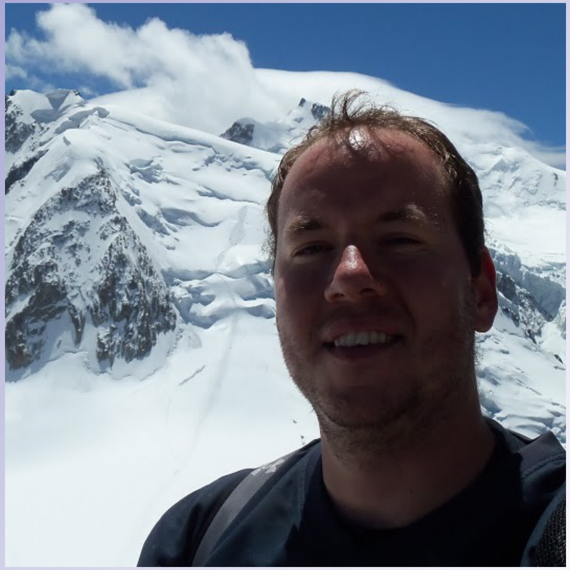
Quarknet:

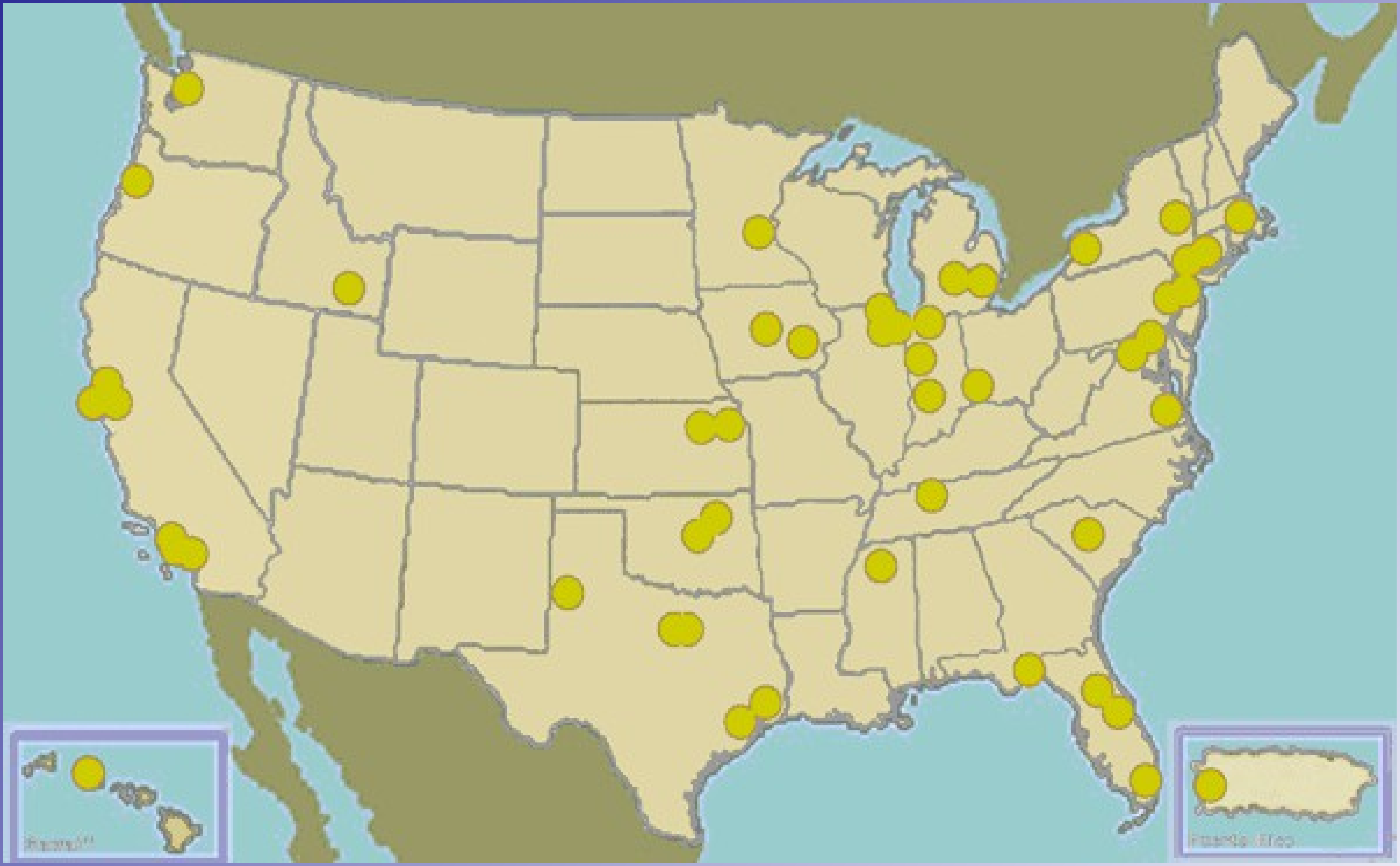
A Teacher's Perspective

Jeremy Smith

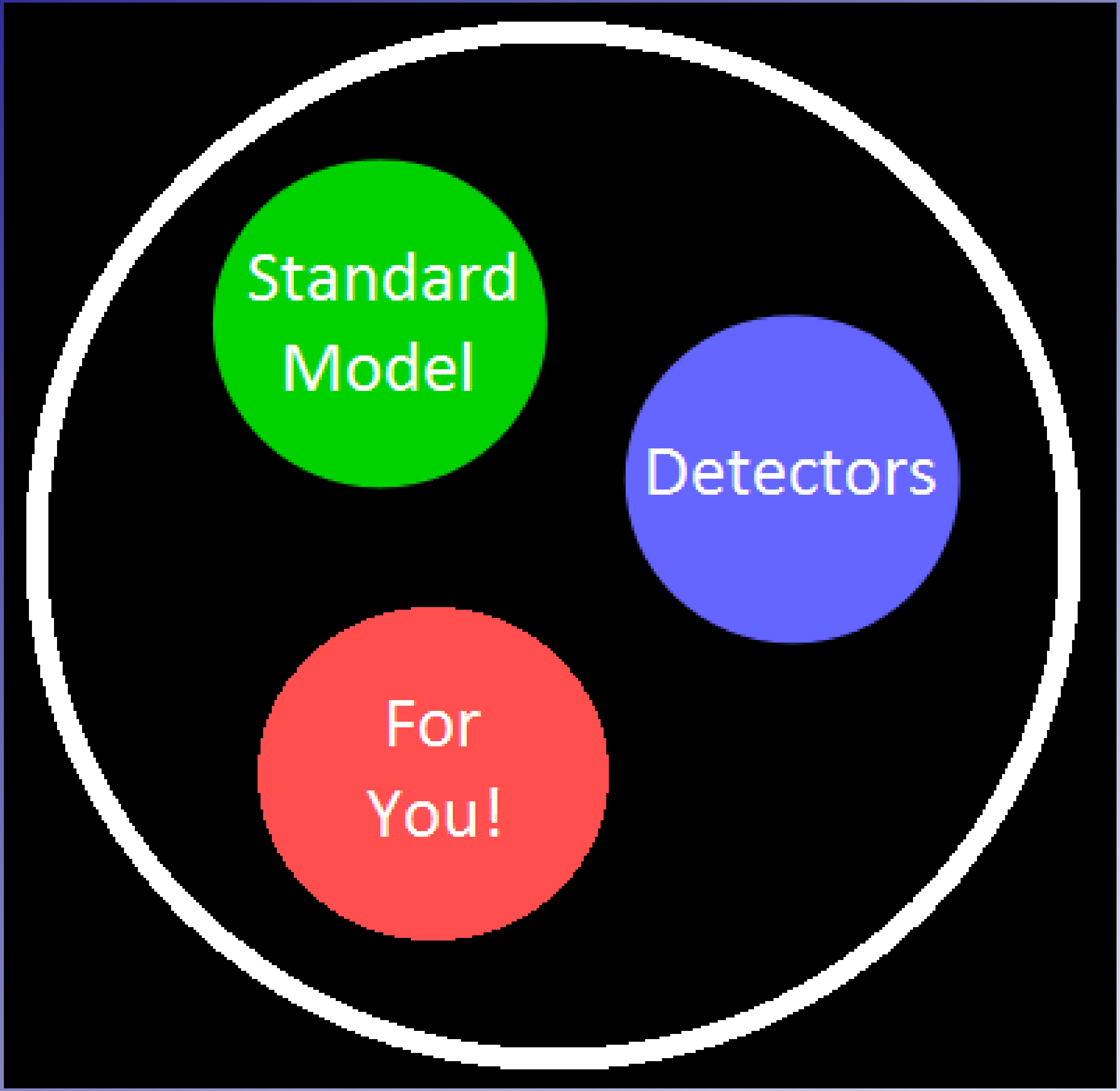
Hereford HS / Quarknet JHU



~50 Centers; ~600 Teachers



Topics



Standard Model

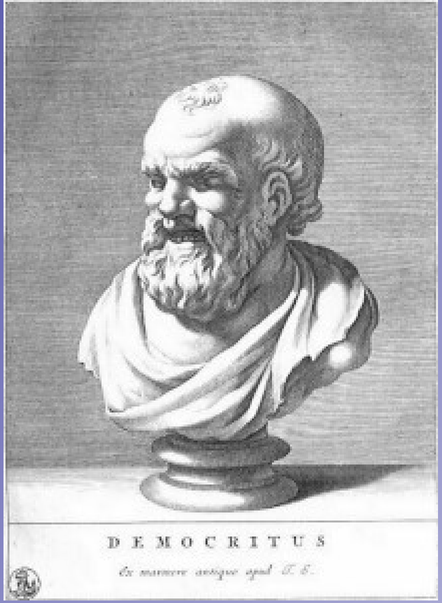
Detectors

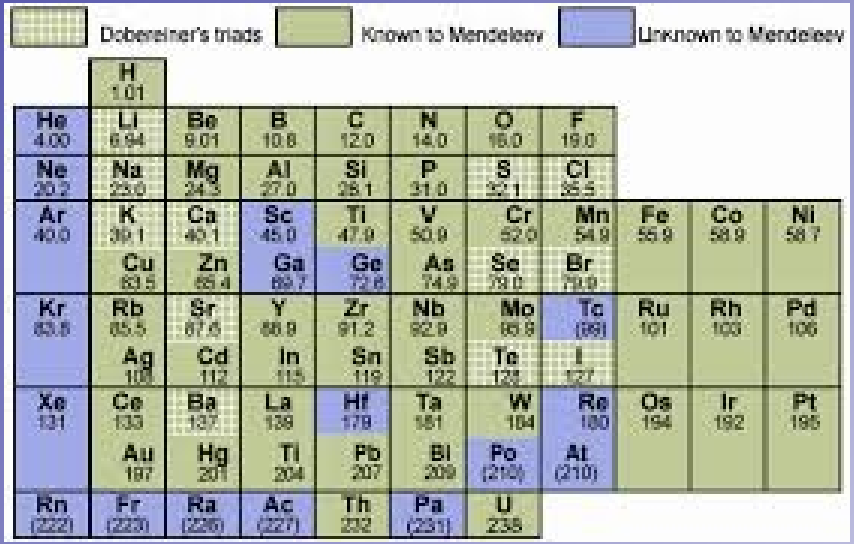
For You!

Models of Matter

- Paleozoic
- Thomson et al
- Quantum
- Fields
- Standard Model

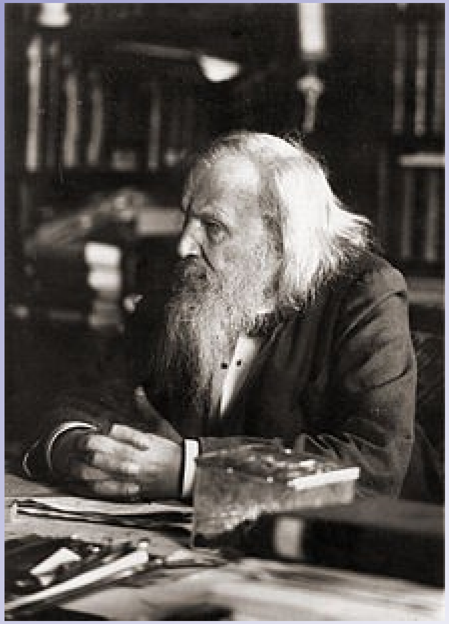
Prehistory





▨ Dobereiner's triads 🟩 Known to Mendeleev 🟦 Unknown to Mendeleev

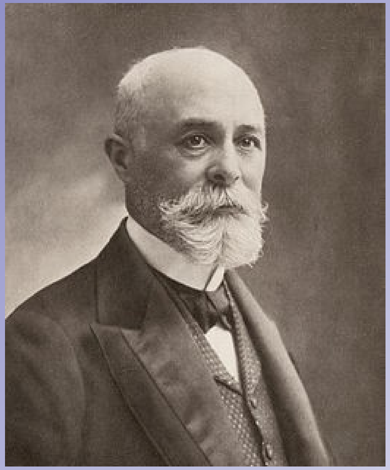
	H 1.01									
He 4.00	Li 6.94	Be 9.01	B 10.8	C 12.0	N 14.0	O 16.0	F 19.0			
Ne 20.2	Na 23.0	Mg 24.3	Al 27.0	Si 28.1	P 31.0	S 32.1	Cl 35.5			
Ar 40.0	K 39.1	Ca 40.1	Sc 45.0	Ti 47.9	V 50.9	Cr 52.0	Mn 54.9	Fe 55.9	Co 58.9	Ni 58.7
	Cu 63.5	Zn 65.4	Ga 69.7	Ge 72.6	As 74.9	Se 79.0	Br 79.9			
Kr 83.8	Rb 85.5	Sr 87.6	Y 88.9	Zr 91.2	Nb 92.9	Mo 95.9	Tc (98)	Ru 101	Rh 103	Pd 106
	Ag 108	Cd 112	In 115	Sn 119	Sb 122	Te 128	I 127			
Xe 131	Cs 133	Ba 137	La 139	Hf 179	Ta 181	W 184	Re 186	Os 194	Ir 192	Pt 195
	Au 197	Hg 201	Tl 204	Pb 207	Bi 209	Po (210)	At (210)			
Rn (222)	Fr (223)	Ra (226)	Ac (227)	Th 232	Pa (231)	U 238				



Royal Society / Continentals

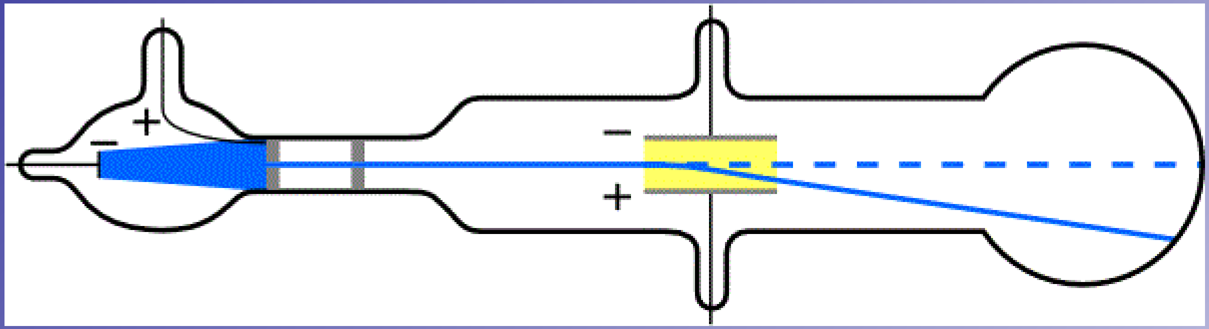
Roentgen, Becquerel, Curies, et al

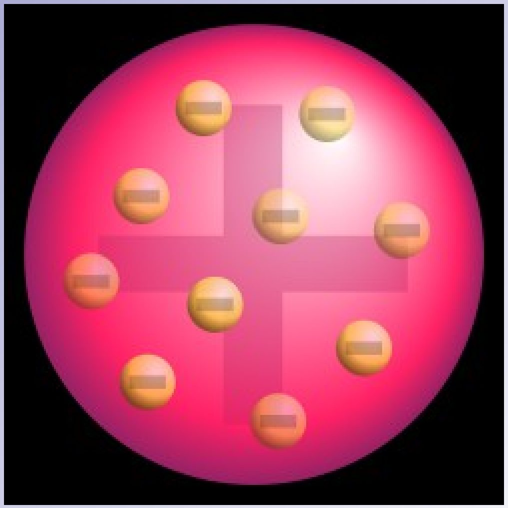
- Particles & Rays!



JJ Thomson

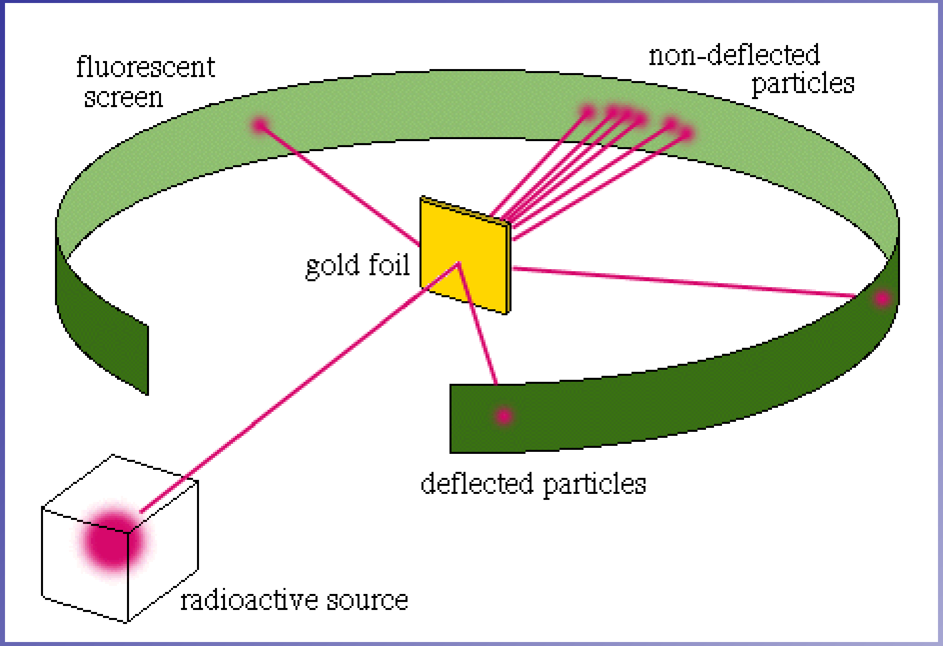
- Atoms have structure!
- Cathode rays are particles!





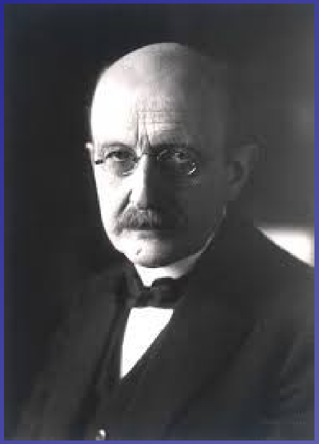
Rutherford (Geiger/Marsden)

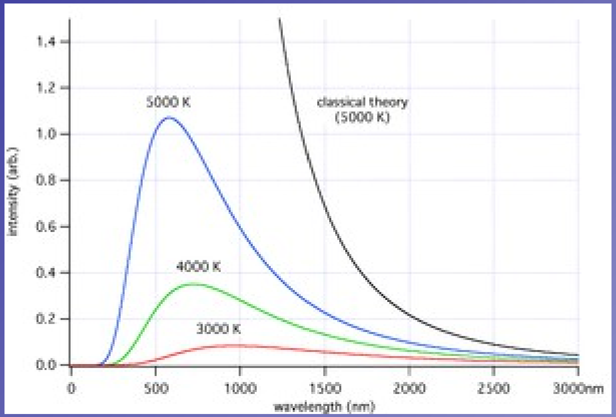
- Nucleus!
- Early “Collider” Experiment

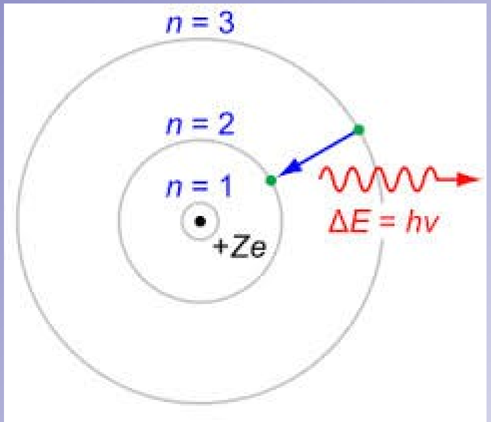


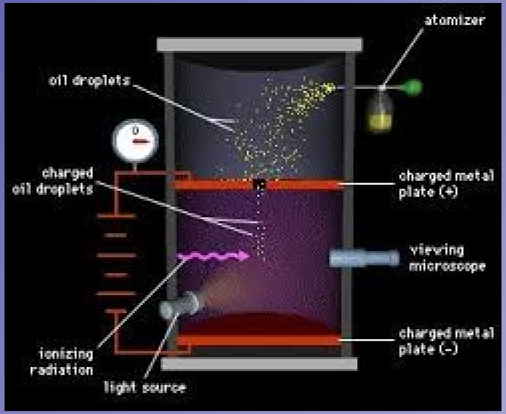
Planck, Millikan, Bohr, Einstein...

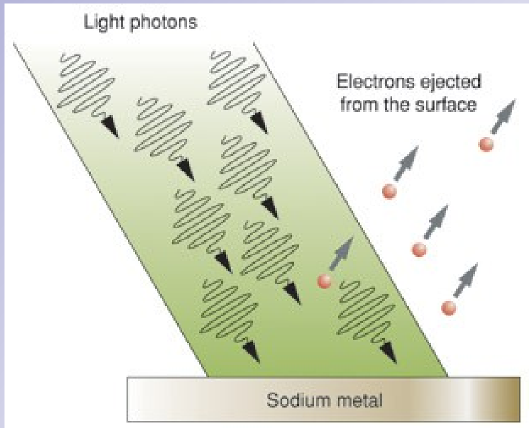
- Continuum → Quantum





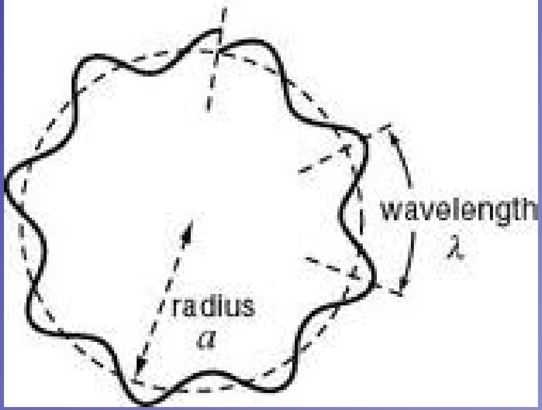




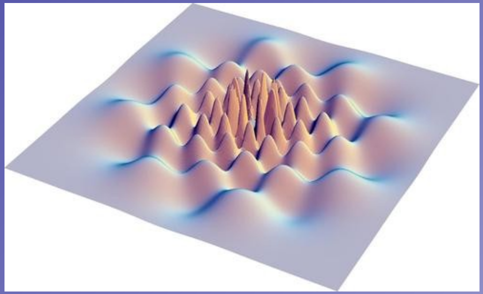


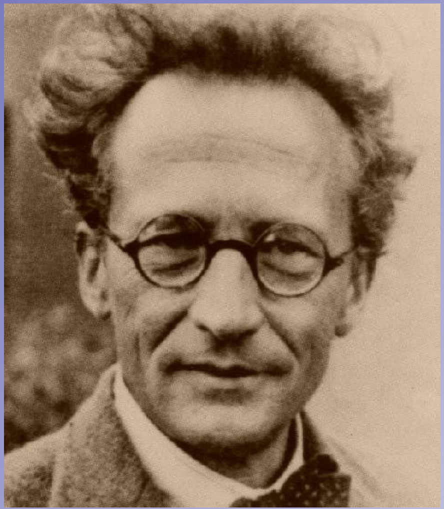
DeBroglie, Schrodinger, Born

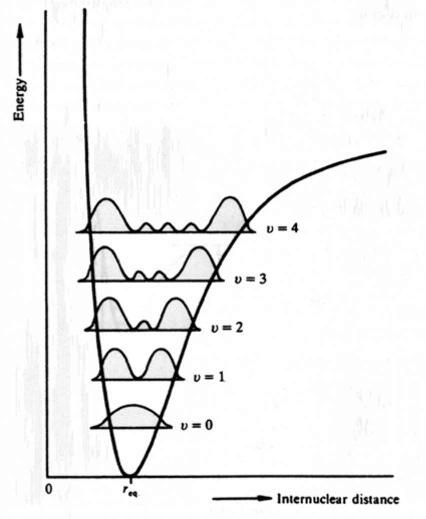
- Wave Theories



$$H(t)\,|\,\psi(t)\rangle = i\hbar\frac{d}{dt}\,|\,\psi(t)\rangle$$







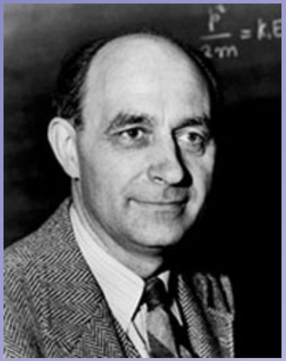
Heisenberg, Born, Jordan

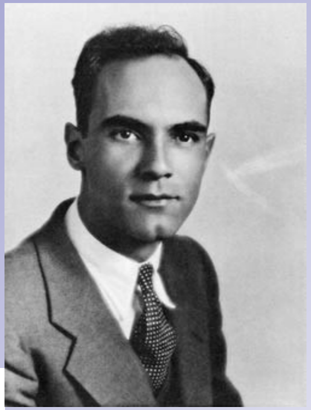
- Quantum (Matrix) Mechanics
- Uncertainty!

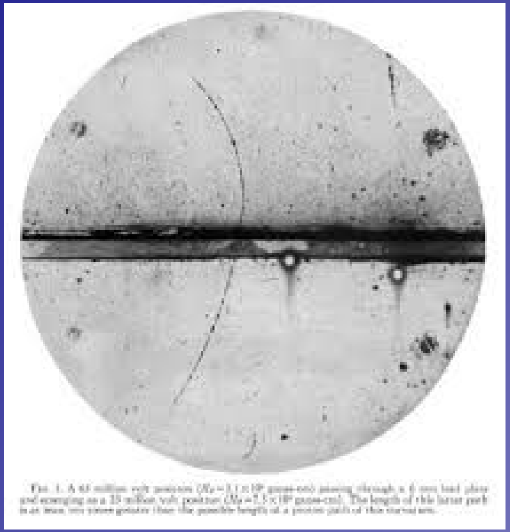
$$S_z \doteq \frac{\hbar}{2}\left(\begin{array}{cccc} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & -1 & 0 \\ 0 & 0 & 0 & -1 \end{array}\right)\begin{array}{c} ++ \\ +- \\ -+ \\ -- \end{array}$$

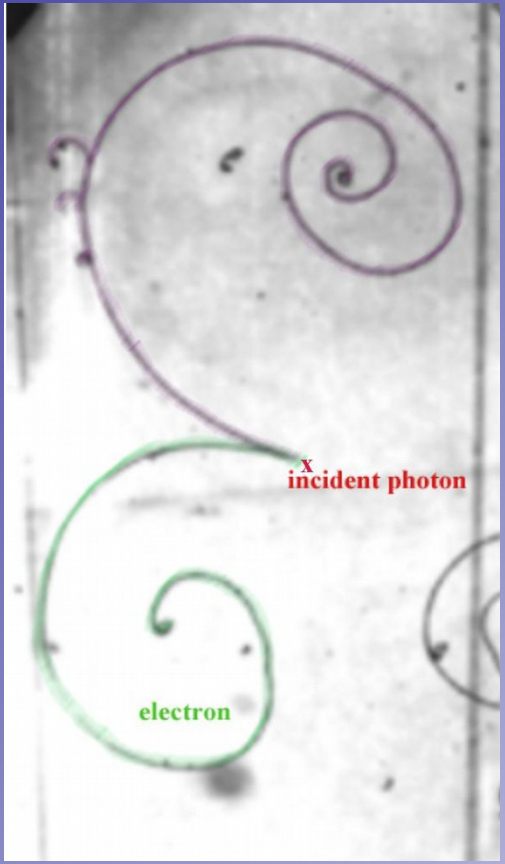
Pauli, Dirac, Fermi, Anderson...

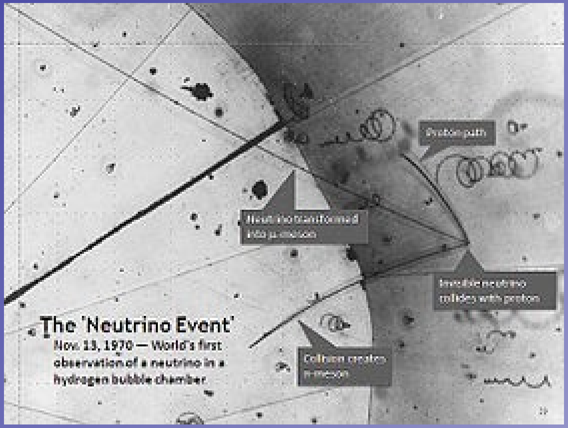
- New particles!

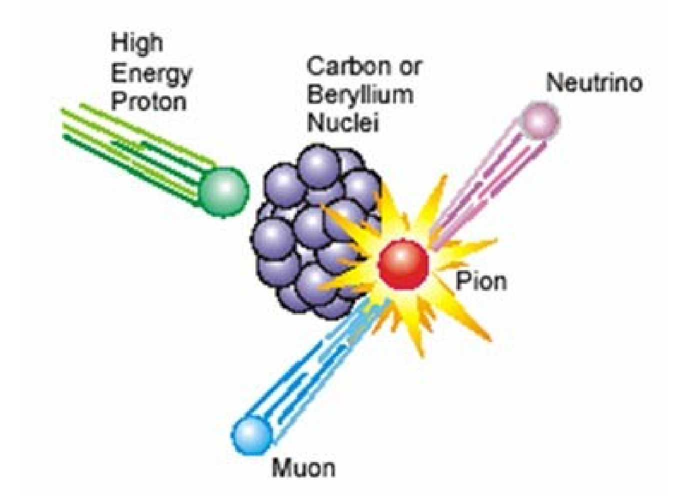










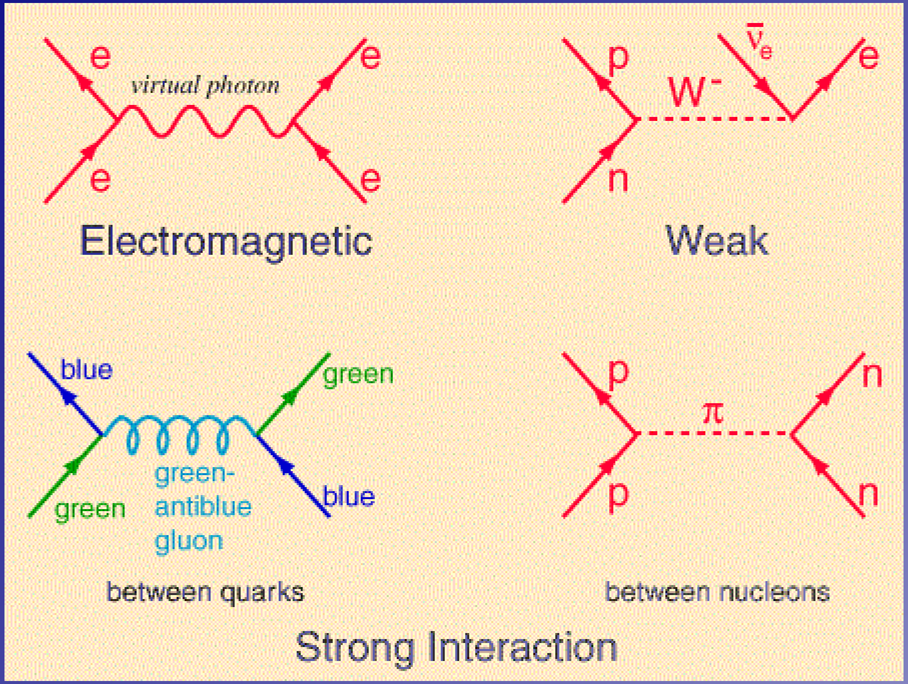


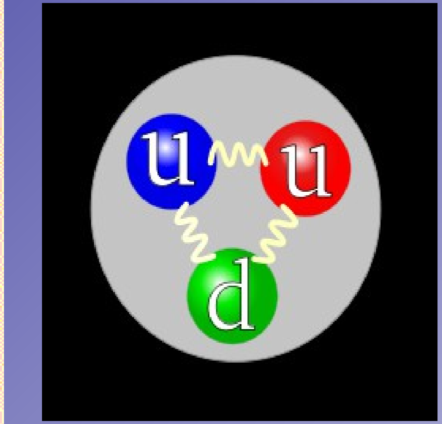
Difficult Questions

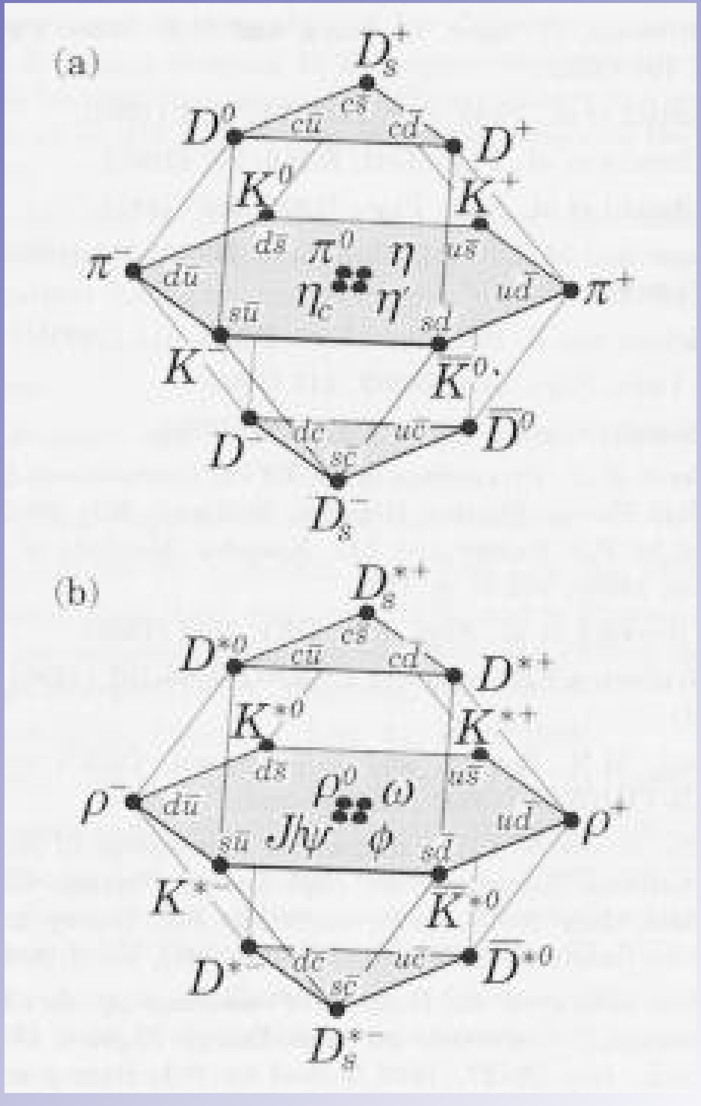
- Nucleus cohesion?
- Interactions?
- Patterns?
- Rules?
- Zoo?
- Infinities?

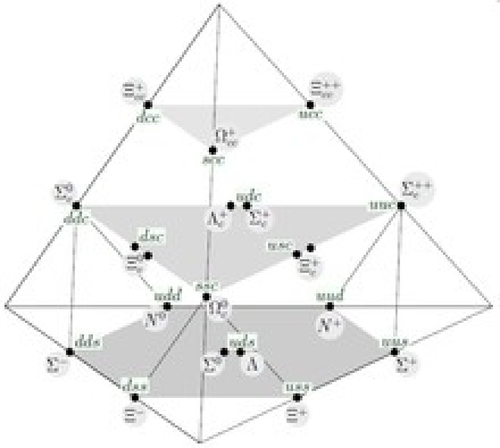
Zoo of Particles; People

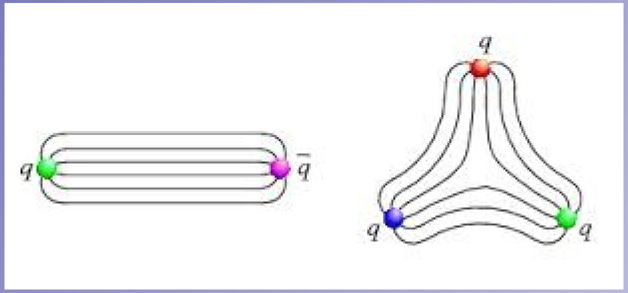
QED, QFT, QCD, QLG...



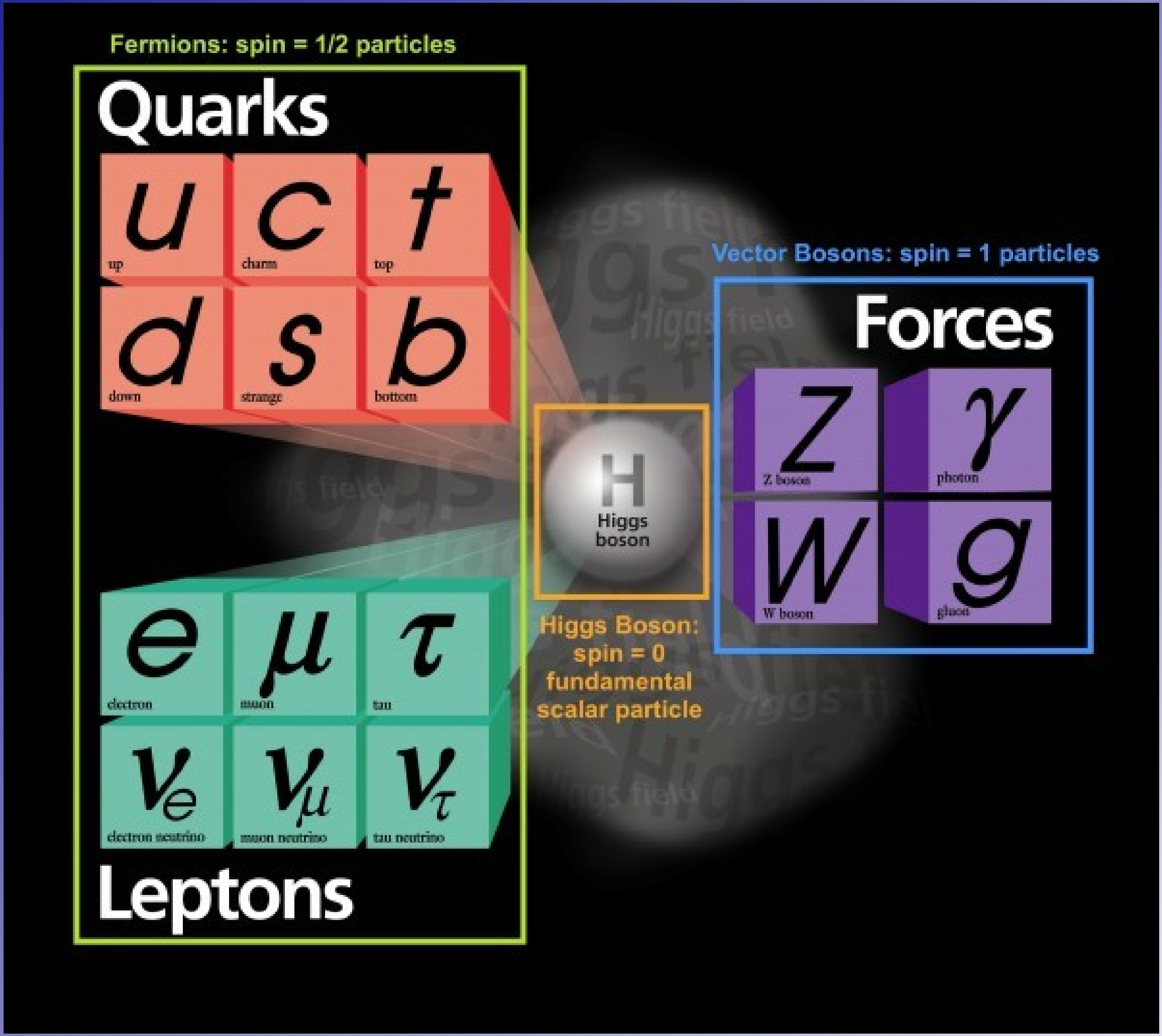


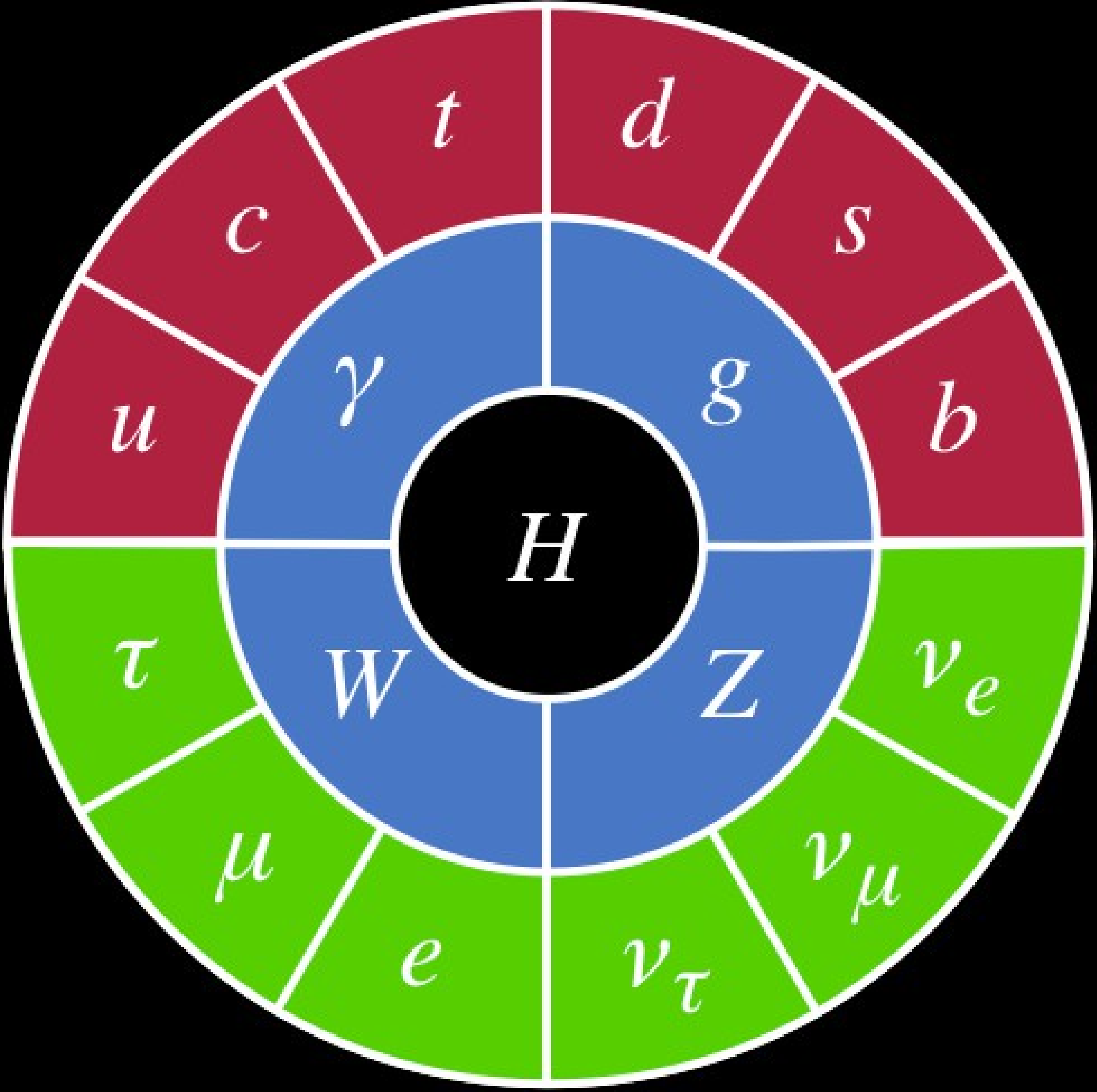






Ahhh....


Fermions: spin = 1/2 particles
Quarks
u
up
c
charm
t
top
d
down
s
strange
b
bottom
e
electron
μ
muon
τ
tau
ν_e
electron neutrino
ν_μ
muon neutrino
ν_τ
tau neutrino
Leptons
H
Higgs boson
Higgs Boson: spin = 0 fundamental scalar particle
Vector Bosons: spin = 1 particles
Forces
Z
Z boson
γ
photon
W
W boson
g
gluon
Higgs field

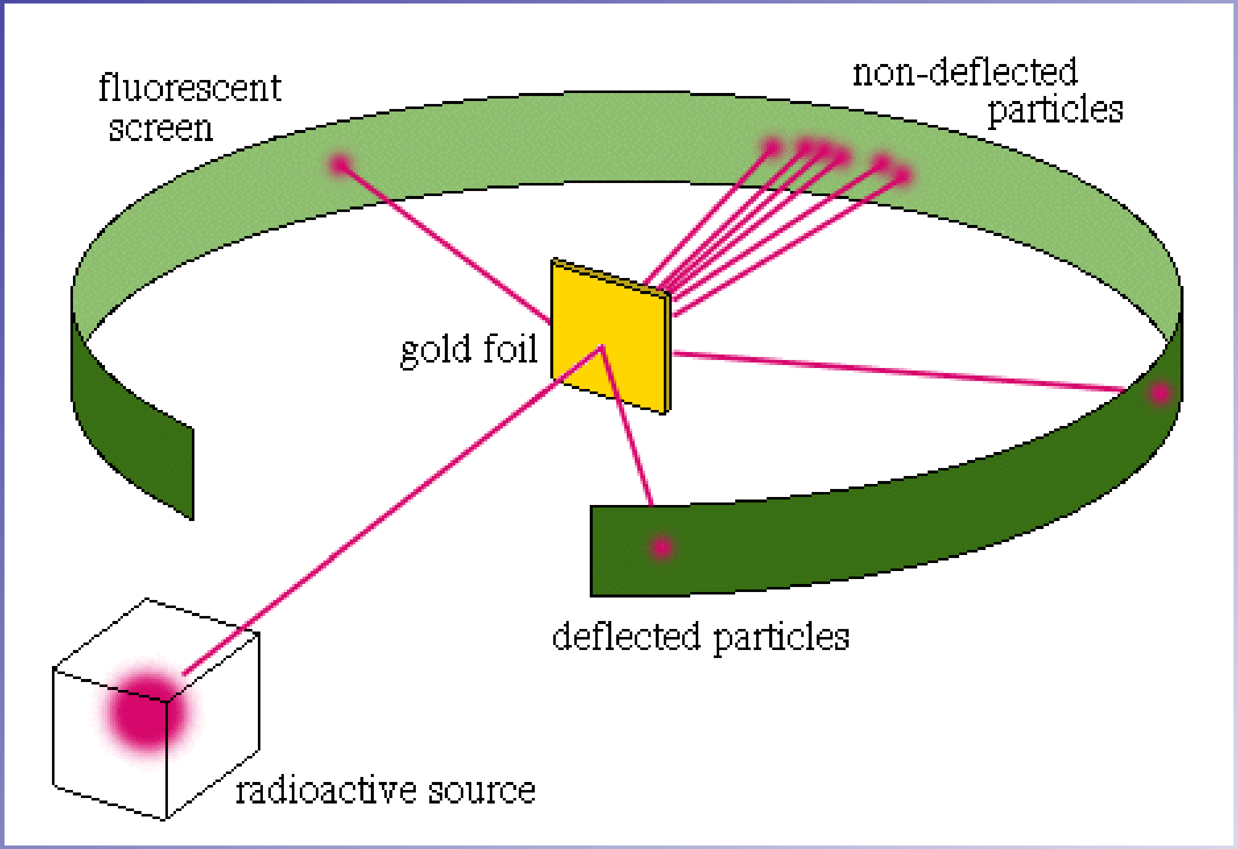


t
d
c
s
u
γ
g
b
H
τ
W
Z
ν_e
μ
ν_μ
e
ν_τ

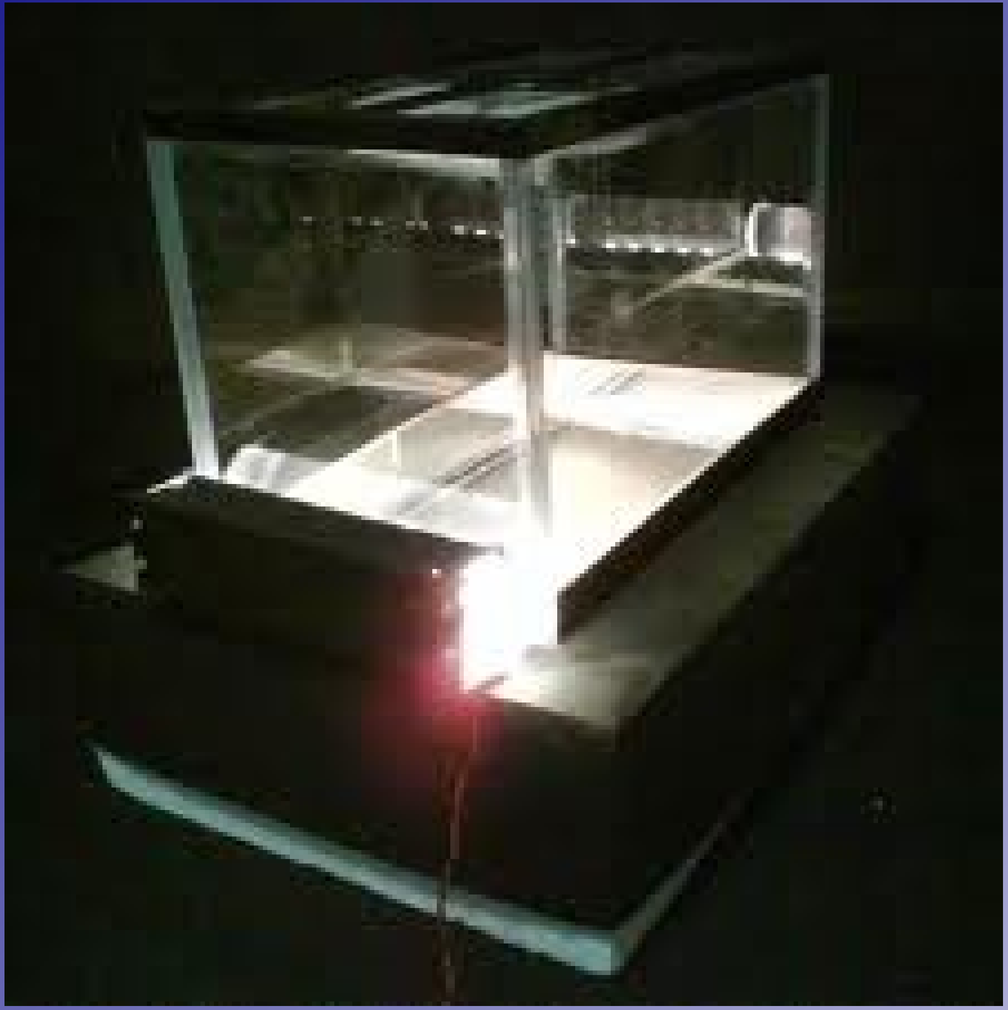
Detectors

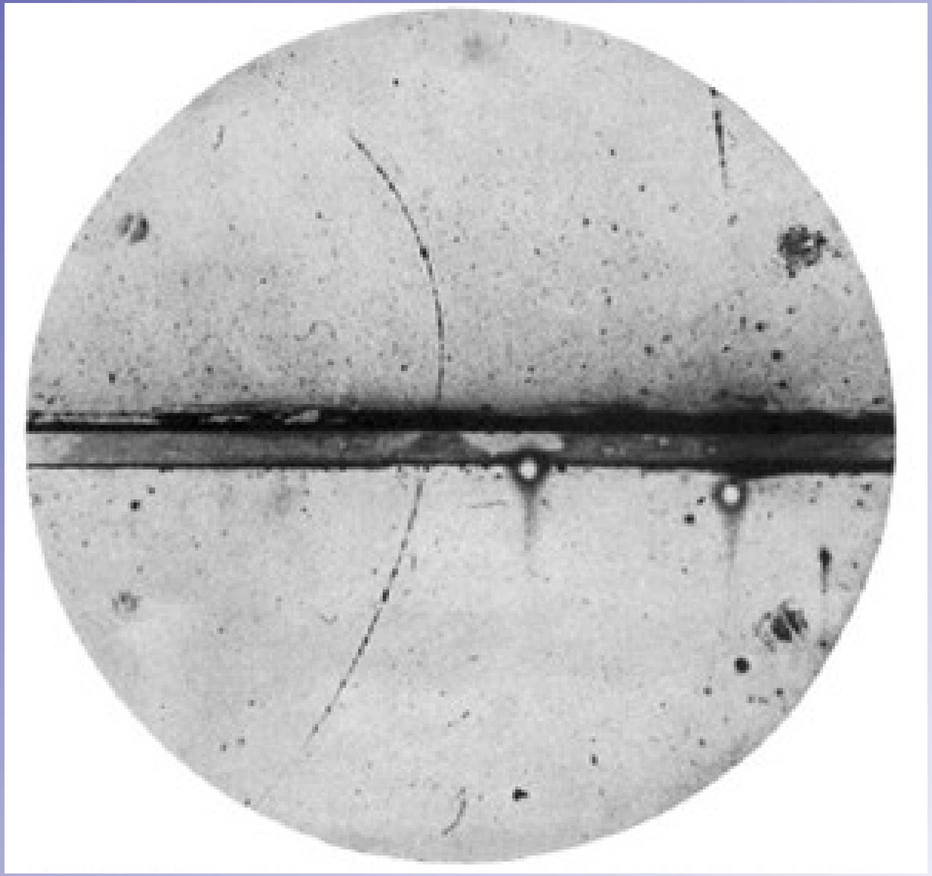
Recall Rutherford

Components: Beam, Target, Detector

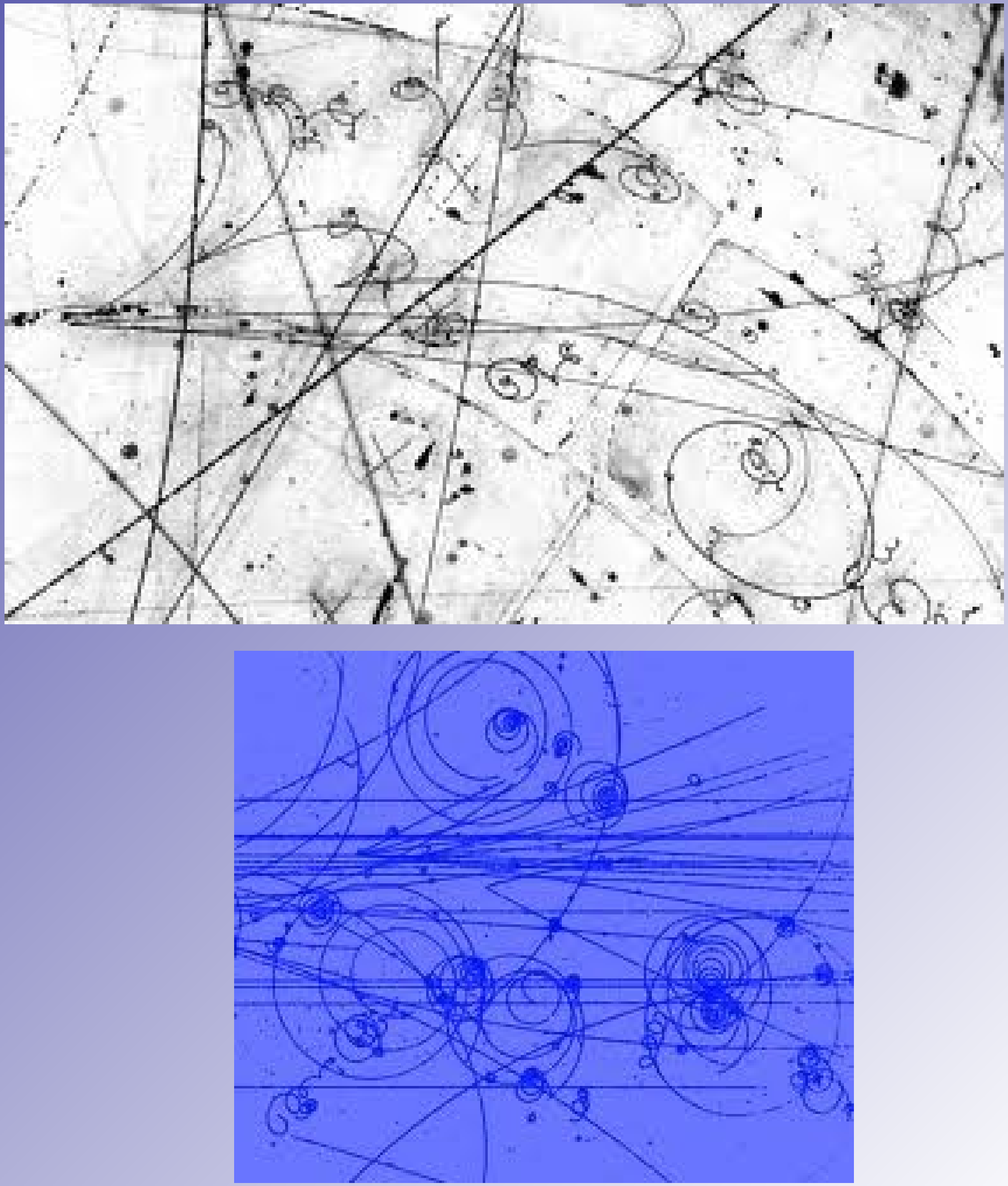


Cloud Chamber

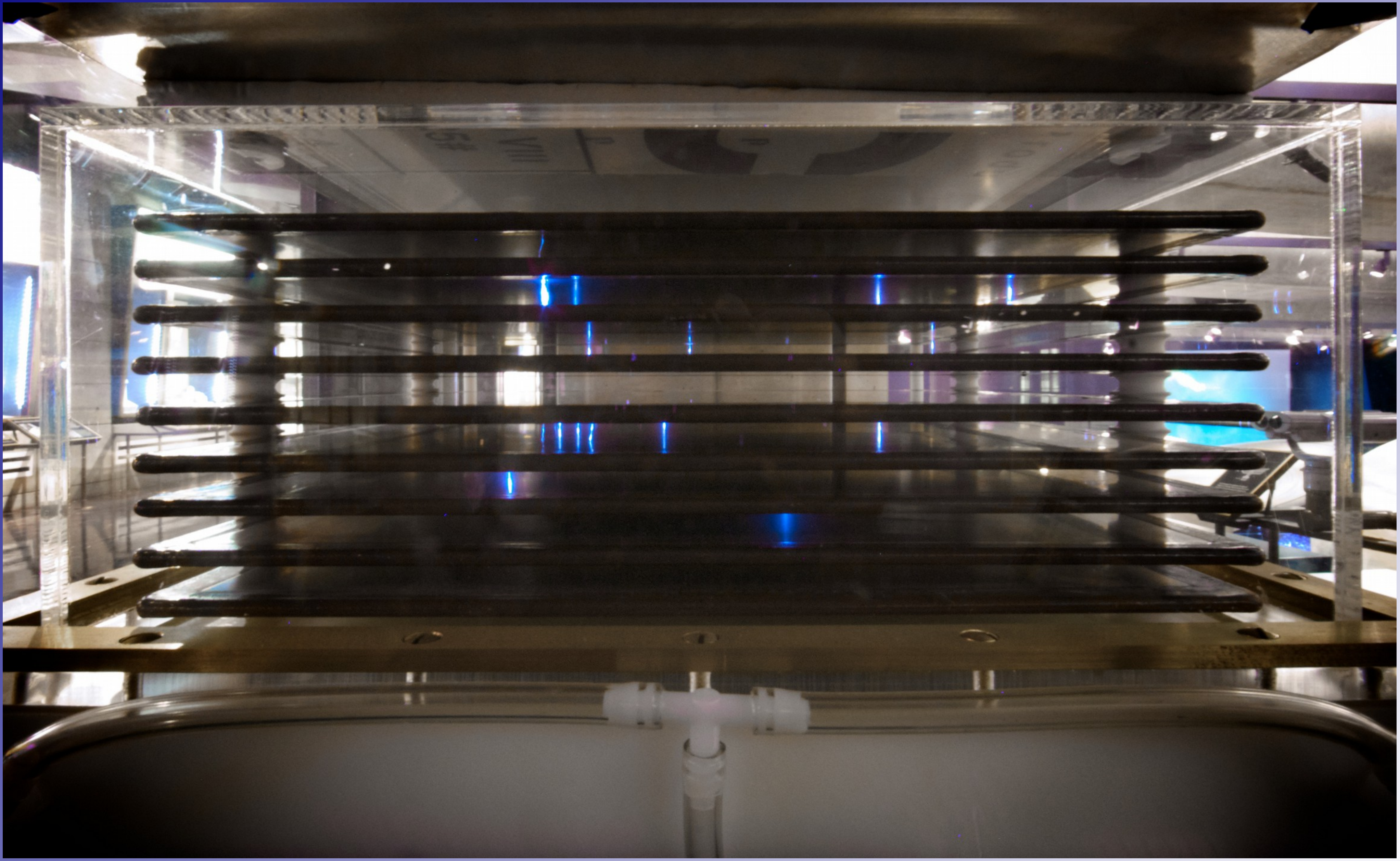




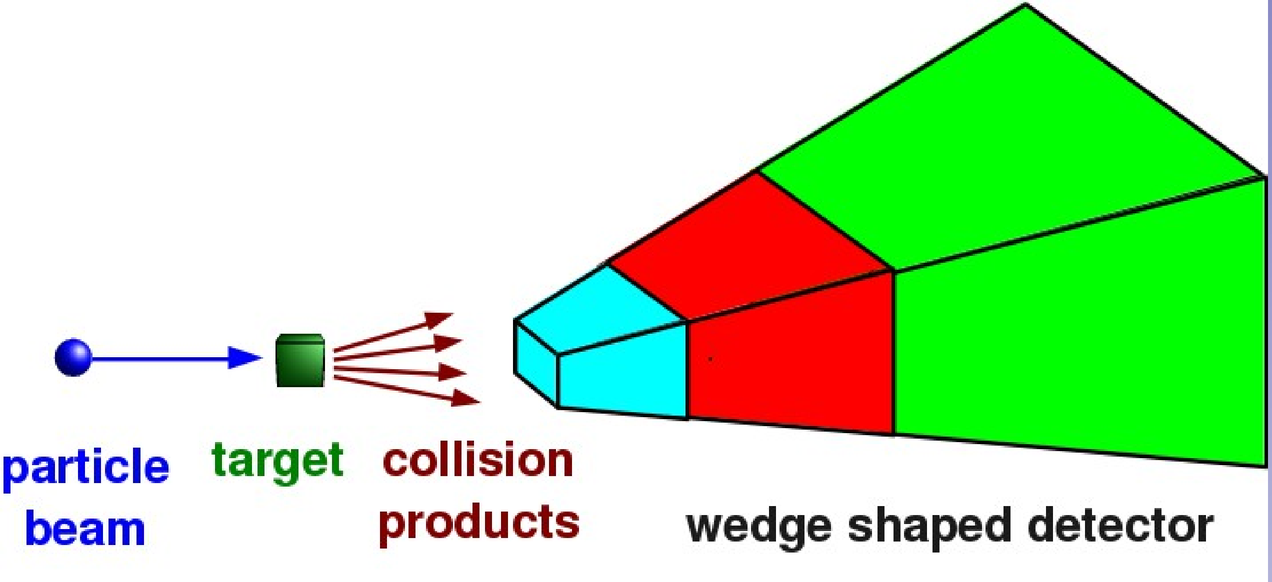
Bubble Chamber

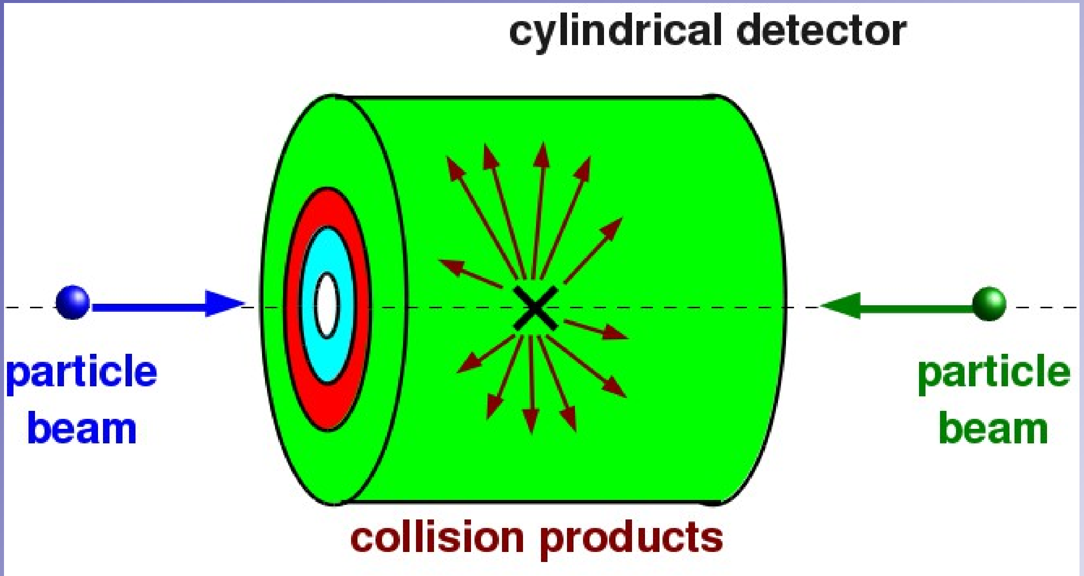


Spark Chamber

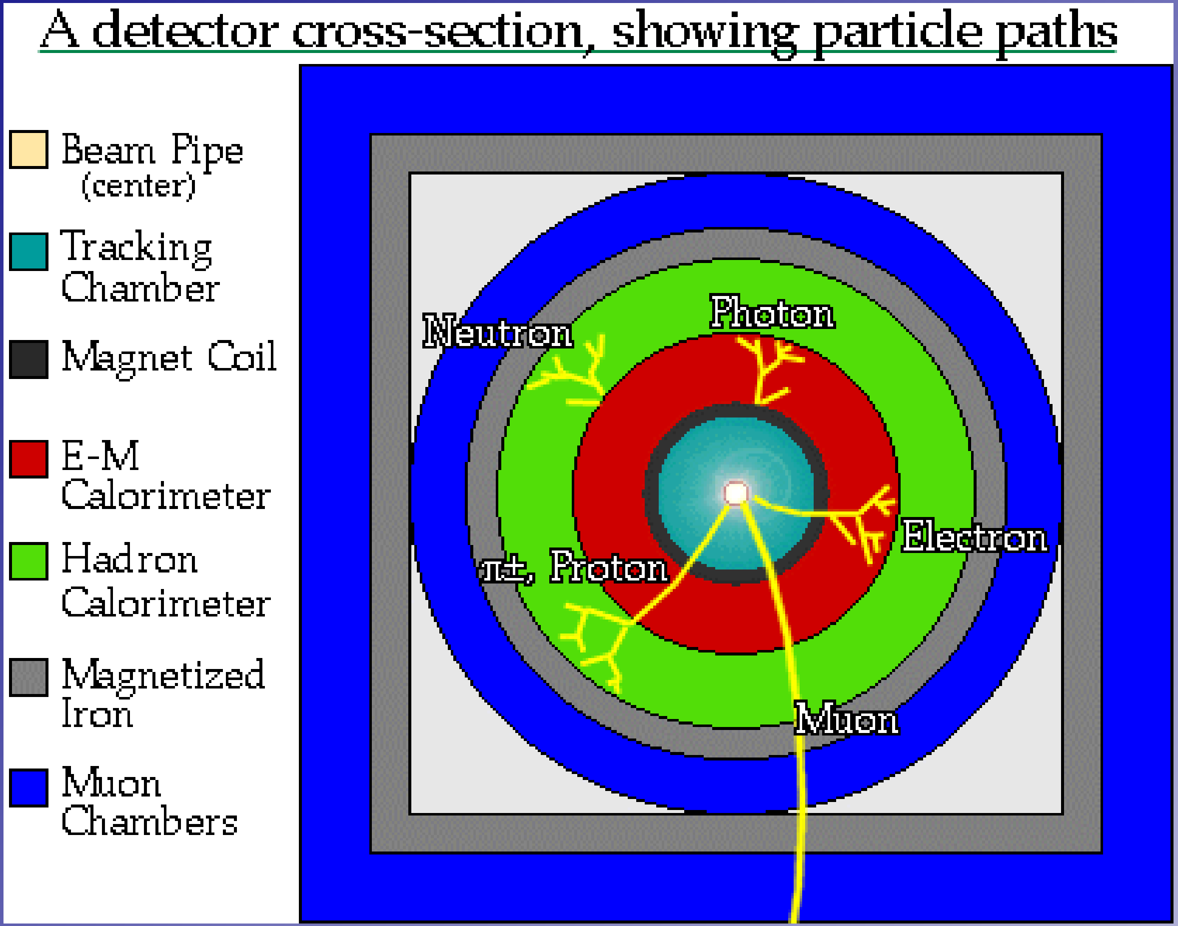


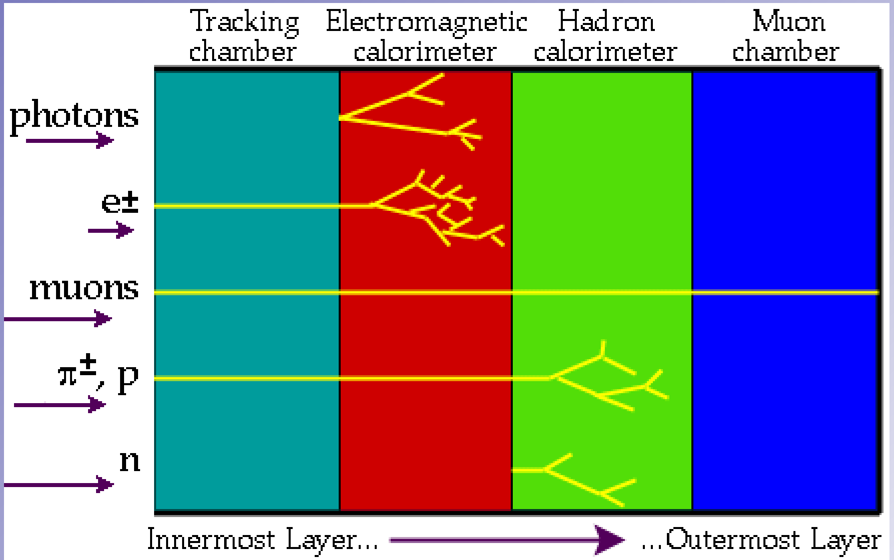
Experiment Types



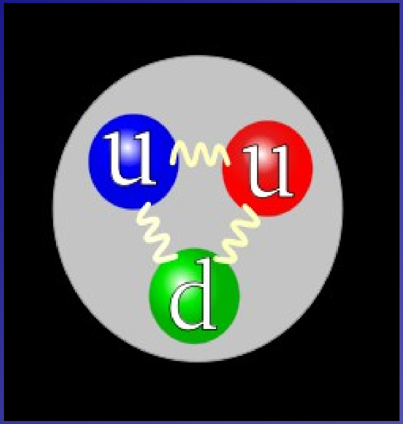


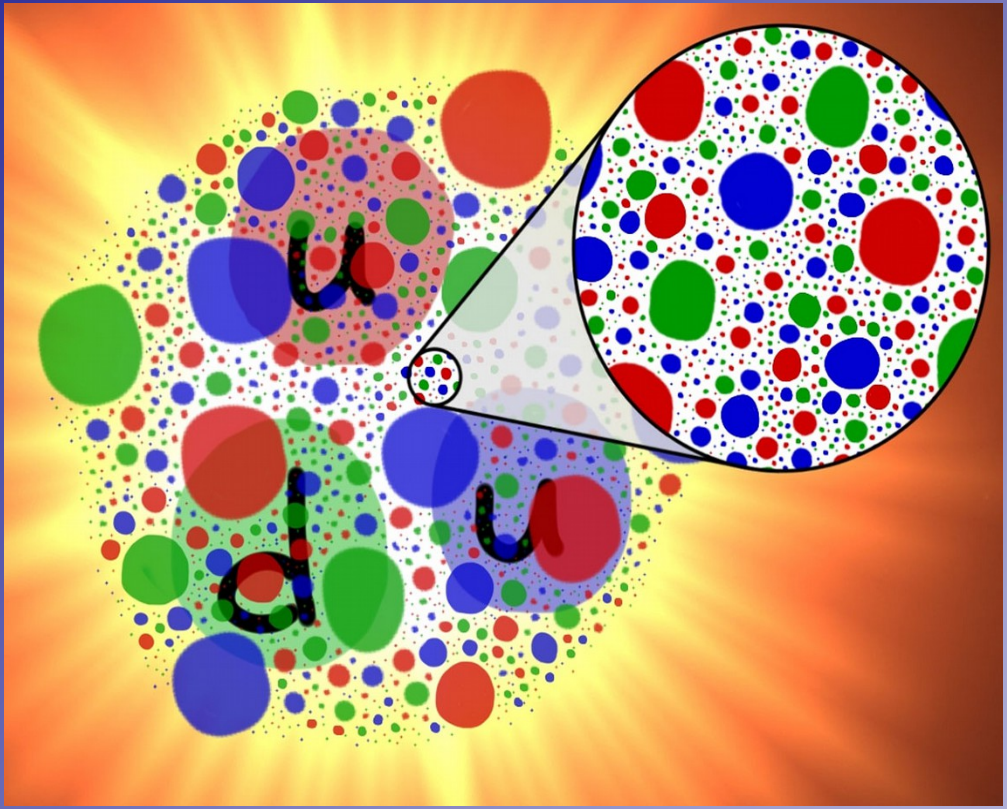
Detector Pieces

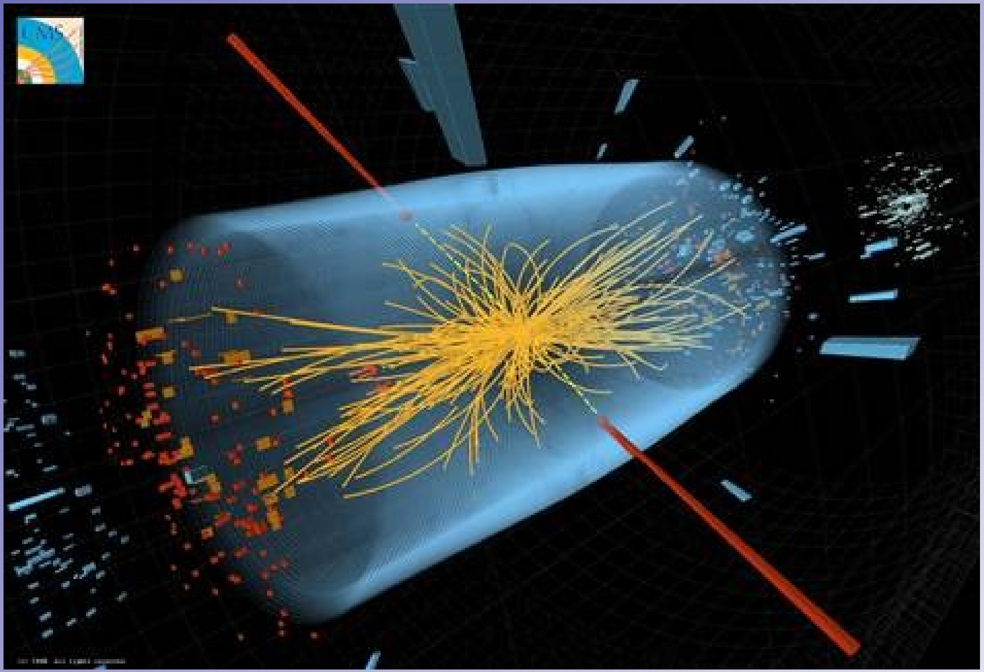

A detector cross-section, showing particle paths

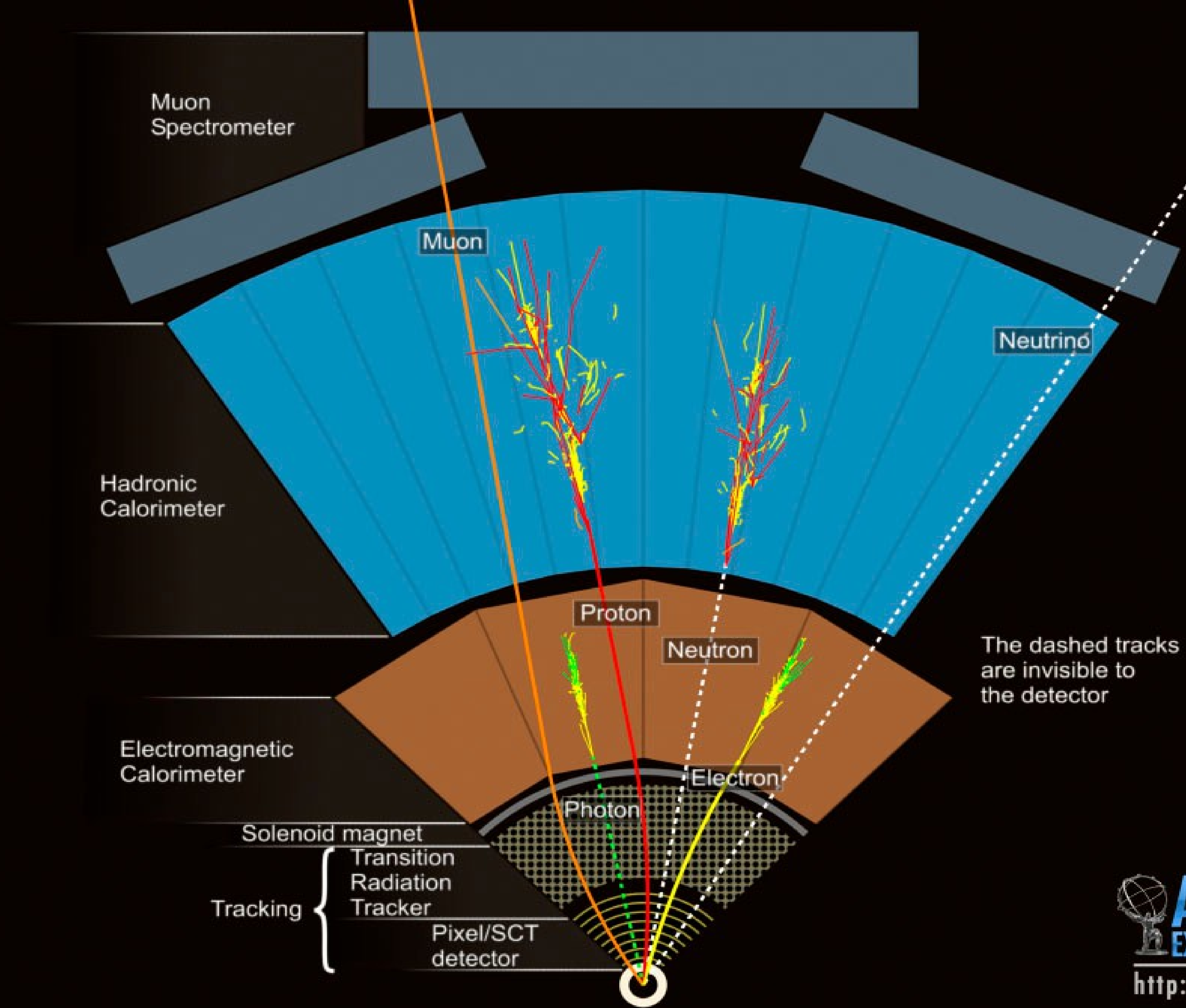


Hadron Colliders







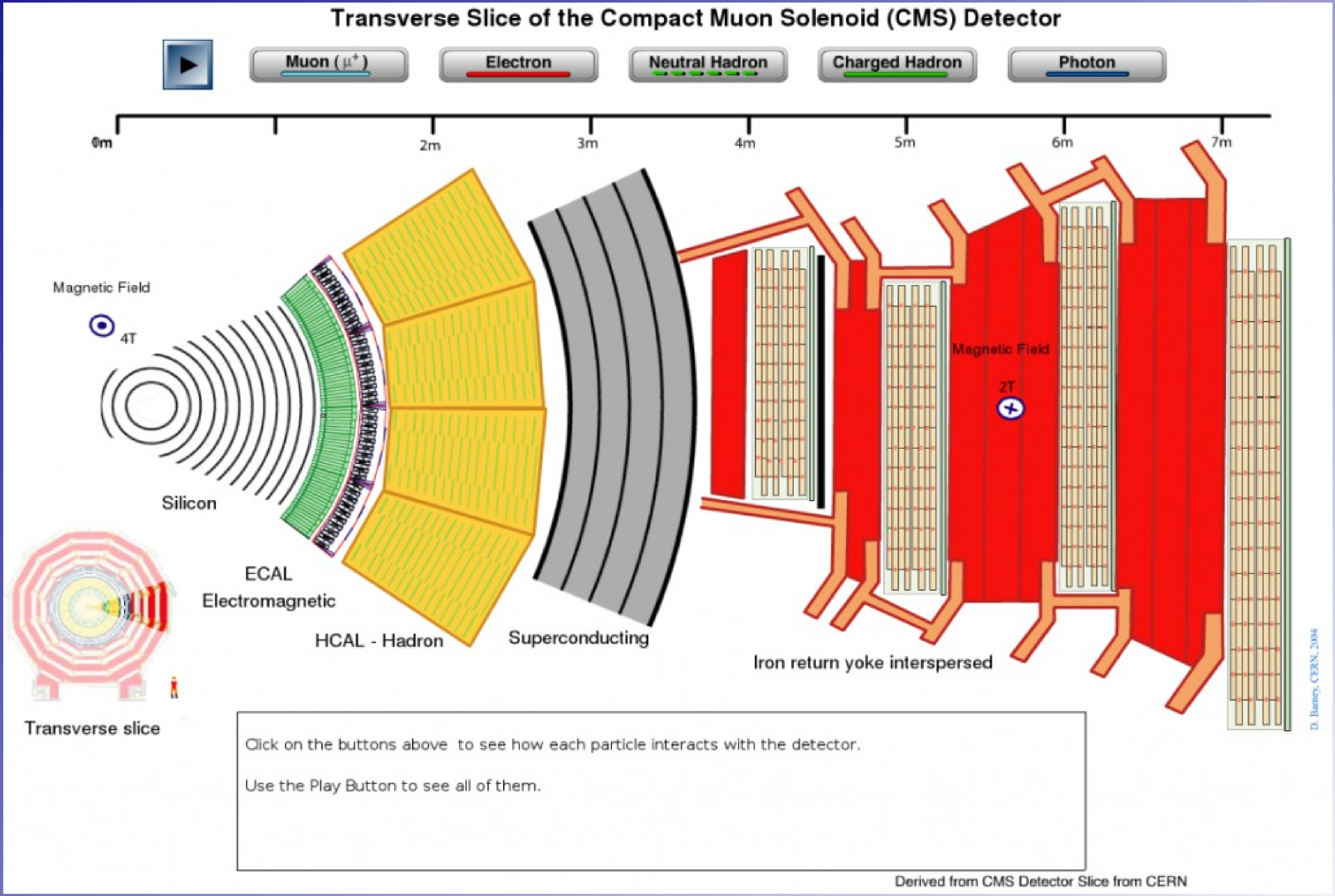


The dashed tracks are invisible to the detector

ATLAS EXPERIMENT

http://atlas.ch

CMS Interactive

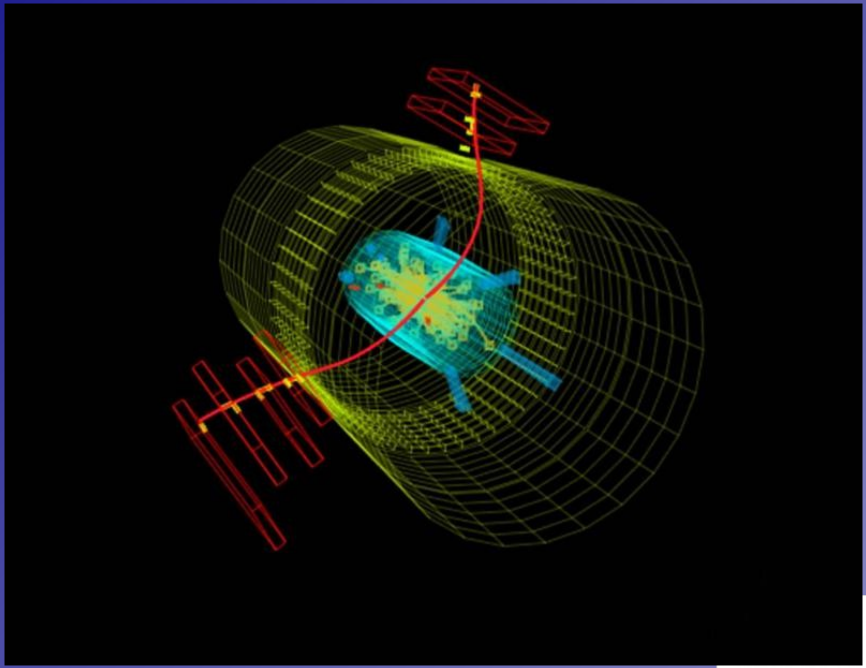


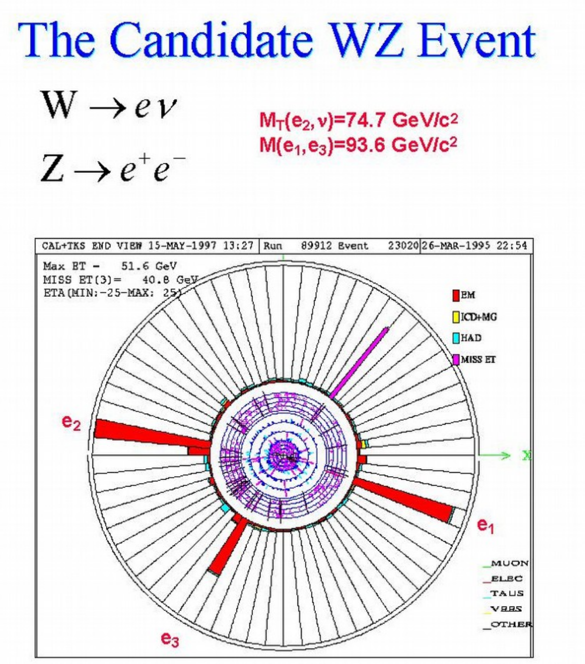
Click on the buttons above to see how each particle interacts with the detector.

Use the Play Button to see all of them.

Derived from CMS Detector Slice from CERN

Event Display




The Candidate WZ Event

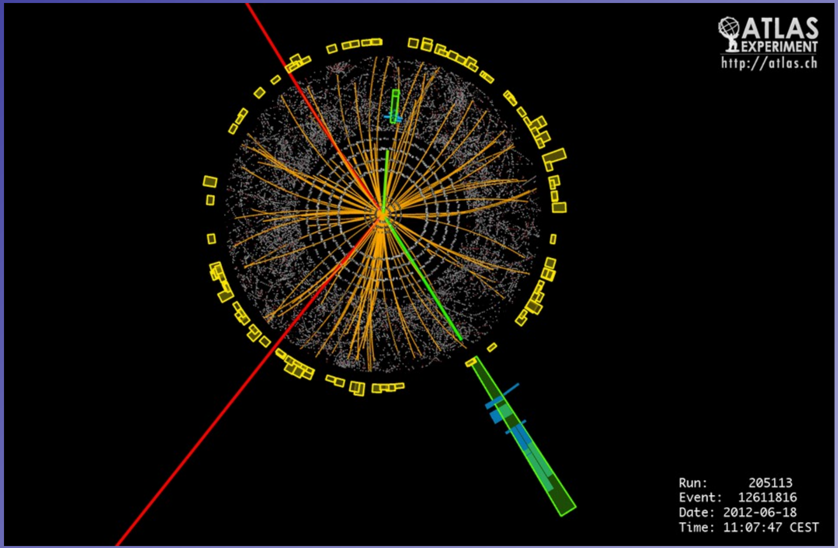
$W \to e\nu$

$Z \to e^+e^-$

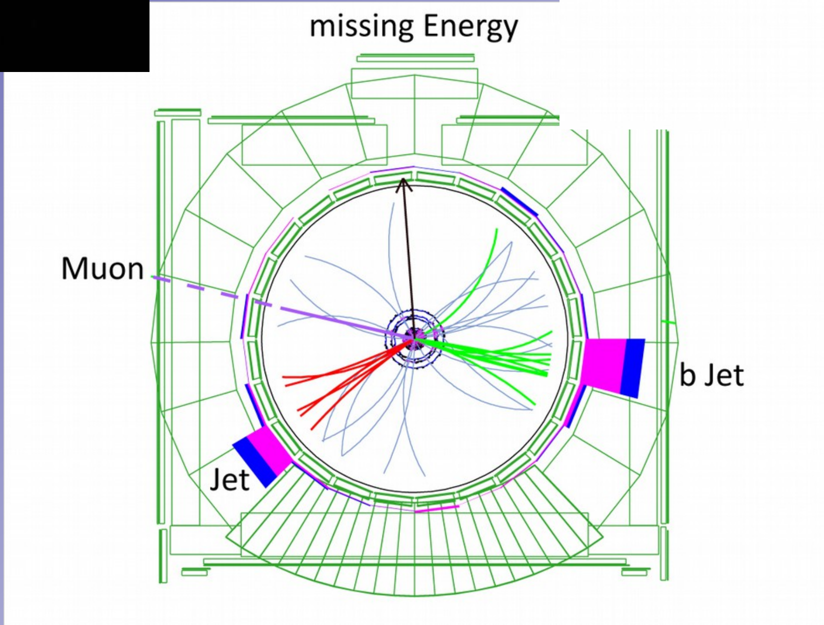
$M_T(e_2,\nu)$=74.7 GeV/c^2

$M(e_1,e_3)$=93.6 GeV/c^2

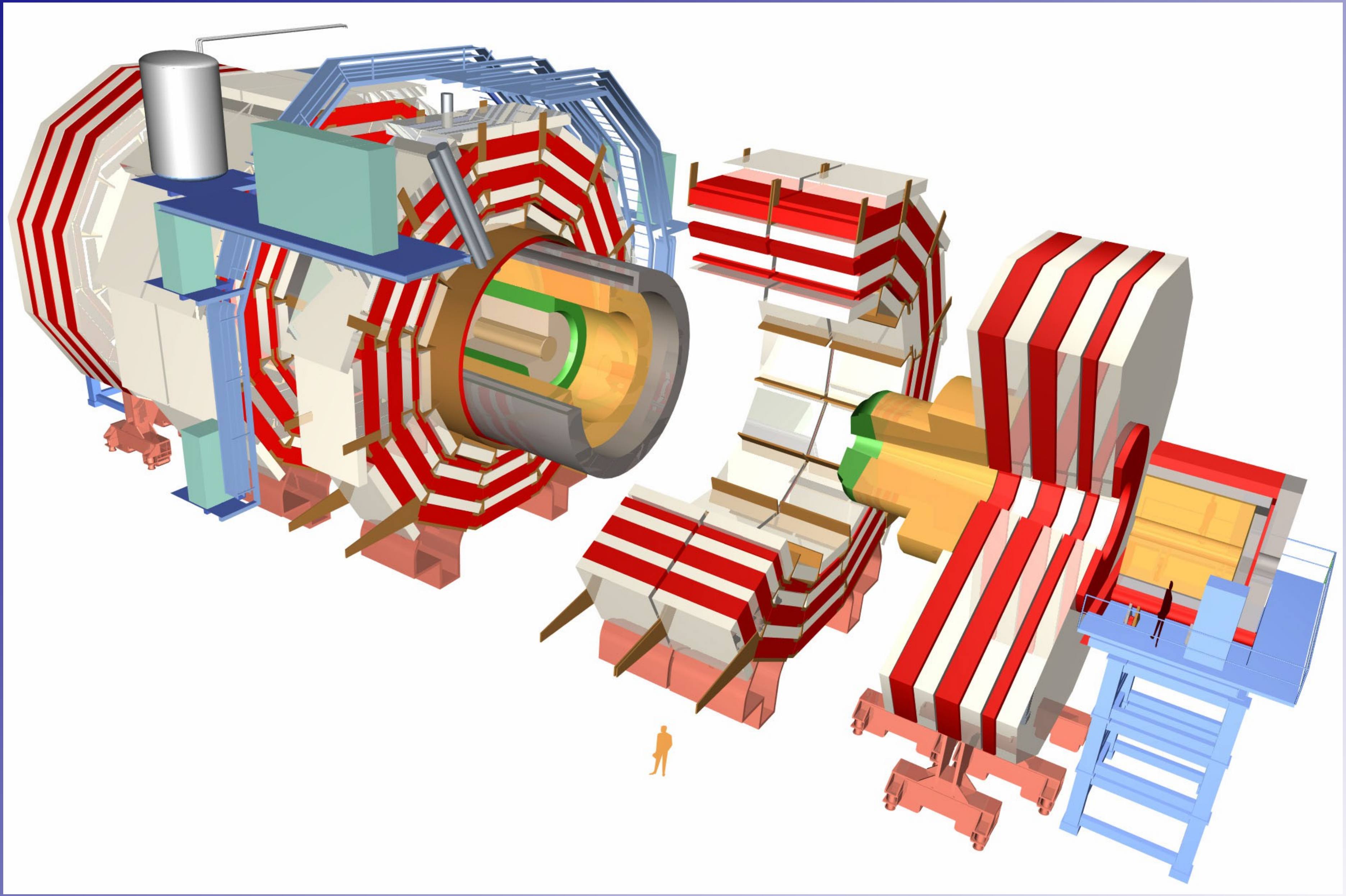
```
CAL+TKS END VIEW 15-MAY-1997 13:27 | Run   89912 Event   23020 | 26-MAR-1995 22:54
Max ET -     51.6 GeV
MISS ET(3)=     40.8 GeV
ETA(MIN:-25-MAX: 25)
```



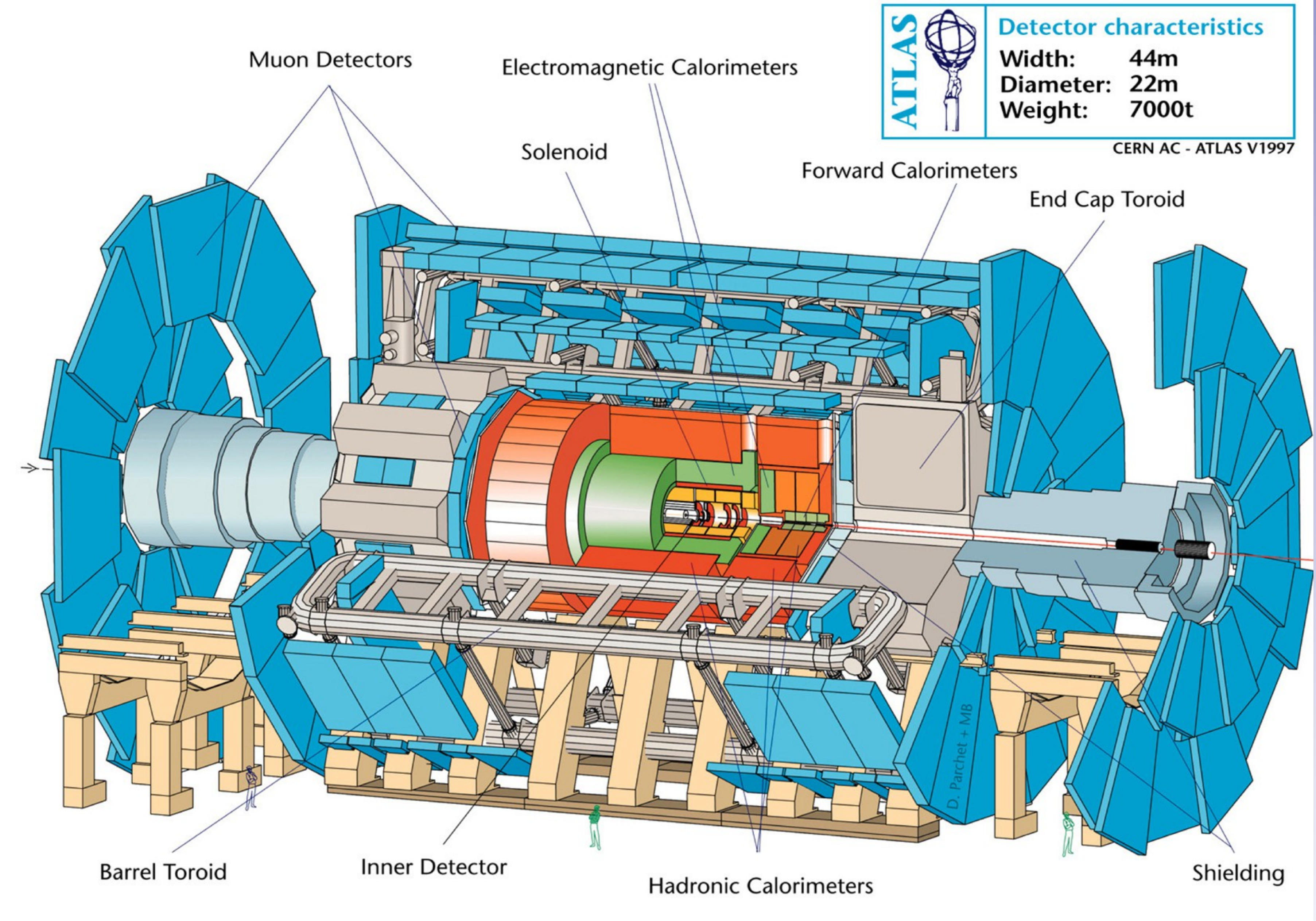
Run: 205113
Event: 12611816
Date: 2012-06-18
Time: 11:07:47 CEST



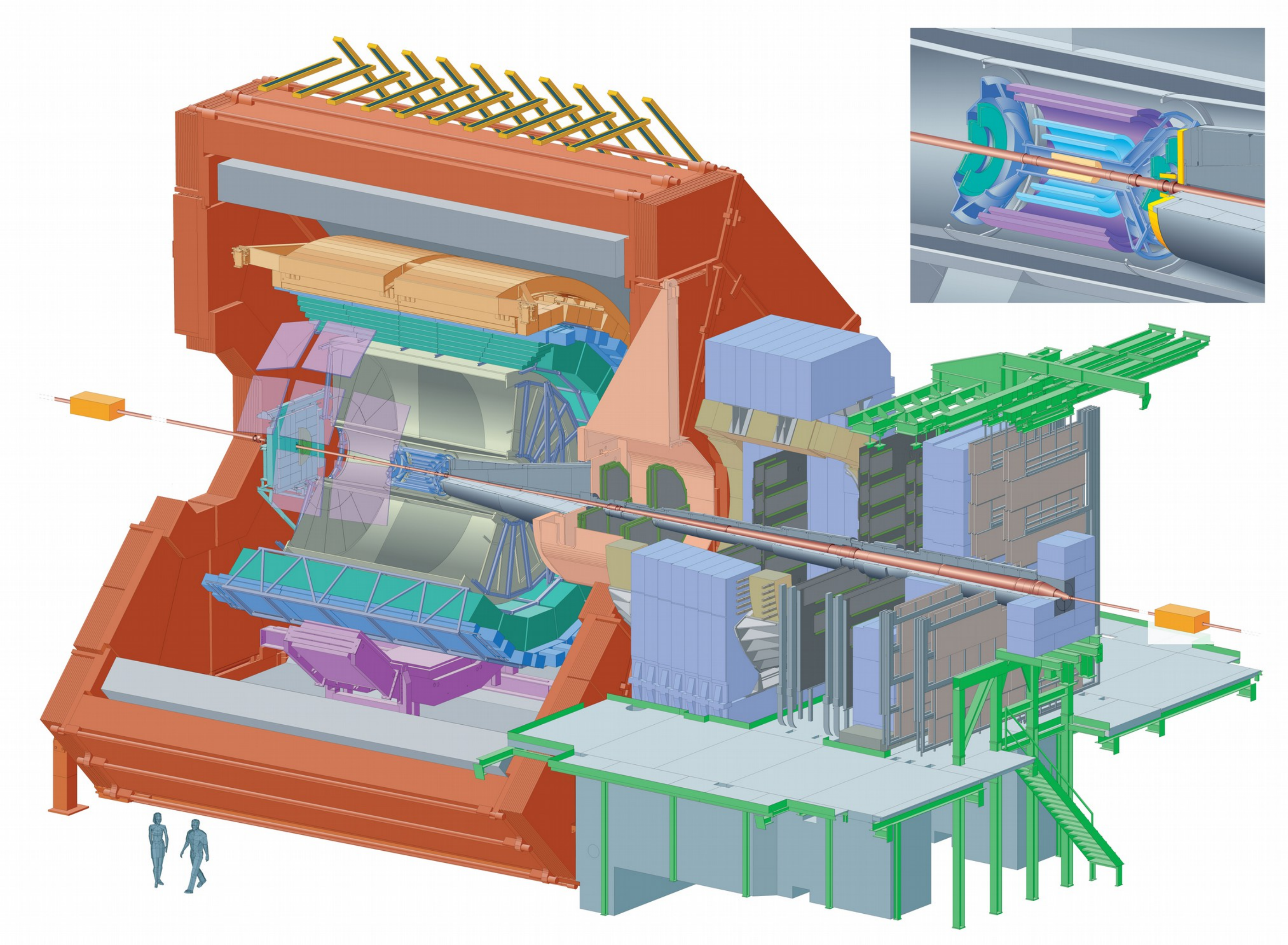
CMS



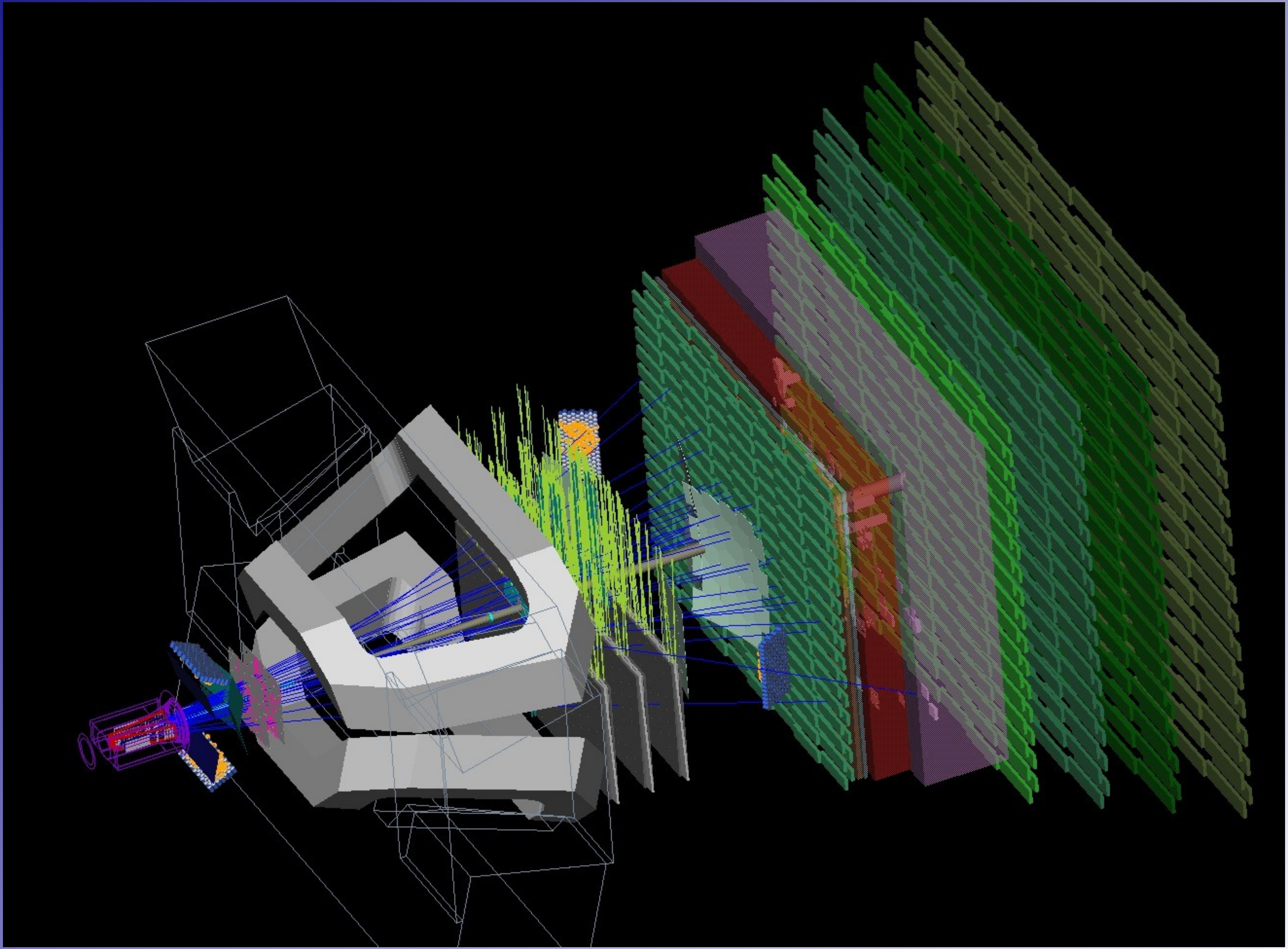
ATLAS


Muon Detectors
Electromagnetic Calorimeters
ATLAS
Detector characteristics
Width: 44m
Diameter: 22m
Weight: 7000t
CERN AC - ATLAS V1997
Solenoid
Forward Calorimeters
End Cap Toroid
D. Parchet + MB
Barrel Toroid
Inner Detector
Hadronic Calorimeters
Shielding

ALICE

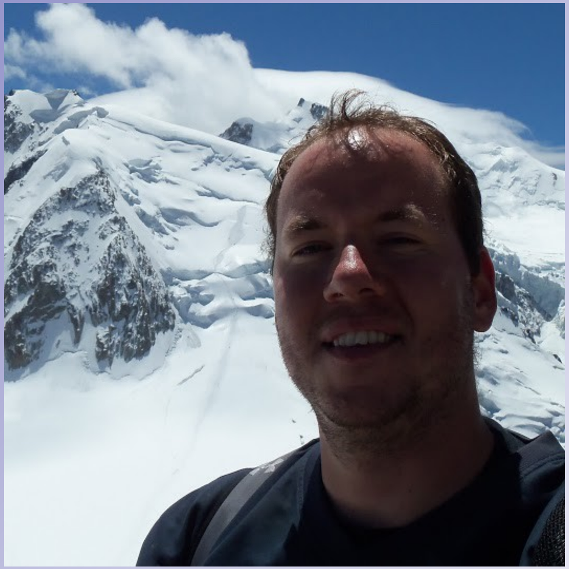


LHCb



The Gifts!

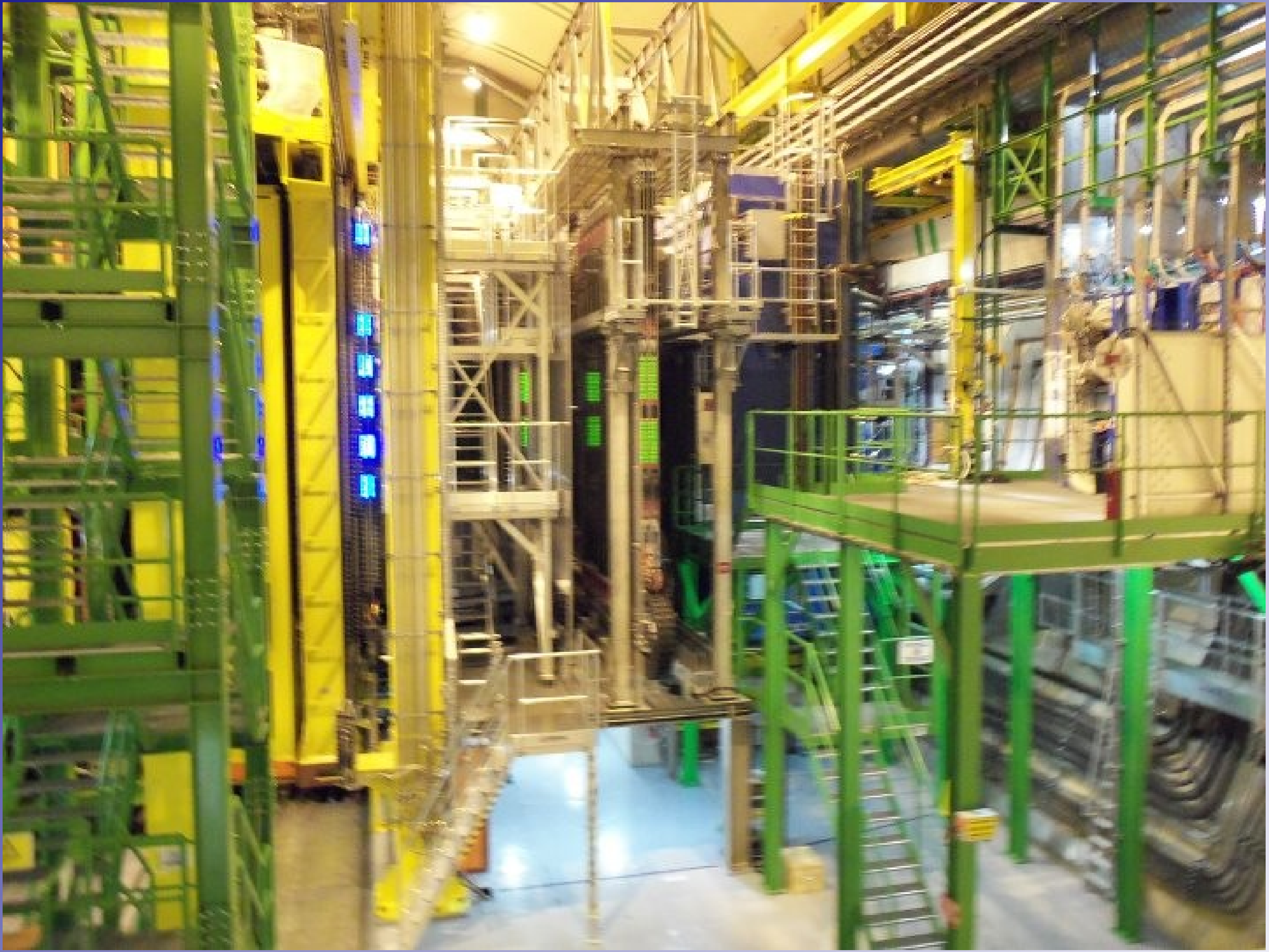
QuarkNet



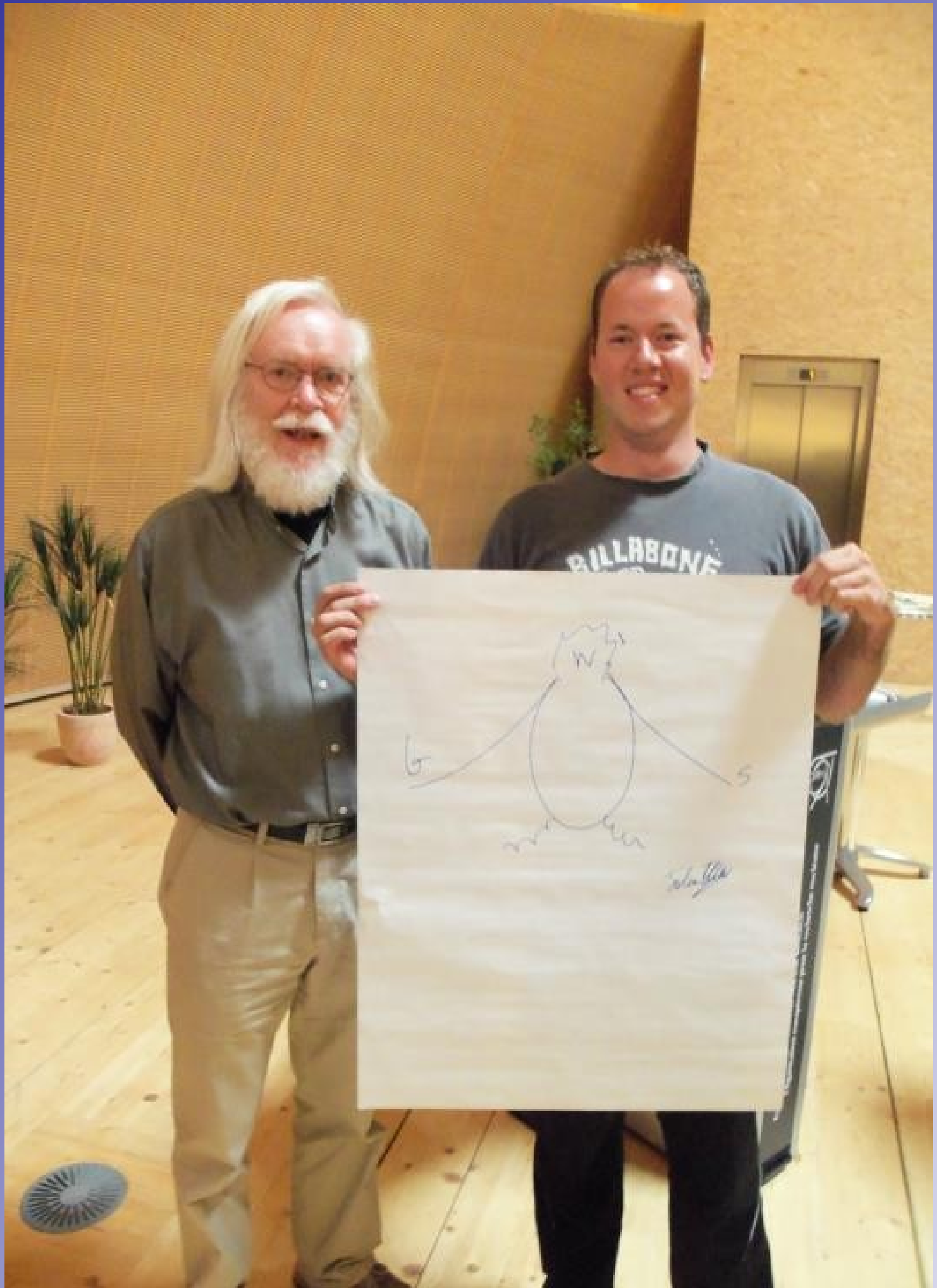
CMS!

Magnet Lab!

LHCb!



Ellis!



Steinberger!

Teachers!!

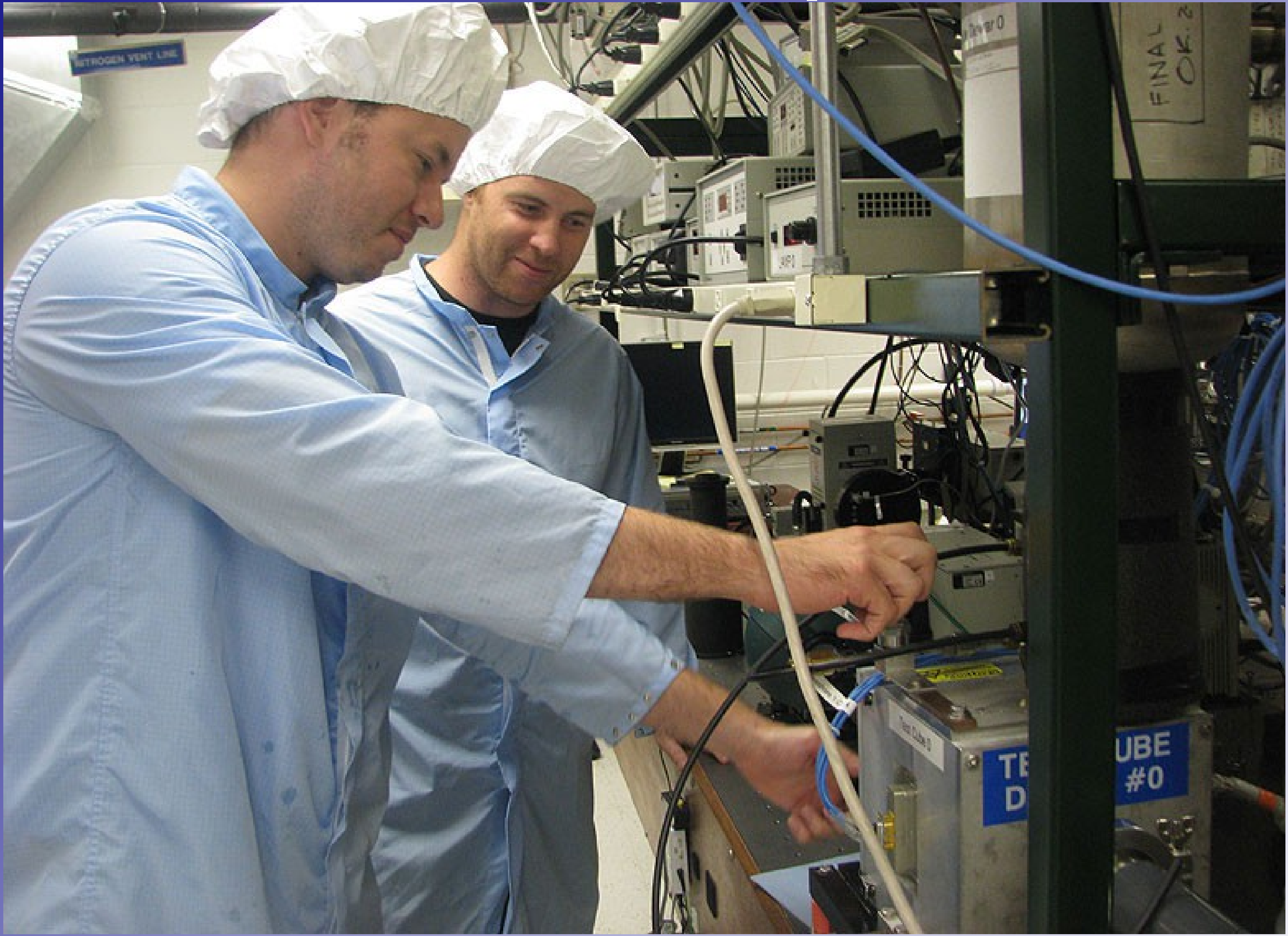
Fermilab!

Cosmic Ray Detector!

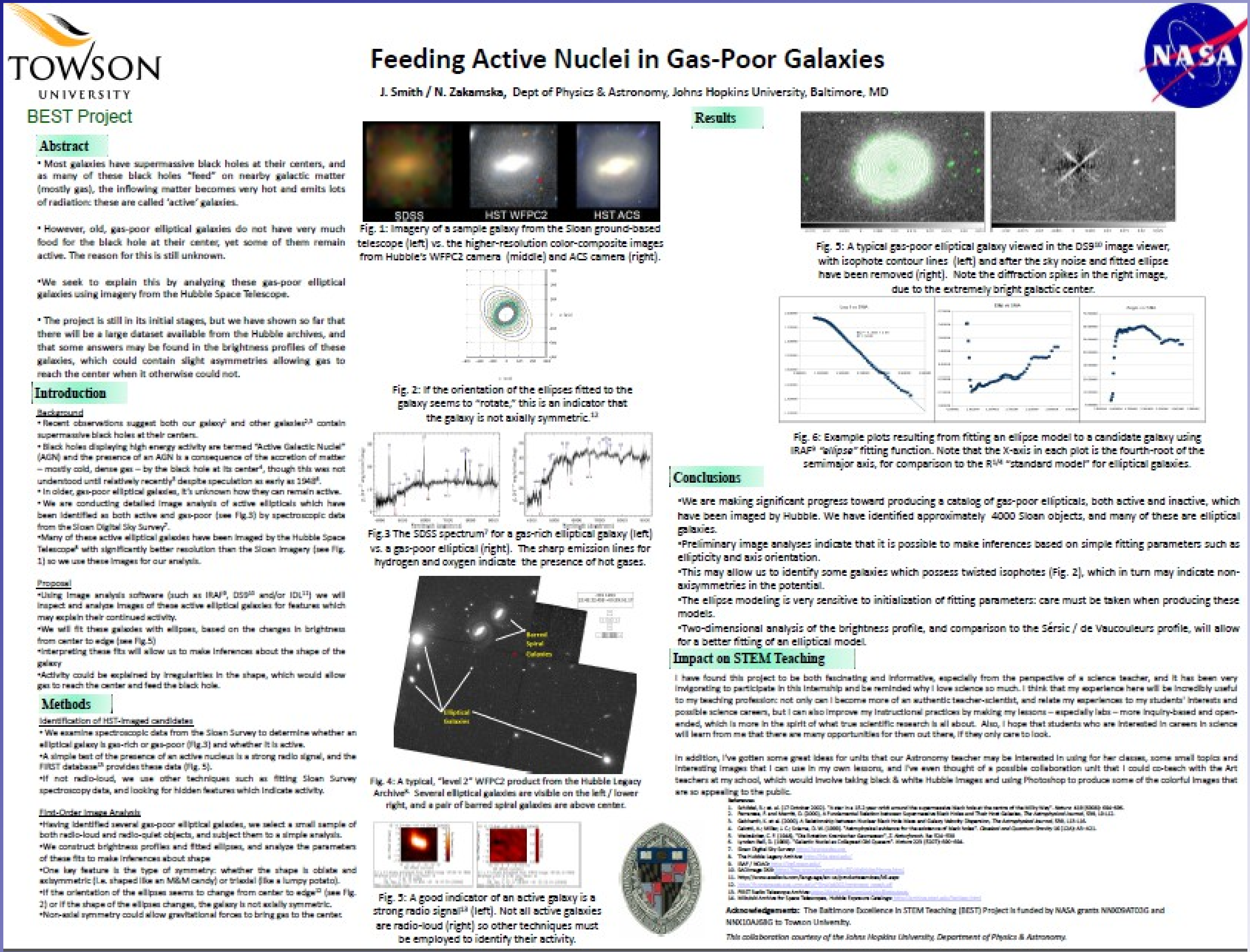
Fermilab Summer Camp!

Bardeen!

Internships!



More Internships!



BEST Project

Feeding Active Nuclei in Gas-Poor Galaxies

J. Smith / N. Zakamska, Dept of Physics & Astronomy, Johns Hopkins University, Baltimore, MD

Abstract

- Most galaxies have supermassive black holes at their centers, and as many of these black holes "feed" on nearby galactic matter (mostly gas), the inflowing matter becomes very hot and emits lots of radiation: these are called 'active' galaxies.

- However, old, gas-poor elliptical galaxies do not have very much food for the black hole at their center, yet some of them remain active. The reason for this is still unknown.

- We seek to explain this by analyzing these gas-poor elliptical galaxies using imagery from the Hubble Space Telescope.

- The project is still in its initial stages, but we have shown so far that there will be a large dataset available from the Hubble archives, and that some answers may be found in the brightness profiles of these galaxies, which could contain slight asymmetries allowing gas to reach the center when it otherwise could not.

Introduction

Background

- Recent observations suggest both our galaxy[1] and other galaxies[2,3] contain supermassive black holes at their centers.
- Black holes displaying high energy activity are termed "Active Galactic Nuclei" (AGN) and the presence of an AGN is a consequence of the accretion of matter – mostly cold, dense gas – by the black hole at its center[4], though this was not understood until relatively recently[5] despite speculation as early as 1948[6].
- In older, gas-poor elliptical galaxies, it's unknown how they can remain active.
- We are conducting detailed image analysis of active ellipticals which have been identified as both active and gas-poor (see Fig.3) by spectroscopic data from the Sloan Digital Sky Survey[7].
- Many of these active elliptical galaxies have been imaged by the Hubble Space Telescope[8] with significantly better resolution than the Sloan imagery (see Fig. 1) so we use these images for our analysis.

Proposal

- Using image analysis software (such as IRAF[9], DS9[10] and/or IDL[11]) we will inspect and analyze images of these active elliptical galaxies for features which may explain their continued activity.
- We will fit these galaxies with ellipses, based on the changes in brightness from center to edge (see Fig.5)
- Interpreting these fits will allow us to make inferences about the shape of the galaxy
- Activity could be explained by irregularities in the shape, which would allow gas to reach the center and feed the black hole.

Methods

Identification of HST-imaged candidates

- We examine spectroscopic data from the Sloan Survey to determine whether an elliptical galaxy is gas-rich or gas-poor (Fig.3) and whether it is active.
- A simple test of the presence of an active nucleus is a strong radio signal, and the FIRST database[13] provides these data (Fig. 5).
- If not radio-loud, we use other techniques such as fitting Sloan Survey spectroscopy data, and looking for hidden features which indicate activity.

First-Order Image Analysis

- Having identified several gas-poor elliptical galaxies, we select a small sample of both radio-loud and radio-quiet objects, and subject them to a simple analysis.
- We construct brightness profiles and fitted ellipses, and analyze the parameters of these fits to make inferences about shape
- One key feature is the type of symmetry: whether the shape is oblate and axisymmetric (i.e. shaped like an M&M candy) or triaxial (like a lumpy potato).
- If the orientation of the ellipses seems to change from center to edge[12] (see Fig. 2) or if the shape of the ellipses changes, the galaxy is not axially symmetric.
- Non-axial symmetry could allow gravitational forces to bring gas to the center.

Fig. 1: Imagery of a sample galaxy from the Sloan ground-based telescope (left) vs. the higher-resolution color-composite images from Hubble's WFPC2 camera (middle) and ACS camera (right).

Fig. 2: If the orientation of the ellipses fitted to the galaxy seems to "rotate," this is an indicator that the galaxy is not axially symmetric.[12]

Fig.3 The SDSS spectrum[7] for a gas-rich elliptical galaxy (left) vs. a gas-poor elliptical (right). The sharp emission lines for hydrogen and oxygen indicate the presence of hot gases.

Fig. 4: A typical, "level 2" WFPC2 product from the Hubble Legacy Archive[8]. Several elliptical galaxies are visible on the left / lower right, and a pair of barred spiral galaxies are above center.

Fig. 5: A good indicator of an active galaxy is a strong radio signal[14] (left). Not all active galaxies are radio-loud (right) so other techniques must be employed to identify their activity.

Results

Fig. 5: A typical gas-poor elliptical galaxy viewed in the DS9[10] image viewer, with isophote contour lines (left) and after the sky noise and fitted ellipse have been removed (right). Note the diffraction spikes in the right image, due to the extremely bright galactic center.

Fig. 6: Example plots resulting from fitting an ellipse model to a candidate galaxy using IRAF[9] *"ellipse"* fitting function. Note that the X-axis in each plot is the fourth-root of the semimajor axis, for comparison to the $R^{1/4}$ "standard model" for elliptical galaxies.

Conclusions

- We are making significant progress toward producing a catalog of gas-poor ellipticals, both active and inactive, which have been imaged by Hubble. We have identified approximately 4000 Sloan objects, and many of these are elliptical galaxies.
- Preliminary image analyses indicate that it is possible to make inferences based on simple fitting parameters such as ellipticity and axis orientation.
- This may allow us to identify some galaxies which possess twisted isophotes (Fig. 2), which in turn may indicate non-axisymmetries in the potential.
- The ellipse modeling is very sensitive to initialization of fitting parameters: care must be taken when producing these models.
- Two-dimensional analysis of the brightness profile, and comparison to the Sérsic / de Vaucouleurs profile, will allow for a better fitting of an elliptical model.

Impact on STEM Teaching

I have found this project to be both fascinating and informative, especially from the perspective of a science teacher, and it has been very invigorating to participate in this internship and be reminded why I love science so much. I think that my experience here will be incredibly useful to my teaching profession: not only can I become more of an authentic teacher-scientist, and relate my experiences to my students' interests and possible science careers, but I can also improve my instructional practices by making my lessons – especially labs – more inquiry-based and open-ended, which is more in the spirit of what true scientific research is all about. Also, I hope that students who are interested in careers in science will learn from me that there are many opportunities for them out there, if they only care to look.

In addition, I've gotten some great ideas for units that our Astronomy teacher may be interested in using for her classes, some small topics and interesting images that I can use in my own lessons, and I've even thought of a possible collaboration unit that I could co-teach with the Art teachers at my school, which would involve taking black & white Hubble images and using Photoshop to produce some of the colorful images that are so appealing to the public.

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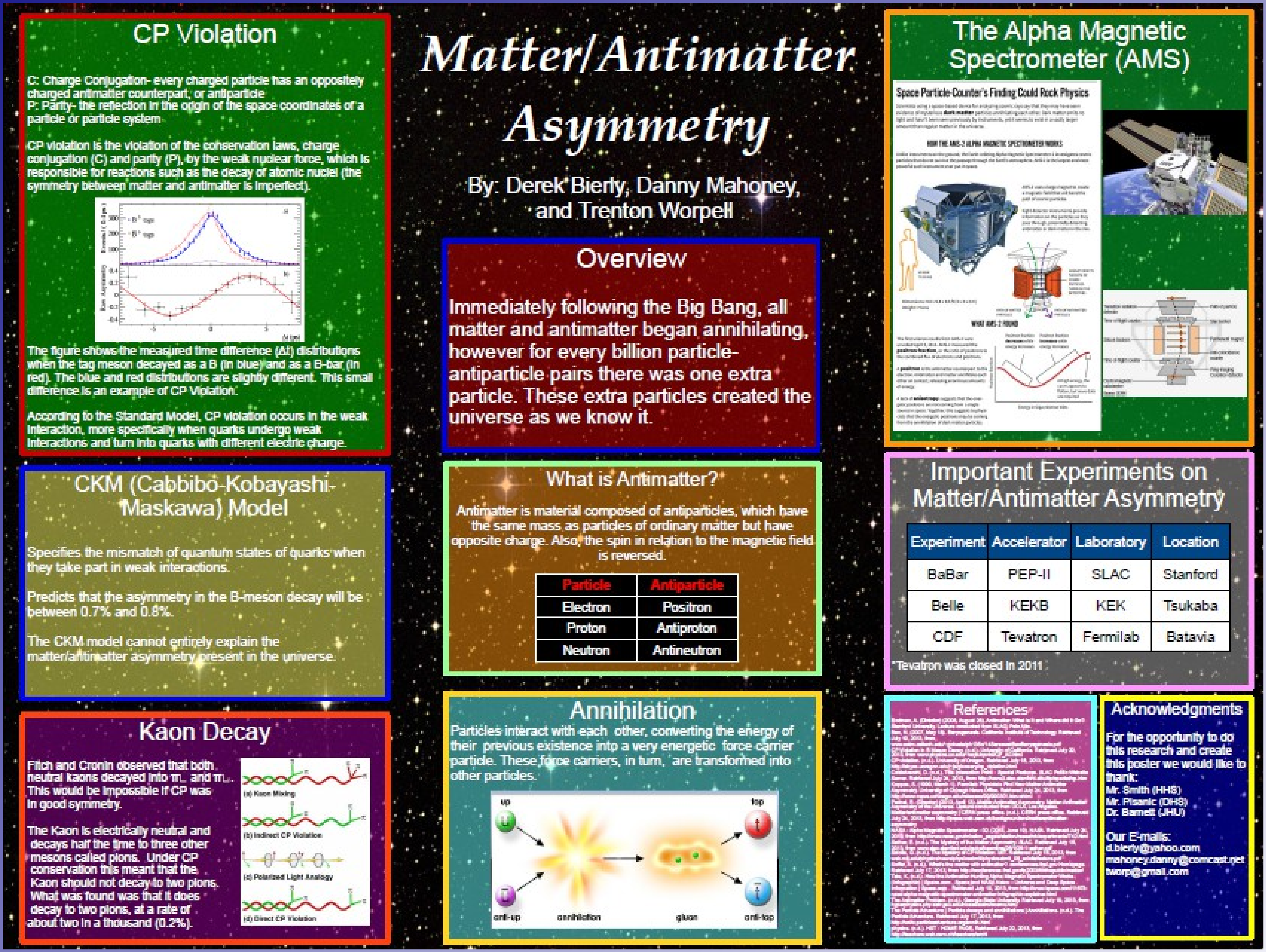
Student Research!



Matter/Antimatter Asymmetry

By: Derek Bierly, Danny Mahoney, and Trenton Worpell

CP Violation

C: Charge Conjugation- every charged particle has an oppositely charged antimatter counterpart, or antiparticle
P: Parity- the reflection in the origin of the space coordinates of a particle or particle system

CP violation is the violation of the conservation laws, charge conjugation (C) and parity (P), by the weak nuclear force, which is responsible for reactions such as the decay of atomic nuclei (the symmetry between matter and antimatter is imperfect).

The figure shows the measured time difference (Δt) distributions when the tag meson decayed as a B (in blue) and as a B-bar (in red). The blue and red distributions are slightly different. This small difference is an example of CP Violation.

According to the Standard Model, CP violation occurs in the weak interaction, more specifically when quarks undergo weak interactions and turn into quarks with different electric charge.

CKM (Cabbibo-Kobayashi-Maskawa) Model

Specifies the mismatch of quantum states of quarks when they take part in weak interactions.

Predicts that the asymmetry in the B-meson decay will be between 0.7% and 0.8%.

The CKM model cannot entirely explain the matter/antimatter asymmetry present in the universe.

Kaon Decay

Fitch and Cronin observed that both neutral kaons decayed into π_+ and π_-. This would be impossible if CP was in good symmetry.

The Kaon is electrically neutral and decays half the time to three other mesons called pions. Under CP conservation this meant that the Kaon should not decay to two pions. What was found was that it does decay to two pions, at a rate of about two in a thousand (0.2%).

Overview

Immediately following the Big Bang, all matter and antimatter began annihilating, however for every billion particle-antiparticle pairs there was one extra particle. These extra particles created the universe as we know it.

What is Antimatter?

Antimatter is material composed of antiparticles, which have the same mass as particles of ordinary matter but have opposite charge. Also, the spin in relation to the magnetic field is reversed.

Particle	Antiparticle
Electron	Positron
Proton	Antiproton
Neutron	Antineutron

Annihilation

Particles interact with each other, converting the energy of their previous existence into a very energetic force carrier particle. These force carriers, in turn, are transformed into other particles.

The Alpha Magnetic Spectrometer (AMS)

Space Particle-Counter's Finding Could Rock Physics

Important Experiments on Matter/Antimatter Asymmetry

Experiment	Accelerator	Laboratory	Location
BaBar	PEP-II	SLAC	Stanford
Belle	KEKB	KEK	Tsukaba
CDF	Tevatron	Fermilab	Batavia

*Tevatron was closed in 2011

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Our E-mails:
d.bierly@yahoo.com
mahoney.danny@comcast.net
tworp@gmail.com

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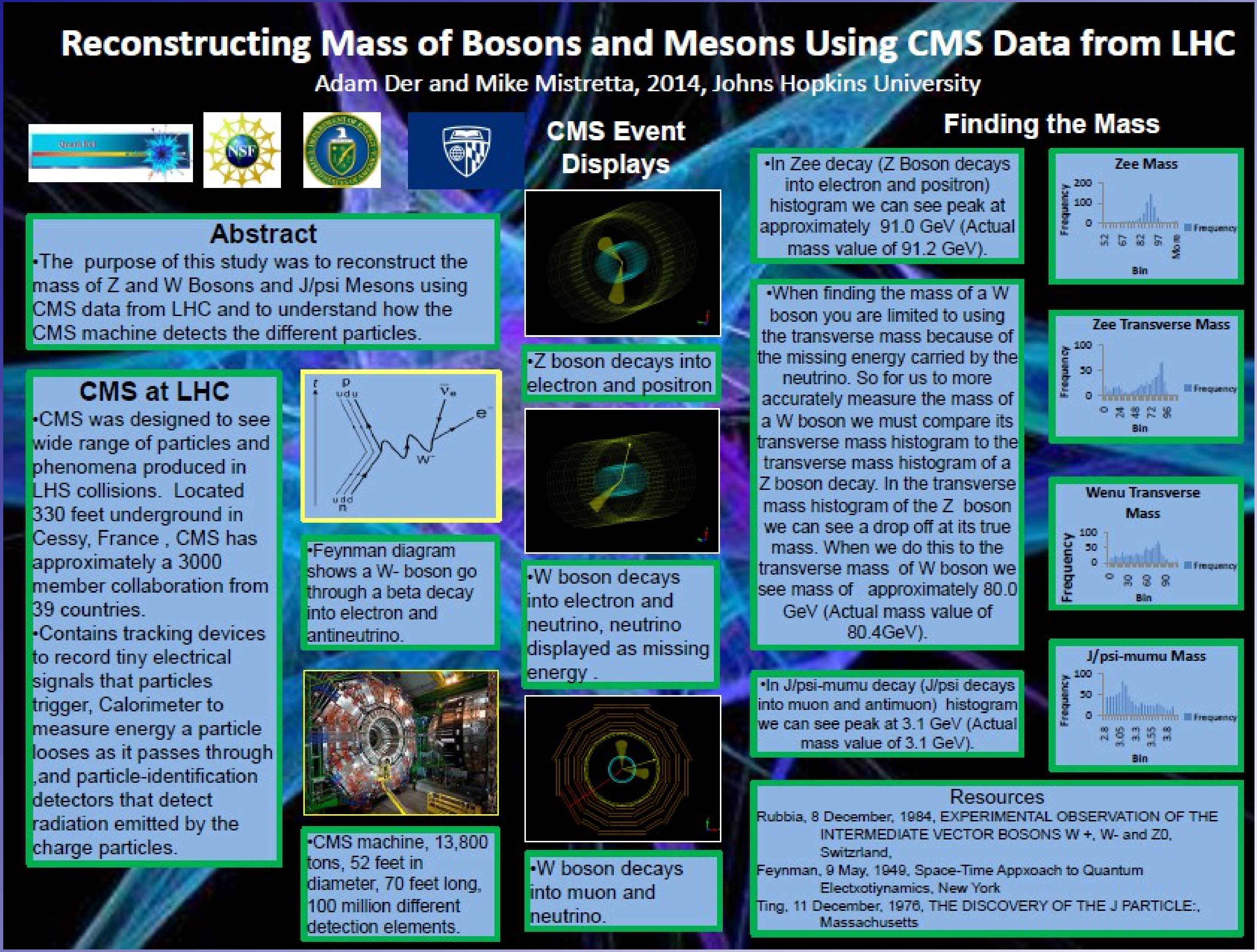

Reconstructing Mass of Bosons and Mesons Using CMS Data from LHC

Adam Der and Mike Mistretta, 2014, Johns Hopkins University

Abstract

•The purpose of this study was to reconstruct the mass of Z and W Bosons and J/psi Mesons using CMS data from LHC and to understand how the CMS machine detects the different particles.

CMS at LHC

•CMS was designed to see wide range of particles and phenomena produced in LHS collisions. Located 330 feet underground in Cessy, France , CMS has approximately a 3000 member collaboration from 39 countries.

•Contains tracking devices to record tiny electrical signals that particles trigger, Calorimeter to measure energy a particle looses as it passes through ,and particle-identification detectors that detect radiation emitted by the charge particles.

•Feynman diagram shows a W- boson go through a beta decay into electron and antineutrino.

•CMS machine, 13,800 tons, 52 feet in diameter, 70 feet long, 100 million different detection elements.

CMS Event Displays

•Z boson decays into electron and positron

•W boson decays into electron and neutrino, neutrino displayed as missing energy .

•W boson decays into muon and neutrino.

Finding the Mass

•In Zee decay (Z Boson decays into electron and positron) histogram we can see peak at approximately 91.0 GeV (Actual mass value of 91.2 GeV).

•When finding the mass of a W boson you are limited to using the transverse mass because of the missing energy carried by the neutrino. So for us to more accurately measure the mass of a W boson we must compare its transverse mass histogram to the transverse mass histogram of a Z boson decay. In the transverse mass histogram of the Z boson we can see a drop off at its true mass. When we do this to the transverse mass of W boson we see mass of approximately 80.0 GeV (Actual mass value of 80.4GeV).

•In J/psi-mumu decay (J/psi decays into muon and antimuon) histogram we can see peak at 3.1 GeV (Actual mass value of 3.1 GeV).

Resources

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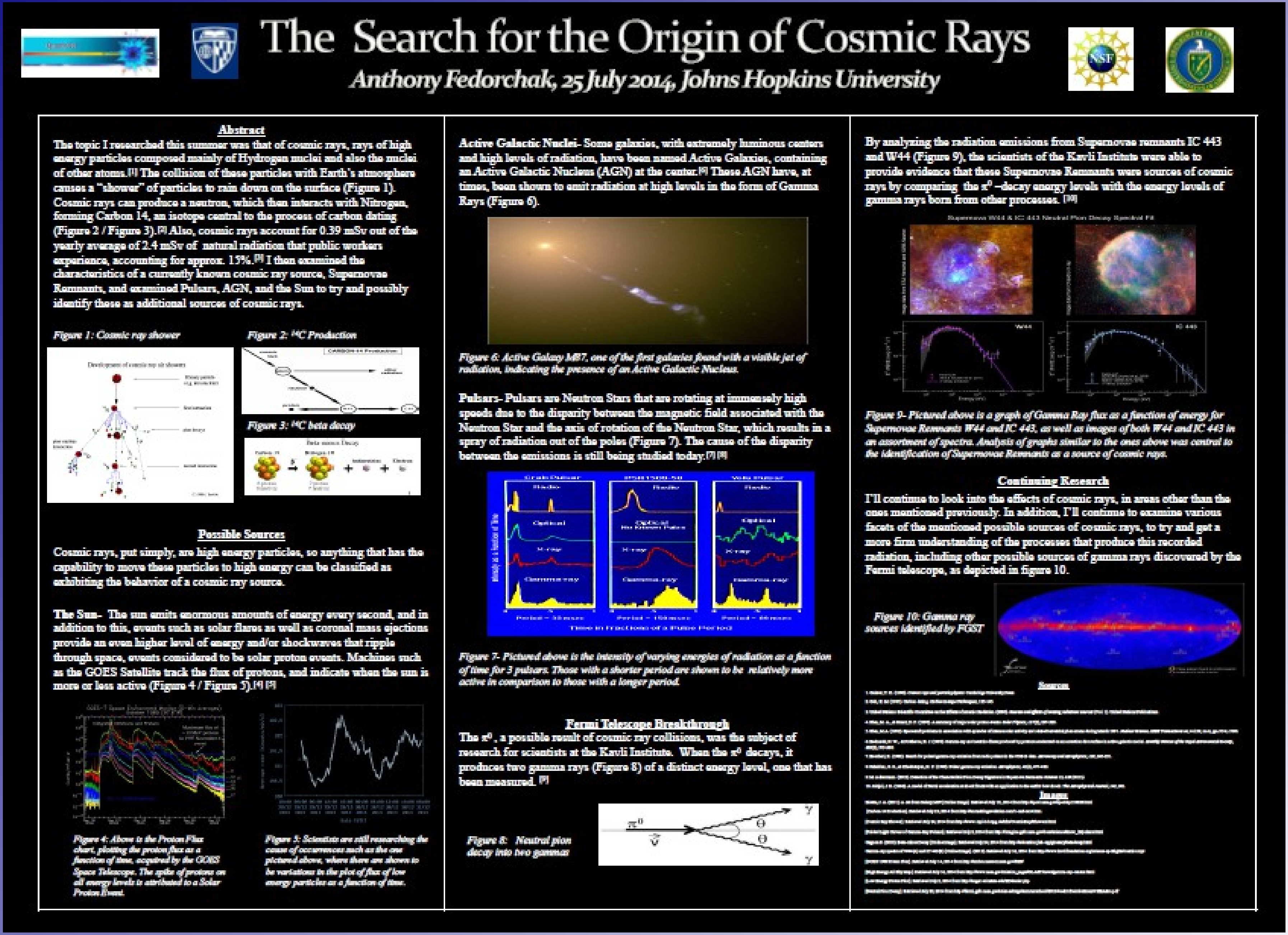


The Search for the Origin of Cosmic Rays

Anthony Fedorchak, 25 July 2014, Johns Hopkins University

Abstract

The topic I researched this summer was that of cosmic rays, rays of high energy particles composed mainly of Hydrogen nuclei and also the nuclei of other atoms.[1] The collision of these particles with Earth's atmosphere causes a "shower" of particles to rain down on the surface (Figure 1). Cosmic rays can produce a neutron, which then interacts with Nitrogen, forming Carbon 14, an isotope central to the process of carbon dating (Figure 2 / Figure 3).[2] Also, cosmic rays account for 0.39 mSv out of the yearly average of 2.4 mSv of natural radiation that public workers experience, accounting for approx. 15%.[3] I then examined the characteristics of a currently known cosmic ray source, Supernovae Remnants, and examined Pulsars, AGN, and the Sun to try and possibly identify these as additional sources of cosmic rays.

Figure 1: Cosmic ray shower

Figure 2: ^{14}C Production

Figure 3: ^{14}C beta decay

Possible Sources

Cosmic rays, put simply, are high energy particles, so anything that has the capability to move these particles to high energy can be classified as exhibiting the behavior of a cosmic ray source.

The Sun- The sun emits enormous amounts of energy every second, and in addition to this, events such as solar flares as well as coronal mass ejections provide an even higher level of energy and/or shockwaves that ripple through space, events considered to be solar proton events. Machines such as the GOES Satellite track the flux of protons, and indicate when the sun is more or less active (Figure 4 / Figure 5).[4] [5]

Figure 4: Above is the Proton Flux chart, plotting the proton flux as a function of time, acquired by the GOES Space Telescope. The spike of protons on all energy levels is attributed to a Solar Proton Event.

Figure 5: Scientists are still researching the cause of occurrences such as the one pictured above, where there are shown to be variations in the plot of flux of low energy particles as a function of time.

Active Galactic Nuclei- Some galaxies, with extremely luminous centers and high levels of radiation, have been named Active Galaxies, containing an Active Galactic Nucleus (AGN) at the center.[6] These AGN have, at times, been shown to emit radiation at high levels in the form of Gamma Rays (Figure 6).

Figure 6: Active Galaxy M87, one of the first galaxies found with a visible jet of radiation, indicating the presence of an Active Galactic Nucleus.

Pulsars- Pulsars are Neutron Stars that are rotating at immensely high speeds due to the disparity between the magnetic field associated with the Neutron Star and the axis of rotation of the Neutron Star, which results in a spray of radiation out of the poles (Figure 7). The cause of the disparity between the emissions is still being studied today.[7] [8]

Figure 7- Pictured above is the intensity of varying energies of radiation as a function of time for 3 pulsars. Those with a shorter period are shown to be relatively more active in comparison to those with a longer period.

Fermi Telescope Breakthrough

The π^0, a possible result of cosmic ray collisions, was the subject of research for scientists at the Kavli Institute. When the π^0 decays, it produces two gamma rays (Figure 8) of a distinct energy level, one that has been measured. [9]

Figure 8: Neutral pion decay into two gammas

By analyzing the radiation emissions from Supernovae remnants IC 443 and W44 (Figure 9), the scientists of the Kavli Institute were able to provide evidence that these Supernovae Remnants were sources of cosmic rays by comparing the π^0 –decay energy levels with the energy levels of gamma rays born from other processes. [10]

Figure 9- Pictured above is a graph of Gamma Ray flux as a function of energy for Supernovae Remnants W44 and IC 443, as well as images of both W44 and IC 443 in an assortment of spectra. Analysis of graphs similar to the ones above was central to the identification of Supernovae Remnants as a source of cosmic rays.

Continuing Research

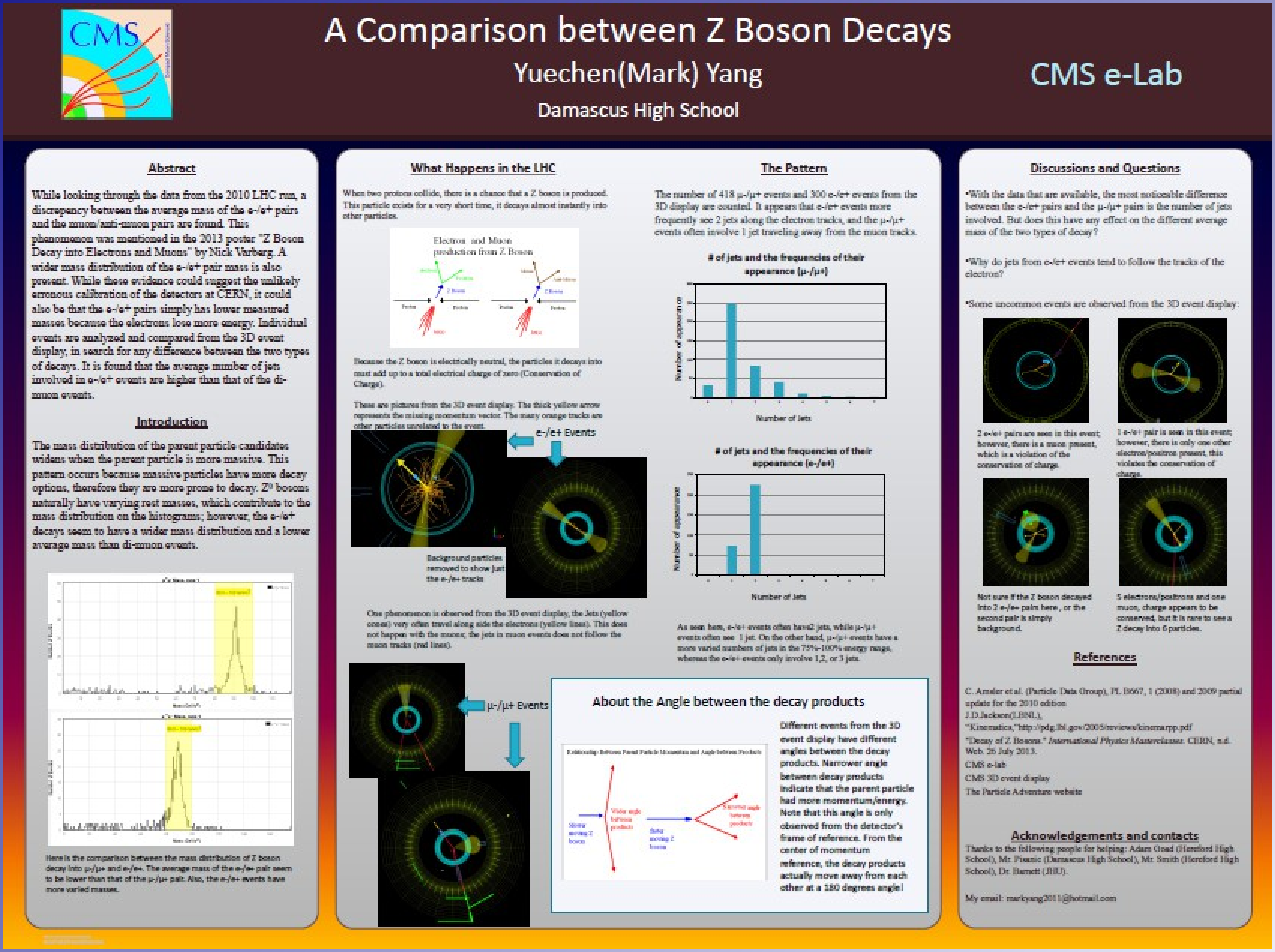
I'll continue to look into the effects of cosmic rays, in areas other than the ones mentioned previously. In addition, I'll continue to examine various facets of the mentioned possible sources of cosmic rays, to try and get a more firm understanding of the processes that produce this recorded radiation, including other possible sources of gamma rays discovered by the Fermi telescope, as depicted in figure 10.

Figure 10: Gamma ray sources identified by FGST

Sources

Images

Masterclass!



A Comparison between Z Boson Decays

Yuechen(Mark) Yang
Damascus High School

CMS e-Lab

Abstract

While looking through the data from the 2010 LHC run, a discrepancy between the average mass of the e-/e+ pairs and the muon/anti-muon pairs are found. This phenomenon was mentioned in the 2013 poster "Z Boson Decay into Electrons and Muons" by Nick Varberg. A wider mass distribution of the e-/e+ pair mass is also present. While these evidence could suggest the unlikely erroneous calibration of the detectors at CERN, it could also be that the e-/e+ pairs simply has lower measured masses because the electrons lose more energy. Individual events are analyzed and compared from the 3D event display, in search for any difference between the two types of decays. It is found that the average number of jets involved in e-/e+ events are higher than that of the di-muon events.

Introduction

The mass distribution of the parent particle candidates widens when the parent particle is more massive. This pattern occurs because massive particles have more decay options, therefore they are more prone to decay. Z^0 bosons naturally have varying rest masses, which contribute to the mass distribution on the histograms; however, the e-/e+ decays seem to have a wider mass distribution and a lower average mass than di-muon events.

Here is the comparison between the mass distribution of Z boson decay into μ-/μ+ and e-/e+. The average mass of the e-/e+ pair seem to be lower than that of the μ-/μ+ pair. Also, the e-/e+ events have more varied masses.

What Happens in the LHC

When two protons collide, there is a chance that a Z boson is produced. This particle exists for a very short time, it decays almost instantly into other particles.

Electron and Muon production from Z Boson

Because the Z boson is electrically neutral, the particles it decays into must add up to a total electrical charge of zero (Conservation of Charge).

These are pictures from the 3D event display. The thick yellow arrow represents the missing momentum vector. The many orange tracks are other particles unrelated to the event.

e-/e+ Events

Background particles removed to show just the e-/e+ tracks

One phenomenon is observed from the 3D event display, the Jets (yellow cones) very often travel along side the electrons (yellow lines). This does not happen with the muons; the jets in muon events does not follow the muon tracks (red lines).

μ-/μ+ Events

The Pattern

The number of 418 μ-/μ+ events and 300 e-/e+ events from the 3D display are counted. It appears that e-/e+ events more frequently see 2 jets along the electron tracks, and the μ-/μ+ events often involve 1 jet traveling away from the muon tracks.

# of jets and the frequencies of their appearance (μ-/μ+)

# of jets and the frequencies of their appearance (e-/e+)

As seen here, e-/e+ events often have2 jets, while μ-/μ+ events often see 1 jet. On the other hand, μ-/μ+ events have a more varied numbers of jets in the 75%-100% energy range, whereas the e-/e+ events only involve 1,2, or 3 jets.

About the Angle between the decay products

Different events from the 3D event display have different angles between the decay products. Narrower angle between decay products indicate that the parent particle had more momentum/energy. Note that this angle is only observed from the detector's frame of reference. From the center of momentum reference, the decay products actually move away from each other at a 180 degrees angle!

Discussions and Questions

•With the data that are available, the most noticeable difference between the e-/e+ pairs and the μ-/μ+ pairs is the number of jets involved. But does this have any effect on the different average mass of the two types of decay?

•Why do jets from e-/e+ events tend to follow the tracks of the electron?

•Some uncommon events are observed from the 3D event display:

2 e-/e+ pairs are seen in this event; however, there is a muon present, which is a violation of the conservation of charge.

1 e-/e+ pair is seen in this event; however, there is only one other electron/positron present, this violates the conservation of charge.

Not sure if the Z boson decayed into 2 e-/e+ pairs here, or the second pair is simply background.

5 electrons/positrons and one muon, charge appears to be conserved, but it is rare to see a Z decay into 6 particles.

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The Particle Adventure website

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My email: markyang2011@hotmail.com

Student Internships!

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