Introduction to Particle Physics

Seyong Kim

Sejong University
Higgs has been found! (Aug. 12, 2012)
July 4th, 2012

S. Kim

KHST2012–Aug. 06, 2012
July 4th, 2012

ATLAS collaboration presentation

The low-mass region

**2011 data**
- m4l < 160 GeV
  - Observed: 39
  - Expected: 34 ± 3

**2012 data**

**2011+2012 data**

### In the region 125 ± 5 GeV

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<td>Data</td>
<td>6</td>
<td>5</td>
<td>2</td>
</tr>
<tr>
<td>Expected S/B</td>
<td>1.6</td>
<td>1</td>
<td>0.5</td>
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July 4th, 2012

CMS collaboration presentation

Results: $m(4\ell)$ spectrum

Yields for $m(4\ell) = 110\ldots 160$ GeV

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$m_H = 126$ GeV:
- 164 events expected in [100, 800 GeV]
- 172 events observed in [100, 800 GeV]
What is “particle physics”? 
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http://en.wikipedia.org/wiki/Particle_physics
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Particle physics is a branch of physics that studies the existence and interactions of particles that are the constituents of what is usually referred to as matter or radiation.
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In current understanding, particles are excitations of quantum fields and interact following their dynamics.

Most of the interest in this area is in fundamental fields, each of which cannot be described as a bound state of other fields. The current set of fundamental fields and their dynamics are summarized in a theory called the Standard Model, therefore particle physics is largely the study of the Standard Model’s particle content and its possible extensions.
What is particle physics?

- Small distance $\rightarrow$ quantum physics

- Uncertainty principle

\[ \Delta x \Delta p \geq \hbar \]  \hspace{1cm} (1)

- Special relativity $\rightarrow$ pair creation is possible

\[ \Delta E \Delta t \geq \hbar \]  \hspace{1cm} (2)

- Based on quantum field theory

- We only “know” probabilities and probability amplitudes
### Standard Model of Fundamental Particles and Interactions

#### Fermions

<table>
<thead>
<tr>
<th>Leptons spin = 1/2</th>
<th>Quarks spin = 1/2</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Flavor</strong></td>
<td><strong>Mass (GeV)</strong></td>
</tr>
<tr>
<td>( \nu_e ) electron</td>
<td>(&lt; 7 \times 10^{-3})</td>
</tr>
<tr>
<td>( e^- ) electron</td>
<td>0.00511</td>
</tr>
<tr>
<td>( \mu^- ) muon</td>
<td>0.00003</td>
</tr>
<tr>
<td>( \tau^- ) tau</td>
<td>0.03</td>
</tr>
</tbody>
</table>

#### Bosons

<table>
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<tr>
<th>Force carriers</th>
<th>spin = 0, 1/2</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Mass (GeV)</strong></td>
<td><strong>Electric Charge</strong></td>
</tr>
<tr>
<td>( g ) gluon</td>
<td>0</td>
</tr>
</tbody>
</table>

#### Properties of the Interactions

<table>
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<tr>
<th>Property</th>
<th>Gravitational</th>
<th>Weak (Eletroweak)</th>
<th>Electromagnetic</th>
<th>Strong (Fermionic)</th>
<th>Strong (Residual)</th>
</tr>
</thead>
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<tr>
<td>Acts on</td>
<td>Particles experiencing</td>
<td>All Quarks, Leptons</td>
<td>Electrally charged Quarks, Gluons</td>
<td>Hadrons</td>
<td></td>
</tr>
<tr>
<td>Strength</td>
<td>for 2 quarks at:</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>&amp; for 2 protons in nucleus</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
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</table>

**Example Bosonic Hadrons**

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Name</th>
<th>Meson q̄q</th>
<th>Spin</th>
</tr>
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<tbody>
<tr>
<td>( \pi^- )</td>
<td>pion</td>
<td>( \bar{u}d )</td>
<td>0.140</td>
</tr>
<tr>
<td>( K^- )</td>
<td>kaon</td>
<td>( \bar{s}d )</td>
<td>0.404</td>
</tr>
<tr>
<td>( \rho^- )</td>
<td>rho</td>
<td>( \bar{u}d )</td>
<td>0.770</td>
</tr>
<tr>
<td>( D^- )</td>
<td>charmed D</td>
<td>( \bar{c}d )</td>
<td>1.809</td>
</tr>
<tr>
<td>( \eta_c )</td>
<td>charmed E</td>
<td>0.279</td>
<td></td>
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#### Figures

- A diagram shows the interaction of quarks and gluons, illustrating the strong force.
- Another diagram depicts the elementary particles and their interactions, emphasizing the weak and electromagnetic forces.

**Contemporary Physics Education Project (CPEP)**

CPEP is a web-based organization of scholars, teachers, and others for the improvement of teaching and learning. Information on the project can be found at: [http://www.cpep.net](http://www.cpep.net) or at [http://info.cpep.net](http://info.cpep.net). Funding is provided by the National Science Foundation.
probabilities and probability amplitudes

experimental particle physicists measure probabilities

theoretical particle physicists calculate probabilities (when they can)
probabilities and probability amplitudes

So, how do you “measure” probabilities?
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an example of dice:
instead of an actual dice, imagine a blackbox which announces a number
probabilities and probability amplitudes

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(2) write down the number each time the box announces a number
probabilities and probability amplitudes

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an example of dice:
instead of an actual dice, imagine a blackbox which announces a number

(1) prepare a notebook
(2) write down the number each time the box announces a number
(3) after n-th try, count how many times each number occurred
• rare events
  \(\rightarrow\) small probabilities
  \(\rightarrow\) need to try more
CMS collaboration presentation

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Yields for \(m(4\ell) = 110 \pm 160 \text{ GeV}\)

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July 4
- 164 events expected in [100, 800 GeV]
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Event-by-event errors

2011+2012
Not so easy!

- missing
- mis-identification
- background
- systematic errors and statistical errors
- ... many more worries
So, how do you “calculate” probabilities?
So, how do you “calculate” probabilities?

(1) construct a lagrangian
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(2) derive Feynman rule from the given lagrangian
probabilities and probability amplitudes

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So, how do you “calculate” probabilities?

1. Construct a lagrangian
2. Derive Feynman rule from the given lagrangian
3. Form Feynman diagrams for a given perturbative order and calculate the probability amplitude corresponding to each diagram
4. Sum the probability amplitudes and calculate the probability
when they can

- So, \textit{lagrangian is important}
- “when they can” means when they know what the lagrangian is.
- Most of time, lagrangian is not known or there are rival theories
\[ \mathcal{L}_{QED} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} + \sum_f \bar{\psi}_f (i\gamma^\mu - m_f) \psi_f \]  

where

\[ F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu \]  

and

\[ \gamma^\mu (\partial_\mu - iQ_f A_\mu) \]
lagrangian and symmetry
lagrangian and symmetry
Newton’s law:

\[
\vec{F} = m \frac{d^2 \vec{x}}{dt^2}
\]  (3)

Hamilton’s principle: dynamics of a physical system is determined by variational problem for a functional based on a single function, lagrangian.

\[
S = \int_{t_i}^{t_f} dt \ L(q, \dot{q} = \frac{dq}{dt})
\]  (4)

\[\rightarrow \text{Euler-Lagrange equation:}\]

\[
\frac{d}{dt} \left( \frac{\partial L}{\partial \dot{q}} \right) - \frac{\partial L}{\partial q} = 0
\]  (5)
lagrangian and symmetry

\[ \frac{d}{dt} \left( \frac{\partial L}{\partial \dot{q}} \right) - \frac{\partial L}{\partial q} = 0 \]  (3)

- a given system is symmetric
  \[ \rightarrow L \text{ is independent of symmetry transform} \]
  \[ \rightarrow \frac{\partial L}{\partial q} = 0 \]
  \[ \rightarrow \frac{\partial L}{\partial \dot{q}} \text{ is independent of time.} \]
If a system has a continuous symmetry property, then there are corresponding quantities whose values are conserved in time.
continuous symmetry and Noether theorem

If a system has a **continuous symmetry** property, then there are corresponding quantities whose values are **conserved in time**.

example 1: a particle’s motion is not changed
continuous symmetry and Noether theorem

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example 2: a system is invariant under rotations
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→ angular momentum is conserved
4-dimensional space-time symmetry (Poincare symmetry) is underlying symmetry

time-translation, space-rotation, Lorentz boost
In electromagnetism, **electric charge is conserved**

Maxwell's equations

\[ \nabla \cdot \vec{E} = \frac{1}{\varepsilon_0} \rho, \quad \nabla \times \vec{E} = -\frac{\partial \vec{B}}{\partial t} \quad (4) \]

\[ \nabla \cdot \vec{B} = 0, \quad \nabla \cdot \vec{B} = \mu_0 \vec{J} + \mu_0 \varepsilon_0 \frac{\partial \vec{E}}{\partial t} \quad (5) \]

(6)

can be formulated in terms of electric potential \( \Phi \) and vector potential \( \vec{A} \)

\[ \vec{E} = -\nabla \Phi - \frac{\partial \vec{A}}{\partial t} \]

\[ \vec{B} = \nabla \times \vec{A} \quad (7) \]
gauge symmetry

Maxwell’s equation is invariant under

\[ \vec{A} \rightarrow \vec{A} + Q_f \vec{\nabla} \Lambda \]

\[ \Phi \rightarrow \Phi - Q_f \frac{\partial \Lambda}{\partial t} \quad (4) \]

QED (Quantum ElectroDynamics) has electrons (Dirac equation)

\[ \mathcal{L}_f = \bar{\psi}_f (i \gamma_\mu \partial_\mu - m_f) \psi_f \quad (5) \]

With

\[ \partial_\mu \rightarrow D_\mu = \partial_\mu - iQ_f A_\mu, \quad (6) \]

E & M system has a global $U(1)$ gauge symmetry

\[ \psi \rightarrow e^{iQ_f \Lambda} \psi, \quad A_\mu \rightarrow A_\mu + Q_f \partial_\mu \Lambda \quad (7) \]
gauge symmetry

QED lagrangian becomes

\[ \mathcal{L}_{\text{QED}} = \sum_f \bar{\psi}_f (i\slashed{D} - m_f) \psi_f - \frac{1}{4} F_{\mu\nu} F^{\mu\nu} \] (4)

Standard model lagrangian is a generalization of gauge theory based on \( SU(3)_c \times SU(2)_{EW} \times U(1)_Y \)

\( SU(3) \) is for the strong interaction, \( SU(2)_{EW} \times U(1)_Y \) is for the electroweak interaction (the electromagnetic interaction + the weak interaction)
In Summary

• fundamental particles consist of fermions (half integer spin particles) and bosons (integer spin particles)
• 6 quarks (up, down), (charm, strange), (top, bottom)
• 6 leptons (e-neutrino, electron), (µ-neutrino, muon), (τ-neutrino, tau)
• photon, gluon, $W^\pm, Z^0$ boson
• interactions are based on gauge symmetries (i.e., massless bosons)
• $SU(3)_c \times SU(2)_{EW} \times U(1)_Y$ gauge interaction
• Higgs boson
ATLAS collaboration presentation

**SM Higgs production cross-section and decay modes**

\[ \sqrt{s} = 8 \text{ TeV} \]

- **Δs=7 → 8 TeV:**
  - Higgs cross-section increases by \( \sim 1.3 \) for \( m_H \sim 125 \text{ GeV} \)
  - Similar increase for several irreducible backgrounds: e.g. 1.2-1.25 for \( \gamma\gamma \), di-bosons
  - Reducible backgrounds increase more: e.g. 1.3-1.4 for \( tt \), \( Zbb \)
  - Expected increase in Higgs sensitivity: 10-15%

**Note:** huge efforts and progress from theory community to compute NLO/NNLO cross-sections for Higgs production and for (often complex !) backgrounds
ATLAS collaboration presentation

The low-mass region

Higgs Boson

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In the region 125 ± 5 GeV

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CMS collaboration presentation

- $\sqrt{s}=8$ TeV: 25–30% higher $\sigma$ than $\sqrt{s}=7$ TeV at low $m_H$
- All production modes to be exploited
  - $gg$ VBF, $VH$, $ttH$
- Latter 3 have smaller cross sections but better $S/B$ in many cases
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<td>$m_H = 126$ GeV</td>
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July 4
164 events expected in [100, 800 GeV]
172 events observed in [100, 800 GeV]
meaning of $5 - \sigma$ event

$1/\sqrt{\pi}\exp(-x^2)$
Question: why is there a distribution in the events per energy bin, not a narrow peak?

for the simplicity, assume $H \rightarrow \gamma\gamma$
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$p_1 = (E_1, \vec{p}_1)$ and $p_2 = (E_2, \vec{p}_2)$ with $p_1^2 = m_\gamma^2 = 0 = p_2^2$
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then, $E_1 + E_2 = M_H$ and $\vec{p}_1 + \vec{p}_2 = \vec{0} \rightarrow \vec{p}_1 = -\vec{p}_2$
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for the simplicity, assume $H \rightarrow \gamma\gamma$

in the rest frame of $H$, $(E_H, \vec{p}_H) = (M_H, \vec{0})$

$p_1 = (E_1, \vec{p}_1)$ and $p_2 = (E_2, \vec{p}_2)$ with $p_1^2 = m_\gamma^2 = 0 = p_2^2$

then, $E_1 + E_2 = M_H$ and $\vec{p}_1 + \vec{p}_2 = \vec{0} \rightarrow \vec{p}_1 = -\vec{p}_2$

$E_1 = |\vec{p}_1|$, $E_2 = |\vec{p}_2| = |\vec{p}_1|$. then $E_1 = E_2 = \frac{M_H}{2}$
When there is a gauge symmetry, the gauge boson is massless (photon is massless). In this case, the interaction range is infinite.

Among four fundamental interactions, the gravity and the electromagnetism are long range interaction. The strong interaction and the weak interaction is short-ranged.

The strong interaction is short-ranged due to “color confinement”.

(1) how can the weak interaction be described in terms of a gauge theory?

(2) why is the weak interaction short-ranged?
photon has the right-handed circular polarization and the left-handed circular polarization because it is massless (two components)

\( \vec{V} \) has three components. Massive particle has three components.
spontaneous symmetry breaking and Goldstone’s theorem

\[ \mathcal{L}_{\text{int}} = \frac{G_F}{\sqrt{2}} \bar{\psi} \gamma_\mu (1 - \gamma_5) \psi_n \bar{\nu} \gamma^\mu (1 - \gamma_5) \nu_e \]  

(5)

Maybe, the lagrangian has the gauge symmetry but the ground state doesn’t have the symmetry \( \rightarrow \) spontaneous symmetry breaking
spontaneous symmetry breaking and Goldstone’s theorem

an example of spontaneous breaking: permanent magnet

Ising model

\[ H = -\kappa \vec{\sigma}_i \cdot \vec{\sigma}_{i+1} \]  \hspace{1cm} (6)
spontaneous symmetry breaking and Goldstone’s theorem

an example of spontaneous breaking: permanent magnet

Ising model

\[ H = -\kappa \sum_i \vec{\sigma}_i \cdot \vec{\sigma}_{i+1} \] (6)
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Ising model

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Goldstone’s theorem states that if a continuous symmetry is spontaneously broken (i.e., the current is conserved but the ground state is not invariant under the action of the corresponding charge), then there should be a massless scalar particle in the spectrum of possible excitations.
spontaneous symmetry breaking and Goldstone’s theorem

\[ 2*(x^2 + y^2 - 4)^2 \]
Higgs mechanism

P. Higgs, Physics Letters B12 (1964), 132
Higgs mechanism introduces a scalar field (elementary or composite) which is self-interacting to a gauge theory. Spontaneous symmetry breaking of gauge symmetry makes the gauge field massive and there is no massless scalar particle left behind.

\[
\mathcal{L}_H = D_\mu \phi D^\mu \phi^* - V(\phi^* \phi) - \frac{1}{4} F_{\mu \nu} F^{\mu \nu}
\]  

(7)

where \( D_\mu \phi = (\partial_\mu + ieA_\mu)\phi \).

For \( \phi \to \eta + iv \), \( D_\mu \phi D^\mu \phi^* \to (\partial_\mu \eta)^2 + e^2 v^2 A^2_\mu \)

\( e^2 v^2 A^2_\mu \) is the mass term for the gauge field.
Are we there yet? (random order and personnel view)

There are many unsolved fundamental problems

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There are many unsolved fundamental problems
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(2) Why is there more matter than anti-matter in the universe?
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many more important problems ···