Introduction to Particle Physics I

Introduction

Risto Orava
Spring 2017
outline

• Lecture I: Introduction, the Standard Model
• Lecture II: Particle detection
• Lecture III: Relativistic kinematics
• Lectures IV: Decay rates and cross sections
• Lecture V: The Dirac equation
• Lecture VI: Particle exchange
• Lecture VII: Electron-positron annihilation
Outline continued...

- Lecture VIII: Electron-proton elastic scattering
- Lecture IX: Deeply inelastic scattering
- Lecture X: Symmetries and the quark model
COURSE INFORMATION

• WEB-OODI WILL CONTAIN COURSE INFORMATION & LINK TO THE HOME PAGE

• HOME PAGE WILL HAVE (LECTURE-BY-LECTURE) PDF-VERSIONS OF THE LECTURES, REFERENCE LITERATURE & LINKS TO RELEVANT WEB SITES

• THE COURSE MOSTLY Follows "Modern Particle Physics" by Mark Thomson, OTHER RECOMMENDED TEXT BOOKS WILL BE LISTED – USE THE PDG & WEB!

• EXERCISES WILL BE HELD FROM NEXT WEEK ON (Mikael Mieskolainen) – THESE WILL CONTRIBUTE TO THE FINAL SCORE

• SPECIAL ASSIGNMENTS ON KEY TOPICS FOR PAIRS OF STUDENTS TO BE PREPARED AND PRESENTED

• ONE INTERMEDIATE AND ONE FINAL EXAM

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personal background – Risto Orava

• **STUDIES:** MSc in physics and theoretical physics (-74, UH), PhD (-81/Fermilab)

• **RESEARCH:**
  (2) Fermilab 1979 – 1984 (Wilson Fellow, staff scientist)

• **EXPERIMENTS:**
  • antiproton-proton/proton-proton/ proton-nucleus/nucleus-nucleus/K±p/
    neutrino- & antineutrino-nucleon/e⁺e⁻ /astroparticle physics experiments
  • physics analysis responsible in a number of experiments
  • leadership positions in collaborations

• **CURRENT RESEARCH ACTIVITIES:**
  • ALICE/LHC: diffractive scattering
  • MoEDAL/LHC: magnetic monopoles, dark matter, susy...
  • LHC Ring as a detector

• **PUBLICATIONS:** ≈1000, h-index > 100
INTRODUCTION TO PARTICLE PHYSICS

- **BUILDING BLOCKS**: Leptons, Quarks, Gauge & Higgs Boson(s), Mesons, Baryons, ...

- **THEORY FRAMEWORK**: QED, QCD, Electroweak Theory, Conservation Laws, Mixing (Quark/Neutrino Types)

- **THE BIG PICTURE**: Grand Unification, Supersymmetry, String Theory, Extra Dimensions, Big Bang, ...

- **TECHNICAL TOOLS**: Quantum Mechanics, Relativistic Kinematics, Mathematics, Physics Constants, Experiments & Detector Physics, Monte Carlo & Physics & Data Analysis Techniques, Probability & Statistics, Accelerators
What do we know about matter and interactions?

- matter particles: quarks and leptons
- carriers of interactions: gluons, photon, W/Z intermediate bosons, graviton?
- the Standard Model (EW+QCD), gravitation theory, supersymmetry?
- Higgs!
what tools are available

how to cover a dynamic range of $10^{42}$ m!
the standard model

57 elementary particles?

\[ \frac{m_{\text{top}}}{m_{\nu}} > 10^{12} ? \]

the Standard Model flavor structure is too complicated for a theory of “elementary” constituents
matter and energy

small energy content

matter molecule atom nucleus

large energy content

proton/neutron quark electron

<10^{-19} m

10^{-15} m

<10^{-19} m

chemistry atom physics nuclear physics

biology

cm

10^{-9} m 10^{-10} m 10^{-14} m
fundamental forces

<table>
<thead>
<tr>
<th>force</th>
<th>mediator</th>
<th>strength</th>
<th>dependence on distance</th>
<th>range [m]</th>
</tr>
</thead>
<tbody>
<tr>
<td>vahva</td>
<td>gluoni</td>
<td>1</td>
<td>~ r</td>
<td>~ 10^{-15}</td>
</tr>
<tr>
<td>sähkö</td>
<td>fotoni</td>
<td>0.01</td>
<td>~ 1/r^2</td>
<td>∞</td>
</tr>
<tr>
<td>heikko</td>
<td>W/Z</td>
<td>10^{-13}</td>
<td>(\frac{d}{dr} \left( \frac{\exp(-m_{W,Z} r)}{r} \right))</td>
<td>~ 10^{-18}</td>
</tr>
<tr>
<td>paino</td>
<td>gravitoni?</td>
<td>10^{-38}</td>
<td>~ 1/r^2</td>
<td>∞</td>
</tr>
</tbody>
</table>

Note: Nuclear energy is based on collective interaction between large number of nucleons (protons & neutrons). The force between nucleons is a tiny remnant of the strong force at distances in excess of 10^{-15} m.
atoms are > 99.999% ‘empty’
protons are
> 99.999% ‘empty’
but this ’empty’ space is full of potential for change: matter and energy is being created and annihilated at extremely high rate

VACUUM FLUCTUATIONS - GROUND STATE OF ENERGY?

Casimir-efekti
the minimum energy?

vacuum fluctuations: continuous matter-energy transitions within $\Delta t \approx 10^{-23}\text{s}$ fills the vacuum

observed experimentally

contradiction between cosmology and particle physics theory: the minimum energy of the universe between $10^{-15}$ - $10^{70}$ J/cm$^3$?
Aine, energia, tila ja aika nivoutuvat yhteen.

Big Bang

supernauhat?

perusvoimien yhteys

inflaatio-äkikininen laajentuminen

perusvoimat erkaantuvat

ydinhiukkaset syntyvät

atomit syntyvät

tähdet syntyvät

tänään

aika

energia

10^{-43}s

10^{-35}s

10^{-10}s

10^{-5}s

300 000 vuotta

10^9 vuotta

15⋅10^9 vuotta

10^{17}TeV

10^{13}TeV

1 TeV

150 MeV

1 eV

4 MeV

0,7 MeV

extrapolaatio

hiukkaskiihdyttimet (LHC, Tevatron)
the highest energy?

estimated energy that corresponds to the over-all mass of the universe:

$10^{70}$ Joule?

Note: With the present level of energy consumption (in 2008 $4.74 \times 10^{20}$ J was used), we would use during the next 14 billion years ($\approx$ afe of the universe) about $10^{-30}$ (=0,000 000 000 000 000 000 000 000 000 000 1 %) of the total in our universe.
fundamental forces and Big Bang

<table>
<thead>
<tr>
<th>E (GeV)</th>
<th>Theories of everything?</th>
<th>Time after Big Bang (seconds)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$10^{19}$</td>
<td>Grand Unified Theories?</td>
<td>$10^{-36}$</td>
</tr>
<tr>
<td>$10^{16}$</td>
<td>Standard Model</td>
<td>$10^{-13}$</td>
</tr>
<tr>
<td>$10^2$</td>
<td>Higgs boson</td>
<td>$10^9$</td>
</tr>
</tbody>
</table>

Relative strength:
- Gravity: $10^{-40}$
- Strong: 1
- Weak: $10^{-14}$
- EM: $10^2$

Experimental reality - LEP et al.
open questions?

(1) number of fundamental families & their hierarchies?
(2) the Standard Model – how far does it work?
(3) QCD – Colour confinement of quarks and gluons?
(4) origin of masses – Higgs boson?
(5) The Big Picture – hints of physics beyond the SM?

How to find answers to these questions?
- what tools are needed?
e^+e^- scattering

What is being measured?

\[
\begin{align*}
\alpha_{em} &= g^2 = \frac{e^2}{4\pi\varepsilon_0 \hbar c} \\
M &\propto g^2 \\
|M|^2 &= MM^* \propto g^4
\end{align*}
\]
Standard Model interactions...
– forces mediated by gauge bosons

- \( Z \) is any fermion in the Standard Model.
- \( g_Z \)
- \( W \) is any quark.
- \( g_s \)
- \( U \) is a up-type quark;
- \( D \) is a down-type quark.
- \( g_w \)
- \( L \) is a lepton and \( \nu \) is the corresponding neutrino.
- \( g \)
- \( X \) is any fermion in the Standard Model.
- \( X \) is electrically charged.
- \( e \)
- \( X \) is any quark.
- \( g_s \)
- \( X \) is a photon or \( Z \)-boson.
- \( W^+ \) and \( W^- \)
- \( X \) and \( Y \) are any two electroweak bosons such that charge is conserved.
\[ e^-e^- \rightarrow e^-e^- \text{ scattering} \]

\[ |M_\gamma|^2 \propto \alpha^2 \]

\[ \alpha = g^2 = \frac{e^2}{4\pi\varepsilon_0 \hbar c} \]

\[ |M_{\gamma\gamma}|^2 \propto \alpha^4 \]
particle decays

\[ \tau^- \rightarrow g_w W^- \]

\[ W^- \rightarrow e^-, \mu^-, d \]

\[ \nu_\tau \rightarrow \bar{\nu}_e, \bar{\nu}_\mu, \bar{u} \]
$\rho^0$ resonance decay

$|M_\gamma|^2 \propto \alpha^2$

$|M_g|^2 \propto \alpha_s^2$

$|M_W|^2 \propto \alpha_W^2$
PARTICLE PHYSICS EVOLVES THROUGH FRONTIER EXPERIMENTS!
World Colliders

What Next?
* $e^+e^-$ Linear Collider
* $\nu$ Factory
* $\mu$ Collider
* Very Big Accelerator
Big Bang level energy densities in laboratory environment!
CMS-experiment

- 40 nationalities
- 200 institutes
- 3000 researchers
- 12500 tons
- 21.5m long
- 4Tesla magnetic field
'big bang' at the LHC collider in 2010

matter and energy created for nothing - vacuum fluctuations
THE BASIC PRINCIPLE OF A COLLIDER EXPERIMENT

E = mc²
$e^+e^- \rightarrow Z^0$ - number of families

$N = 2$
$N = 3$
$N = 4$

$N_v = 3.$
within $<< 1\%$
Higgs searches - the Bjorken process

$Z^0 \rightarrow \ell^+\ell^-, q\bar{q}, \nu\bar{\nu}$

Higgs boson decays to the heaviest fermions possible.

$H^0 \rightarrow b\bar{b}, \tau^+\tau^-, g\bar{g}, c\bar{c}$

$\approx 75\%$
Quarks & Gluons are confined inside the hadrons-
-How to tell where the quarks & gluons are?
Fermion-Boson Symmetric

Particles

Supersymmetric "shadow" particles

Coupling to ordinary matter?

Masses of the susy particles?
SUPERSYMMETRY

Standard particles

SUSY particles
supersymmetry?

- unifies matter and energy
  every know particle has its supersymmetric sparticle
- unifies fundamental forces
- unified theory of matter & energy?
- explains dark matter/energy?
extra dimensions?
what is the physics that hides extra dimensions?

if extra spatial dimensions exist, they are difficult to probe experimentally – several possible explanations

the extra spatial dimensions are compact and small

Nordstrom, Kaluza, and Klein, circa 1920
particles from strings

a microscopic -wiggling - string looks like a particle, its dimensions and wigglings are are too small to be seen

the momentum of the string vibrations, and the energy of the string stretching, produce the mass of the “particle”

in the rest frame of the cm of the string, this is

\[ m^2 = E_{\text{stretch}}^2 - p_x^2 - p_y^2 - p_z^2 \]
three more reasons to take extra dimensions seriously

• cosmology

• the Standard Model of particle physics

• string theory
classical general relativity already tells us that spacetime is dynamical

the three spatial dimensions that are observed are changing – expanding – and the process is not understood

what is the dark energy driving the expansion?
it is not understood what drove cosmic inflation in the early universe

it is not understood what this is

..in fact, little is understood!
extra dimensions may help explain the dynamical evolution of the 3 spatial dimensions that we observe
the shape, content, and dynamics of extra dimensions may account for complexities of particle physics

slice of a 6 dimensional Calabi-Yau manifold
the basic matter/energy entities as unknown today...
SOME COSMOLOGICAL PARAMETERS

THE ENERGY DENSITY BUDGET

$$\Omega_B$$  BARYONS

$$\Omega_{CDM}$$  COLD DARK MATTER

$$\Omega_\nu$$  NEUTRINOS

$$\Omega_{DE}$$  DARK ENERGY

$$\Omega_{TOT} = \Omega_B + \Omega_{CDM} + \Omega_\nu + \Omega_{DE}$$
TIME AND ENERGY ARE BORN TOGETHER
NEXT:
Lecture II
Particle detection

CERN Summer Student program:
http://www.hip.fi/?page_id=2124