String Theory in the LHC Era

J Marsano (marsano@uchicago.edu)
String Theory in the LHC Era

1. Electromagnetism and Special Relativity
2. The Quantum World
3. Why do we need the Higgs?
4. The Standard Model and Beyond
5. Supersymmetry
6. Einstein’s Gravity
7. Why is Quantum Gravity so Hard?
8. String Theory and Unification
9. String Theory and Particle Physics
Electromagnetic Waves

Wavelength $\lambda$

Maxwell $\rightarrow$ fixed speed $c$

Characterized by:

- Intensity $|E|^2$
- Wavelength $\lambda$

Frequency $\nu = \frac{c}{\lambda}$
Photoelectric Effect

How does emission depend on

- Intensity of beam?
- Wavelength of beam?
Photoelectric Effect

Robert Millikan
UChicago Professor!

\[ \text{gradient} = \frac{h}{e} \]

\[ v_0 = \frac{W}{h} \]

← Wavelength $\lambda$
Photoelectric Effect

At large wavelengths, no electrons emitted

→ Independent of intensity of the incident radiation
Photoelectric Effect

Electromagnetic waves have a ‘smallest piece’
Photoelectric Effect

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Photoelectric Effect

Electromagnetic waves have a ‘smallest piece’
Photoelectric Effect

Electromagnetic waves have a ‘smallest piece’

Smallest pieces - ‘quanta’

Photon energy is determined by its wavelength

\[ E = \frac{hc}{\lambda} = h\nu \]

Planck constant

\[ h \sim 6.626 \times 10^{-34} \text{J} \cdot \text{s} \]
Photoelectric Effect

Wavelength, $\lambda$ $\leftrightarrow$ Energy of each photon
Beam intensity $\leftrightarrow$ # of photons

Photon energy is determined by wavelength

$$E = \frac{hc}{\lambda} = h\nu$$

Electron interacts with one photon at a time

→ Ejected only if wavelength short enough

Incident light (photons)
Two Important Points:

1. ‘Particle-like’ behavior of light

2. Correlation between energy and length scales

\[ E = \frac{hc}{\lambda} \]
We observe the world through scattering experiments

Wavelength of light limits distance scales that we can resolve
We observe the world through scattering experiments.

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Wavelength of light limits distance scales that we can resolve.
Need $\lambda < d_{\text{atom}}$ to study atoms

\[ \leftrightarrow E > \frac{hc}{d_{\text{atom}}} \]

Need $\lambda < d_{\text{nucleus}}$ to study atomic nucleus

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\[ \leftrightarrow E > \frac{hc}{d_{\text{atom}}} \]

Need $\lambda < d_{\text{nucleus}}$ to study atomic nucleus

\[ \leftrightarrow E > \frac{hc}{d_{\text{nucleus}}} \]
Must go to higher energies to probe small distance scales

$LHC \sim 10^{-18} \text{ cm}
(0.000000000000000001 \text{ cm})$

Strings: $10^{-33} \text{ cm}$?
Waves and Particles

Sometimes light behaves like a wave....

....and sometimes like a particle

...depends on the question we ask

Let’s examine some important wave behavior and its implications
Waves and Uncertainty

A photon in this wave carries momentum

\[ E = \frac{hc}{\lambda} \]

\[ p = \frac{h}{\lambda} \]

But where is it?
Interference

Constructive

Destructive
Interference

Constructive

Destructive
Interference

Constructive

Destructive
Interference

Constructive

Destructive
Interference

Waves can ‘cancel’ one another

Constructive

Destructive
Waves and Uncertainty

\[ \Delta x \]
Waves and Uncertainty

\[ \Delta x \Delta \left( \frac{1}{\lambda} \right) \gtrsim 1 \]

General property of waves
Heisenberg Uncertainty

Quantum Theory:
Light composed of photons

\[ p = \frac{h}{\lambda} \]

\[ \Delta x \Delta \left( \frac{1}{\lambda} \right) \gtrsim 1 \]

\[ \Delta x \Delta p \gtrsim h \]

Cannot pin down position and momentum of a photon

(more fundamental than our treatment suggests)
So Far:

1. Light waves composed of many quanta -- photons
   - Wave can behave like stream of particles

2. Energy $E$ and momentum $p$ determined by wavelength

3. Cannot pin down $x$ and $p$ to arbitrary precision

What about particles (eg electrons)?
Do they behave like waves?
Diffraction

Incident wave

Slit

Screen

Intensity

\[ I \sim |E|^2 \]
Diffraction

Incident wave

Slit

Intensity

$I \sim |E|^2$

Screen

Interference!
Electrons too!

\[ e^- \text{ source} \]

Source \rightarrow Slit \rightarrow Number of Electrons \rightarrow Screen
Electrons too!

- **source**
- **Slit**
- **Number of Electrons**
- **Screen**
Electrons too!
Electrons too!

Source

Slit

Number of Electrons

Screen
Electrons too!

Source

Slit

Number of Electrons

Screen
Electrons too!

- $e^-_{\text{source}}$
- Slit
- Number of Electrons
- Screen
Electrons too!

Source \( e^- \)

Slit

Number of Electrons

Screen
Electrons too!

\[ e^- \text{ source} \]

Slit

Number of Electrons

Screen
Electrons too!

e$^-$ source

Slit

Number of Electrons

Screen
Particle of momentum \( p \) has an intrinsic **wavelength**

\[ \lambda = \frac{h}{p} \]

What is ‘waving’?
Associate an abstract ‘wave function’ $\Psi$ to each electron

$|\Psi|^2 \leftrightarrow$ probability

Intensity $\leftrightarrow$ # of photons

Intensity profile $\leftrightarrow$

probability for an individual photon to hit a particular spot on the screen

$I \sim |E|^2$
What is waveling?

...it is a wave so we can get interference effects

Classical EM Wave

Probability!

Electron wave

Intensity

Probability

$|E|^2$

$|\Psi|^2$

Thursday, April 12, 12
Double Slit Experiment

Incident wave

Intensity

\[ I \sim |E|^2 \]
Double Slit Experiment

\[ I \sim |E|^2 \]
Double Slit Experiment

\[ I \sim |E|^2 \]
What about Electrons?

$\text{Probability } \sim |\Psi|^2$

Screen

Interference

$e$

source

Thursday, April 12, 12
What about Electrons?

\[ e \text{ source} \rightarrow \text{Detectors} \rightarrow \text{Screen} \]

Probability \( \sim |\Psi|^2 \)

Interference
What about Electrons?

$Probability \sim |\Psi|^2$
Electrons passing through different slits do not interfere with one another after we add the detectors.

How can we understand this?
Before measurement

Electron probability

Slits
After measurement

Electron probability

Slits
Measurement causes
‘Wave function collapse’

‘Copenhagen Interpretation’

Niels Bohr

Electron probability

Slits
About ‘wave function collapse’.....

Wave from top slit

Wave from bottom slit

'Detector state space'

Direction of ‘waving’

Detectors
About ‘wave function collapse’..

Wave from top slit

Wave from bottom slit

‘Detector state space’

Direction of ‘waving’
About ‘wave function collapse’.....

Wave from top slit

Wave from bottom slit

Direction of ‘waving’

'Detector state space'
About ‘wave function collapse’.....

Wave from top slit
Wave from bottom slit

Direction of ‘waving’

'Detector state space'

Detectors
Electron passing through each slit becomes ‘entangled’ with its detector

Spoils cancellation that caused interference pattern

→ ‘Decoherence’
Decoherence is **not** ‘wave function collapse’....

Explains why the wave function ‘**seems**’ to collapse

Interaction with environment spoils quantum ‘cancellations’, leading to ‘classical behavior’
Expects why detectors destroy the interference pattern

...but not the whole story
Particles as Waves:

1. Particles exhibit wave-like behavior
   • Waves describe ‘probabilities’

2. Particle wavelength determined by momentum $p$

3. We disturb the system when we make observations
‘Wave-particle duality’ forces us to take a probabilistic view of nature
What about relativity???

Relativity

+ Quantum mechanics

Quantum field theory

Language of particle physics
What about relativity???

Relativity

+ Quantum mechanics

Quantum field theory

Language of particle physics

Sidney Coleman
(Illinois Institute of Technology alumnus!)

Lecture notes:  http://arxiv.org/abs/1110.5013

Videos:  http://www.physics.harvard.edu/about/Phys253.html
Suppose we could trap an electron...

....and then we release it
Suppose we could trap an electron...

....and then we release it

Nonzero probability to detect it here!

Quantum mechanics doesn’t care about the speed of light

Release trapped particle

Light Cone

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Significant probability of huge momenta and energies in the box

\[ \Delta x \Delta p \gtrsim h \]

\[ \Delta x \to 0 \quad \Longrightarrow \quad \Delta p \to \infty! \]

Enough to create new particles out of the vacuum
\[ \Delta x \Delta p \gtrsim h \]

\[ \Delta x \to 0 \implies \Delta p \to \infty! \]

Significant probability of huge momenta and energies in the box

Enough to create new particles out of the vacuum
Sometimes one particle comes out.....

...and sometimes several do

Light Cone

New particles interfere to give zero probability of detection here
Effect of adding relativity:

Particle number is not conserved

Even in vacuum!!!
Interaction of electron with photon
Interaction of electron with photon

\[ e^- \rightarrow e^- \]

or

\[ \text{or} \]

\[ \text{or} \]
Must sum over all possibilities weighted by their ‘probability amplitudes’

\[ + \]

\[ + \]

\[ + \]

\[ + \ldots \]

...sum over histories

Richard Feynman
Quantum Electrodynamics

These diagrams determine the ‘anomalous magnetic moment’ of the electron.
Quantum Electrodynamics

These diagrams determine the ‘anomalous magnetic moment’ of the electron

\[ \frac{g - 2}{2} \text{(theory)} = 1\,159\,652\,175.86(8.48) \times 10^{-12} \]

\[ \frac{g - 2}{2} \text{(exp)} = 1\,159\,652\,180.73(2.8) \times 10^{-12} \]
Quantum Electrodynamics (QED) works incredibly well

\[ \mathcal{L} \sim \bar{\psi} (i \gamma^\mu D_\mu - m) \psi - \frac{1}{4e^2} F_{\mu\nu} F^{\mu\nu} \]

Electron
\[ \downarrow \]
Photon
\[ \text{Electron mass} \]
\[ \text{Charge} \]

Sin-Itiro Tomonoga
Julian Schwinger
Richard Feynman
\[ \mathcal{L} \sim \bar{\psi} (i \gamma^\mu D_\mu - m) \psi - \frac{1}{4 e^2} F_{\mu \nu} F^{\mu \nu} \]

Electron mass

Photon

Charge

Mass without Higgs......

so why all the fuss......
Next time:

Why do we need the Higgs?
SUMMARY

• Electromagnetic waves can behave like streams of particles
  • Energy of ‘smallest piece’ (photon) determined by wavelength
  • Fundamental relation between energy and distance scales

• Particles can behave like waves
  • Each particle has a Broglie wavelength determined by momentum
  • The quantity that ‘waves’ is probability
  • We are forced to take a probabilistic view of nature!

• Observation cannot be separated from the act of measurement
  • Measurement entangles the system we observe with our detectors

• When we add relativity, particle number is not conserved
  • Vacuum not empty--particles popping in and out of existence
  • Must sum over all histories (Feynman diagrams)