

Our Journey from the smallest to the largest.

Rohini M. Godbole

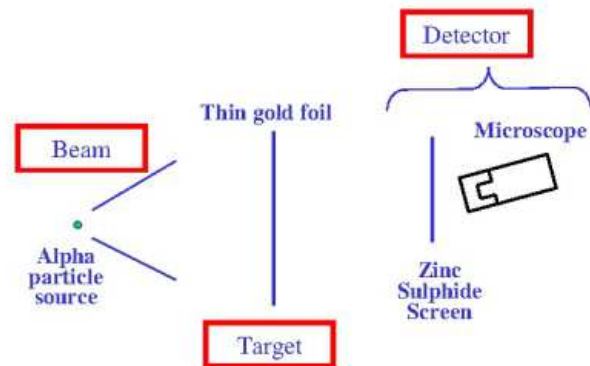
Centre for High Energy Physics, IISc, Bangalore, India

Master Your Physics, UvA, Amsterdam, June 9, 2022.

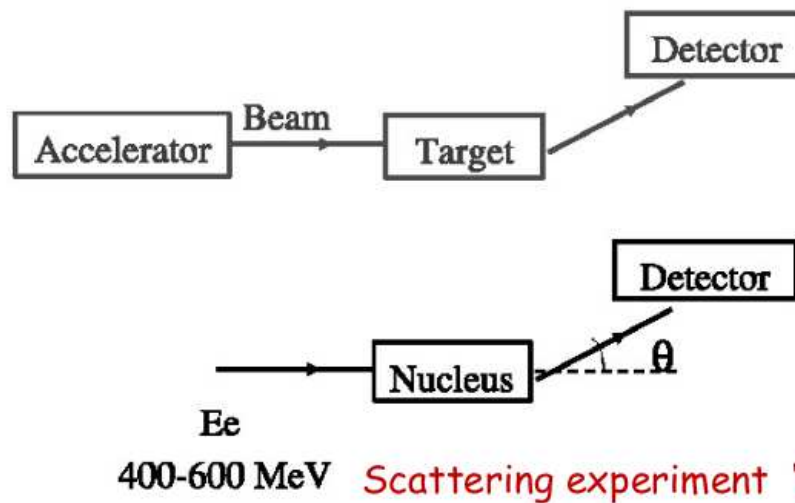
Ref:

- 1) e-Print: 1007.0946 , "From Rutherford to LHC and story onwards" ,
- 2) 'Saga of the Periodic Table of the Standard Model', Physics News Vol. 51, 34, (2021).

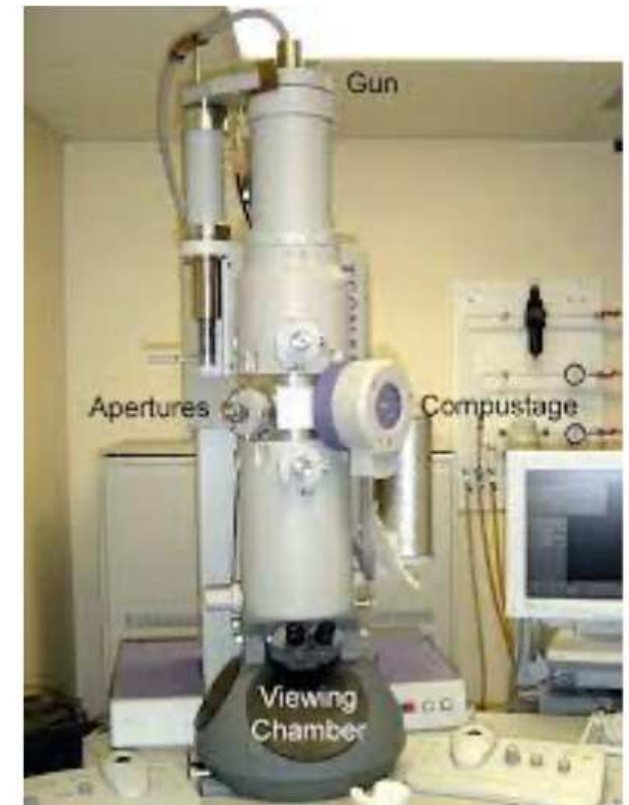
Looking at the heart of matter!



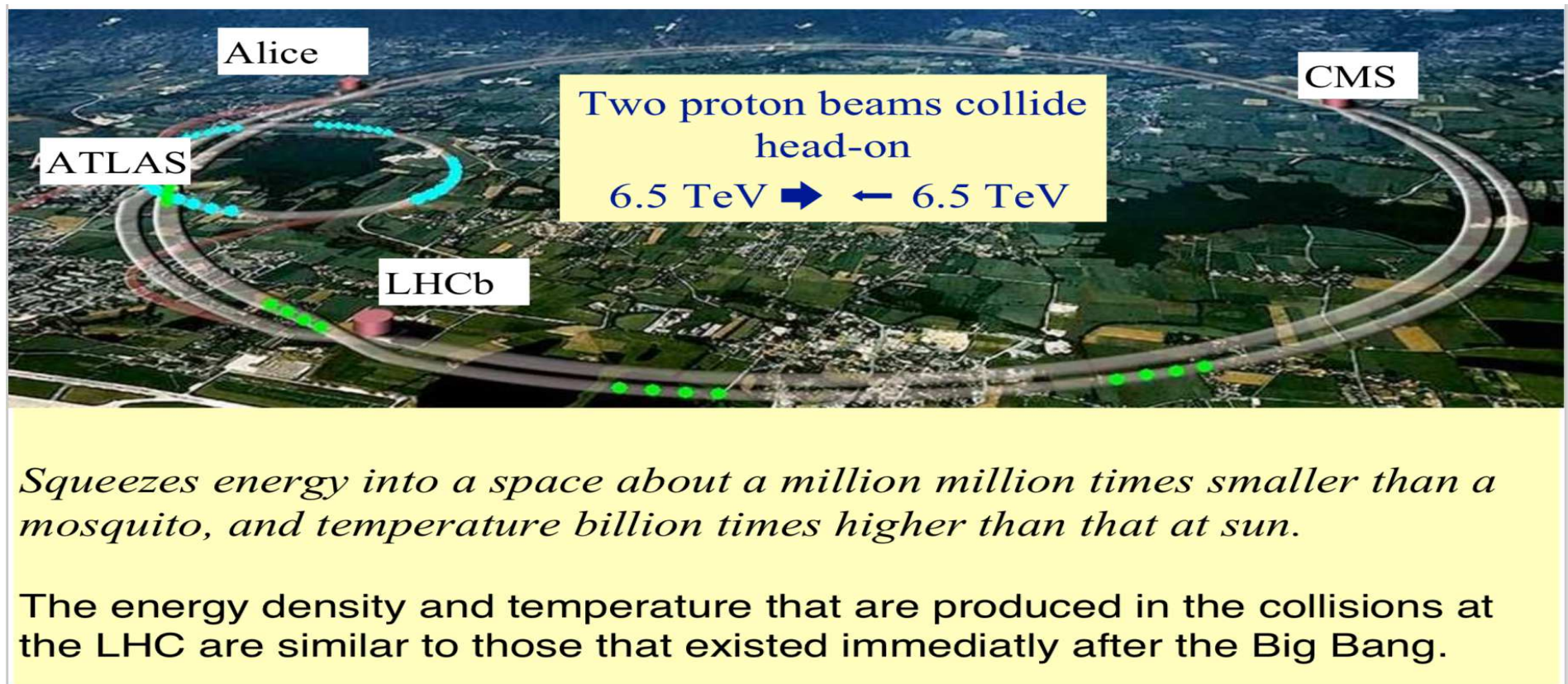
Rutherford Scattering Expt probed the atom.



Scattering experiment 'picturing' a proton



Electron scattering to picture the DNA



It found the Higgs in 2012 and the physics Nobel prize in 2013 was awarded for the discovery. Would have been impossible without the LHC and the experiments CMS/ATLAS. Also recreated conditions of the Early Universe!

Probing the richness of the Universe in various ways!

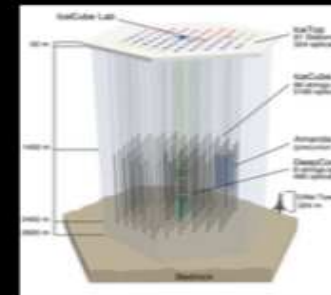
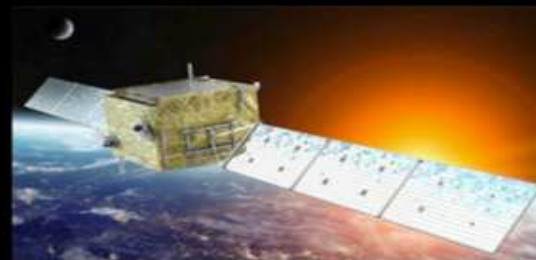
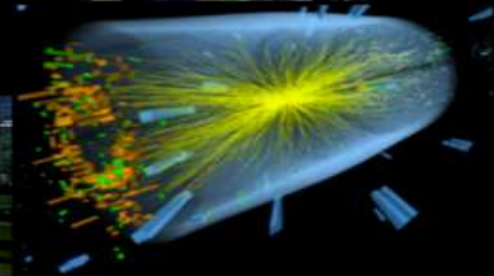
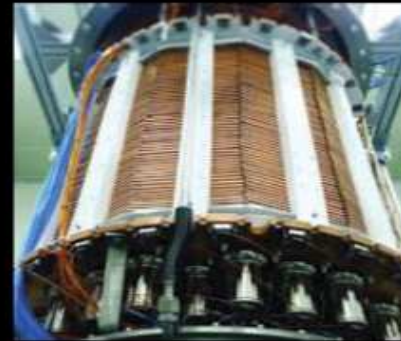
Laser interferometry gravitational wave observatory (LIGO). Artist's conception of LIGO (India). Looking for gravitational waves from the edges of the Universe!



Square Kilometer Array of Radio Antennas to 'look' into the far reaches of the universe

Dark Matter Identification

- Direct Detection
- Collider searches
- Indirect detection



Kenny CY Ng, 24th Feb 2021 IISC CHEP Seminar

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UvA and NIKHEF involved in theoretical and experimental explorations, both current and future, on all these frontiers!

ATLAS, ALICE, LHCb, VIRGO, AUGER, AMS., EHT, KM3NET, DARWIN.....

GRAPPA, Institute of Physics, UvA, NIKHEF Theory Group.....

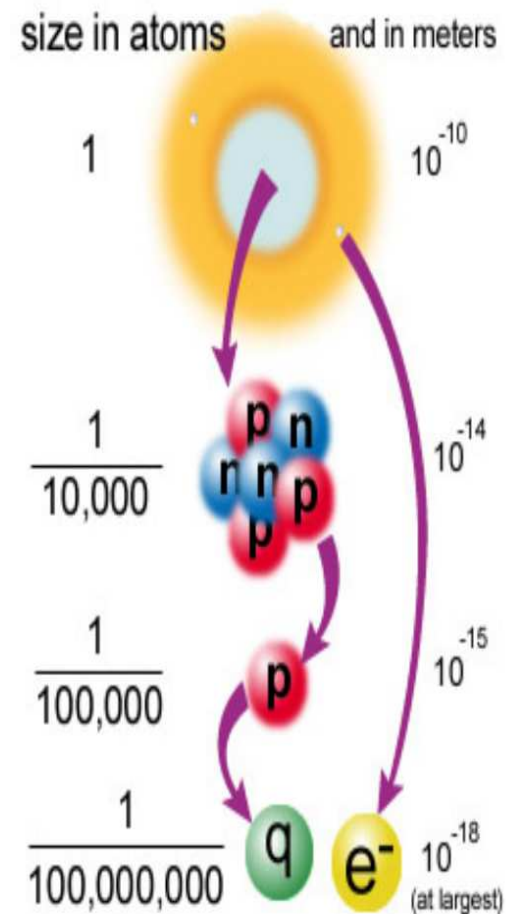
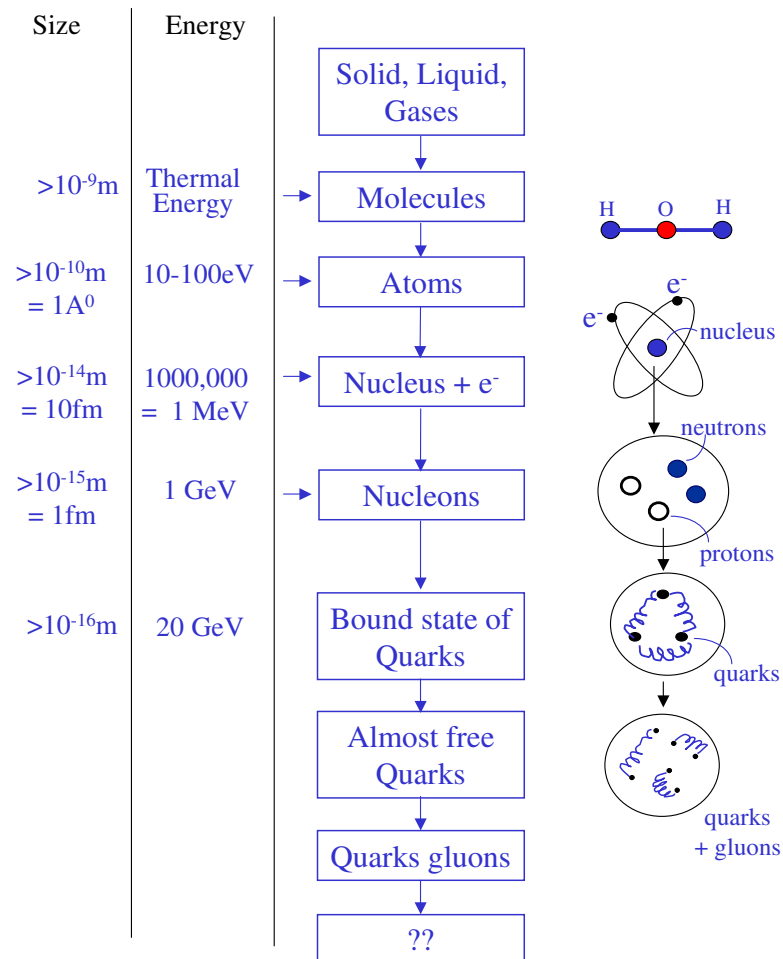
One thread I will follow is why/how, as we looked deeper and deeper inside the heart of matter and explored physics at shorter and shorter distances, we needed larger and larger instruments.

A second thread is to understand that our theoretical understanding of how these fundamental constituents make the whole, has implications for the happenings at the distance scales of the Universe and Cosmos and likely at the beginning of the Universe!

The order of the day is to study the **physics of the large** by **studying the physics of the small** and **at large facilities** and **viceversa**.

Astroparticle physics has arrived.

- ◇ Introduction and Periodic Table of Particle Physics
- ◇ Journey begins: discovery of the electron, photon and nucleus.
- ◇ The age of Nucleons and quarks.
- ◇ Standard Model (SM) of Particle Physics.
- ◇ Next Steps?



Development in Human Scientific understanding has revealed layers within layers. In this talk I want to trace part of the inward bound journey. The methods that uncovered this structure at essentially the same at each level.

Mainly two different ways in which we, the scientists, have inferred what lies at the heart of matter.

- Static methods: ie. use the systematics observed in the properties of the system at macroscopic scale, such as pressure, volume, mass, spin,... etc. **Other word for this is symmetry**
- Scattering experiments: Use scattering of a probe off a body to get information about its structure.

Existence of **atoms** (**electron**) **postulated** from patterns **in molecular and atomic weights** (**ionisation**).

Existence of photon indicated by the **photoelectric effect** , **confirmed** by **Compton Scattering** and **change in the wavelength of light in the scattering!**

Existence of a Nucleus inferred from one of the first scattering experiments: **the Rutherford Experiment**.

In case of scattering experiments we are used to using this method as a way for learning about the interaction between the two bodies which undergo scattering.

So the second way of probing the structure is possible only when one has **some** knowledge of the dynamics at work.

I wish to point out how essentially structure at **all** the levels has been understood through an interplay of these two methods.

So our knowledge what the fundamental building blocks of nature are, has grown as we have understood more and more how these blocks are put together!

Our belief as to what is elemental changed from the 'four/five elements' from the times B.C. to thermodynamics which described three states of matter graduating to Mendeleev's idea of chemical elements obtained using systematics of observed properties of various objects. This then led to Dalton's idea of Atoms (which were really molecules) and order in atomic weights led to the idea of proton! Chemistry and Atomic Physics. The last step was taken by Rutherford when he had already 'discovered' the 'nucleus'!

The branch of science that explored the fundamental constituents of matter has then changed from 'thermodynamics' to 'chemistry' to 'atomic physics' to 'nuclear physics' to now 'elementary particle physics'!

How important is the idea of 'atoms' ?

In the words of R.P. Feynman:

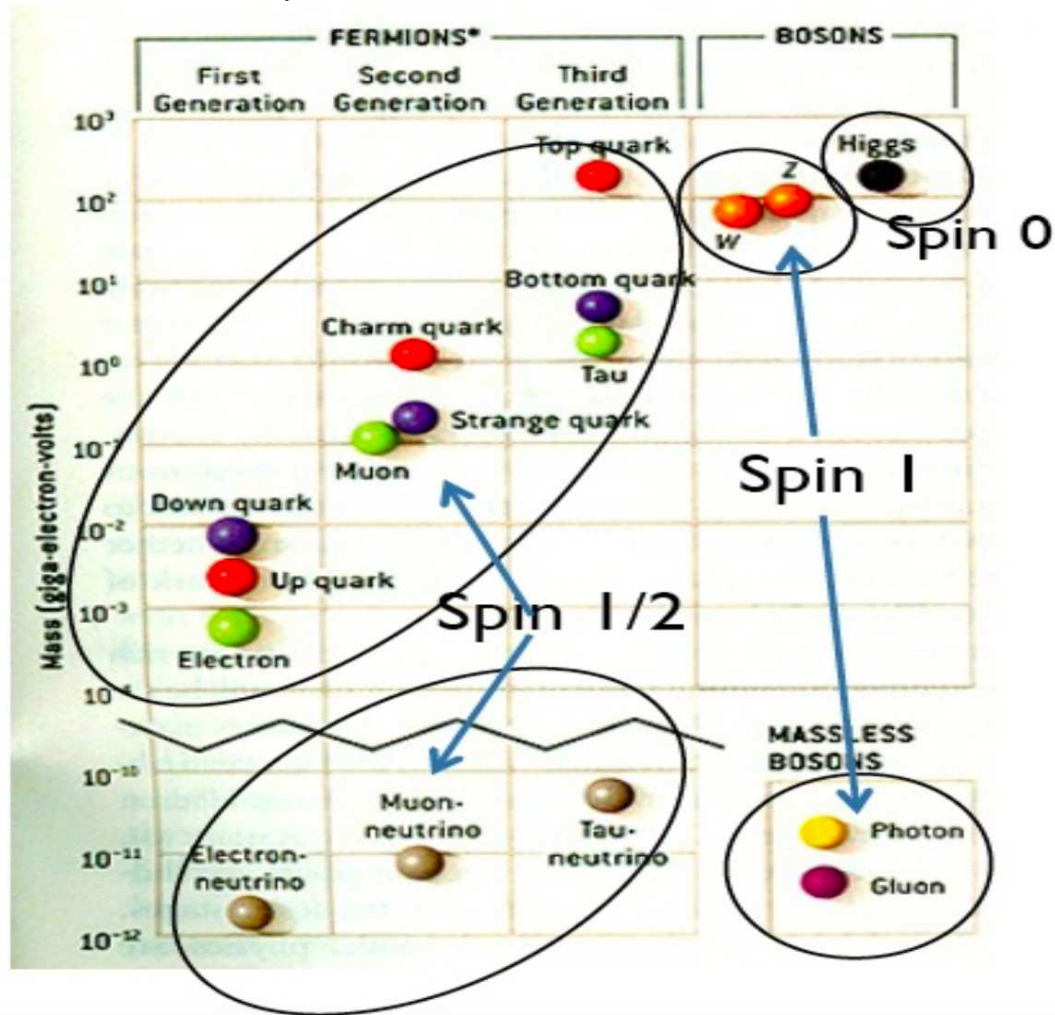
*" If all the scientific knowledge in the world were to be destroyed and I can choose only one piece of understanding to be passed on to future, I would choose to pass on the message that **matter is composed of atoms, ceaselessly moving and bouncing** against each other."*

Finally elementary particle physics has fulfilled Newton's order.
What does this subject deal with?

1. What are the elementary constituents of matter?
2. What holds them together?
3. What is the mathematical framework to describe how the constituents are put together to form matter, how do they interact with each other and how can one predict its behaviour under different conditions?

Trying to understand '2' and '3' taught Particle Physicists the importance of Symmetries and led to prediction of new particles which were found in scattering experiments which in turn fuelled the theoretical development!

SM matter particles and force carriers



Particle content of the STANDARD MODEL (SM) OF PARTICLE PHYSICS!

The 'Periodic Table' of Fundamental particles and their interactions has arrived!

Addition of gravitational interaction and spin-2 graviton will complete the picture!. We only touch upon it here.



Nobel Prize 2013 was given for the last entry. It was awarded jointly to **François Englert and Peter W. Higgs** "for the theoretical discovery of a mechanism that contributes to our understanding of the origin of mass of subatomic particles, and which recently was confirmed through the discovery of the predicted fundamental particle, by the ATLAS and CMS experiments at CERN's Large Hadron Collider"

It's existence was predicted by Weinberg/Salam in the unified Model of Electromagnetic and Weak interaction in 1967. The machine planning began in 1986, indirectly confirmed in 1999, discovered finally in 2012.

Hunting the 'Higgs' was a major expedition.

Was it always so for all the particles?

Not so. Some were accidentally discovered, some were predicted but the 'hunt' was not necessarily so difficult or so expensive.

We essentially want to follow this journey!

Along the way we discovered some objects which we thought were elementary but then discovered they were composites!. These were intermediate stops of the train of knowledge in this journey!

How long was this journey?

Table 3: *History of lepton discovery. Apart from e^+ , the information about the anti-lepton is the same.*

Lepton	Postulated	Indirect	Discovery
e^-	1894		1897
e^+	1931		1932
ν_e		1930	1956
μ			1936
ν_μ		1948	1962
τ	1973		1975

Table 4: *History of quark discovery. Information about the anti-quarks is the same.*

Quarks	Postulated	Indirect info.	Discovery
u, d, s	1964		1969
c	1964, 1970	1974	1974
b	1973	1975	1977
t	1973	1994	1995

Table 5: *History of discovery of the bosons.*

Bosons	Postulated	Indirect info.	Discovery
γ			2005
W^\pm	1961	1961, 1979	1983
Z	1961	1967, 1973, 1979	1983
h	1964	1999	2012

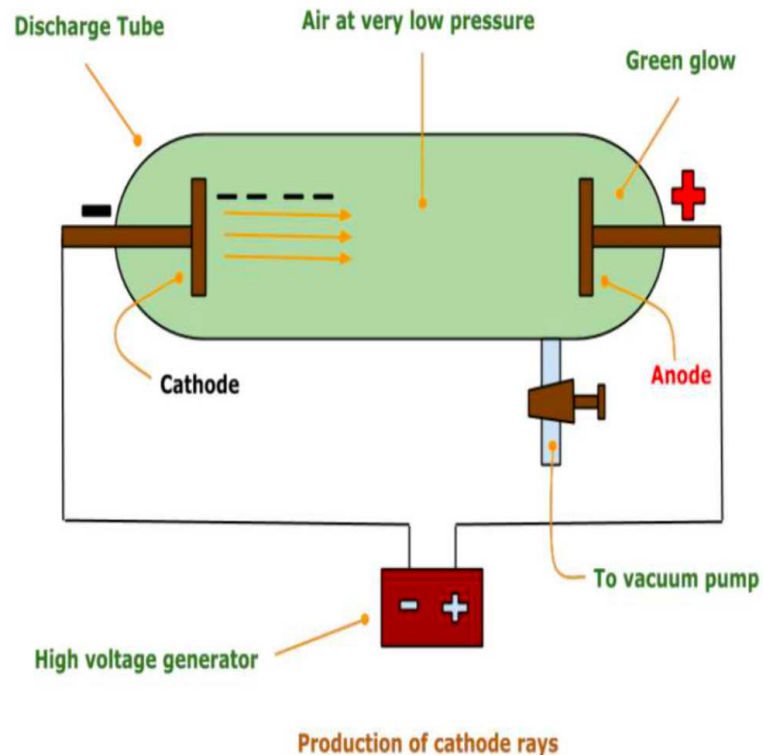
Intermediate stops at the elementarity station:

1)Nucleus: 'discovered' by Rutherford in α particle scattering (1911).
This truly began the inward bound journey into the heart of matter!

2)Pions : predicted by Yukawa (1935), found in cosmic ray experiments (1947).

3)Existence of protons was inferred from observations and that of neutrons from properties of nuclei and then neutron was discovered in 1932.

These were considered elementary at these intermediate points in the journey.



Second half of 19th Century:
Faraday: electricity too comes in multiples of a basic unit.



Experiments with Cathode Rays by Thompson and Discovery of the electron: A particle with e/m ratio different from the hydrogen ion. **The first elementary particle.**

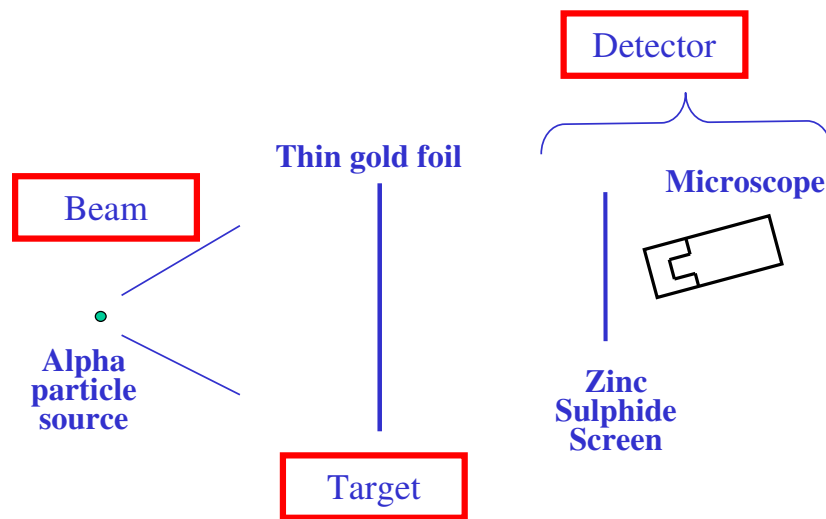
1897: In this discovery of the electron by Thompson, the world of elementary particles of today was born.

Three basic processes in the transition from electron being a "postulated entity" to a "physical reality" :1894.. > 1899.

- 1) Observation by Farady that the electricity comes in units from patterns in ionisation,
- 2) The experiments made by Thompson that Cathode rays behave under the action of electric and magnetic fields as though they consisted of particles with a ratio of charge to mass (the famous e/m) quite different from the Hydrogen ion,
- 3) Lorenz calculated splitting of the atomic spectral lines in a magnetic field. The prediction agreed with Zeeman's measurement if value of e/m was equal to that found by Thomson! The 'corpuscle' seen by Thomson in his Cathode Ray Tube was the same that exists in an 'atom'.

Thompson: Plum pudding model of Atom with electrons sticking out like plums.

The Rutherford scattering experiment: shaped the physics of the Century!



of α particles scattered from the gold foil at different angles were counted.

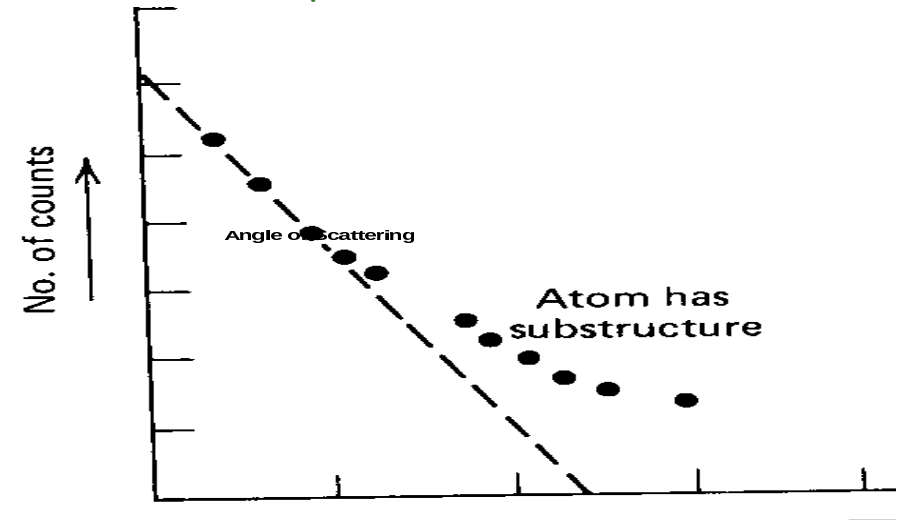
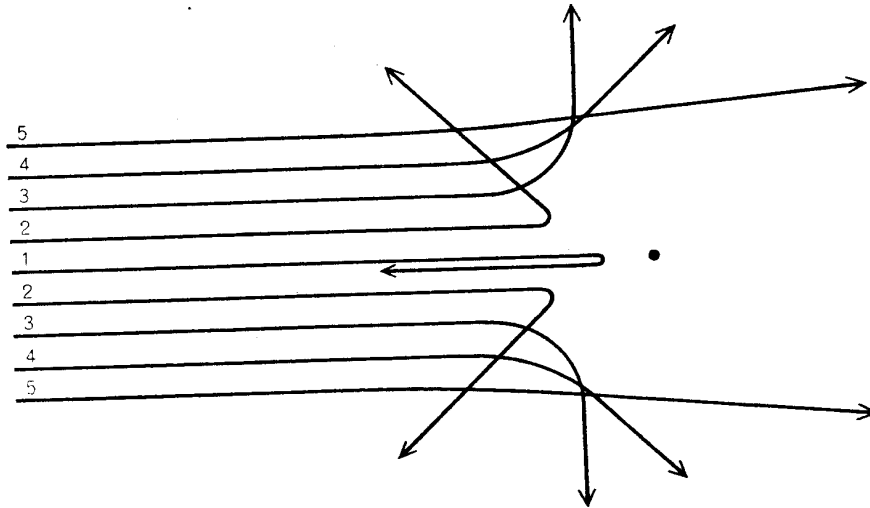
Most α particles went undeflected.

BUT SOME RE-BOUNDED

Completely opposite to that expected if 'plum pudding model' was true.

Rutherford concluded from this: atom has a point like nucleus.

Rutherford truly split the atom into nucleus and electrons! Why did this mean that positive charge of the atom is a 'point': the nucleus?



Distance of closest approach will be where the α particle comes to a stop and then rebounds. For given energies of α particle the distance was about 60 Fermi. So the charge was concentrated in region smaller than that!

Rebound velocity also gave an estimate of the mass at the centre!

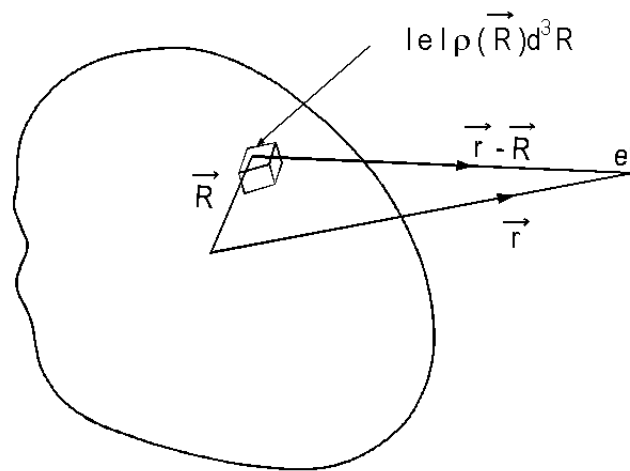
Weinberg, Modern Physics.

Study the distribution of the counts as a function of scattering angle and compare it with that expected from a point target. If they differ the target has a structure.

Simple calculation showed that for a point, screened charge one would expect:

$$\frac{d\sigma}{d\Omega} \propto \frac{1}{\sin^4(\theta/2)}$$

Modification from this then can be used to extract information about the 'spatial extent (the 'size') of the target.



The kinematics of this scattering process is defined in terms of angle θ .

If $\vec{Q} = \vec{p} - \vec{p}'$, normally convenient to use Q^2 instead of θ

If $\rho(\vec{R})$ is the space distribution of the scattering centres one can show that

$$\left(\frac{d\sigma}{d\Omega}\right)_{\text{charge distn.}} = |F(Q^2)|^2 \left(\frac{d\sigma}{d\Omega}\right)_{\text{point}}$$

where $F(Q^2)$ is the Fourier Transform of the 'normalised' charged distribution.

Thus spatial distribution will modify the Q^2 dependence compared to the expectation for a point and for a point $F(Q^2)$ will be a *constant*.

In fact it can be shown that at $Q^2 \ll 1 / \langle R^2 \rangle$,

$$F(Q^2) \sim 1 - \langle R^2 \rangle Q^2$$

This then explains why Rutherford found the nucleus to be pointlike eventhough we NOW know it to have size of the order of a few Fermis.

Our ability to infer and study structure of an object from scattering experiments is possible only when $\langle R^2 \rangle Q^2 \simeq 1$. I.e. smaller the spatial extension higher the energy required.

The existence of atoms was inferred from many properties of matter on macroscopic scale.

BUT

For the *Nucleus* the first indication of its existence came from the scattering experiments.

If the nucleus is made up of nucleons and nucleons made of quarks why did Rutherford 'see' the nucleus as a 'point'?

To understand this recall how we measure 'sizes' of objects? How do we resolve them into their constituents?

Microscopes were used to 'see' things. Smaller the wavelength, higher the energy higher the resolution.

γ behaved as a 'wave' and a 'particle' \Rightarrow De Broglie : Same is true for the electron too! **The wave particle duality.**

$$\lambda = \frac{h}{2\pi p},$$

Use high energy particles to 'see' smaller things. Higher the energy, shorter the wavelength, better is the resolution.

Rutherford used α particles to 'look' inside the atom.

the α particles had energy \sim MeV, wavelength $\sim \frac{1}{100}$ Angstrom.

It could therefore 'resolve' atom into nucleus and electrons.

The nuclear size is smaller than this resolution.

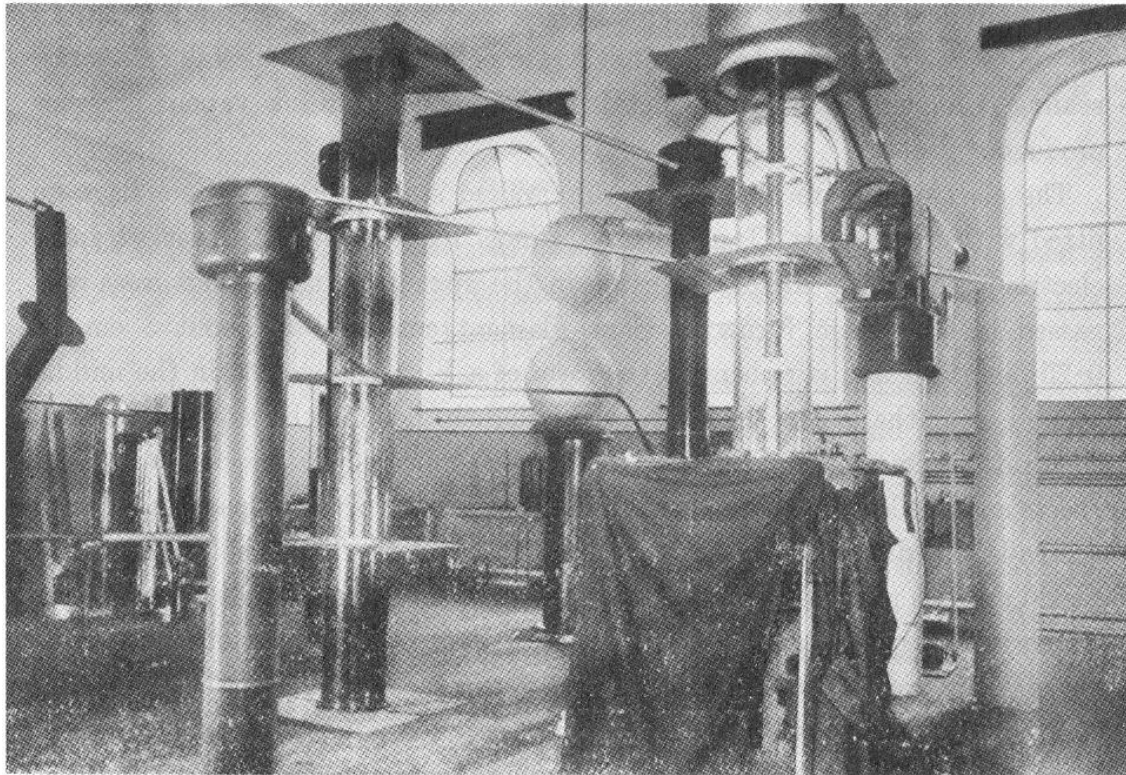
Hence Rutherford 'saw' it as a 'point'!

Need higher energy 'beams': *Rutherford: It has been long been my ambition to have available a copious supply of atoms and electrons which will have energies transcending those of the α, β particles.*

Protons and e^- were accelerated to high energies beginning from the accelerators built by Cockroft, Walton and Van de Graf!

Development in High Energy Physics went hand in hand with the development in accelerating particles to higher and higher energy.

Particle Physics : Journey from the very small to very large! made accelerators: humble beginnings



Cockroft-Walton Accelerator
Fitted inside a room (1931)



First Cyclotron(4.5 inches)
Lawrence-Livingston (1933)
11 inch: accn. to 1 MeV.

(from aip/history web site)



Tevatron Van de Graf generator



LHC Tunnel : 27 km

Patterns in nuclear masses, their spin angular momenta \Rightarrow nuclei too are made up of smaller units : proton and the neutron.

If the 'size' seems to be smaller the least count of our best measuring stick does not mean the object may not have constituents.

Fundamental objects at this point: the photon γ , electron e , the proton(p) and the neutron (n).

AND one more!

THE NEUTRINO.

In β decays:

Nucleus (Z p , N n) \rightarrow Nucleus' ($Z \mp 1$ p , $N \pm 1$ n).

Thus effectively a proton converts into a neutron or vice versa and a positron or electron is emitted.

Free neutron was discovered by Chadwick in 1936!

Found to decay $n \rightarrow p + e^-$

The electron energy seemed to vary continuously in β decays as well as the n decay: at variance with conservation of energy, also of linear and angular momentum!!

'Small neutron': neutrino postulated by Pauli to preserve conservation of energy, angular momentum in nuclear β decay.

All the conservation laws are related to some symmetry or the other!

Example: Conservation of linear momentum: laws of physics do not depend on the position where the experiment is performed.

An example of an invariance being used to posit the existence of a particle!

To repeat again and again!

Note that the conclusion that the nucleus is not an **elementary** object, but a **composite of protons and neutrons** was arrived at by observation of **patterns in properties** of nuclei.

The nucleons *neutrons and protons* were also observed outside the nucleus.

Heisenberg's uncertainty principle also told us that electrons observed in the β decays could not have **existed inside the nucleus** before the decay and hence could not be the **constituents** of the Nucleus!

Facts:

Proton and neutron have very similar masses.

Nuclei are formed with them.

Both have spin $1/2$.

pp, *pn* and *nn* forces in nuclei very similar in strength and range: this was inferred from existence of pairs of mirror nuclei.

Hypothesis: One can imagine the proton and neutron as two states of a particle to be called a 'Nucleon'.

Nucleon with 'I(nternal) spin (I-spin)' in the up direction : proton

Nucleon with 'I(nternal) spin (I-spin)' in the down direction : neutron

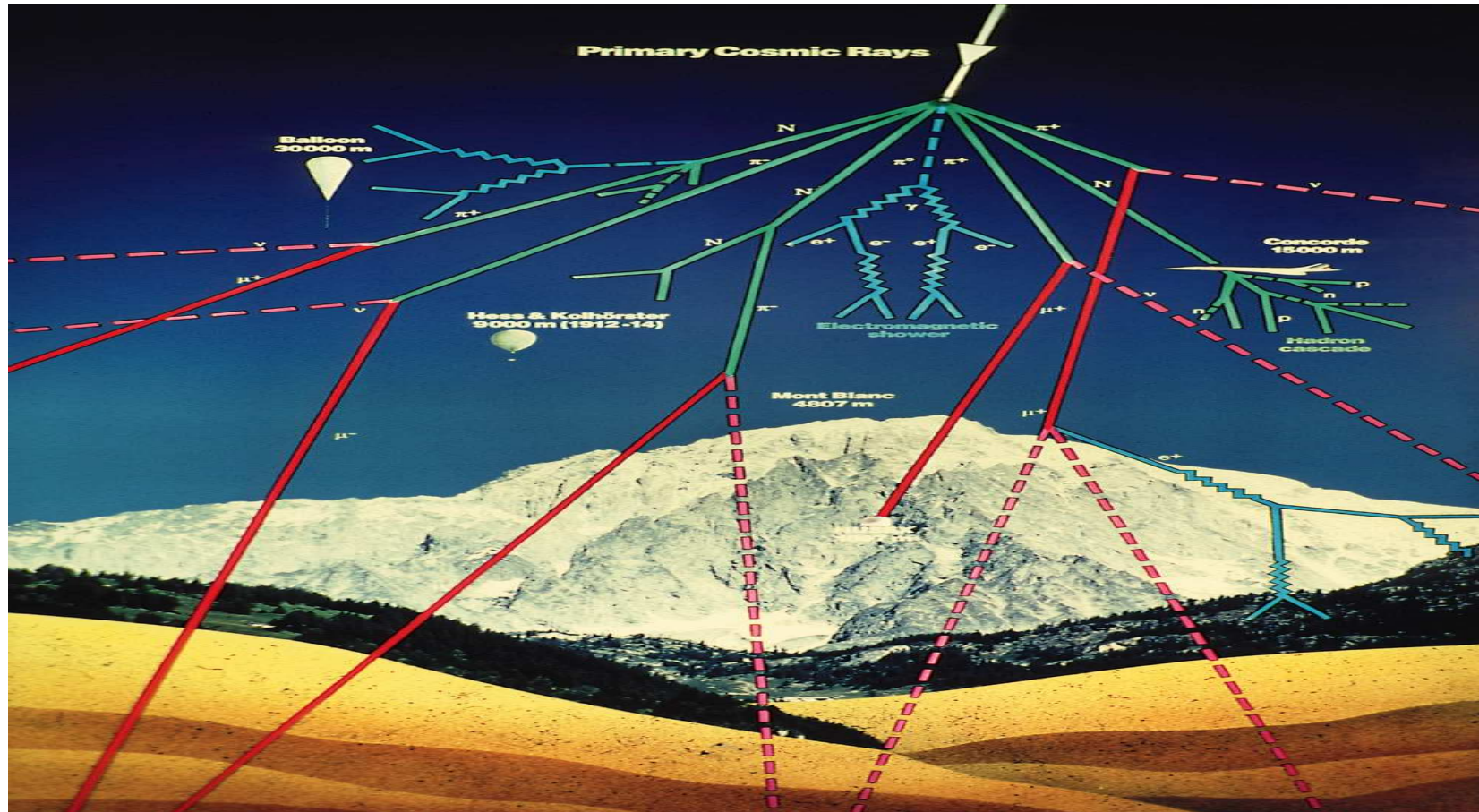
A rotation in real space can change a state of electron with spin along positive z axis to a state with spin along negative z axis.

In the presence of only an electrostatic potential $\propto (1/r)$ we can not detect the difference between these two states.

This is related to the fact that $V(\vec{r}) = 1/r$, i.e. the potential is unchanged (invariant) under a rotation of coordinate axes.

A rotation in the hypothetical/internal space converts a 'Nucleon' in 'spin up' state (proton) into a 'Nucleon' in 'spin down' state (neutron).

Hence the 'interaction' among two protons or neutrons remains unchanged ('invariant') under a rotation in the I-spin space.

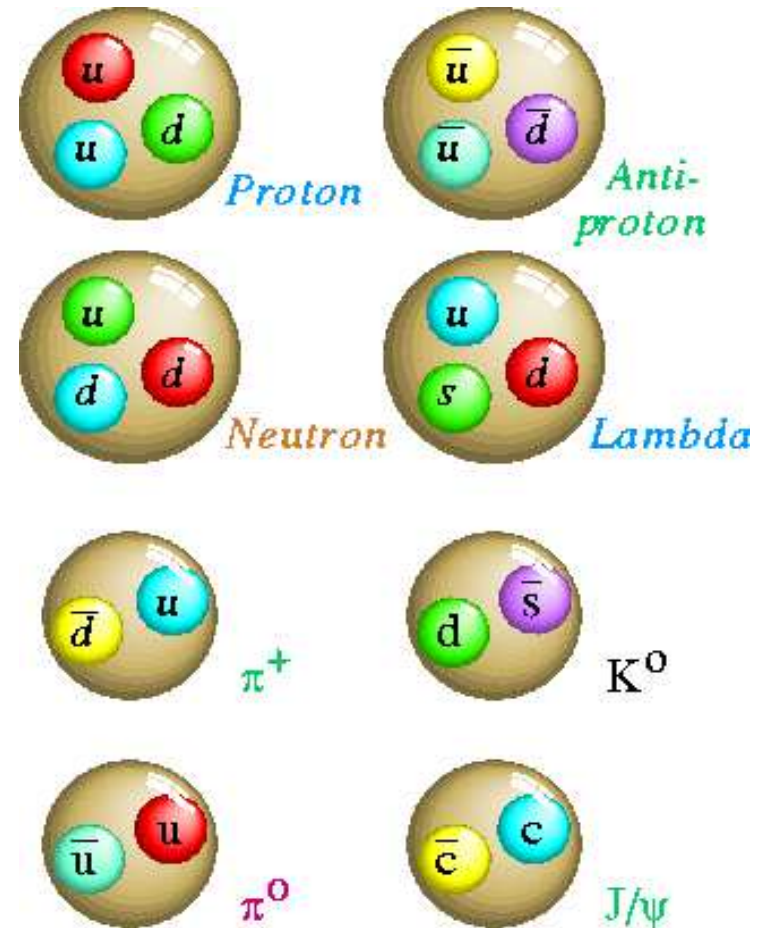


Discovery of a 'Zoo' of particles in 'Cosmic' rays and also in the accelerator experiments in the USA. Large number of particles just like the proton, neutron. **All** of them can not be **fundamental**.

Gell-Mann-Zweig presented an extension of the **I-spin idea** which was by then supported by a lot of data in Nuclear physics!

All these observed 'heavy' particles **Hadrons** (Baryons and Mesons) are made of even more fundamental objects **Quarks**. Based on ideas of symmetries!

The u, d, s Quarks had arrived. Story of c, b, t is more complicated.



Observation by Gell-Mann and Zweig: Pattern and the regularity exhibited in the properties of the members of particle 'ZOO' \Rightarrow Smaller number of constituents: quarks.

Nobody could till then break up the protons and neutrons into quarks.

Perhaps quarks were not “real” entities, but some kind of mathematical abstraction.

Worse, they were required to possess fractional electric charges (one-third or two-third the charge of an electron)

Many Physicists decided maybe quarks are abstract entities. Just like the Chemists of 19th century who had decided 'atoms' and 'molecules' were not real!

Even worse: they needed to come in three different varieties, called colour, to avoid a clash with Pauli's exclusion principle!

Gell-Mann Predicted existence and mass of a particle called Ω . Confirmed experimentally. Got the Nobel Prize!

So where were the quarks? Can a Rutherford type experiment see them?

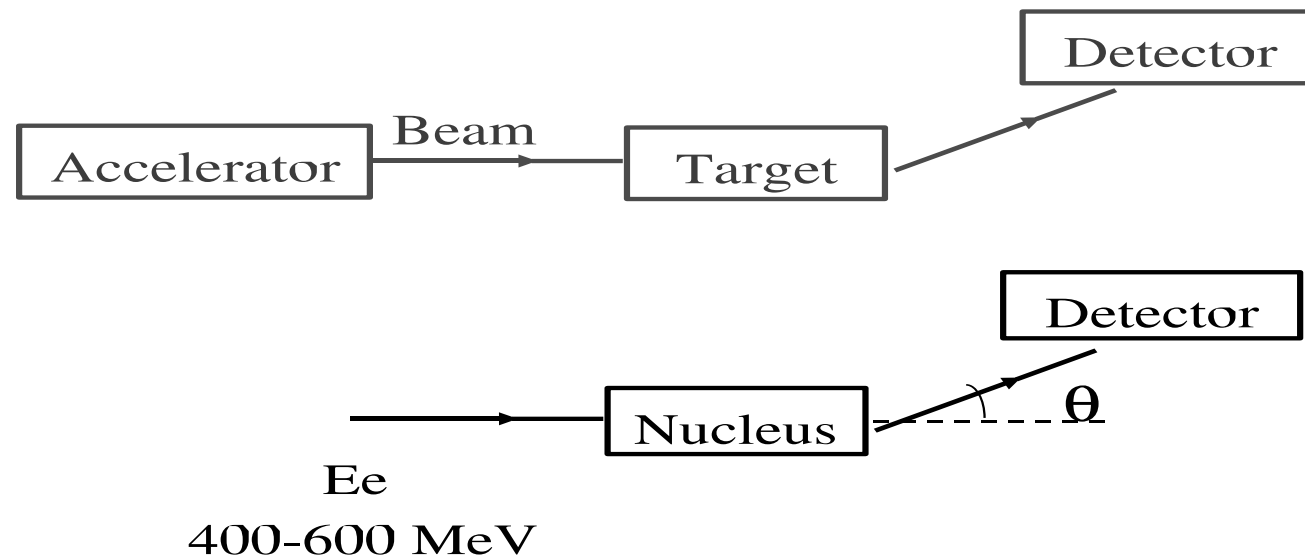
Why do they not appear free in space?

Can we see them when we break open a proton?

How do we break it?

Note the difference from the case of nuclei and nucleons.

The Hofstadter Experiment: The nucleus/proton version of Rutherford Scattering experiment. **Stanford Linear Accelerator: S.L.A.C.**



Note similarity with Rutherford experiment. The $\lambda_e \sim$ a 1000-10,000 times smaller than λ_α . Count the number of electrons scattered at an angle θ compare it with the number expected for a 'point' nucleus/proton.

Particle Physics : Journey from the very small to very large! The actual accelerator and detector



from : [Interactions.org](https://interactions.org)

The nucleus and proton have a finite size!

The ratio with expectations with a point nucleus/proton, calculated from 'known' dynamics, ~ 1 for $\lambda_e \gg R_{target}$

If $\lambda_e \sim R_{target}$ ratio will differ from 1.

R_{target} is the radius of the nucleus/proton.

Nuclei about 10,000 – 100,000 times smaller than atoms.

Establishing nucleus has finite size which was to be expected because it consisted of nucleons.

WHAT ABOUT THE PROTON?

Hofstadter studied:

$$e(E_e) + p \rightarrow e(E'_e) + p$$

For a given E_e and θ there will be a fixed value of E'_e .

Finite size of the proton was confirmed by the scattering experiments (just like nuclei). Size $\sim 100,000$ times smaller than an atom: a Fermi.

Confirmed the inference obtained from measurements of static properties.

The surprise came when E_e was increased even further!

Increase E_e to 10,000 – 20,000 million electron volts. Resolution 1/100 compared to the size of the p/n .

E'_e for a given angle of scattering had many different values. May be the p had something inside it.

At still higher values of E_e the scattered electron again began to have a unique value E'_0 , different from that for a proton. $\Rightarrow \lambda_e$ small enough to feel the individual scatterers inside the proton.

The exact value of E'_0 could be used to extract their number, which was found to be three.

It is thus revealed existence of 'elementary' quarks inside the 'composite' proton like Rutherford's large angle scattering revealed existence of 'pointlike' nucleus inside the atom.

This is what Gell-Mann's model needed. The quarks thus made a second coming!

Measuring the e^- energies for different angles, the spin of the scatterers could be determined. These seemed to have all the properties as required by Quark Model: even the funny charges!

Scattering experiments thus substantiated the conclusions drawn from observing the 'patterns' (or the 'symmetries')

But they did something more:

The same experiments also showed that there existed scatterers inside the proton, which can not 'see' the electron as they are neutral!

In fact in the theory of strong interactions being developed around the same time, such neutral force carriers called gluons, were indicated.

The change in the number of scattered electrons with different energies and at different angles was consistent with the predictions of the theory of Quantum Chromo Dynamics.

This was the first glimpse of the 'gluons' and first clue to the correct theory of strong interactions! This got the Nobel Prize for Physics in 2004, although the theory was put forward in 1974!

It took 30 odd years for experiments to confirm that this was indeed the correct theory!

See the interplay between theory and experiments!

Increase the energy E_e further, the number of constituents goes on increasing. More and more quarks and gluons are created inside the proton, when one tries to probe it with higher and higher energy.

The increasing energies do not reveal any new constituents but reveal only this increasing number of quarks and gluons inside. Completely consistent with the predictions of theory of interactions between quarks and gluons!

At present experiments with highest energy e 's $\sim E_e = 100 \text{Billion eV}$ no evidence for any substructure of a quark up to a 1000^{th} Fermi.

END OF ROAD IN SUBSTRUCTURE???

YES we think so!

Are we saying this simply because we don't have high enough energy probes? No.

This is where the dynamics, comes into play with full strength. Scattering (or equivalently "seeing") of the constituents only *one* way in which we hunt for what is at the heart of the matter.

At present every single piece of experimental observation agrees to a very high accuracy, better than to one part in a 100 Millions at times, with the predictions of a theory which treats these quarks and leptons as point-like in the calculations up to energies ~ 10 billion billion eV.

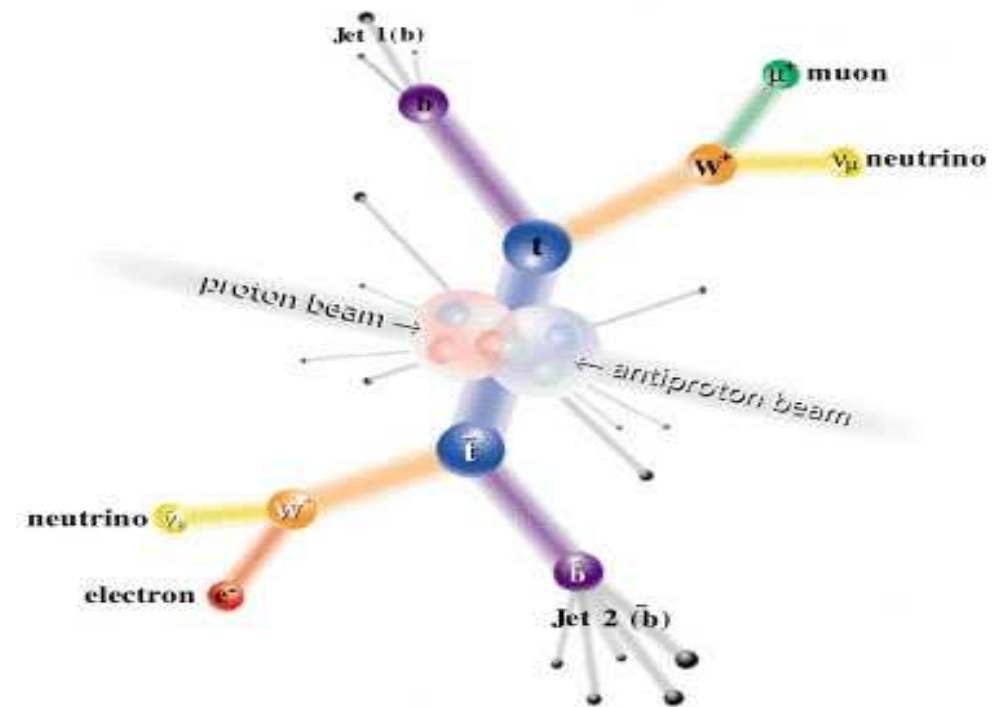
Thus we have an "indirect" *but very strong* proof that the quarks and the leptons are indeed point-like and have no further substructure.

Once one has an understanding of the dynamics of the fundamental constituents i.e interactions among them, one can perform high energy experiments where these scatter off each other, shedding light on

1) The way these interact with each other

2) Give information on sub-structure if there is any.

This is part of what the LHC is doing!



So far I had followed only one track of the journey of particle physicists asking questions of what are the ultimate constituents of matter!

I have covered so far only the 'elementary' constituents

$e^+, e^-, \mu^+, \mu^-, \nu_e, \nu_\mu, u, d, s$ quarks and the γ . !

What is the story of the discovery of the rest of the quarks c, b, t , leptons τ, ν_τ , the heavier force carriers W, Z , the massless gluons g and the spinless Higgs h ?

The second track is how to find the mathematical framework describing the elementary interactions among these fundamental blocks which then form the whole?

In the 60's many different things were happening simultaneously in the world of elementary particles!

I presented the journey into the heart of the matter by probing it with higher and higher energy probes!

But this would have been impossible without corresponding strides in our understanding of the dynamics!

The story of discovery of the remaining particles is closely intertwined with those developments!

The existence of the heavy gauge bosons W, Z and the Higgs boson h was predicted in the SM.

Masses of only the W/Z were predicted and they were discovered with the right mass and right couplings to matter. (Rubbia and Van der Meer got the Nobel for that)

Heavier quarks and leptons: c quark was predicted by till then developed part of the Standard Model!, but the actual discovery was accidental (1974 , November revolution).

The b, τ were not required by consistency of theory but were found unlooked. (1974-1977) Once these were found t quark HAD to exist if the SM was right and its mass was predicted too!. (1995)

Measurements of the Z boson properties at the Large Electron Positron Collider (LEP) had provided indirect estimate of its mass.

The Higgs h was predicted but not its mass. Theory gave only limits!

Finding the Higgs at that mass with the right properties was the crowning success of the SM.

$$\begin{aligned}\mathcal{L} = & -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} \\ & + i \bar{\psi} \not{D} \psi + \text{h.c.} \\ & + \chi_i y_{ij} \chi_j \phi + \text{h.c.} \\ & + |D_\mu \phi|^2 - V(\phi)\end{aligned}$$

Sir Issac Newton (circa 1700 A.D.). The beginning of what Steven Weinberg called 'Age of Enlightenment'!

Newton in Optics defined a process of substantiating the idea:
Now the smallest Particles of matter may cohere by the strongest attractions and compose bigger particles of weaker virtue....There are therefore agents in nature able to make particles of Bodies stick together by very strong attractions and it is the Business of experimental Philosophy to find them out'.

Branch of Science dealing with elementary constituents of nature :
'Experimental Philosophy'

Particle physics seems to have full filled this order by Newton!

LHC accelerator and LHC experiments were the end station of a journey which began in a small room in 1897 in a small table top experiment.

This experiment allowed us to establish the correctness of the Standard Model(SM) of Particle Physics.

What next?

Is it the end of the journey?

Far from it!

There exist many **observational** reasons, some in the world of particles and some cosmological which indicate that physics **particles and interactions beyond the SM** (BSM) exists.

- 1) $g-2$ of the muon
- 2) Flavour non universality
- 3) Precision measurement of the mass of the W .

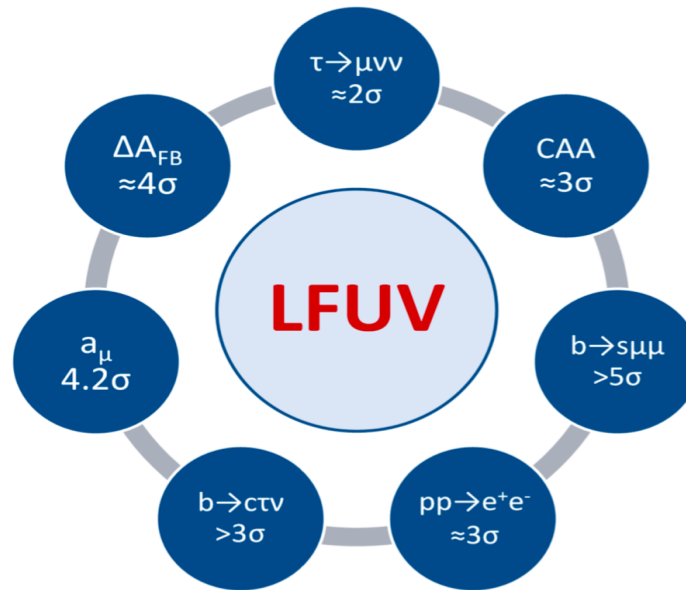
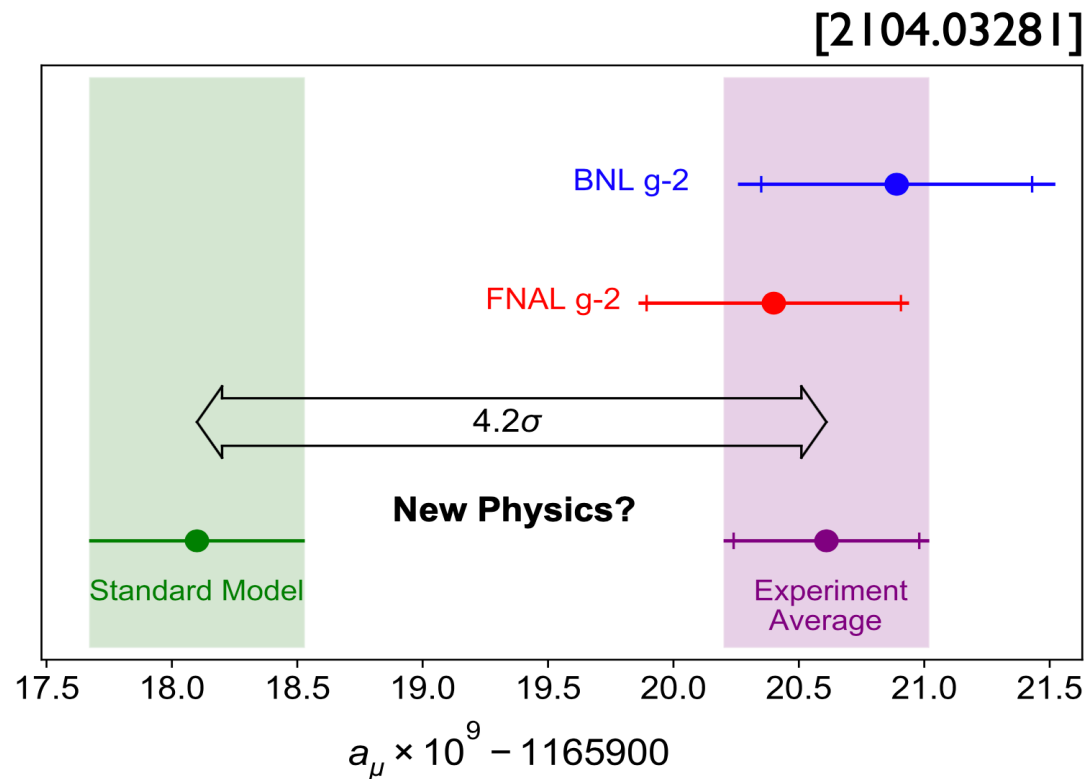
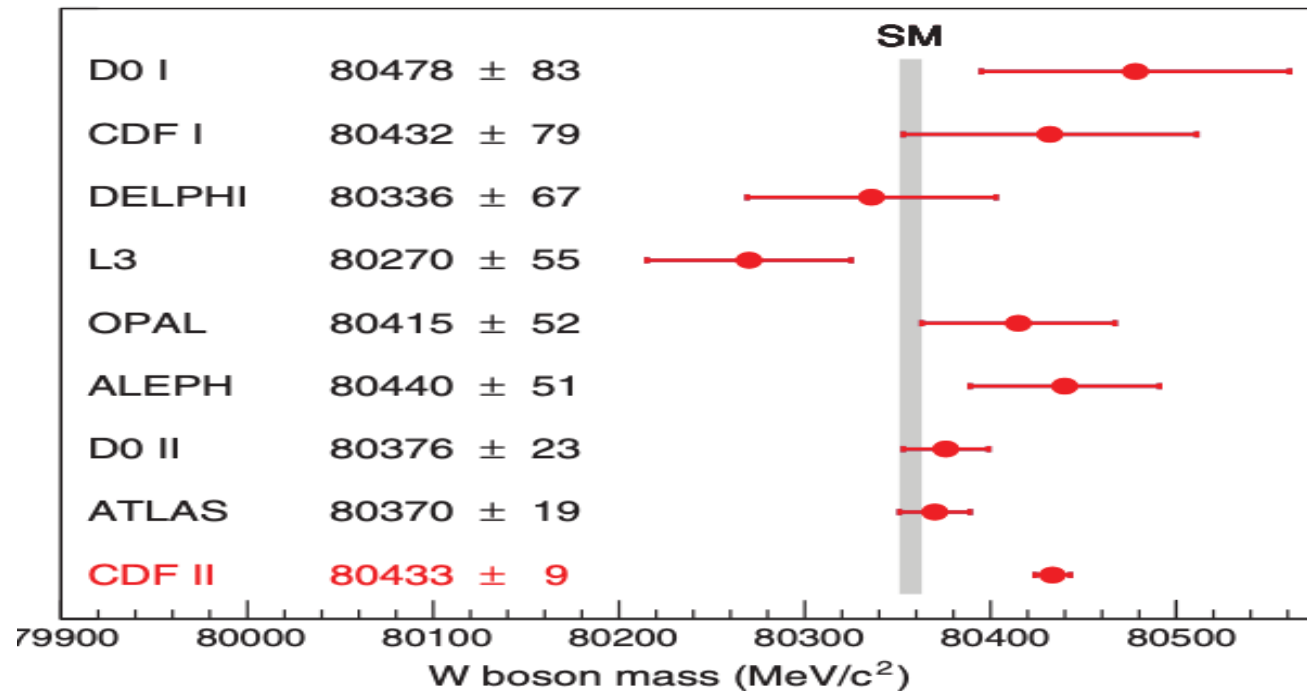


Figure 1: Summary of the experimental hints for LFUV beyond the SM.

Lepton Flavour Universality Violation: is that the thin edge of the wedge? Ref: Unveiling Hidden Physics at the LHC [[arXiv:2109.06065 \[hep-ph\]](#)], To appear in EJPC.

Difference between the theoretical expectation in the SM and measured value at one ppb. (Phys. Rev. Lett. 126, 141801). Evidence for new physics seems compelling. Critical evaluation of theory 'prediction' necessary.



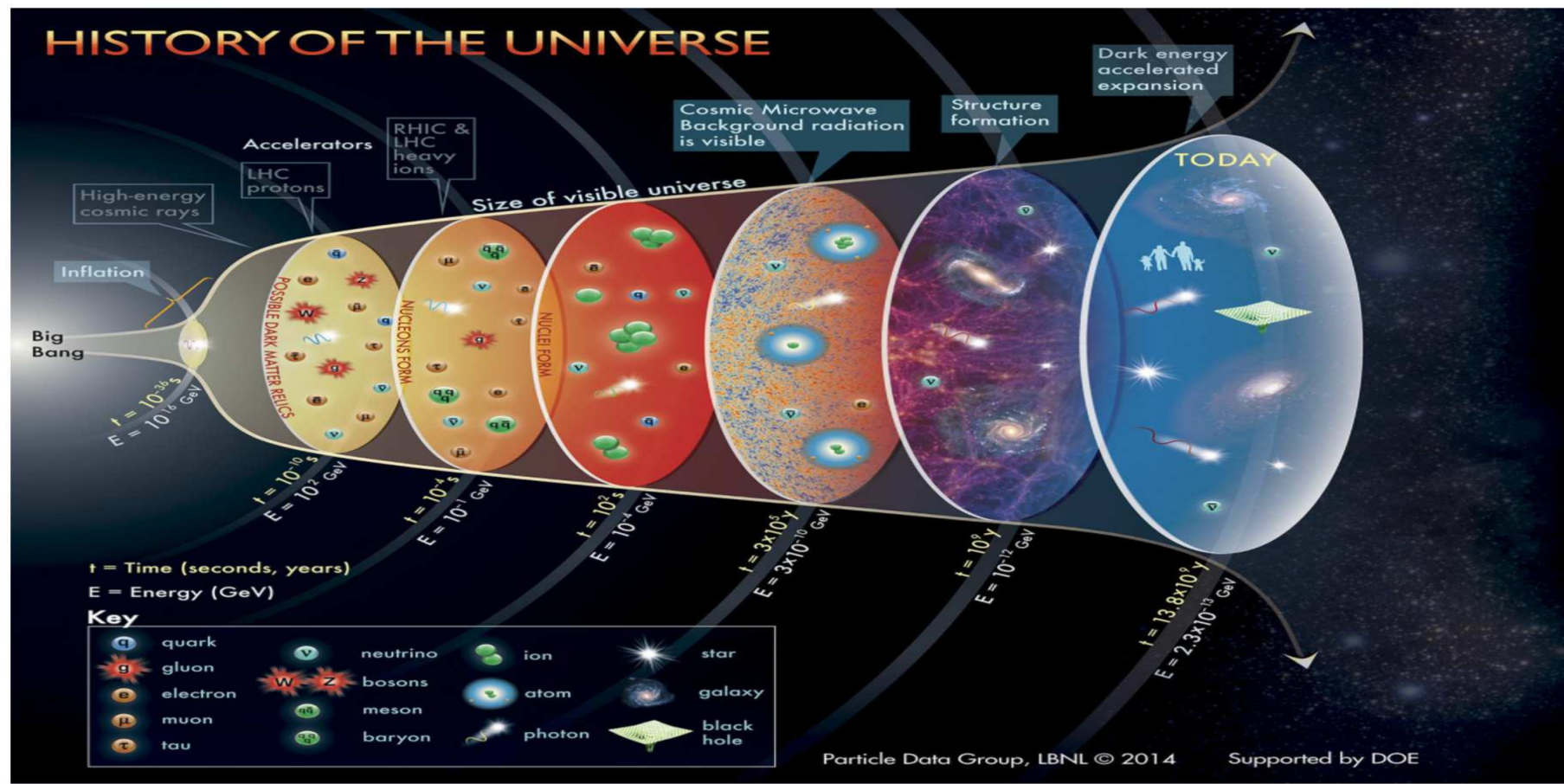


In this case it is the precision of the new experimental result that needs scrutiny!

We also have 'cosmic' reasons! There are many cosmological observations which still lack an understanding or have an incomplete understanding in the framework of the Standard Model (SM).

These puzzles are of relevance for particle physics because of the cosmic implications of theories of particle physics. (Bethe, Gamow and Weinberg were the three giants who pioneered these cosmic connections of Nuclear and Particle Physics)

These are the pragmatic reasons to believe in physics (particles and/or interactions) beyond those in the SM : BSM.



Deep connections between particle physics and cosmology

There are three cosmic reasons:

1) Dark Matter in the Universe:

2) Matter-antimatter asymmetry in the Universe

3) Universe seems to be accelerating. (Dark Energy)

Particle physicists have a few more reasons

4) To explain why the Higgs light!.

5) Nonzero mass of the Neutrinos + Understand hierarchy of fermion masses.

6) Some BSM ideas play with the fact that t and *Higgs* are composite!.. the compositeness scale has to be above a few 100,000 GeV!

The micro and macro connection indicates that one needs to think of new uses for the old tools and new tools specifically designed for the purpose.

Welcome to the world of astroparticle physics.

Theories of particle physics have implications for cosmic observations and events. Measurements at particle colliders can perhaps give information about what happened in the early Universe!

E.g. : Heavy ion experiments at the LHC can offer a probe of some of the physics that we think went on *before* $T \sim \text{MeV}$!



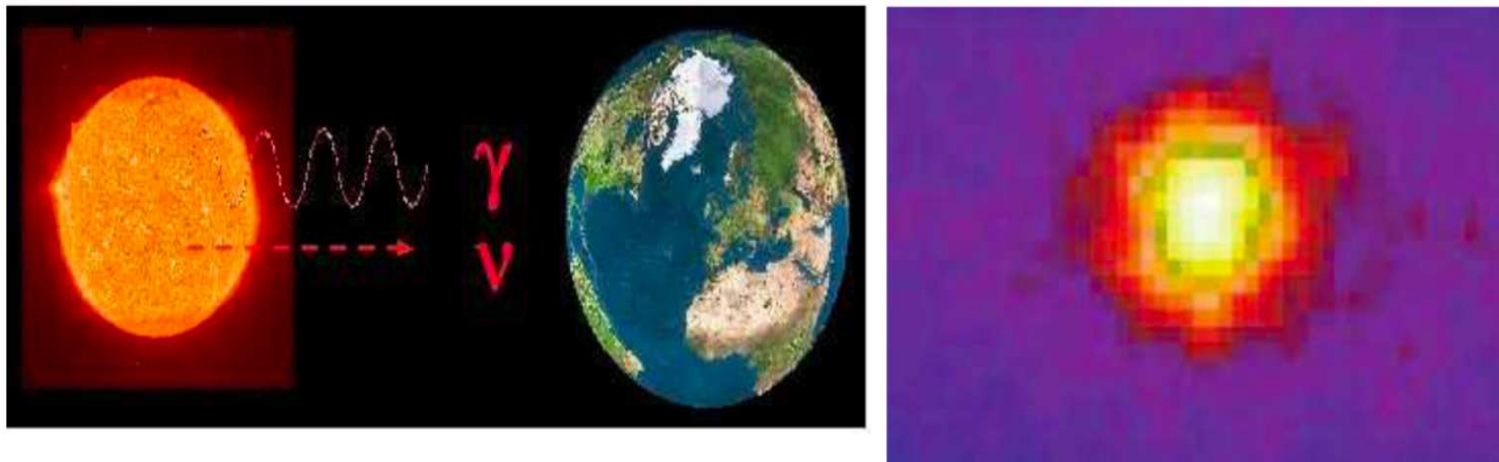
These can, for example, probe for various suggestions to go beyond the Standard Model but also to probe the Dark Matter, CP violation, big bang.....

Terrestrial experiments and those in the sky have to probe the wonders of nature together!

We will probe the universe through diff. probes:

- 1) The optical (Hanley),
- 2) The radio (GMRT, SKA, [Auger](#)),
- 3) Gravitational ([Virgo](#), LIGO),
- 4) Neutrinos (Kamiokande, Icecube, [DUNE](#), [INO](#), [KM3NET](#)) ,
- 5) Dark matter experiments ([Xenon-1T](#), [DARWIN](#))
- 6) Colliders ([LHC](#), [ILC](#)).
- 7) Space based experiments : PLANCK, [AMS](#)....

An example of multiwavelength probe that I find fun!



$$\begin{aligned}
\mathcal{L} = \sqrt{g} \{ & R - \frac{1}{4} F^{\mu\nu} F_{\mu\nu} + \theta F^{\mu\nu} \tilde{F}_{\mu\nu} \\
& + i \bar{\Psi} \not{D} \Psi + Y_{ij} H \Psi_i \Psi_j + \text{h.c.} \\
& + |D_\mu H|^2 - V(H) \} \\
\cong & \text{Our Universe... so far}
\end{aligned}$$

Us theorists are trying to push on the theory of gravitation and its implications, for example, for PLANCK like experiment.

So future of particle physics is tied with future of cosmology and astrophysics and looks good!

Lots we do not understand! But that is good!

Advice from Steven Weinberg:

“My advice is to go for the messes — that’s where the action is.”

He said:

“Particle physics... really was a mess in the 1960s, but since that time the work of many theoretical and experimental physicists has been able to sort it out, and put everything (well, almost everything) together in a beautiful theory known as the standard model.....
to continue using my oceanographic metaphor, is that while you are swimming and not sinking you should aim for rough water.”

BACKUP

Logical sequence of steps leading to the structure of matter.

1. Seek the regularities/patterns in properties such as masses, spins etc. Very often these reflect *possible* existence of a more basic fundamental units which makes the whole
2. Measure the "size" of the constituents, which at the level of atomic distances and smaller, is simply doing scattering experiments using beams of higher energy particles to get probes of shorter and shorter wavelengths: **example at the atomic level of this is Rutherford's experiment**
3. A parallel and necessary step is also the development of a theory of the dynamics that holds these units together. See if the observed properties of the composites agree with the predictions of the theory

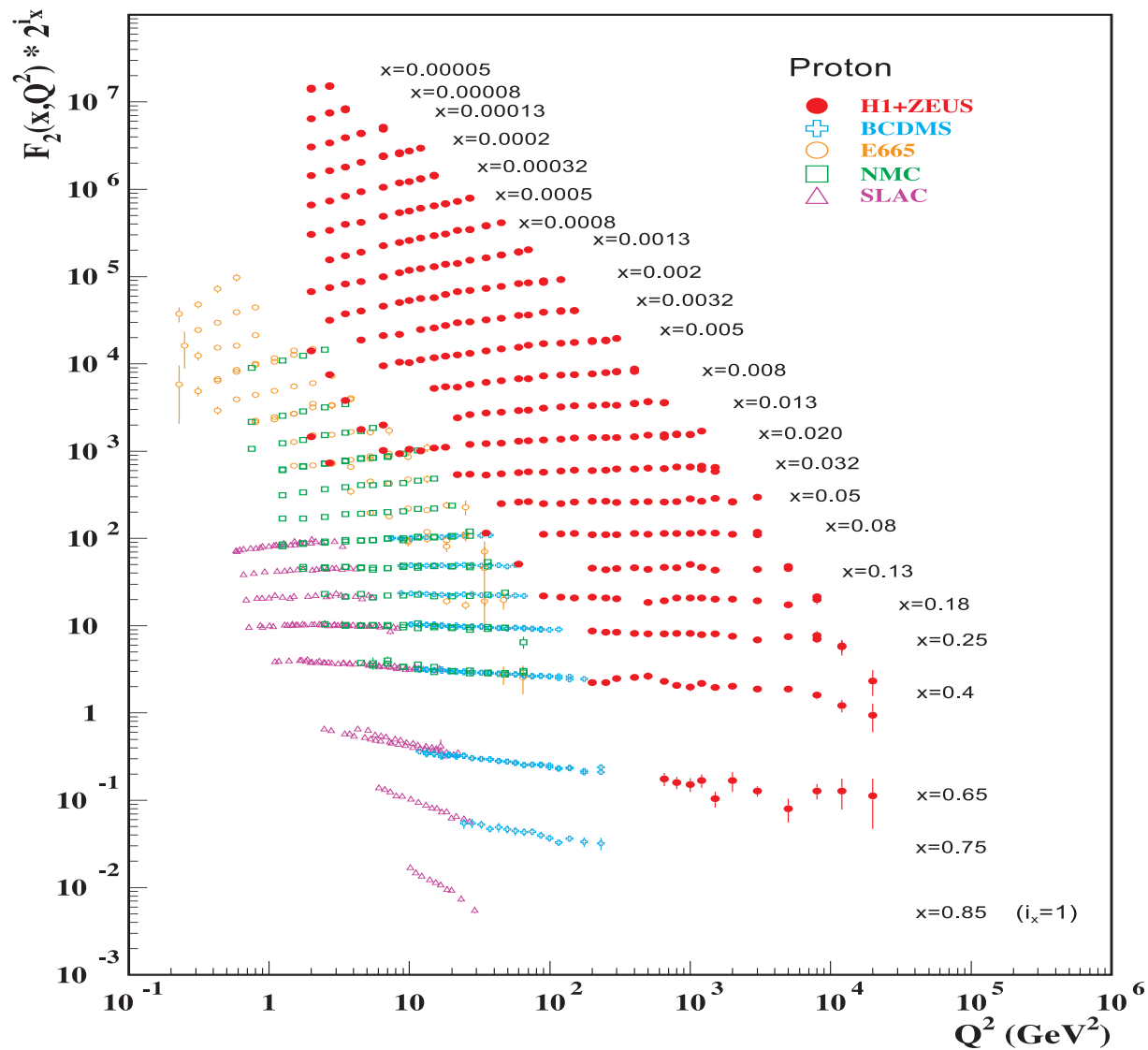
Interaction of a charged particle with magnetic field is decided by its magnetic moment. Ratio of magnetic moment to the spin is called the Gyromagnetic ratio.

Proton had **gyromagnetic ratio** ~ 2.75 . According to Dirac a spin half point particle should have value 2.0.

Neutron which is neutral should have no magnetic moment at all, but it does!

This already implied proton and neutron must be at least charge distributions

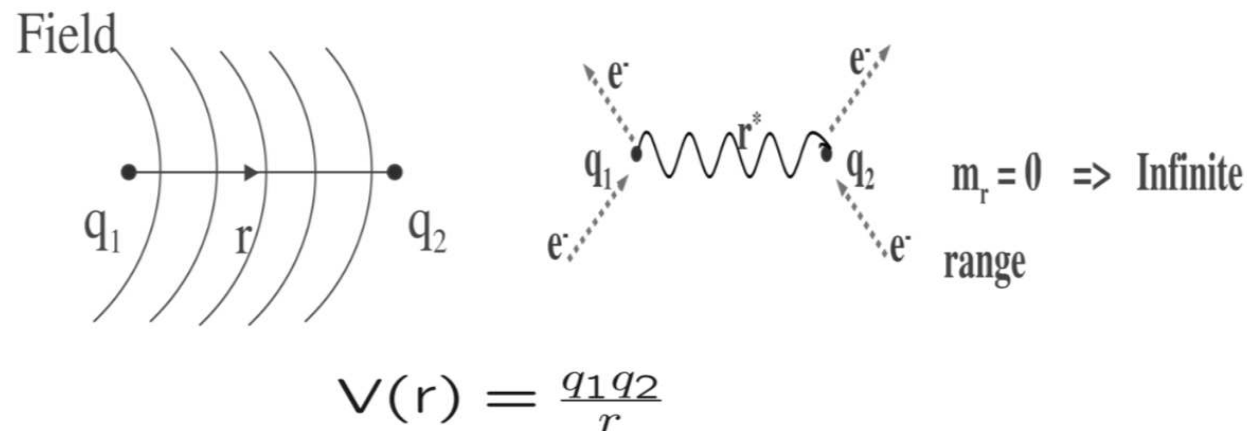
Can we get information on the spatial extent of these distributions?



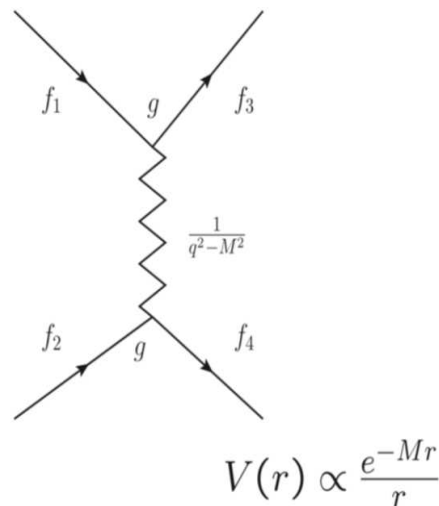
The data follow theory prediction over orders of magnitude of measured cross-sections and energy at which they are measured.

A mathematical framework to describe the interactions among the particles in terms of an exchange of force carriers was developed based on twin pillars of Quantum Mechanics and Special Theory of relativity.

Quantum Gauge Field theories were found to be the 'correct' framework for description of particle interactions. Feynman, Tomanaga and Schwinger did that for electromagnetic interactions.



Development of Gauge Field Theory of Weak interactions was indicated by the work of E.C.G. Sudarshan and Marshak, Feynman and Gell-Mann and Schwinger. The general idea was that like the 'photon' there is a 'weak analog of the photon'.



The photon had **zero mass** and it had played an essential role in being able to describe interactions mediated by it as a Quantum Gauge Field Theory.

Short range of the weak interactions meant that the '**mediators**' were **super heavy**.

The predictions of such a quantum field theory made no sense at high energies or in higher orders of perturbation theory.

Work of S. Glashow, P. Higgs, A. Salam and S. Weinberg all together helped in sorting this mess out. By 1967 one had a 'Model of Leptons' of unification of Electromagnetic and Weak Interactions.

The Standard Model (SM) is nothing but the model of leptons extended to include the quarks and strong interactions.

Predictions of Electroweak Unification:

- 1) Existence of a heavy counterpart of the photon which would mediate new weak interactions, the so called 'neutral current interactions'
- 2) Predictions of the masses for the W and Z and also of couplings of leptons with the Z boson in terms of the electron charge e and a parameter θ_w .

Discovery of the new type of weak interactions with strengths as predicted by the model was enough for the Nobel Prize to be given to the three heroes, even though W/Z were not discovered at that time!

Carlo Rubbia and van der Meer won the Nobel prize for making their discovery possible.