From Quarks To Cosmos

A Physicist's View Of The World

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Introduction

Physics is the science of uncovering laws of Nature.

Implicit concepts and philosophical stands:

- There exists a Nature (Realistic viewpoint).
- Nature has Laws. It works upon pregiven/preassigned laws.
- We, the humans, have the potential to uncover these laws.

Introduction

- These laws are describable through mathematical equations/formulations, i.e.
- Our mental abilities/(mathematical) logic have the potential to *model the Nature*.
- This is the Nature, experiment or observation, which decides whether our modeling is the right one.

Introduction

- Laws of Nature generically describe the dynamics, how the systems evolve,
- systems of all possible scales, from the smallest to the largest we have been able to observe/detect.
- As time goes by this range is expanding......

Plan of the talk

I'll touch upon three different topics:

- How physicists work.
- World in the eyes of a theoretical physicist.
- Our vision, possible future revelations.

Disclaimers

- Each of the above topics is a tall tale I will only be able to sketch through.
- This is my take and viewpoint and not all of it is shared by all physicists.

Work distribution among physicists

- Job division basis among physicists:
  - Subjectwise,
  - Theory vs. experiment

Work distribution among physicists

- Theory vs. experiment, which is *applicable to all empirical sciences,* means
  - Preparing the theory (framework)
  - Model building
  - Phenomenology
  - Data analysis
  - Experiment/Observation

Work distribution among physicists

- Subject classification is based on:
  - *Decoupling of scales, physics at different energy or length scales are decoupled, and*
  - The degree of freedom under study.

- Through this classification we have, e.g.

  optics, atomic physics, condensed matter physics, soft matter and biophysics, astrophysics, cosmology, particle physics, mesoscopic and statistical systems,$\cdots$

Decoupling of scales

- Decoupling of scales is among the most fundamental and intuitive ideas in physics,

  motion of the Earth motion is independent of details of what Earth is made of, or what is going on in the nearby galaxy.

- The bigger the energy the shorter the length or time scale: Heisenberg uncertainty relation in quantum mechanics

$$\Delta X \Delta P \geq \hbar/2\,, \qquad \Delta E \Delta T \geq \hbar/2$$

HEP is based on.....

- Einstein Special Relativity: mass and energy, and space and time are essentially the same.
- Three pillars of High Energy Physics
  - Decoupling of scales
  - Quantum theory
  - Relativity, special and general

HEP is based on.....

- HEP has three main branches,
  - Elementary Particle Physics
  - Early Universe Cosmology or astrophysics
  - Theory, framework for modeling.

HEP deals with...

- High Energy Physics then deals with short time or length scales.

- These days "high" typically means

$$\ell \lesssim 10^{-15}\text{m}\,, \qquad t \lesssim 10^{-22}\text{sec}$$

- In HEP, we usually use "natural units" and measure energy in electron-Volts.

$$1\text{GeV} \sim 10^{-15}\text{m}^{-1}$$

Comparative scales

- Cosmos, farthest we have seen 8.80×10^{26}m
  Age of the Universe $1.38 \times 10^{10} yr$
- Galactic scale 10^{21}m
- Solar radius 6.96×10^{8}m
- Earth radius 6.4×10^{6}m

- Atomic size 10^{-10}m,
  Atomic energy scale 10eV
- Proton size and mass 10^{-15}m, $m_p \simeq 1$GeV

Comparative scales

- Proton size and mass 10^{-15}m, $m_p \simeq 1$GeV
- Electron size and mass:
  classical radius$\sim 10^{-15}$m, $m_e \simeq 0.5$MeV
- Nucleons, Protons and Neutron, are made of three Quarks, $m_q \simeq 5$MeV
- Neutrinos, are the second most (after light, photons) abundant particle in the Universe, their mass: still unknown, but $m_\nu \lesssim 1$eV.

Comparative scales

- Do that we know/have other time or energy scales in HEP?! Yes.
- For example life times or masses of elementary particles.
  - τ-lepton, $m_\tau = 1.8$GeV, $\tau_\tau \sim 10^{-13} sec$.
  - W, Z bosons: $M_W \sim M_Z \sim 100 GeV$; $\tau_Z \sim 10^{-25} sec$.
  - Higgs boson: $M_H \sim 126$GeV.

Comparative scales

- Typical Time scales
  - Atomic reactions, $\gtrsim 10^{-1}$sec.
  - Weak nuclear reactions 10^{-13}sec.
  - Atomic Radiations, 10^{-18}sec.
  - Strong nuclear reactions 10^{-22}sec.
  - Higgs boson life time $\sim 10^{-25}$sec.

Elementary Particles and their interactions

- Particle physics Standard Model formulates FOUR (out of five):
  - ElectroMagentic (EM),
  - nuclear Weak (W)
  - nuclear Strong (S)
  - *Higgs-Yukawa (HY)*,

  types of fundamental interactions.
- Fifths force we know, is GRAVITY.
- Gravity formulated by General Relativity.

Elementary Particles and their interactions

Particle in the standard model are classified by the interactions they take part in:

$$\begin{cases} \text{Charged Leptons}: & \text{EM \& W \& HY}, \\ \text{Neutrinos}: & \text{W},\ \text{Higgs–Yukawa?!} \\ \text{Quarks}: & \text{EM \& W \& S \& HY}, \end{cases}$$

$$\begin{cases} \text{Photon: EM}, \\ \text{Gloun: S}, \\ W^{\pm}: \text{EM \& W \& HY}, \qquad Z: \text{W \& HY}, \end{cases}$$

Higgs: W & HY,

Questions before SM?

- Stability of Higgs potential and symmetry breaking sector? Hierarchy problem?
- What happens if we go to still shorter scales/higher energies?
- Internal structure for elementary particles?!
- Other type of interactions?!
- Mass of neutrinos?!
- Mass of nucleons and nuclei?!

Is cosmology a part of HEP?!

- The farther we look, we are observing a Universe when it was younger.
- According to the Big Bang Theory, Early Universe has been Very Hot and very dense.
- It has then evolved to what we see today, cold and dark. So,
- *Early Universe Cosmology is a part of HEP*.

Is astrophysics a part of HEP?!

- After Universe cooled down, it entered the standard cosmic expansion, structures (galaxy clusters and galaxies) have formed.
- In these structures various kinds of stars formed and is still forming today.
- Energy per particle in the typical stars is usually less than MeV, not really in HEP area.
- However, some parts of astrophysics are relevant to HEP, very special stars, e.g. pulsars, supernovae and black holes,....

Questions before Early Universe Cosmology

- We have a good knowledge of *basic elements* of cosmology three minutes After Big Bang.
- Before three minute, well?!
- What Banged?!
- Infant Universe, $10^{-37} - 10^{-32}$sec A.B.B, has undergone cosmic inflation.
- It is then heated up, reheating era. How?!
- Entered into "standard cosmological expansion".

Questions before Cosmology

- Since a few billion years ago Universe has entered accelerated expansion phase.
- ΛCDM model: Universe is composed of
  - 4.9% ordinary (baryonic) matter,
  - 26.8% dark matter,
  - 68.3% dark energy.
- What is dark matter?!
- How is Universe accelerating?! (Dark Energy problem).

Questions before Early Universe Cosmology

- What caused Inflation?!
- How far back in time can we testing traces left from Inflationary era?
- What about pre-inflation physics?
- How the Universe was reheated?
- What caused matter-antimatter asymmetry we see today?

Questions before Inflationary Cosmology

- Main observational window to early Universe has been CMB:
  - Temperature anisotropies, their power spectrum and spectral tilt.
  - CMB polarization.
  - possibly CMB statistical anisotropy?!
  - Non-Gaussianity is already to a good extent ruled out.
- What are other possible observational windows?!

Theoretical Challenges in HEP

- What Banged? How Banged?
- Mass of baryons and baryonic matter?
- Fate of Universe after expansion.
- Black holes?! Do they Hawking radiate? Do they evaporate?
- Information paradox, what remains of information in the process of formation and evaporation of black holes?

Theoretical Challenges in HEP

- Framework for other forces.
- Why parameters of the SM have the values they have?
- Stability of Higgs potential, hierarchy problem
- Does either of the three pillars of HEP, Quantum theory, Relativity & Decouplig of scales need revision?! If yes, How?!
- Dark Energy problem?!

You are cordially invited to take part in this endeavor.

Thank You
For Your Attention