Class Performance Today

- All Homework has been marked up and I have graded HW #7 myself.
- I am returning all HW in my possession, old and new, today. All your HW is stapled together.
- The Total Standing is written in red on each sheet. You can compare it to the “straw” grade assignments listen in the Table.
- Please do not copy each other’s HW
- Please read the questions carefully!
- Please write legibly and staple multiple sheets together.
The particles of the Standard Model I

- Six quarks are the “bricks” of the strongly interacting matter. They have mass.
- They are grouped into three families or generations: In each family the top member has electric charge +2/3 e, the bottom member has -1/3 e.
- All quarks have spin $\frac{1}{2}$ hbar.
- They interact strongly by exchanging gluons, which transfer “color” from one quark to another.
- Because quarks are charged they interact electromagnetically with other charged particles by exchanging $\gamma$’s.
- Quarks can interact with through the weak interaction by exchanging $W^\pm$ and $Z^0$ bosons.
The particles of the Standard Model II

- There are 3 equivalent families of leptons ("light particles").
- The top member in each family is an electrically neutral neutrino, the bottom member is a singly-charged light particle.
- Leptons all have spin $\frac{1}{2}$ hbar.
- Leptons interact with each other by exchanging $W^\pm$ and $Z^0$ bosons.
- Charged leptons interact with other charged particles by exchanging $\gamma$’s.
- The lepton families are strictly separated from each other and individually conserved: when we create a lepton in a given family we need to create an anti-lepton from the same family.
The Force Carriers of the Standard Model

- There are force carriers associated with each of the three interactions: they all have spin 1 hbar.

1. The Gluons transmit the “color” of the strong interaction (“color charge”). There are 8 gluons which have no electric charge.
2. The Photon mediates the EM interaction. It has no charge.
3. The W and Z bosons mediate the weak interaction. They couple to leptons and quarks.
4. Note: the carrier of the gravitational force is still unknown.

<table>
<thead>
<tr>
<th>Name</th>
<th>Symbol</th>
<th>Spin h/2π</th>
<th>Rest mass GeV</th>
<th>Lifetime 10^{-25} s</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gluon</td>
<td>g</td>
<td>1</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>Photon</td>
<td>γ</td>
<td>1</td>
<td>&lt; 6×10^{-25}</td>
<td>stable</td>
</tr>
<tr>
<td>W-Boson</td>
<td>W±</td>
<td>1</td>
<td>80.22</td>
<td>3.2</td>
</tr>
<tr>
<td>Z-Boson</td>
<td>Z0</td>
<td>1</td>
<td>91.19</td>
<td>2.6</td>
</tr>
</tbody>
</table>
What have we learned last time

- Quarks are bound together with a force that increases as we try to pull them apart (Confinement). There is never a solitary quark.
- However, the theory of the strong interaction, QCD, predicts quite reliably that during the first microsecond after the Big Bang, when the Universe had a temperature > 170 MeV, quarks were free to roam around as a form of matter called the Quark-Gluon Plasma (QGP).
- We can hope to recreate this state by smashing Gold (AU) nuclei together at ultra-relativistic speed.
- This is done at the Relativistic Heavy Ion Collider (RHIC)

- Gold ions can be accelerated like all charged particles by injecting them into an electric field.
- These can be D.D. field, like in your TV, or r.f. fields that are built up in resonators.
- In a D.C. field particles can accelerated all the time, but in r.f. fields particles must be bunched to arrive at the electric field at a time of high amplitude and with the right polarity.
- Resonators can accelerate particles in a straight-line arrangement (LINACs) or can be bend in circles by magnets to pass through the resonators many times (Synchrotrons). In a synchrotron the beam bunches go around synchronously (in-step) with the r.f. frequency
What have we learned II

• The most powerful accelerators today are colliders; these are (mostly) synchrotrons that store energetic beam bunches that circle clockwise and counterclockwise colliding in the center of a (or more) large detector.
• RHIC is a collider that can store any kind of ion beam, from protons to Gold.
• Energetic charged particles can be detected by their ionization in gas or in solid materials. The ionization products (gas ions and electrons) are then detected on wires or small plates and the path of the original ionizing particle can be reconstructed.
• Usually the charged participles are deflected in a magnetic field inside the detector to determine the momentum (mass x velocity) and charge of the particle.
• Gamma rays are detected by the electrons that they free up in a semiconductor
• Neutrons are detected by the recoil protons produced in a plastic material that contains lots of hydrogen, or in gas detectors where the neutron produces charged particles in a nuclear reaction.
The Force between quarks (QCD Potential)

- **In vacuum the potential shows**
  - strong attractive force at short distance between quarks
  - linear increase with distance from color charge
  - confinement of quarks to hadrons: baryons (qqq) and mesons (qq-bar)
  - This is a consequence of the fact that gluons carry color.
- **in dense and hot matter**
  - screening of color charges makes potential vanish for large distance
  - deconfinement of quarks → QGP
Required conditions to study quark gluon plasma

\[ \frac{\varepsilon}{T^4} \]

Karsch, Laermann, Peikert ‘99

\( T_c \sim 170 \pm 10 \text{ MeV} \)  \( (10^{12} \text{ K}) \)

\( \varepsilon \sim 3 \text{ GeV/fm}^3 \)

\( \varepsilon = g \frac{\pi^2}{30} T^4 \)

\( \sim 15\% \text{ from ideal gas of weakly interacting quarks & gluons} \)
Evolution of the Universe

Too hot for quarks to bind!!! $10^{12}$ K
Standard Model (N/P) Physics

Too hot for nuclei to bind $10^{10}$ K
Nuclear/Particle (N/P) Physics

Nucleosynthesis builds nuclei up to He
Nuclear Force...Nuclear Physics

Universe too hot for electrons to bind
E-M...Atomic (Plasma) Physics $10^4$ K

Today’s Cold Universe
Gravity...Newtonian/General Relativity

PHY313-CEI544 Spring-05
Schematic View of a Heavy Ion Collision

- hadrons such as $\pi$, $K$, $p$ - lots, produced “late” when particles stop to interact (freeze-out)

- electro-magnetic radiation $\gamma$, $e^+e^-$, $\mu^+\mu^-$ - few, emitted “any time”;

http://www.bnl.gov/heavy_ion.htm
Properties of a plasma

- 4\textsuperscript{th} state of matter (after solid, liquid and gas)
- a plasma is:
  - ionized gas which is macroscopically neutral but has electrons and ions floating around independently
  - exhibits collective effects

- interactions among charges of multiple particles
  - spreads charge out into characteristic (Debye) length, $\lambda_D$
  - multiple particles inside this length
  - plasma size $> \lambda_D$

- “normal” plasmas are electromagnetic: electrons and ions
  - quark-gluon plasma interacts via strong interaction
    - color forces rather than EM
    - exchanged particles: g instead of $\gamma$
You have seen the experiments

**STAR**
specialty: large acceptance measurement of hadrons

**PHENIX**
specialty: rare probes, leptons, and photons
At what temperature does quark matter freeze out

Assume all particle production described by a temperature $T$ and a (baryon) chemical potential $\mu$:
\[ dn \sim e^{-(E-\mu)/T} d^3p \]

One ratio (e.g., $p/\pi$) determines $\mu / T$

Second ratio (e.g., $K / \pi$) provides $T \rightarrow \mu$; predict others

\[ T_f \sim 175 \text{ MeV} \]
Approaching the Early Universe

- Early Universe: The hot early universe contained equal numbers of particles and anti-particles
  - Anti-proton/proton = 0.999999999

- We’ve created “pure” matter approaching this value

![Graph showing beam energy vs. pbar/p ratio with points for E866 Au+Au, NA44 Pb+Pb, and RHIC]
How to actively probe the deep interior?

- Particles that come out with much energy perpendicular to the incoming beam directing must have strongly interacted in the medium: high $p_T$ events.
- Particles that come out with a shallow angle relative to the beam direction did had only feeble interaction.
- Note: the large number of particles indicate that this reaction is a “direct hit”.

![Diagram](image.png)
Hadrons are stopped in hot matter

Peripheral

\[ N_{\text{coll}} = 12.3 \pm 4.0 \]

central

\[ N_{\text{coll}} = 975 \pm 94 \]
Photons come from the inside, Pions don’t

- Direct photons are *not* inhibited by hot/dense medium
- Pions (all hadrons) *are* inhibited by hot/dense medium
What conditions have been created?

- The calibrated probes allow (rough) determination of the density formed in these collisions:
  - Energy Density $\sim 15 \text{ GeV} / \text{fm}^3$
    $\sim 100$ normal nuclear density
  - This is 5x more than what was thought necessary to produce QGP
  - Mass Density $\sim 2.5 \times 10^{16} \text{ gm} / \text{cm}^3$

- $T > 170 \text{ MeV} \sim 2 \times 10^{12} \text{ K}$
  - This is above the transition temperature of the QGP phase transition
  - The highest temperatures and densities ever formed in laboratory experiments
  - Conditions found in the first few microseconds of the Early Universe
Collective motion called “elliptic flow”

Origin: spatial anisotropy of the system when created, followed by multiple scattering of particles in the evolving system.

Spatial anisotropy $\rightarrow$ momentum anisotropy

$v_2$: 2nd harmonic Fourier coefficient in azimuthal distribution of particles with respect to the reaction plane.

$$v_2 = \left< \cos 2\phi \right> \quad \phi = \arctan \frac{p_y}{p_x}$$

Almond shape overlap region in coordinate space.

$$\varepsilon = \frac{\left< y^2 - x^2 \right>}{\left< y^2 + x^2 \right>}$$
The data show the shape of the original collision

Particle emission really is azimuthally anisotropic

Magnitude of the anisotropy grows with beam energy, then flattens
Conservation laws

- A physical quantity is “conserved” if it remains unchanged during a reaction, transformation or decay.
- Conservation laws imply that a higher principle is at work.
- Conserved quantities that we already encountered:
  1. Total Energy
  2. Momentum
  3. Angular momentum
  4. Electric Charge
  5. Baryon Number
  6. Lepton Number
  7. Strangeness

- The most fundamental Conservation Laws stem from the assumption that physical equations should be independent of the system in which they are observed. e.g.
  - Equations should be invariant to Lorentz transformation
    Translational transformation
    Rotational transformation
    Gauge invariance
  - Implicit in the Standard Model
Conservation laws in beta decay

- Energy Conservation
- Angular momentum conservation
- Charge conservation
- Baryon number conservation
- Lepton conservation

**Please note:** When the d quark changes into a u quark by producing a W Boson the quark color is preserved. Thus I have drawn the d & u arrows in the same color.

- It was noted by a smart student in class that the W cannot carry away color and the color must be preserved.

\[
\begin{align*}
n &\rightarrow p + e^- + \bar{\nu}_e \\
u dd &\rightarrow uud + e^- + \bar{\nu}_e \\
d &\rightarrow u + e^- + \bar{\nu}_e
\end{align*}
\]
Symmetries of shapes and bodies

• *If a shape or body is turned or changed in some operation and afterwards looks the same as before, the body is symmetric under that operation.*

• Similarly, physical equations can have symmetries. In fact the most elegant and basic equations derive their beauty and perhaps their insightfulness from their symmetry.

http://www.ctms.nist.gov/wulffman.html

A sphere like Earth is symmetric for rotations around *any* axis – unless we look at the details on the surface.

A box has symmetries for rotations by 90 degrees **to any surface**
Symmetries of simple shapes

This triangle is symmetric to rotations by $60^0$ or reflection by $180^0$ around the red axis.

This triangle is only symmetric to $180^0$ reflection around the red axis: less symmetric.

This football is rotational symmetric around the vertical (red) axis, but not the brown axis.

Find the symmetries of this body in the plane of the page.
Snowflakes, like other crystals display beautiful symmetries.

The human body is largely left-right symmetric in appearance. The human hands are symmetric in respect to left-right reflection.

All proteins turn out to be twisted in only one direction: left-handed. This is because all functioning amino-acids are left-handed. Right-handed amino-acids and proteins can be made on the bench but they are not leading to functioning proteins.

This puzzled already Louis Pasteur. (we will come back to this mystery)
Mirror Symmetry

• The Parity operation \( P(1) \) in one dimension flips the shape of an object into its mirror image: If \( P(1) \) operates on an arrow it will change it from a right arrow to a left arrow.

Mirror reflection changes a right-handed screw into a left-handed screw.

The Laws of Nature should not depend on whether we live in a right-handed or a left-handed world.

It should not matter whether we look at the real object or its picture image.

C.N. Yang and T. D. Lee proposed that this statement was wrong for the weak interaction.

http://www.phy.ntnu.edu/java/optics/mirror_e.html

http://www.phy.ntnu.edu/java/optics/mirror_e.html

http://www.phy.ntnu.edu/java/optics/mirror_e.html

Which is the real picture?
The Parity Operation

- The full parity operation reflects a 3-dimensional object around each direction: the x-axis, the y-axis and the z-axis. Thus we use 3 mirrors, one for each reflection.
- The operation $P(x)$ reflects with a mirror that lies in the y-z plane.
- The operation $P(y)$ reflects with a mirror that lies in the x-z plane.
- The operation $P(z)$ reflects with a mirror that lies in the x-y plane.
- Note: After the first reflection the rotation marker changes direction, but the arrow stays upright. After 3 reflections the rotation has its original sense back but the arrow is inverted.

$P \cdot \text{Shape (x, y, z)} = \text{Shape (-x, -y, -z)}$
Parity violation in the weak interaction

- Parity conservation was first tested in the beta decay of $^{60}\text{Co}$:

\[ ^{60}\text{Co} \rightarrow ^{60}\text{Ni} + e^- + \bar{\nu}_e \]

- The Co nuclei can be aligned by orienting their spins upwards in a magnetic field. Suppose the electrons are emitted preferentially downward (in the real world), i.e. opposite to the spin direction.

- In the mirror world the spin direction faces downward. The beta rays will still come out downwards. Thus they would now come out in the same direction as the spin.
Wu’s experiment

- The only way that the mirror image could NOT be differentiated from the real world is with electrons coming out equally in the upward and the downward direction.
- But Mrs. Wu et al observed that the electrons came out preferentially up or down. Thus Parity was NOT conserved.
- Nuclear polarisation through spin alignment in a large magnetic field at 0.01°K. At low temperature thermal motion does not destroy the alignment. Beta particles from $^{60}$Co decay were detected by a thin scintillator placed above the $^{60}$Co source.
- Flipping the magnetic field flips the $^{60}$Co spin direction, thus producing the mirror situation.
Wu’s results

- Top and middle graph - gamma anisotropy (difference in counting rate between two NaI crystals) shows control of polarization;
- Bottom - β asymmetry - counting rate in the anthracene crystal relative to the rate without polarization (after the set up was warmed up) for two orientations of magnetic field.
- Similar behavior of gamma anisotropy and beta asymmetry.
- Rate was different for the two magnetic field orientations indicating that Parity symmetry was violated.
Particles & Antiparticles: The Dirac Equation

- Starting ~ 1930 Dirac extended quantum mechanics to include Special Relativity.
- Einstein had written:

\[ E^2 = p^2 + m^2 c^4 \]

- With spin-1/2 electrons, e.g. can never stand still and thus \( p \) is never zero.
- If we solve for \( E \) we obtain

\[ E = \pm \sqrt{p^2 + m^2 c^4} \]

- What does the \( \pm \) sign possibility mean?

- Can Energy ever be negative?
- Lifting an electron from a sea of bound particles leaves behind a positive hole: **Positron.**

Paul M. Dirac

Free particles

Bound particles
1. Describe briefly the various distinct stages of the evolution of the Universe as it cooled down after the Big Bang.

2. How does the Relativistic Heavy Ion Collider (RHIC) reproduce the conditions of the Universe when quarks were “deconfined”. For how long a time period can experiment hope to recreate this early universe?

3. What experimental evidence shows that experiment has succeeded in recreating these conditions? Explain one piece briefly. (Hint: consider how long it takes for a relativistic quark to fly through the hot nuclear volume!)

4. How can we understand the Baryon Conservation in terms of the quark model. Use the example of the beta decay of the proton.

5. Are the human hands mirror symmetric? Do the experiment with a mirror!

6. Describe the symmetries of the rectangle shown in slide 28, in two dimensions (i.e. in the plane of the paper).