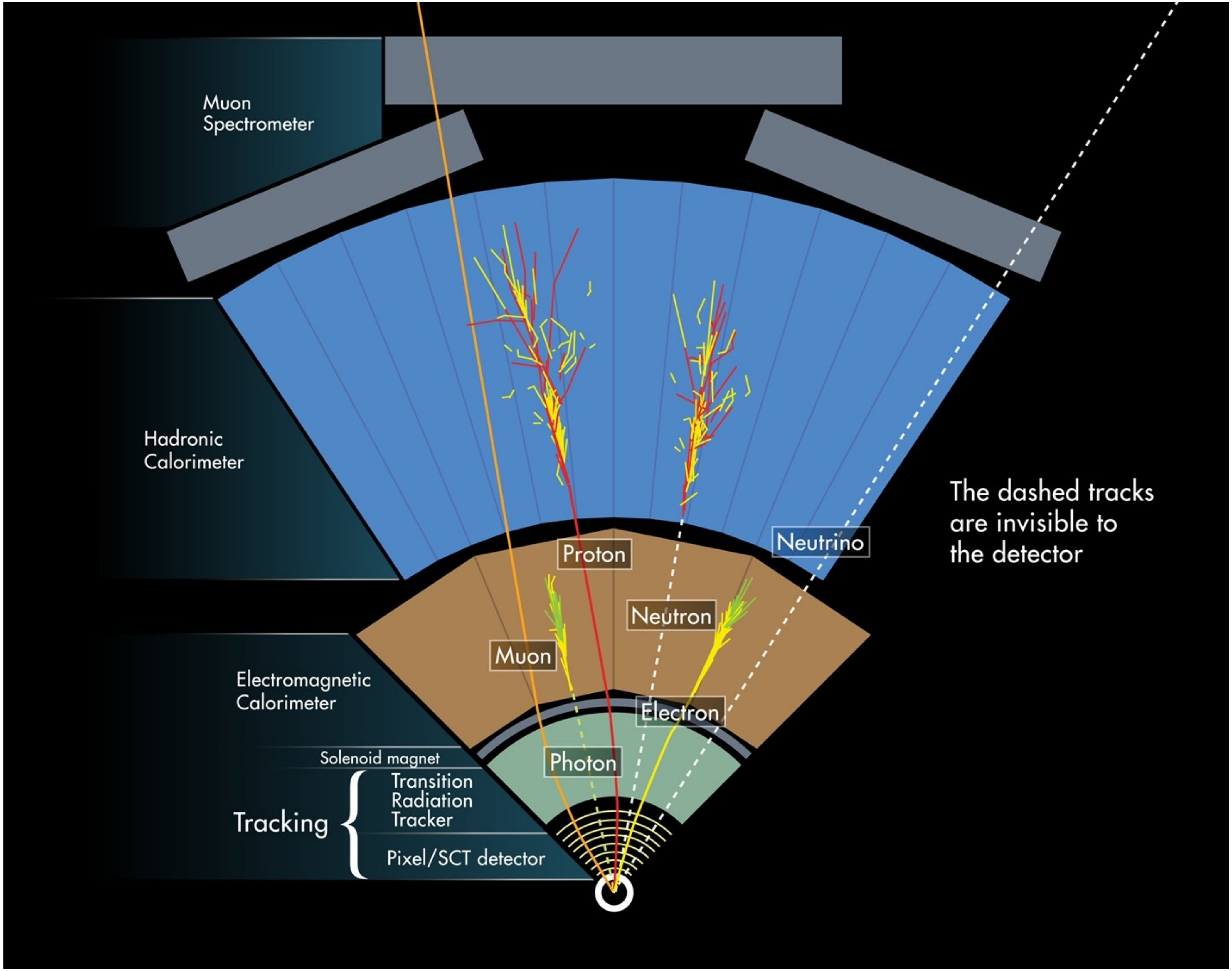
Groups in the MIDDLE

A Higgs boson that decays to two b-quarks (jets) produced with a Z boson that decays to electron or muon pairs

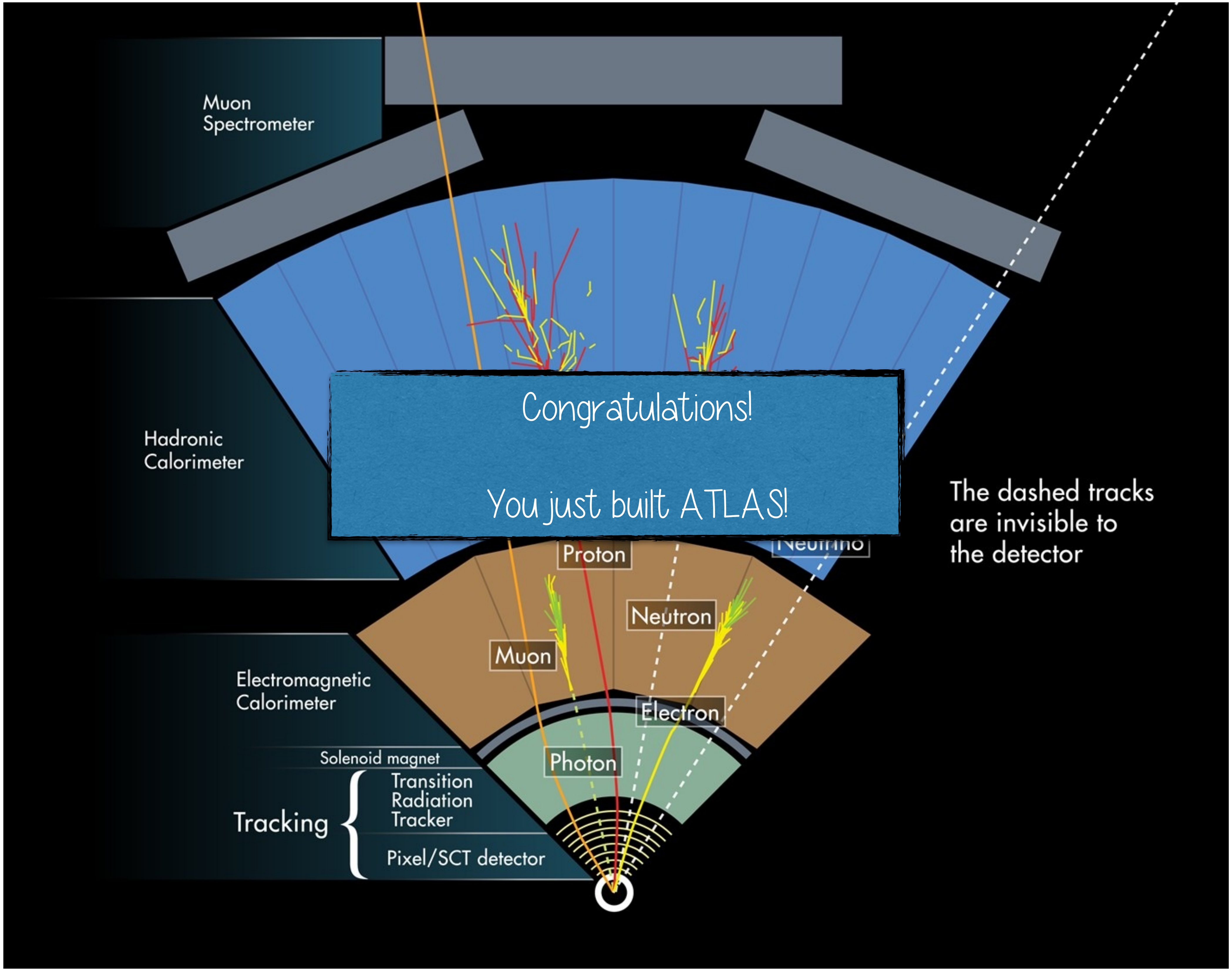
Groups on the RIGHT

A W boson that decays to an electron or muon, and a neutrino

Did you build something like this?



Did you build something like this?

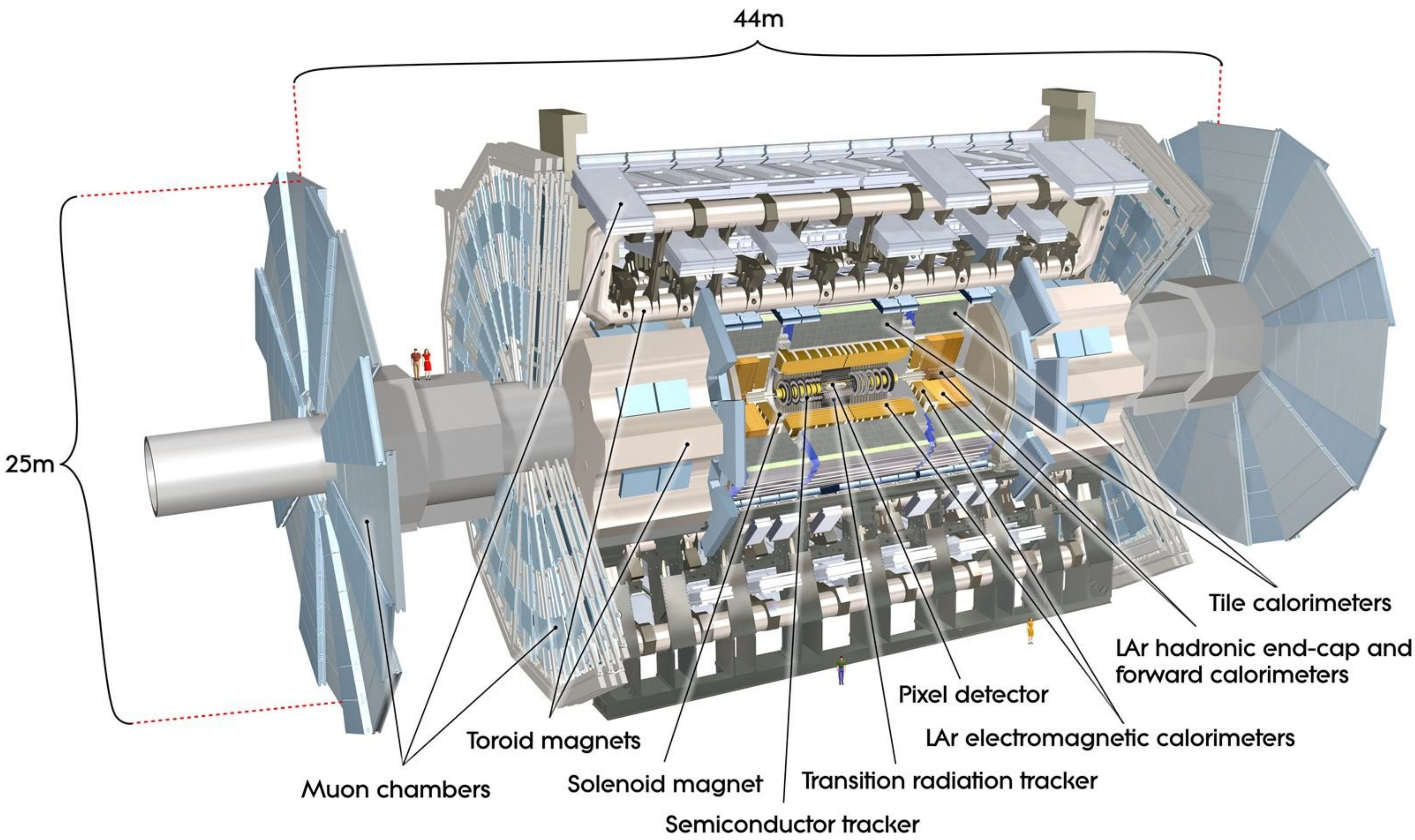


The dashed tracks are invisible to the detector

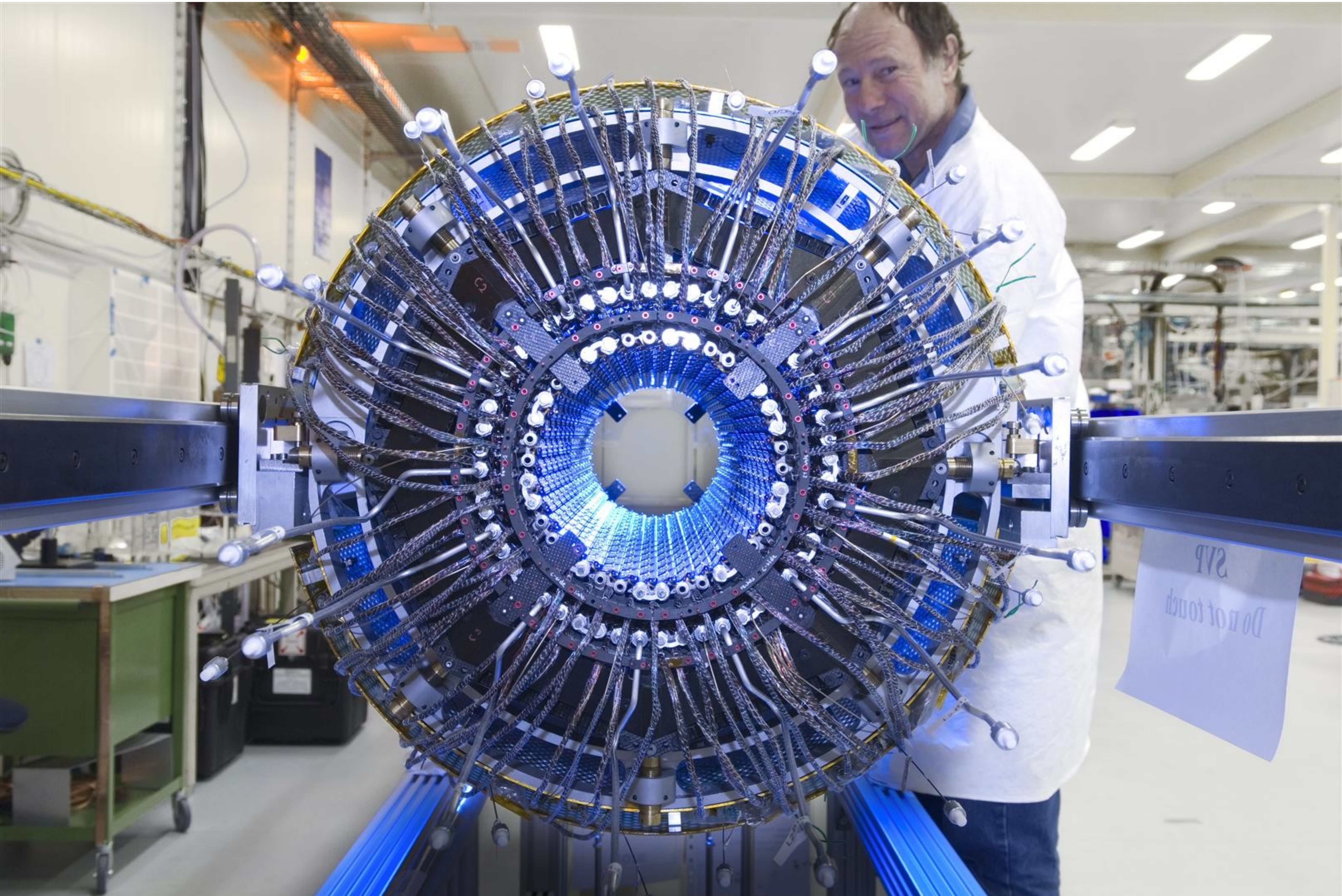
Congratulations!

You just built ATLAS!

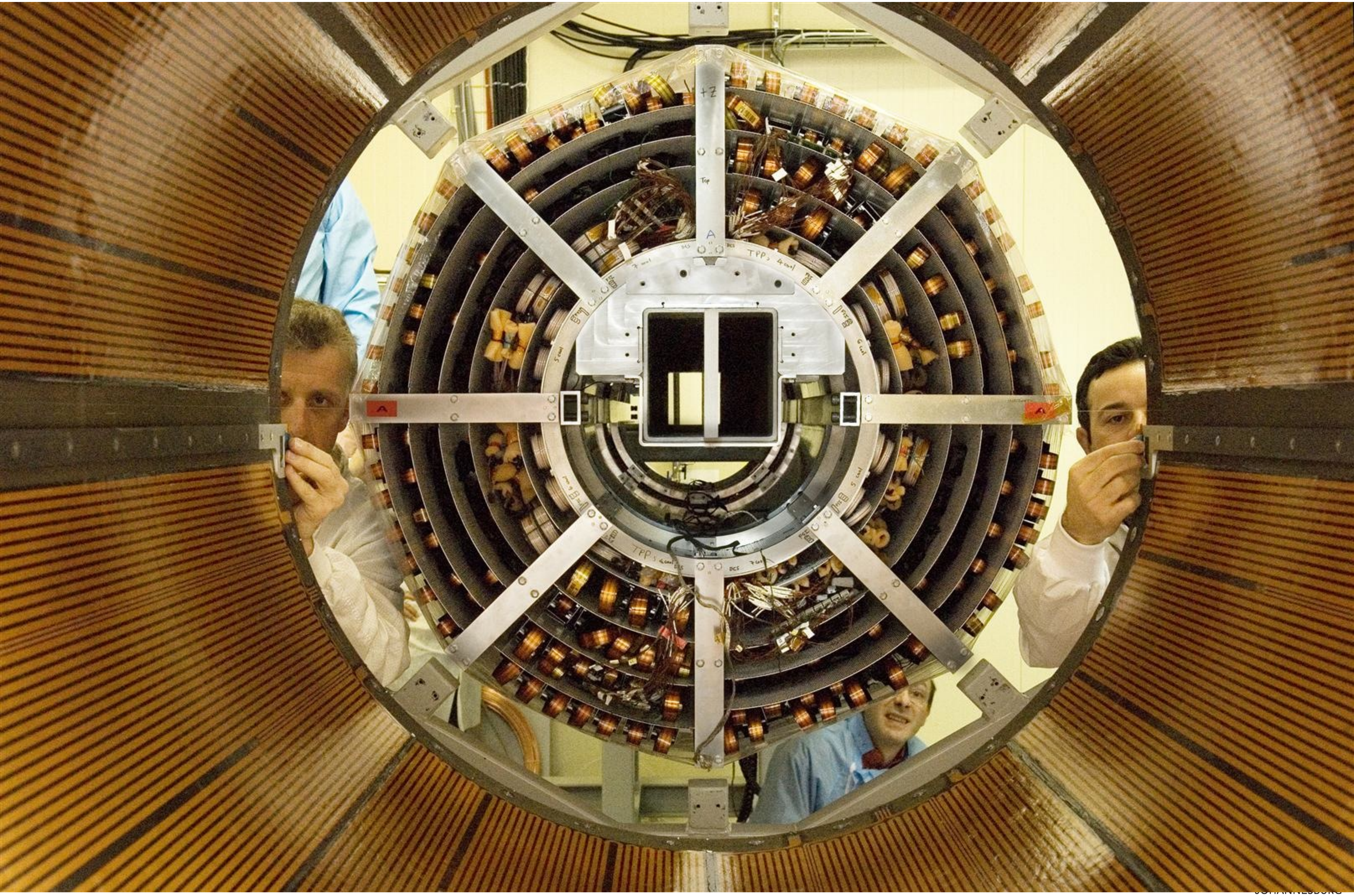
The ATLAS Detector at the LHC



ATLAS Pixel detector

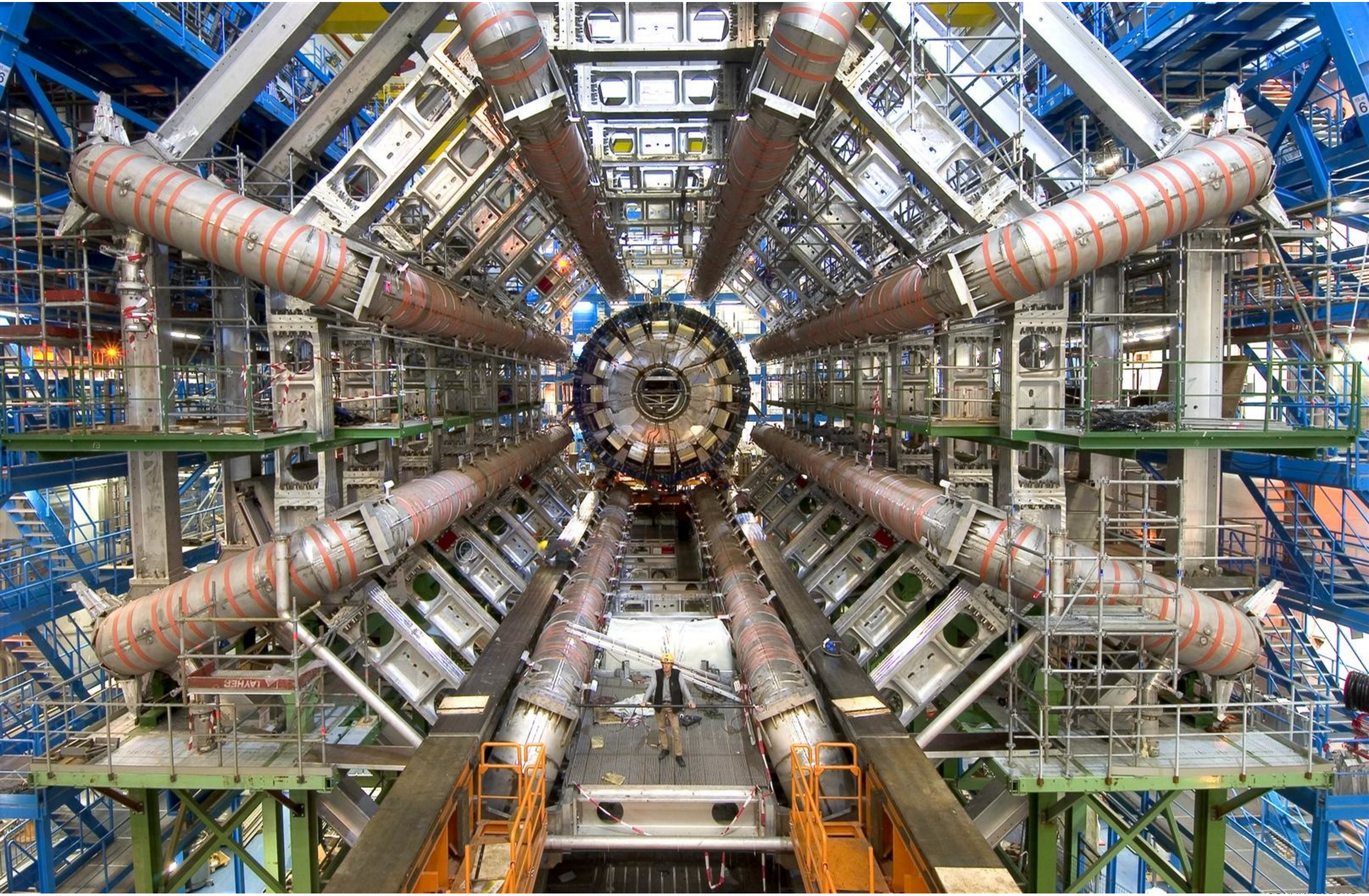


ATLAS SCT going into the TRT

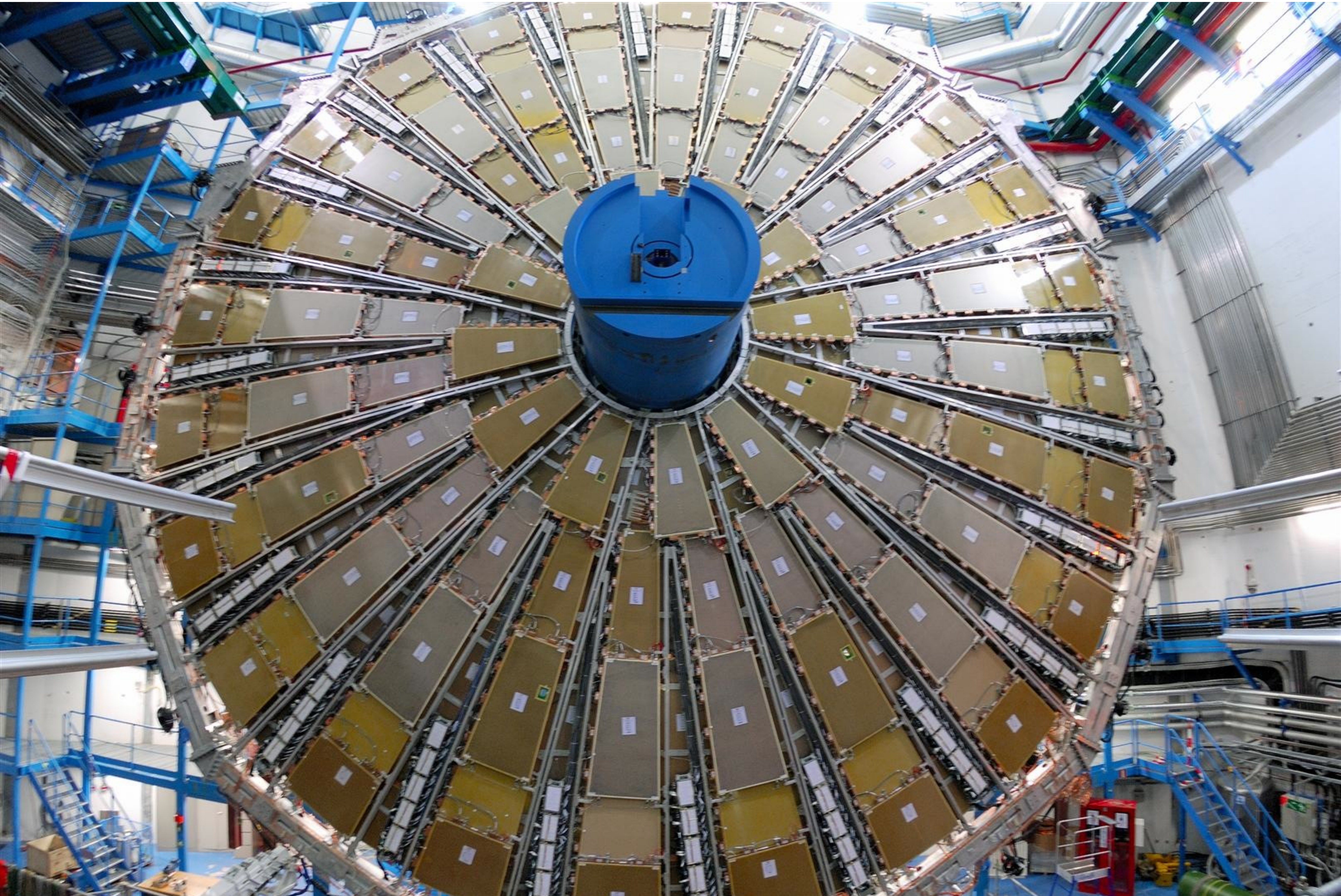


ATLAS EM Calorimeter endcap

ATLAS Toroid Magnet System

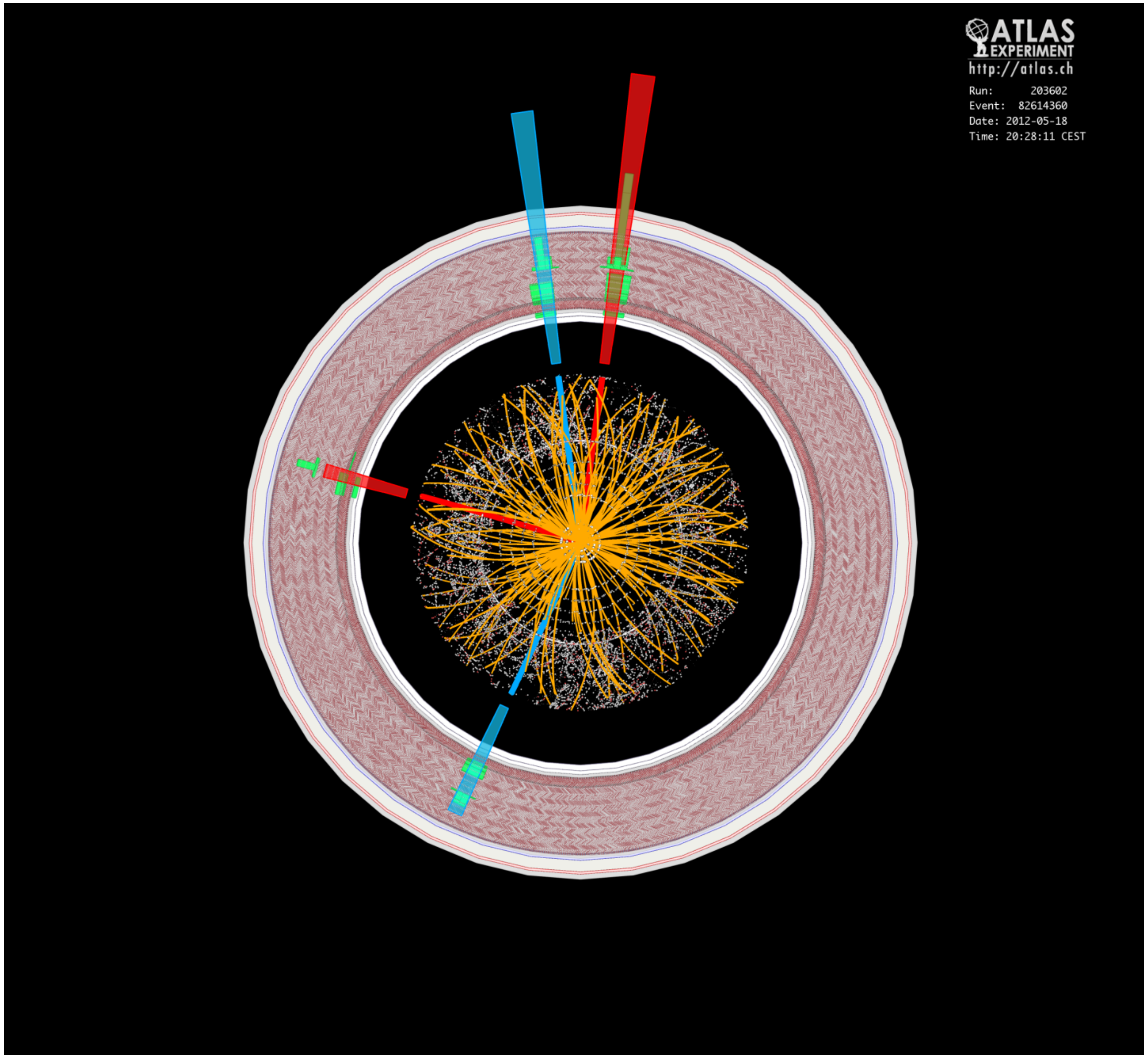


ATLAS Muon Thin Gap Chambers

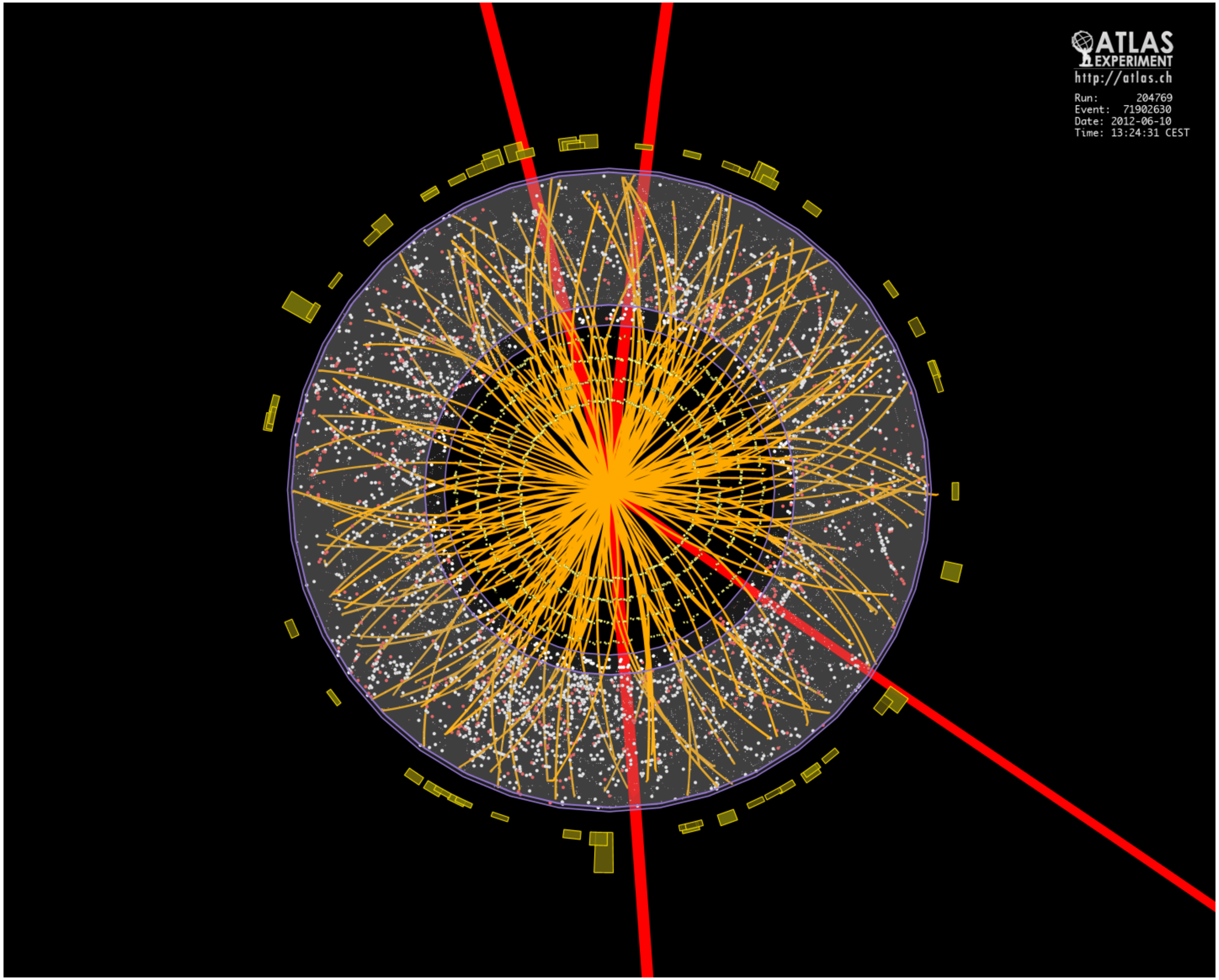


Some actual ATLAS events…

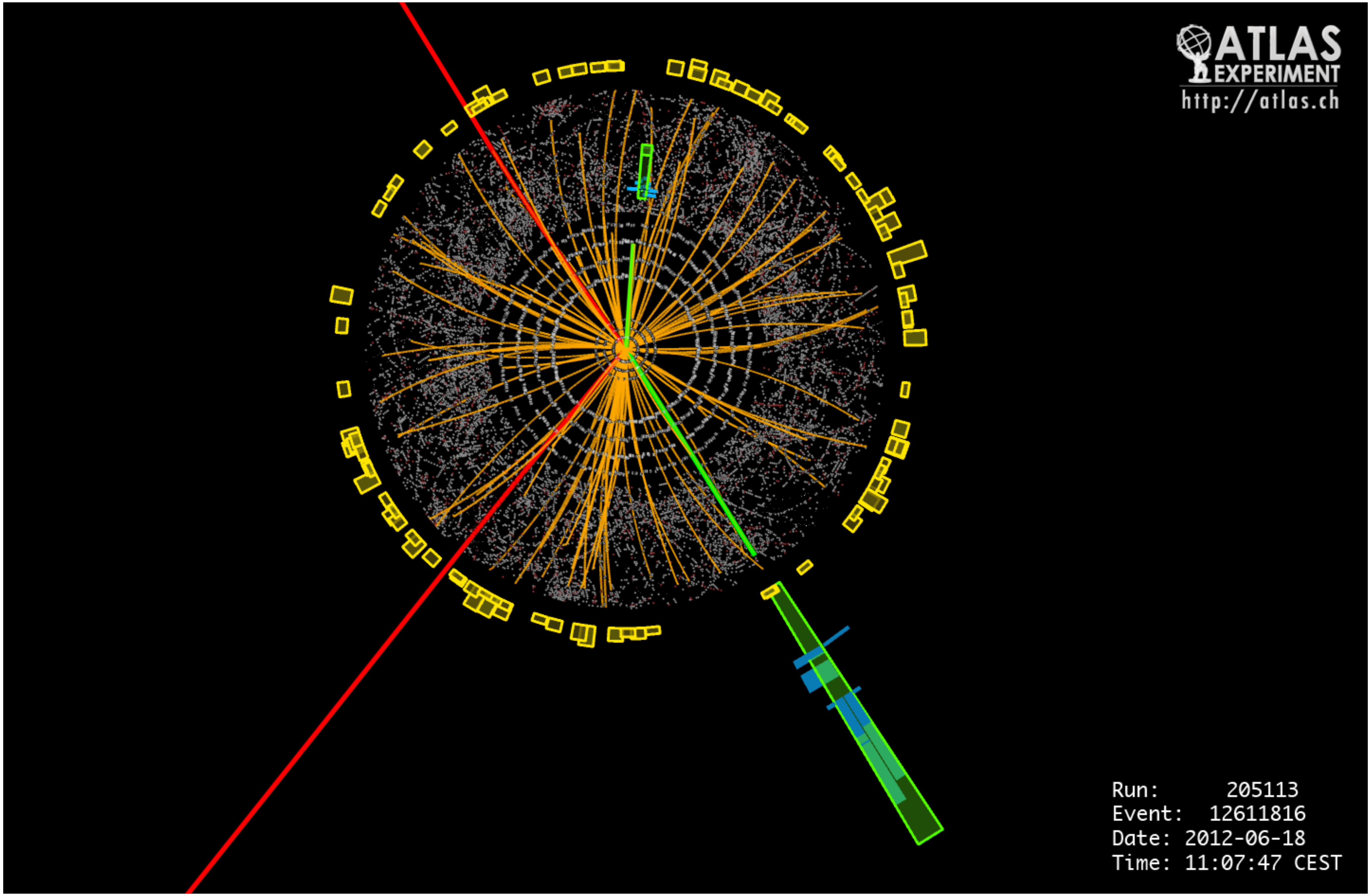
Higgs decay to 4 electron



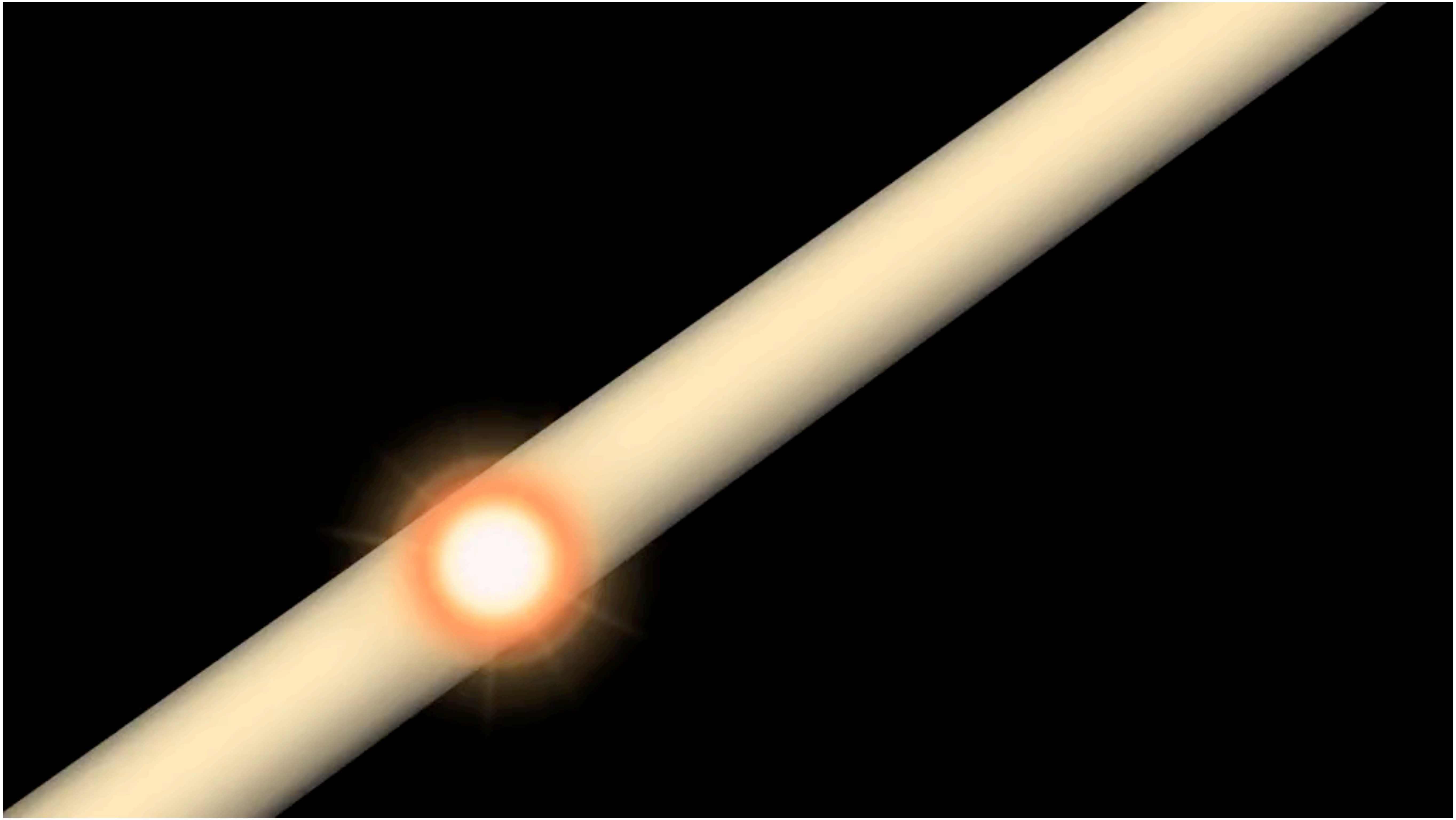
Higgs decay to 4 muon



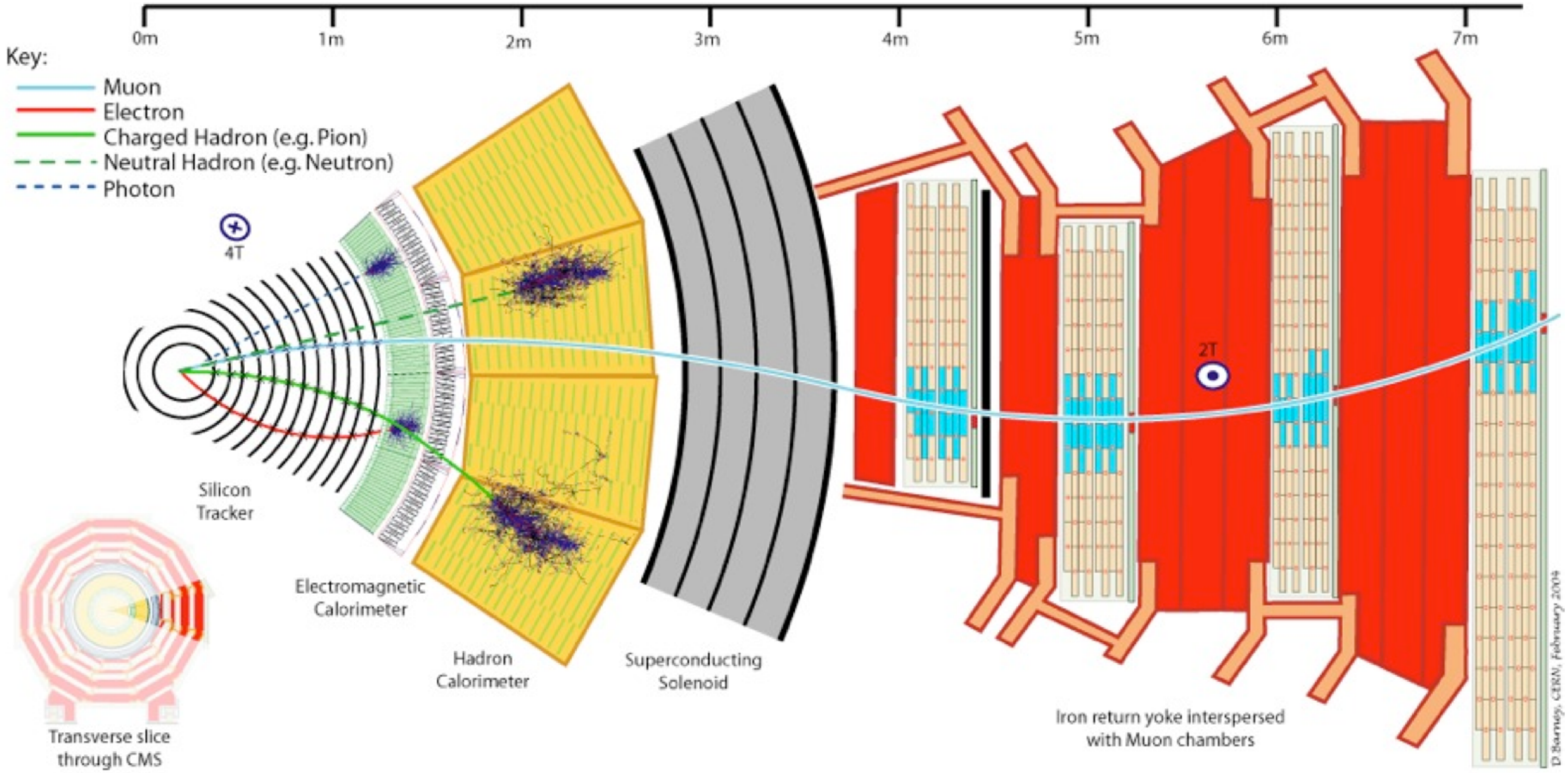
Higgs decay to 2e 2mu



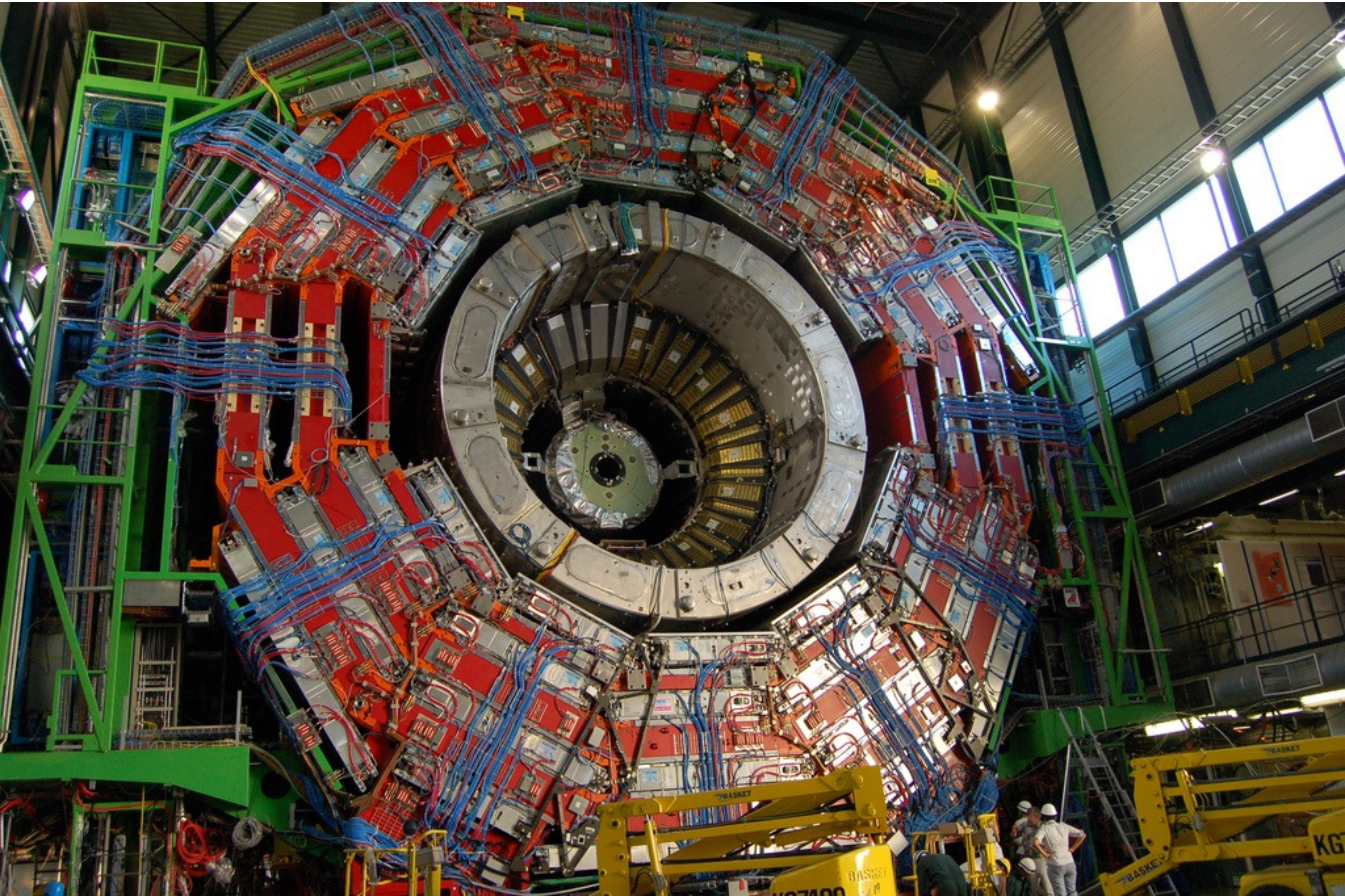
Higgs decay to 2 photons



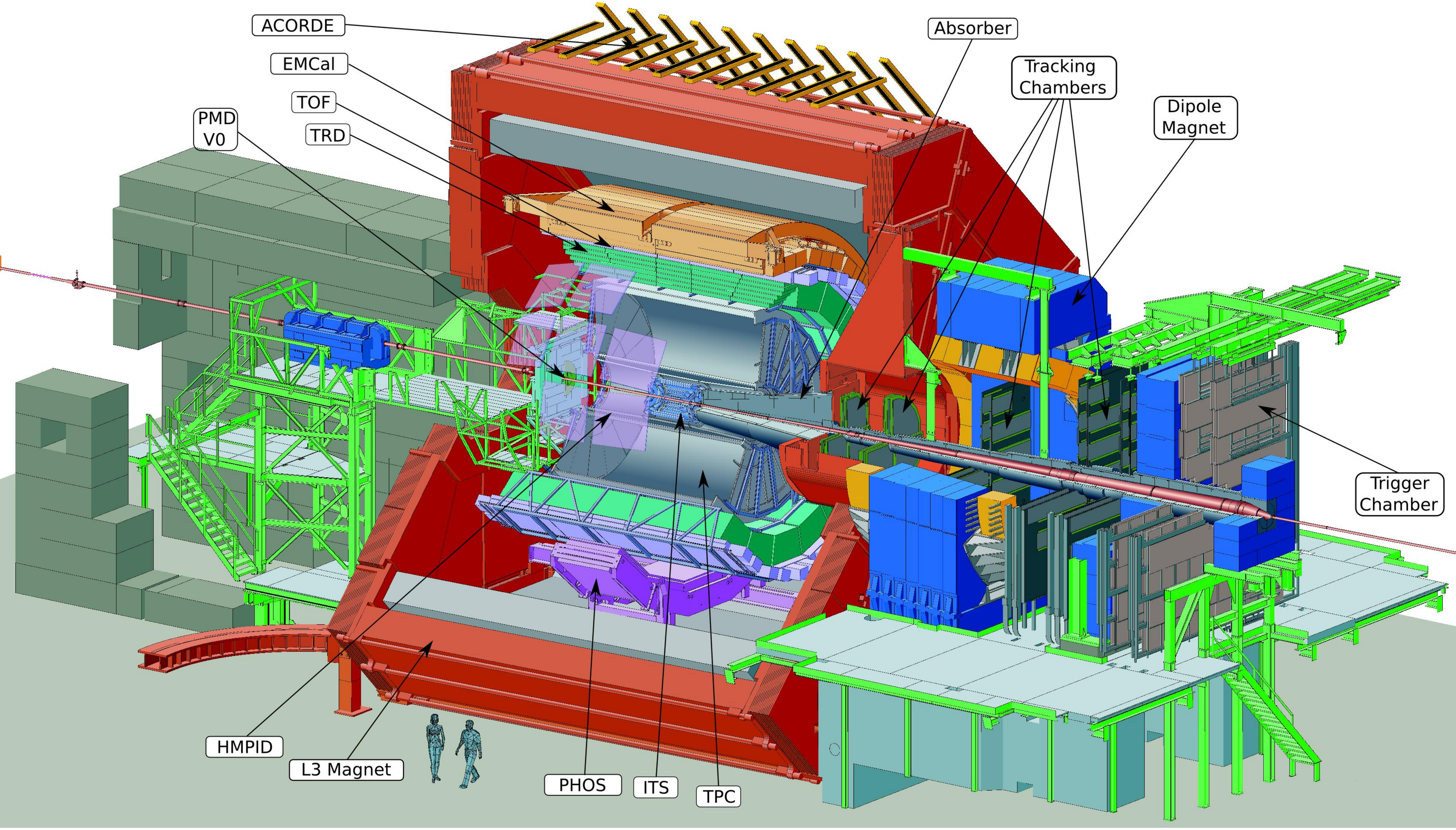
Other Examples of Detectors: The CMS Detector



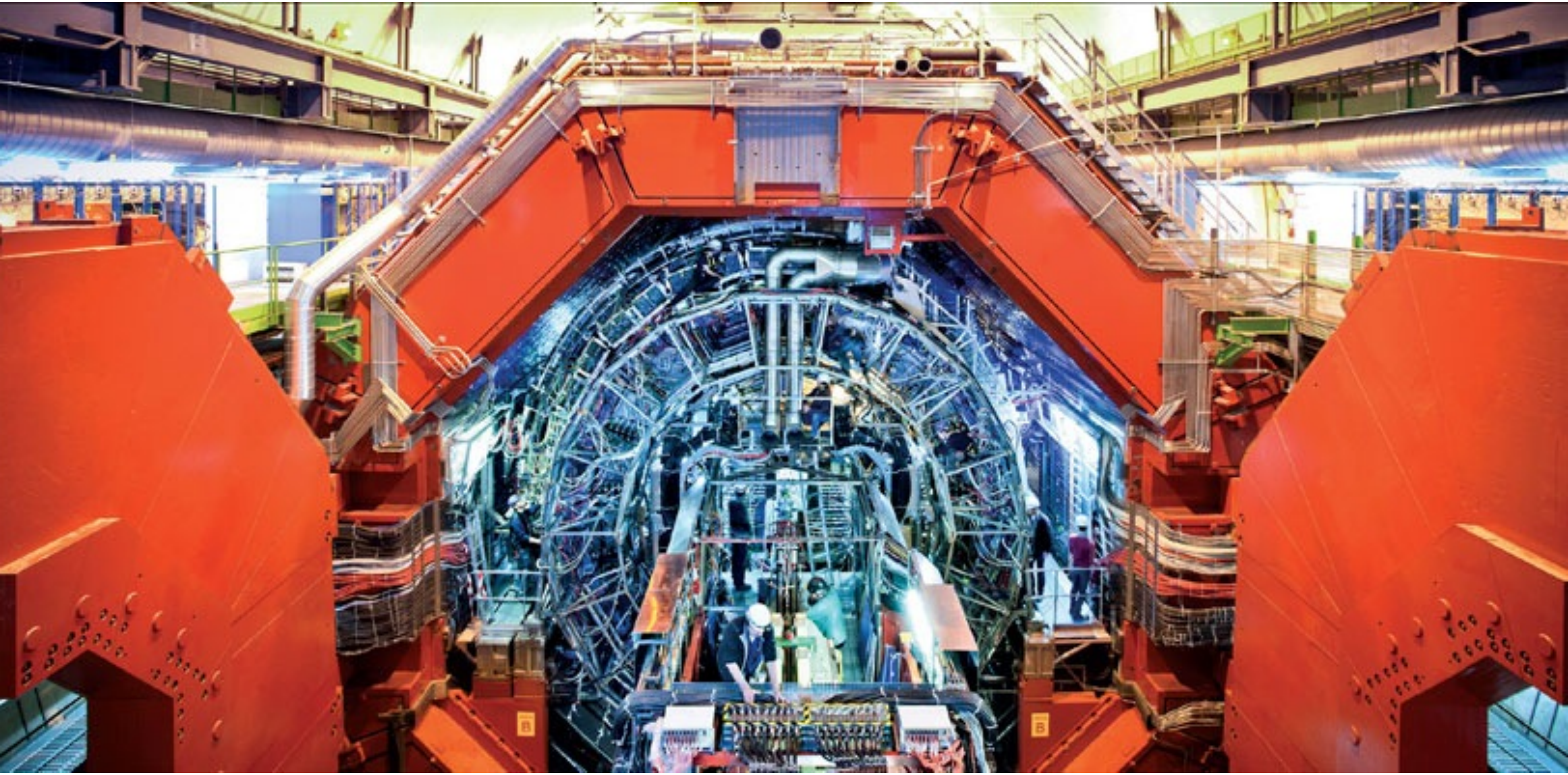
Other Examples of Detectors: The CMS Detector



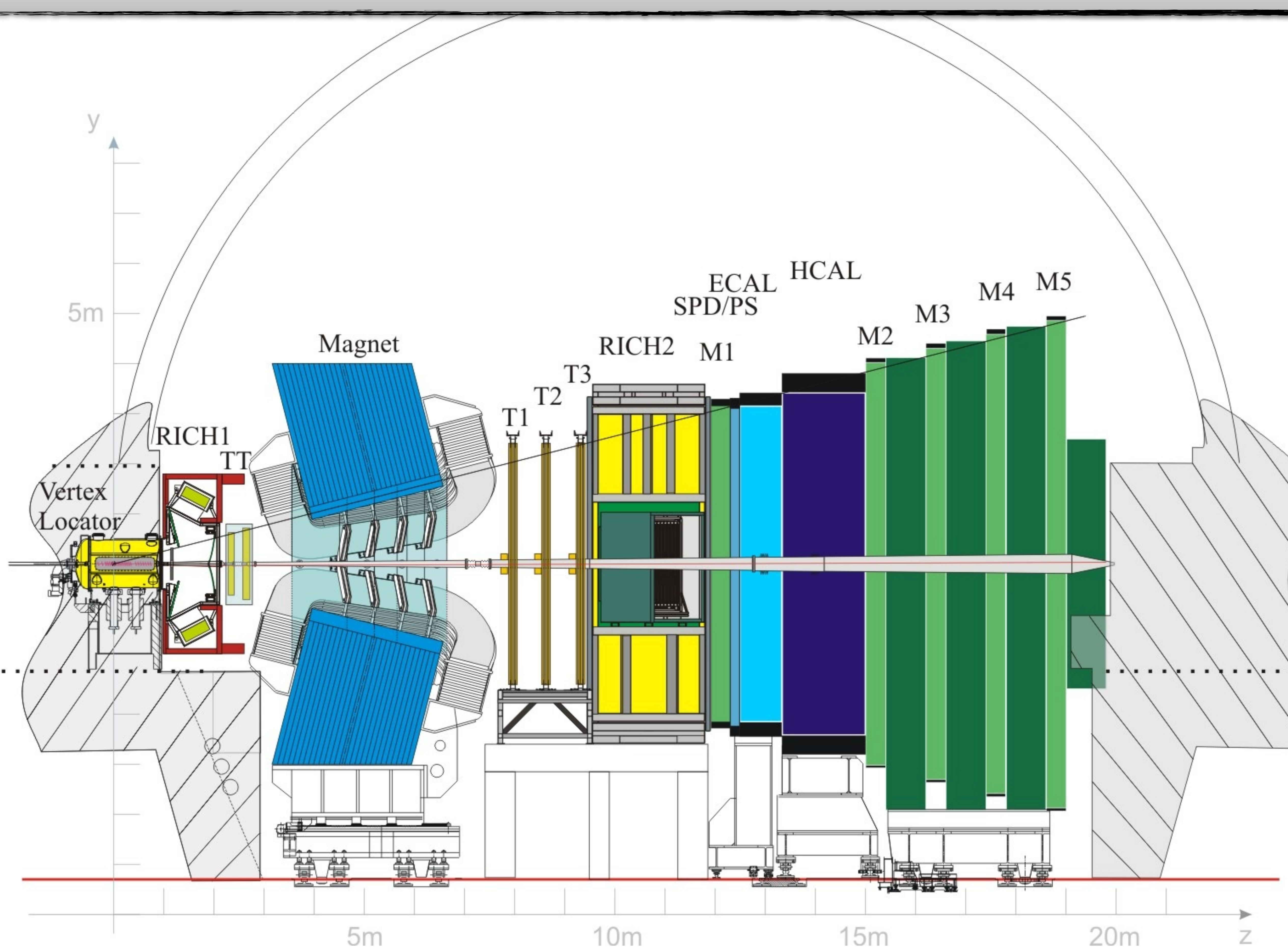
Other Examples of Detectors: The ALICE Detector



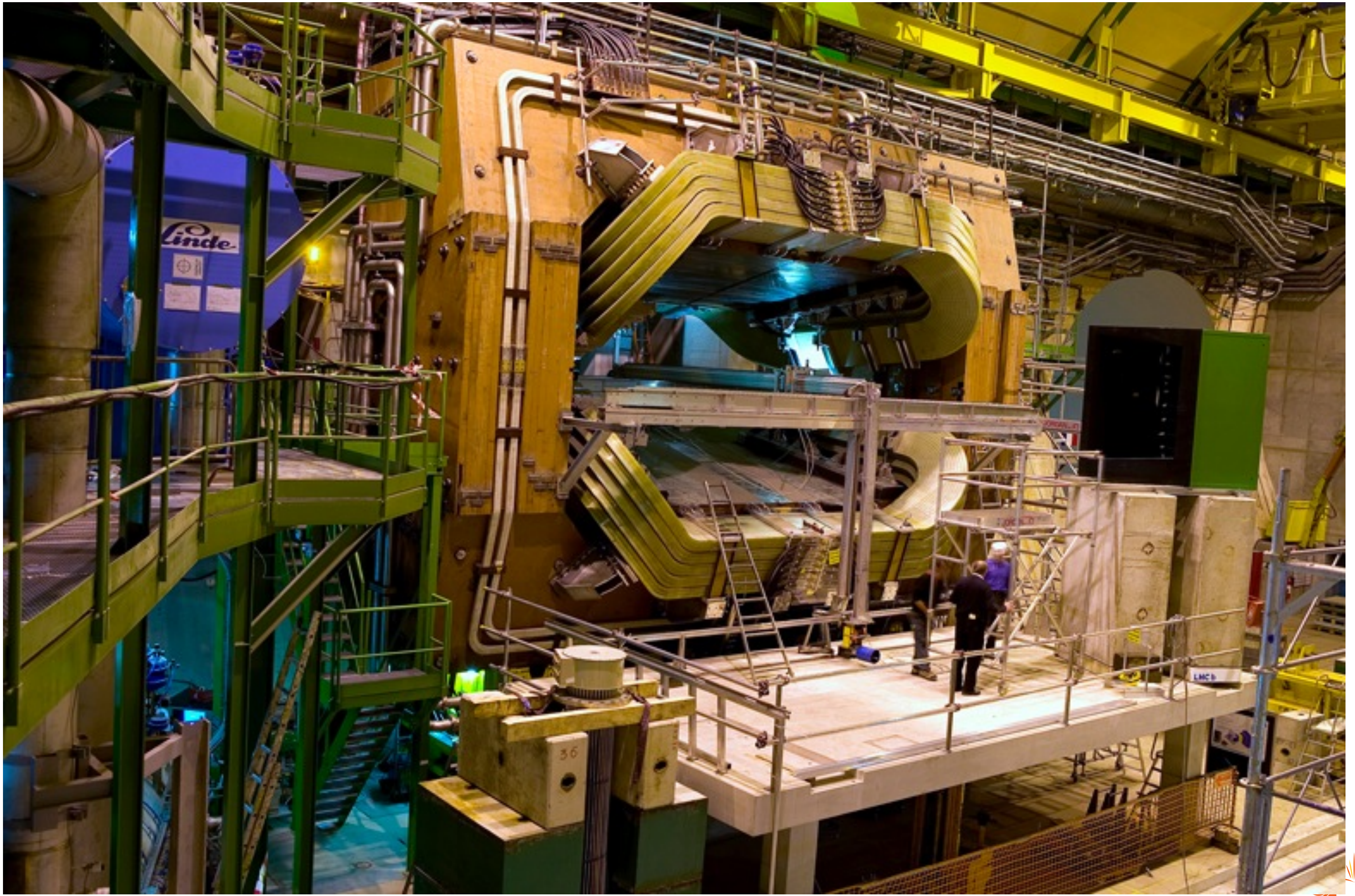
Other Examples of Detectors: The ALICE Detector



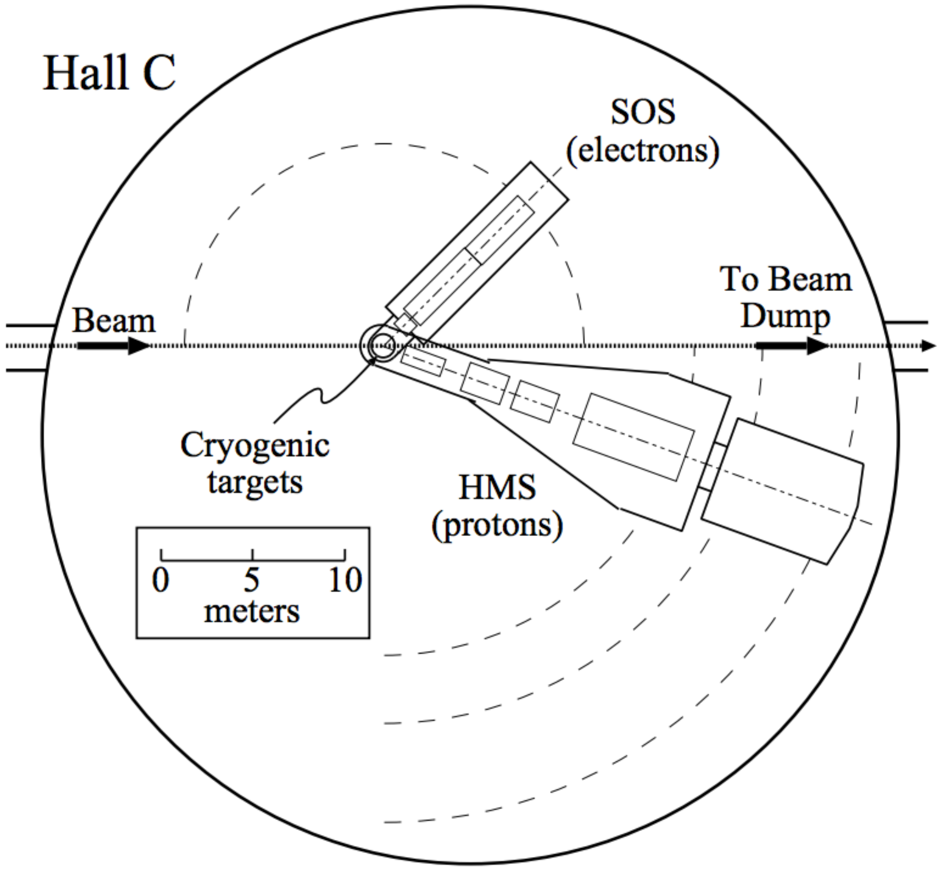
Other Examples of Detectors: The LCHb Detector

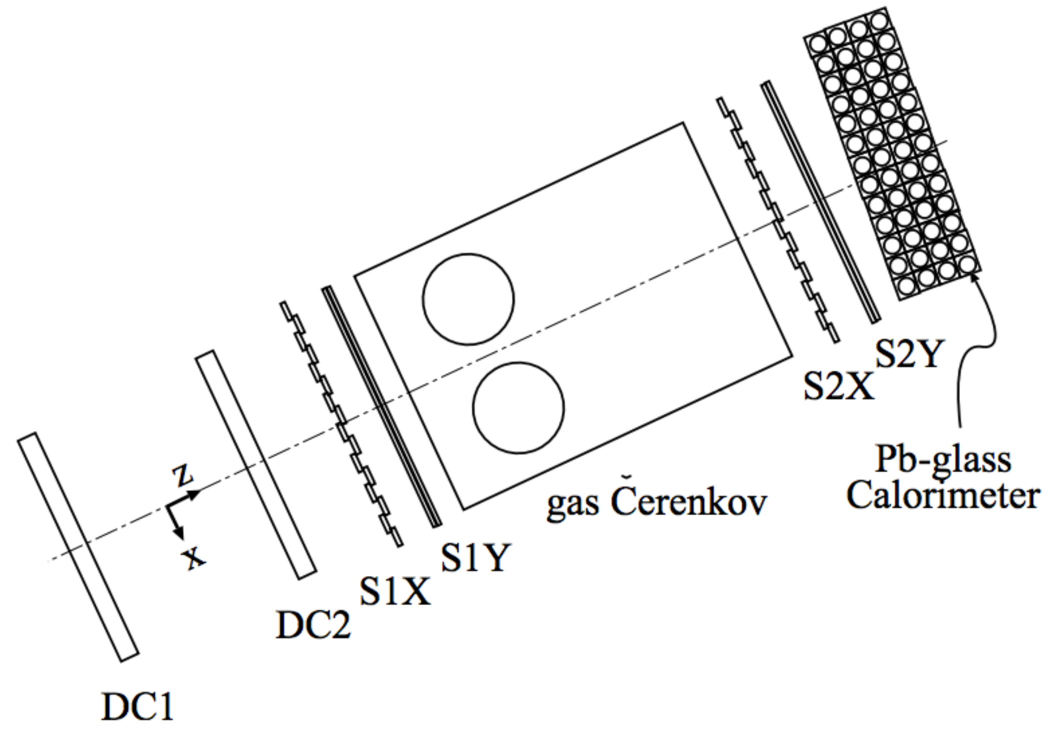


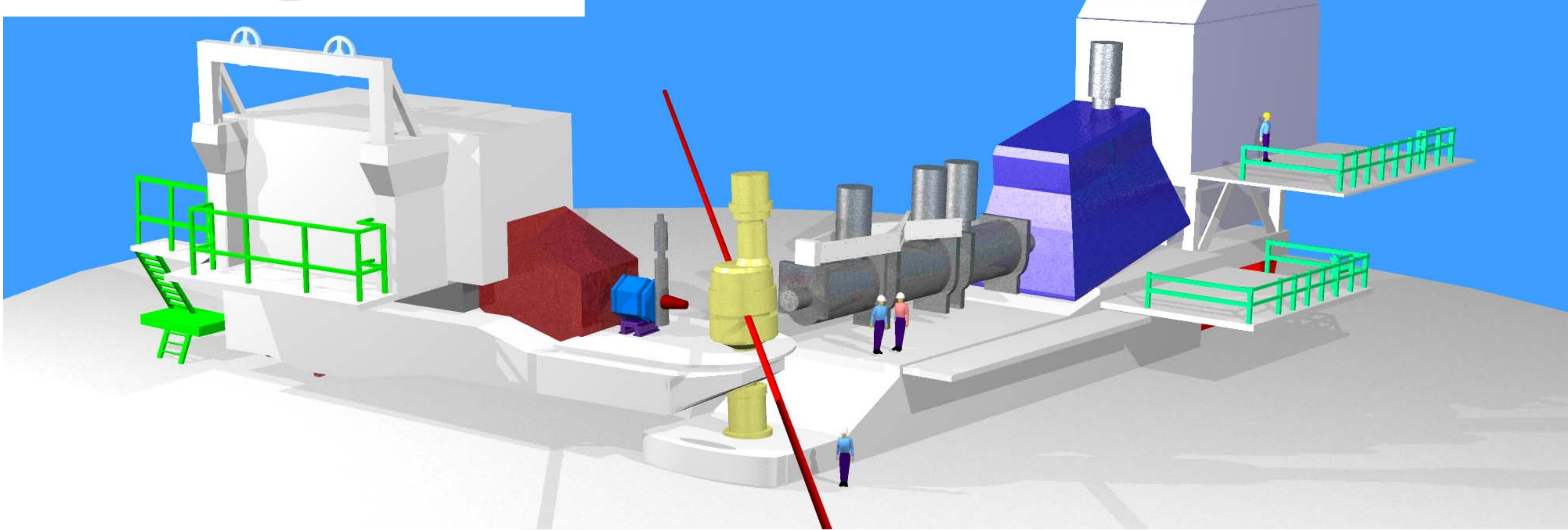
Other Examples of Detectors: The LCHb Detector



Other Examples of Detectors: Hall C Spectrometers at JLab







Other Examples of Detectors: HESS

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Thank you!

The End!

- Email: claire.lee@cern.ch

- The ALICE Experiment: http://aliceinfo.cern.ch/
- The ATLAS Experiment: http://atlas.ch/
- The CMS Experiment: http://cms.web.cern.ch/
- The LHCb Experiment: https://lhcb-public.web.cern.ch/lhcb-public/

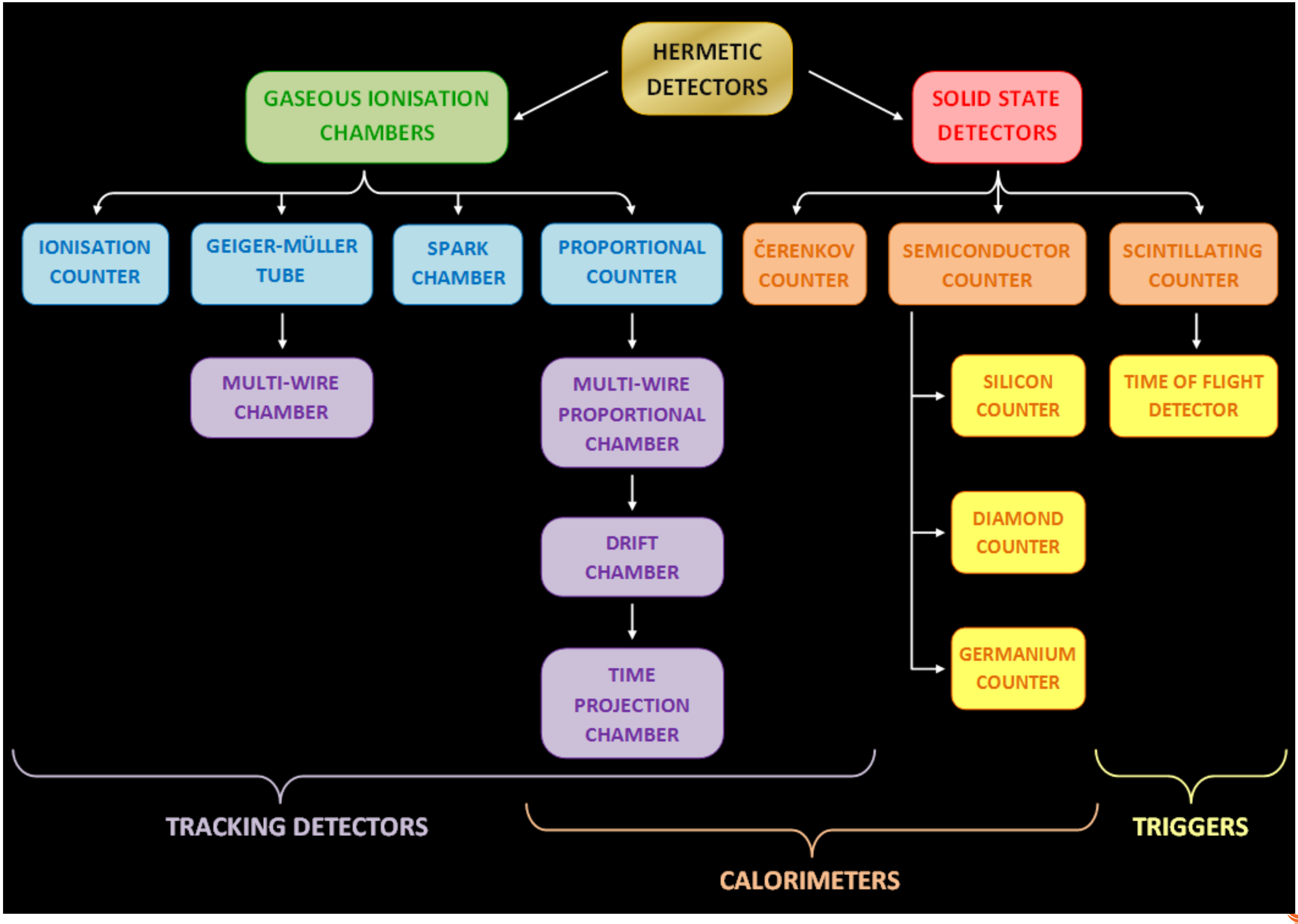
BACKUP

Useful Units

Quantity	HEP units	SI Units
length	1 fm	10^{-15} m
energy	1 GeV	$1.602 \cdot 10^{-10}$ J
mass	1 GeV/c^2	$1.78 \cdot 10^{-27}$ kg
$\hbar = h/2$	$6.588 \cdot 10^{-25}$ GeV s	$1.055 \cdot 10^{-34}$ Js
c	$2.988 \cdot 10^{23}$ fm/s	$2.988 \cdot 10^{8}$ m/s
$\hbar c$	0.1973 GeV fm	$3.162 \cdot 10^{-26}$ Jm

Natural units ($\hbar = c = 1$)	
mass	1 GeV
length	1 GeV^{-1} = 0.1973 fm
time	1 GeV^{-1} = $6.59 \cdot 10^{-25}$ s

Detector Types Summary



HERMETIC DETECTORS

GASEOUS IONISATION CHAMBERS

SOLID STATE DETECTORS

IONISATION COUNTER

GEIGER-MÜLLER TUBE

SPARK CHAMBER

PROPORTIONAL COUNTER

ČERENKOV COUNTER

SEMICONDUCTOR COUNTER

SCINTILLATING COUNTER

MULTI-WIRE CHAMBER

MULTI-WIRE PROPORTIONAL CHAMBER

DRIFT CHAMBER

TIME PROJECTION CHAMBER

SILICON COUNTER

DIAMOND COUNTER

GERMANIUM COUNTER

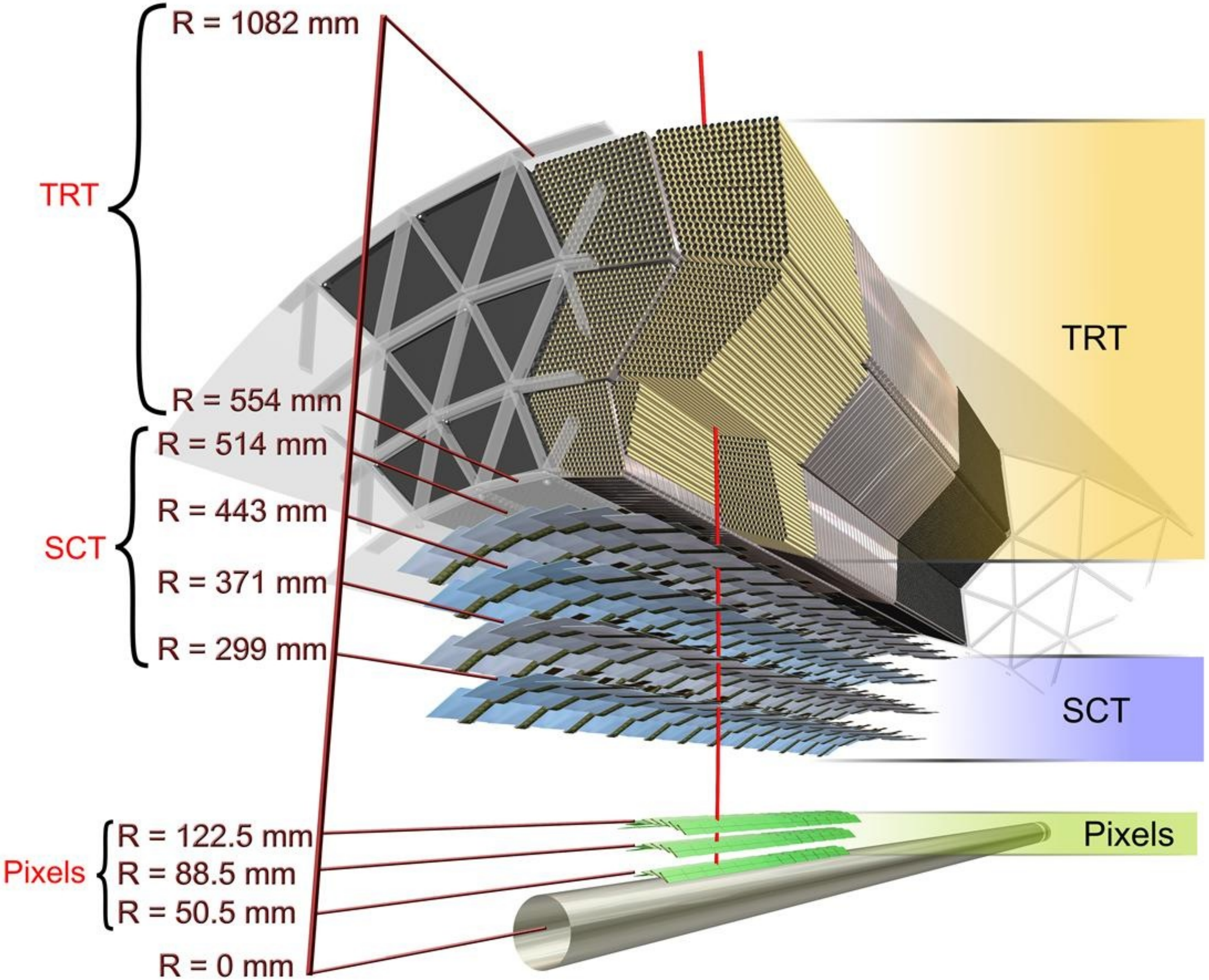
TIME OF FLIGHT DETECTOR

TRACKING DETECTORS

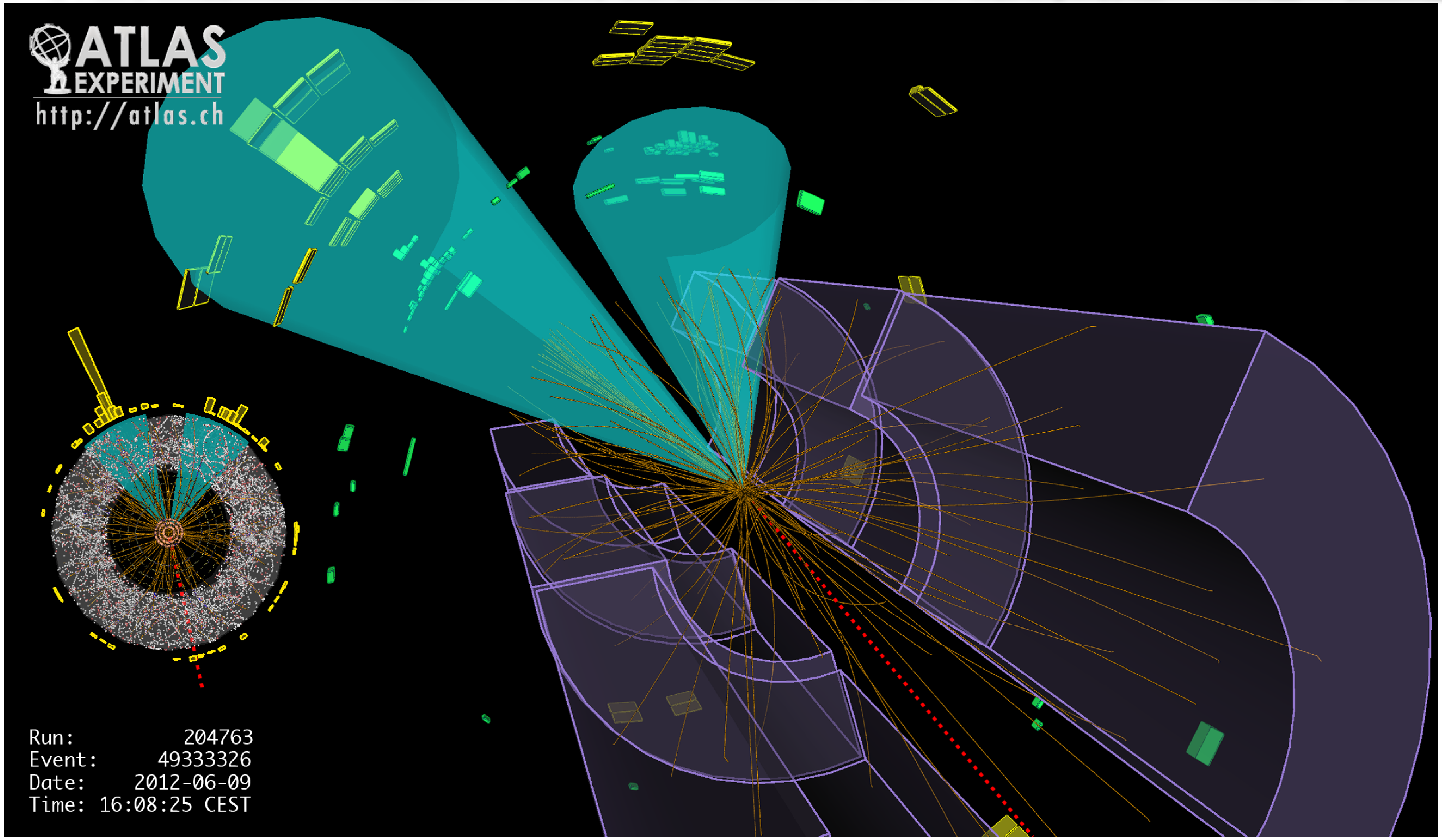
CALORIMETERS

TRIGGERS

ATLAS Inner Tracking Detector System



Measuring energy in ATLAS (ETmiss)



Advantage: provides a complete measurement of the magnitude of the missing energy from all events (vertices)

Disadvantage: sensitive to pileup

$$E_{x,y}^{\text{miss}} = E_{x,y}^{\text{miss},\ e} + E_{x,y}^{\text{miss},\ \gamma} + E_{x,y}^{\text{miss},\ \tau_{had}} + E_{x,y}^{\text{miss},\ jets} + E_{x,y}^{\text{miss},\ \mu} + E_{x,y}^{\text{miss},\ soft\ term}$$

$$\boxed{E_{\text{T}}^{\text{miss}} = \sqrt{(E_x^{\text{miss}})^2 + \left(E_y^{\text{miss}}\right)^2}}$$

$$\sum E_T = \sum E_{\text{T}}^{e} + \sum E_{\text{T}}^{\gamma} + \sum E_{\text{T}}^{\tau_{had}} + \sum E_{\text{T}}^{jets} + \sum p_{\text{T}}^{\mu} + \sum E_{\text{T}}^{soft\ term}$$