More on the Standard Model
• Wave-particle duality: particles exhibit both particle- and wave-like behavior

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

particle momentum \[ p \] Planck’s constant \[ h \] wavelength \[ \lambda \]

• If you want to probe short length scales, use high momenta particles!

• We collide high energy protons to study the smallest length scales (particles)
Easiest way to achieve high center-of-mass energy is colliding beams of protons or anti-protons

heavy, so no synchrotron radiation
stable, so can take time accelerating

But: messy!

hadron colliders are really quark/gluon colliders

“constituents” of proton that carry large fraction of its energy

“constituents” of proton that carry small fraction of its energy
The LHC is the world’s highest energy particle collider. Two beams of protons are accelerated around the ring (to 4 TeV of energy) and collide with each other at various points around the ring.
Why is colliding two particles together so effective?

Suppose you collide a proton with $E=8$ TeV against another proton at rest.

  Compare that to a colliding two protons each with $E=4$ TeV against each other.

Which process produces the more massive/energetic particles?
Consider the reaction

\[ p + \bar{p} \rightarrow X \]

where \( X \) is an unknown particle you want to create.

In the center of mass frame, the \( X \) is produced at rest. This means that the energy required to produce the \( X \) is

\[ K_p + K_{\bar{p}} + m_p c^2 + m_{\bar{p}} c^2 = m_X c^2 \]

Since the mass of the proton and antiproton are the same, and the momentum are equal (but opposite)

\[ K_p = m_X c^2 / 2 - m_p c^2 \quad \rightarrow \quad E_p = m_X c^2 / 2 \]

is the minimum energy needed to produce the \( X \).
What happens if the antiproton is at rest?

We can use our old nuclear physics equation to help.

\[ K_{Th} = -Q \cdot \frac{\text{Sum of all masses}}{2 \times \text{target mass}} \]

\[ Q = (m_p + m_{\bar{p}} - m_X) \, c^2 \]

Sum of all masses = \( m_p + m_{\bar{p}} + m_X \)

target mass = \( m_{\bar{p}} \)

Therefore,

\[ K_{Th} = \frac{m_X^2 - 4m_p^2}{2m_p} \, c^2 \rightarrow E_{Th} = \frac{m_X^2 - 2m_p^2}{2m_p} \, c^2 \]
Now, suppose the mass of the X is much greater than the mass of the proton.

\[ E_{\text{Th}} \approx \frac{m_X^2}{2m_p} c^2 = \left( \frac{m_X c^2}{2} \right) \frac{m_X}{m_p} \]

Compare this with two protons colliding with equal but opposite momenta:

\[ E = \frac{m_X c^2}{2} \]

Notice the extra factor?
Suppose $M_X=1000 \, m_p$.

Two protons colliding head on would each need a total energy of $500 \, m_p c^2$ to create the $X$.

That is approximately $469 \, \text{GeV each}$.

If the antiproton was at rest, the colliding proton would need $500000 \, m_p c^2$ to create the $X$.

This is approximately $469 \, \text{TeV}$. 
Celestial Gravity

\[ F = -\frac{G_N m_1 m_2}{r^2} \hat{r} \]

Terrestrial Gravity
• In 1797-98, 110 years after Newton published *Principia*, Cavendish performed his famous torsion experiment.

• this confirmed the principle of Universal gravitation and determined Newton’s constant.
Weak Force

Electromagnetic Force

\[ S(\phi, A) = \int -\frac{1}{4} F^{\mu\nu} F_{\mu\nu} + |(\partial - iqA)\phi|^2 - \lambda(|\phi|^2 - \Phi^2)^2. \]
• The standard model doesn’t explain a lot of things...
  • There are many free parameters (CKM phases, fermion masses)
  • Why is there a generational structure? Why three generations?
  • Why is the top quark so massive?
  • The gravitational force is neglected entirely from the SM
  • No coupling constant unification

• **Hierarchy problem:** why is gravity so weak?
• **Dark Matter**
  • **From studying microwave background:**
    • ~70% of the universe is dark energy
    • ~5% is baryonic matter
    • ~25% is some non-baryonic cold dark matter
  • **Confirmation from galactic rotation curves, type IA supernovae and gravitational lensing**

• **Baryon (matter/antimatter) Asymmetry**
  • More CP violation (and phase transition) need to satisfy Sakharov conditions