Where are we?

- Matter is made of atoms and molecules.
- Atoms consist of nuclei that are held together by unknown forces and electron clouds that are governed by quantum mechanics.
- The nuclear forces that explain nuclear behavior and decays have to be addressed.
- Quantum mechanics is static – it explains the stationary states all right, but it does not explain the dynamics – qualities as spin are phenomenological.
- Additional “complications” because of discoveries of many new particles in the 1930s...
- It has to be simple and elegant!
Towards quantum electrodynamics (QED)

P.A.M. Dirac suggested relativistic theory of electron (1928) theory of holes, 1930.

- Introduced electron field consistent with relativity
- Had to introduce the positron, electron antiparticle which has then be discovered by Carl Anderson (1932) in cosmic rays
- Pair production and annihilation related with electromagnetic field

- Since then: almost every particle is expected to “have” an “anti-partner” - a similar particle with the opposite sign... or a neutral combination of anti-partners
- Where are they?

Paul A.M. Dirac (1902-1984)  
Carl D. Anderson (1905-1991)
Quantum Electro Dynamics - QED

- Ernst Stueckelberg, Freeman Dyson, Richard Feynman, Sin-Itiro Tomonaga, Julian Schwinger, Suraj Gupta, and others... developed Quantum theory of electrons, positrons and the electromagnetic field:
  - charged particles interact via electromagnetic field
  - Electromagnetic waves (photons) are emitted by charged particles
QED at work

- Compton scattering - photon scattering on electron
- Electron - electron scattering
- Positron - electron scattering
- Positron-positron scattering
- Electron-positron annihilation
- Electron positron pair creation
- Bremsstrahlung radiation

\[ \Delta E \times \Delta t \geq \frac{h}{2\pi} \]

- Energy - time uncertainty - interaction takes time the conservation equations are being solved by nature in this time!
What about nuclear forces?

- EM field (photon) mediates electron-positron interactions
- What field (particle) mediates interactions of nucleons

- Hideki Yukawa - predicted mesons and suggested a phenomenological potential that keeps the nucleons together
- Discovery of new particles - good and bad

The main groups of particles:

Leptons (light) - electron, muon, neutrino
  - participate in weak interactions - $\beta$-decay
  - do not participate in strong interactions

Baryons (heavy) - proton, neutron

Mesons (medium) - pions
  - participate in strong interactions - hadrons
After much ado...

Quark Model

Pattern of particle masses and charges explained by substructure called quarks

Gell-Mann, Néeman and Zweig 1962-64
Introduction of Color charge

- \( \Omega^- \), for instance, is composed of \( sss \), but they cannot be in the same state according to Pauli exclusion principle.
- O.W. Greenberg, M.Y. Han, and Yoichiro Nambu introduced the quark property of color charge. All observed hadrons are color neutral. 1965
- Color has nothing to do with color as we know it – certain wavelengths of EM radiation – just property – quantum number.
Deeply inelastic scattering - test of the quark model, 1968-1969

- Scattering energetic (high frequency - short wavelength) electrons on protons at SLAC to probe the proton structure
- Similarly to Rutherford experiment - unexpectedly large scattering angles - there are charged “points” inside protons
- Fractional charge as predicted by quark model
- Protons do not survive - multiple particle formation
Towards - the new theory

- Yang-Mills equations to describe the strong interactions of elementary particles – somewhat similar to Maxwell equations, but non-linear
- James Bjorken and Richard Feynman analyze this data in terms of a model of constituent particles inside the proton
- The quarks are real!
- The gluons somewhat similar to photons are introduced
- Neither quarks, nor gluons can be isolated
Quantum Chromo Dynamics -QCD

1973, A quantum field theory of strong interaction is formulated. This theory of quarks and gluons is similar in structure to quantum electrodynamics (QED), but since strong interaction deals with color charge this theory is called quantum chromodynamics (QCD). Quarks are determined to be real particles, carrying a color charge. Gluons are massless quanta of the strong-interaction field. This strong interaction theory was first suggested by Harald Fritzsch and Murray Gell-Mann.

1973, David Politzer, David Gross, and Frank Wilczek discover that the color theory of the strong interaction has a special property, now called "asymptotic freedom." The property is necessary to describe the 1968-69 data on the substrate of the proton.
QCD – the theory of the strong force

- Confinement and asymptotic freedom
- There are still problems –
  - The quarks, u and d are very light, 3-5 MeV/c², while proton is about 938 MeV/c², “free and constituent masses”
  - The dynamics inside the proton is not understood
  - The quarks are just the “modes” of the destroyed proton
  - Does it really consist or made of them?

Color force be with you always
Further developments

- 1967, Steven Weinberg and Abdus Salam separately propose a theory that unifies electromagnetic and weak interactions into the electroweak interaction. Their theory requires the existence of a neutral, weakly interacting boson (now called the $Z^0$) that mediates a weak interaction that had not been observed at that time. They also predict an additional massive boson called the Higgs Boson that has not yet been observed.

- Burton Richter and Samuel Ting, leading independent experiments, announce on the same day that they discovered the same new particle. Ting at Brookhaven - $J$ particle, Richter at SLAC - $\psi$ particle. The particle is commonly known as the $J/\psi$ particle. The $J/\psi$ particle is a charm-anticharm meson.
Electro-weak theory

- The electroweak theory introduces particles that act as mediators of weak interactions in the same way that photons mediate EM interactions.
- In the electroweak theory, these four particles (photons, $W^-$, $W^+$, and $Z^0$) are closely related. The strength of the interaction of the $W$ and $Z$ bosons is comparable to that of the photon.
- $W$ and $Z$ bosons are massive. This causes the beta decay weak interactions to occur at rates much lower than electromagnetic decays (which produce photons) with comparable energy release.
- The mass of the exchanged particle also leads to an interaction probability that falls off much more rapidly with distance than in the electromagnetic case.
Weak interactions - standard model

- 1976 Gerson Goldhaber and Francois Pierre find the D0 meson (anti-up and charm quarks) - support for the Standard Model.
- 1976 The tau lepton is discovered by Martin Perl at SLAC. Since this lepton is the first recorded particle of the third generation, it is completely unexpected.
- 1977 Leon Lederman at Fermilab discover yet another quark (and its antiquark). This quark was called the "bottom" quark. Since physicists figured that quarks came in pairs, this discovery adds impetus to search for the sixth quark - "top."
- 1978 Charles Prescott and Richard Taylor observe a Z^0 mediated weak interaction in the scattering of polarized electrons from deuterium which shows a violation of parity conservation, as predicted by the Standard Model, confirming the theory's prediction.
Weak interactions - standard model

- 1983 The $W^\pm$ and $Z^0$ intermediate bosons demanded by the electroweak theory are observed by two experiments using the CERN synchrotron using techniques developed by Carlo Rubbia and Simon Van der Meer to collide protons and antiprotons.

- 1989 Experiments carried out in SLAC and CERN strongly suggest that there are three and only three generations of fundamental particles. This is inferred by showing that the $Z^0$-boson lifetime is consistent only with the existence of exactly three very light (or massless) neutrinos.

- 1995 After eighteen years of searching at many accelerators, the CDF and D0 experiments at Fermilab discover the top quark at the unexpected mass of 175 GeV. No one understands why the mass is so different from the other five quarks.
More quarks and leptons

- Three generations of quarks and leptons
- Anti-partners are not shown
- Higgs?

<table>
<thead>
<tr>
<th>Flavor</th>
<th>Mass(GeV/c²)</th>
<th>Elect. Charge</th>
</tr>
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<tr>
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<td>0.005</td>
<td>+2/3</td>
</tr>
<tr>
<td>d down</td>
<td>0.01</td>
<td>-1/3</td>
</tr>
<tr>
<td>c charm</td>
<td>1.5</td>
<td>+2/3</td>
</tr>
<tr>
<td>s strange</td>
<td>0.2</td>
<td>-1/3</td>
</tr>
<tr>
<td>t top</td>
<td>180</td>
<td>+2/3</td>
</tr>
<tr>
<td>b bottom</td>
<td>4.7</td>
<td>-1/3</td>
</tr>
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</table>
Standard Model of FUNDAMENTAL PARTICLES AND INTERACTIONS

The Standard Model summarizes the current knowledge in Particle Physics. It is the quantum theory that includes the theory of strong interactions (quantum chromodynamics or QCD) and the unified theory of weak and electromagnetic interactions (electroweak). Gravity is included on this chart because it is one of the fundamental interactions even though not part of the "Standard Model."

**Fermions**

<table>
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<th>Mass (GeV/c²)</th>
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<td>τ⁻</td>
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<td>μ⁺</td>
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<td>μ⁻</td>
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<td>-1</td>
</tr>
<tr>
<td>ν⁺</td>
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<td>0</td>
</tr>
<tr>
<td>ν⁻</td>
<td>&lt;2.10⁻²⁸</td>
<td>0</td>
</tr>
<tr>
<td>e⁺</td>
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<tr>
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<td>-1</td>
</tr>
<tr>
<td>νₑ</td>
<td>&lt;2.10⁻²⁸</td>
<td>0</td>
</tr>
<tr>
<td>νₑ</td>
<td>&lt;2.10⁻²⁸</td>
<td>0</td>
</tr>
<tr>
<td>νₑ</td>
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<tr>
<td>νₑ</td>
<td>&lt;2.10⁻²⁸</td>
<td>0</td>
</tr>
<tr>
<td>νₑ</td>
<td>&lt;2.10⁻²⁸</td>
<td>0</td>
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**Bosons**

<table>
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<th>Name</th>
<th>Mass (GeV/c²)</th>
<th>Electric Charge</th>
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<td>γ</td>
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<tr>
<td>g</td>
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<td>0</td>
</tr>
</tbody>
</table>

**Properties of the Interactions**

- **Gravitational**
- **Weak (Electroweak)**
- **Electromagnetic**
- **Fundamental**
- **Residual**

**Baryons and Antibaryons**

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Name</th>
<th>Quark content</th>
<th>Electric charge</th>
<th>Mass (GeV/c²)</th>
<th>Spin</th>
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<tbody>
<tr>
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<td>proton</td>
<td>uud</td>
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<td>938</td>
<td>1/2</td>
</tr>
<tr>
<td>p⁻</td>
<td>antiproton</td>
<td>uud</td>
<td>-1</td>
<td>938</td>
<td>1/2</td>
</tr>
<tr>
<td>n</td>
<td>neutron</td>
<td>udd</td>
<td>0</td>
<td>940</td>
<td>0</td>
</tr>
<tr>
<td>λ⁺</td>
<td>lambda</td>
<td>sds</td>
<td>1/2</td>
<td>1116</td>
<td>3/2</td>
</tr>
<tr>
<td>λ⁻</td>
<td>antibar</td>
<td>sds</td>
<td>-1</td>
<td>1172</td>
<td>3/2</td>
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</table>

**Mesons**

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<tr>
<th>Symbol</th>
<th>Name</th>
<th>Quark content</th>
<th>Electric charge</th>
<th>Mass (GeV/c²)</th>
<th>Spin</th>
</tr>
</thead>
<tbody>
<tr>
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<td>kaon</td>
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<td>493</td>
<td>1/2</td>
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<tr>
<td>K⁻</td>
<td>antikaon</td>
<td>sű</td>
<td>1</td>
<td>493</td>
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<tr>
<td>ρ⁺</td>
<td>rho</td>
<td>sű</td>
<td>-1</td>
<td>770</td>
<td>1/2</td>
</tr>
<tr>
<td>ρ⁻</td>
<td>antibar</td>
<td>sű</td>
<td>1</td>
<td>770</td>
<td>1/2</td>
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<td>B⁺</td>
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<td>0</td>
<td>5379</td>
<td>3/2</td>
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<td>B⁻</td>
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<td>0</td>
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<td>cc</td>
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<td>2880</td>
<td>0</td>
</tr>
</tbody>
</table>

**Matter and Antimatter**

- Matter - a particle type whose existence is accompanied by a corresponding antiparticle type, denoted by a bar over the particle symbol (unless e or e⁻ charge is shown).
- Particles and antiparticles have identical mass and spin but opposite charge. Some electrically neutral bosons (e.g., Z⁰, ρ⁻, and η_c = ω, ω⁻, or η = η⁻) are their own antiparticles.

**Figures**

- These diagrams are an artist's conception of physical processes. They are not exact and have no meaningful scale. Green shaded areas represent the cloud of gluons in the gluon field, and red lines the quark paths.

- A neutron decays to a proton, an electron, and an antineutrino via a virtual (mediating) W boson. This is neutron β decay.

- An electron and positron electron-positron collision (pair production) results in a neutral Z boson. This is called Z²⁻ decay.

- Two protons colliding at high energy can produce various hadrons plus very high mass particles such as Z bosons. Events such as these are rare but can yield vital clues to the structure of matter.
Quantum theory of interactions

- All interactions are resonant:
  - Certain conservation laws related to symmetries have to be obeyed
  - Such constraints quantize the nature of interactions
  - Quantum mechanics implies probability, but the constraints are obeyed!
- We only observe the initial and final states, or parts of them...
- The standard model works, but the more fundamental theory is still needed
- The difference between matter and antimatter has still to be explained, and not only phenomenologically
Quantum nature of interactions

- All interactions are resonant:
  - Certain conservation laws related to symmetries have to be obeyed - such constraints quantize the nature of interactions
  - Is our brain quantum?
- The theories mostly produce good results when you can use "perturbations" on the level of something known - e.g., the scattering is done over vacuum, the decay is into vacuum, excitation above the ground state
- The standard model works, but the more fundamental theory is still needed
- We need to understand vacuum per se, particles or fields in all states - is it possible?
Unification of fields

- At this point, the quantum electrodynamics, electro-weak theory, and quantum chromo dynamics are unified in principle - at a certain scale there expected to be no difference between the three...

- The gravity, however, has not yet yielded: there are similarities and dissimilarities between the gravity and other fields

- Are there gravitational waves?

- Can it be unified in some other way?

- What is elegance?
Discovery of the Expanding Universe: Hubble 1929

Measured distances to 25 galaxies:
- Used cepheids for Andromeda and Local Group
- Used brightest stars in the others
- Compared distances with recession velocities.

Discovered: velocity gets larger with distance

Universe is expanding
Hubble's Law

Each galaxy is moving away from every other galaxy.

Velocity \( v \) depends on distance \( d \):

\[ v = H \times d \]

- \( H \) is Hubble's constant - slope of the plot.
- Best estimate: \( H = 22 \pm 2 \text{ km/s per million light years} \)
Nature of Hubble expansion

- All observers in different galaxies see **same** expansion around them.
- No center - all observers **appear** to be at the center.
- **NOT** motion **through** space...
- Expansion **of** space-time: galaxies carried along.
- **sizes** of the galaxies remain the same.
  - galaxies are bound together by gravitation **locally**
  - do not share in the **global** expansion of space-time around them.
What time is it?

- Hubble's Law says
  - a galaxy a distance \( "d" \) away has a recession speed, \( v \), given by:

\[
v = H \times d
\]

- If \( v \) is about its average speed, then:
  - time \( T = d / v \)
  - but \( v = H \, d \), and \( T = d/(H \, d) = 1 / H \)

- Estimate the age of the universe:
  \( T = 1 / H \sim 14 \times 10^9 \) years = 14 BY

- Best Estimate of the Age: \( T = 13.7 \pm 0.2 \) BY
The Big Bang Theory

- **Today:**
  - the Universe is cold and low density.
  - as it expands, it cools
  - matter (galaxies) gets further apart.

- **In the past:**
  - Universe was smaller, hotter, and denser

- **Big Bang:**
  - describes how early hot phase grew into today’s Universe
  - leads to predictions that can be tested
History of Time

- Big Bang: $0 \text{ to } 10^{-32} \text{ Sec.}
- Inflation
- Quark Soup
- Big Freeze Out: 1 Second
- Parting Company: 300,000 Years
- First Galaxies: 1 Billion Years
- Modern Universe: 12-15 Billion Years

Age of the Universe
Evidence for the Big Bang

1. Expansion of the universe
   - first clue that there was a Big Bang

2. Abundance of the light elements H, He, Li
   - light elements fused from protons and neutrons in the first few minutes after the Big Bang

3. Formation of galaxies and spatial structure

4. The cosmic microwave background (CMB) radiation
   - remnant of heat leftover from the Big Bang.
temperatures range from blue for 2.724 K to red for 2.732 K. The double-lobe pattern shows the Doppler effect from the motion of the Sun with respect to the background radiation
Universe was once homogeneous

- early universe was opaque
  - electrons scatter photons
  - light can't get out
  - entire universe like Sun's core

- universe became transparent after $10^5$ years
  - universe cooled
  - electrons an protons form atoms

- cosmic microwave background: radiation from the instant when universe became transparent
Why 3K?

- universe small and **opaque** 10 billion years ago
- temperature $T = 3000$ K when universe became **transparent**

Hubble expansion from then to now:
- Stretching space $\lambda \rightarrow 1000 \times \lambda$
- Wien’s law $\Rightarrow T \rightarrow T/1000 = 3$ K now
Big Bang must explain Hubble expansion

- Expansion: like a rocket
  - Big Bang $\Rightarrow$ initial thrust
  - gravity resists expansion

- Long term fate depends on total mass of universe
  - big chill: endless expansion
  - big crunch: turnover from expansion to contraction
New Hubble Diagram ⇒ Acceleration!

evidence for accelerating expansion

- acceleration??

- Dark Energy:
  - acts like a pressure pushing space apart
  - predicted by Einstein
  - no evidence for it - until now
Dark Energy Increases Expansion Rate

Gravity decreases expansion rate

Dark energy drives expansion faster and faster
Universe: contents under pressure!
Dark Energy: evidence from CMB

- New studies of cosmic microwave background
- further support for dark energy
- Sachs-Wolfe effect:
  - regions of high density ⇒ greater redshift for CMB
  - regions appear cooler

The scattering of photons from perturbations in the early universe. Photons which last interacted with an overdense region suffer a gravitational redshift, whereas those which last scattered from an underdense region are blueshifted.
Summary

To discover a proper unified theory of fields we need to:

- Understand strong interactions better – understand vacuum
- Finalize the electro-weak interactions (Higgs)
- Understand CP violations... on the theoretical level
- Find a proper place for gravity

“A complete consistent unified theory is only the first step: our goal is a complete understanding of the events around us, and of our own existence”.

There are many things that we have not talked about, such as condensed matter, coherent systems, plasma physics, and many many more...