What Do We Know About the Structure of Matter?

The structure of matter.

→ Table of Elements (TOE)

The current TOE!

→ quarks and leptons.

We are made mostly of triplets of quarks.

→ protons and neutrons → the nucleons

More than 99% of 'our mass' is in quark triplets.

The color force binds quarks together.


→ Can't be solved at the energies of nuclei. Yet!

Need new data to guide and challenge theory.

Worldwide effort to unravel QCD in nuclei.
What Do We Know About the Structure of Matter?

- The structure of matter.
  → Table of Elements (TOE)

The current TOE includes quarks and leptons. We are made mostly of triplets of quarks, which are protons and neutrons, the nucleons. More than 99% of 'our mass' is in quark triplets. The color force binds quarks together.


Can't be solved at the energies of nuclei. Yet! Need new data to guide and challenge theory. Worldwide effort to unravel QCD in nuclei.
The structure of matter.
→ Table of Elements (TOE)

The current TOE!
→ quarks and leptons.
What Do We Know About the Structure of Matter?

- The structure of matter.
  - Table of Elements (TOE)

- The current TOE!
  - quarks and leptons.

- We are made mostly of triplets of quarks.
  - protons and neutrons
  - the nucleons

---

**Table of Elements (TOE)**

<table>
<thead>
<tr>
<th>Flavors</th>
<th>Mass GeV/c²</th>
<th>Electric charge</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\nu_L$</td>
<td>$(0-2) \times 10^{-9}$</td>
<td>0</td>
</tr>
<tr>
<td>e electron</td>
<td>0.000511</td>
<td>-1</td>
</tr>
<tr>
<td>$\nu_M$ middle neutrino</td>
<td>$(0.009-2) \times 10^{-9}$</td>
<td>0</td>
</tr>
<tr>
<td>$\nu_H$ heaviest neutrino</td>
<td>$(0.05-2) \times 10^{-9}$</td>
<td>0</td>
</tr>
<tr>
<td>$\tau$ tau</td>
<td>1.777</td>
<td>-1</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Matter Constituents spin = 1/2</th>
</tr>
</thead>
</table>

<table>
<thead>
<tr>
<th>Flavor</th>
<th>Approx. Mass GeV/c²</th>
<th>Electric charge</th>
</tr>
</thead>
<tbody>
<tr>
<td>u up</td>
<td>0.002</td>
<td>2/3</td>
</tr>
<tr>
<td>d down</td>
<td>0.005</td>
<td>-1/3</td>
</tr>
<tr>
<td>c charm</td>
<td>1.3</td>
<td>2/3</td>
</tr>
<tr>
<td>s strange</td>
<td>0.1</td>
<td>-1/3</td>
</tr>
<tr>
<td>t top</td>
<td>173</td>
<td>2/3</td>
</tr>
<tr>
<td>b bottom</td>
<td>4.2</td>
<td>-1/3</td>
</tr>
</tbody>
</table>
What Do We Know About the Structure of Matter?

- The structure of matter.  
  → Table of Elements (TOE)
- The current TOE!  
  → quarks and leptons.
- We are made mostly of triplets of quarks.
  → protons and neutrons
  → the nucleons
- More than 99% of ‘our mass’ is in quark triplets.
What Do We Know About the Structure of Matter?

- The structure of matter.
  → Table of Elements (TOE)
- The current TOE!
  → quarks and leptons.
- We are made mostly of triplets of quarks.
  → protons and neutrons
  → the nucleons
- More than 99% of ‘our mass’ is in quark triplets.
- The color force binds quarks together.
What Do We Know About the Structure of Matter?

- The structure of matter.
  → Table of Elements (TOE)
- The current TOE!
  → quarks and leptons.
- We are made mostly of triplets of quarks.
  → protons and neutrons
  → the nucleons
- More than 99% of ‘our mass’ is in quark triplets.
- The color force binds quarks together.
What Do We Know About the Structure of Matter?

- The structure of matter.
  → Table of Elements (TOE)

- The current TOE!
  → quarks and leptons.

- We are made mostly of triplets of quarks.
  → protons and neutrons
  → the nucleons

- More than 99% of ‘our mass’ is in quark triplets.

- The color force binds quarks together.
  → Can’t be solved at the energies of nuclei. Yet!
What Do We Know About the Structure of Matter?

- The structure of matter.
  → Table of Elements (TOE)

- The current TOE!
  → quarks and leptons.

- We are made mostly of triplets of quarks.
  → protons and neutrons
  → the nucleons

- More than 99% of ‘our mass’ is in quark triplets.

- The color force binds quarks together.
  → Can’t be solved at the energies of nuclei. Yet!

- Need new data to guide and challenge theory.

### Table of Elements (TOE)

**Leptons**

<table>
<thead>
<tr>
<th>Flavor</th>
<th>Mass GeV/c²</th>
<th>Electric charge</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\nu_L$</td>
<td>$(0-2) \times 10^{-9}$</td>
<td>0</td>
</tr>
<tr>
<td>electron</td>
<td>0.000511</td>
<td>−1</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Flavor</th>
<th>Mass GeV/c²</th>
<th>Electric charge</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\nu_M$</td>
<td>$(0.009-2) \times 10^{-9}$</td>
<td>0</td>
</tr>
<tr>
<td>middle neutrino</td>
<td>0.106</td>
<td>−1</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Flavor</th>
<th>Mass GeV/c²</th>
<th>Electric charge</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\nu_H$</td>
<td>$(0.05-2) \times 10^{-9}$</td>
<td>0</td>
</tr>
<tr>
<td>heaviest neutrino</td>
<td>1.777</td>
<td>−1</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Flavor</th>
<th>Approx. Mass GeV/c²</th>
<th>Electric charge</th>
</tr>
</thead>
<tbody>
<tr>
<td>$u$ up</td>
<td>0.002</td>
<td>2/3</td>
</tr>
<tr>
<td>$d$ down</td>
<td>0.005</td>
<td>−1/3</td>
</tr>
<tr>
<td>$c$ charm</td>
<td>1.3</td>
<td>2/3</td>
</tr>
<tr>
<td>$s$ strange</td>
<td>0.1</td>
<td>−1/3</td>
</tr>
<tr>
<td>$t$ top</td>
<td>173</td>
<td>2/3</td>
</tr>
<tr>
<td>$b$ bottom</td>
<td>4.2</td>
<td>−1/3</td>
</tr>
</tbody>
</table>
What Do We Know About the Structure of Matter?

- The structure of matter.
  - Table of Elements (TOE)
- The current TOE!
  - quarks and leptons.
- We are made mostly of triplets of quarks.
  - protons and neutrons
  - the nucleons
- More than 99% of ‘our mass’ is in quark triplets.
- The color force binds quarks together.
  - Can’t be solved at the energies of nuclei. Yet!
- Need new data to guide and challenge theory.
- Worldwide effort to unravel QCD in nuclei.

### Table of Elements (TOE)

<table>
<thead>
<tr>
<th>Flavor</th>
<th>Mass GeV/c²</th>
<th>Electric charge</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\nu_L$ lightest neutrino*</td>
<td>$(0-2) \times 10^{-9}$</td>
<td>0</td>
</tr>
<tr>
<td>e electron</td>
<td>0.000511</td>
<td>$-1$</td>
</tr>
<tr>
<td>$\nu_e$ middle neutrino*</td>
<td>$(0.009-2) \times 10^{-9}$</td>
<td>0</td>
</tr>
<tr>
<td>$\mu$ muon</td>
<td>0.106</td>
<td>$-1$</td>
</tr>
<tr>
<td>$\nu_\mu$ heaviest neutrino*</td>
<td>$(0.05-2) \times 10^{-9}$</td>
<td>0</td>
</tr>
<tr>
<td>$\tau$ tau</td>
<td>1.777</td>
<td>$-1$</td>
</tr>
<tr>
<td>u up</td>
<td>0.002</td>
<td>2/3</td>
</tr>
<tr>
<td>d down</td>
<td>0.005</td>
<td>$-1/3$</td>
</tr>
<tr>
<td>c charm</td>
<td>1.3</td>
<td>2/3</td>
</tr>
<tr>
<td>s strange</td>
<td>0.1</td>
<td>$-1/3$</td>
</tr>
<tr>
<td>t top</td>
<td>173</td>
<td>2/3</td>
</tr>
<tr>
<td>b bottom</td>
<td>4.2</td>
<td>$-1/3$</td>
</tr>
</tbody>
</table>
How Do We Turn on the Lights Inside a Nucleus?

- Build the newest US national lab Jefferson Lab (JLab) in Newport News, VA
- The accelerator CEBAF is a mile-long, racetrack-shaped, superconducting linear accelerator.
- Rapidly varying electric fields push electrons to 12 GeV.
- Electron beam distributed to four halls.
- Just completing a $330M Upgrade.
How Do We Turn on the Lights Inside a Nucleus?

- Build the newest US national lab Jefferson Lab (JLab) in Newport News, VA
- The accelerator CEBAF is a mile-long, racetrack-shaped, superconducting linear accelerator.
- Rapidly varying electric fields push electrons to 12 GeV.
- Electron beam distributed to four halls.
- Just completing a $330M Upgrade.

It’s a QCD laboratory!
How Do We See Quarks?

- Build a large (3-story, 45-ton) particle detector called CLAS12 in Hall B.
- Many layers measure the debris from electron-target collisions.
- Over 100,000 readouts in $\approx 40$ layers.
- Large magnet bends charged particles to measure 4-momenta of the debris.
- Will write 5-10 TByte to disk each day.
How Do We See Quarks?

- Build a large (3-story, 45-ton) particle detector called CLAS12 in Hall B.
- Many layers measure the debris from electron-target collisions.
- Over 100,000 readouts in ≈ 40 layers.
- Large magnet bends charged particles to measure 4-momenta of the debris.
- Will write 5-10 TByte to disk each day.

First production data spring, 2018!
How Do We See Quarks?

- Build a large (3-story, 45-ton) particle detector called CLAS12 in Hall B.
- Many layers measure the debris from electron-target collisions.
- Over 100,000 readouts in \( \approx 40 \) layers.
- Large magnet bends charged particles to measure 4-momenta of the debris.
- Will write 5-10 TByte to disk each day.

First production data spring, 2018!
How Do We See Quarks?

- Build a large (3-story, 45-ton) particle detector called CLAS12 in Hall B.
- Many layers measure the debris from electron-target collisions.
- Over 100,000 readouts in \( \approx 40 \) layers.
- Large magnet bends charged particles to measure 4-momenta of the debris.
- Will write 5-10 TByte to disk each day.

First production data spring, 2018!
Additional Slides
Where does mass come from?

- The proton is 2 ups + 1 down; the neutron is 1 up + 2 downs.
Where does mass come from?

- The proton is 2 ups + 1 down; the neutron is 1 up + 2 downs.
- A quiz: How much does the proton weigh?

### FERMIONS

<table>
<thead>
<tr>
<th>Flavor</th>
<th>Mass GeV/c²</th>
<th>Electric charge</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\nu_e$</td>
<td>$(0-2) \times 10^{-9}$</td>
<td>0</td>
</tr>
<tr>
<td>$e^{-}$</td>
<td>0.000511</td>
<td>-1</td>
</tr>
<tr>
<td>$\nu_{\mu}$</td>
<td>$(0.009-2) \times 10^{-9}$</td>
<td>0</td>
</tr>
<tr>
<td>$\mu^{-}$</td>
<td>0.106</td>
<td>-1</td>
</tr>
<tr>
<td>$\nu_{\tau}$</td>
<td>$(0.05-2) \times 10^{-9}$</td>
<td>0</td>
</tr>
<tr>
<td>$\tau^{-}$</td>
<td>1.777</td>
<td>-1</td>
</tr>
</tbody>
</table>

### Matter Constituents

<table>
<thead>
<tr>
<th>Flavor</th>
<th>Approx. Mass GeV/c²</th>
<th>Electric charge</th>
</tr>
</thead>
<tbody>
<tr>
<td>$u$</td>
<td>0.002</td>
<td>2/3</td>
</tr>
<tr>
<td>$d$</td>
<td>0.005</td>
<td>-1/3</td>
</tr>
<tr>
<td>$c$</td>
<td>1.3</td>
<td>2/3</td>
</tr>
<tr>
<td>$s$</td>
<td>0.1</td>
<td>-1/3</td>
</tr>
<tr>
<td>$t$</td>
<td>173</td>
<td>2/3</td>
</tr>
<tr>
<td>$b$</td>
<td>4.2</td>
<td>-1/3</td>
</tr>
</tbody>
</table>
The proton is 2 ups + 1 down; the neutron is 1 up + 2 downs.

A quiz: How much does the proton weigh?

\[ m_p = 2m_{up} + m_{down} \]
Where does mass come from?

- The proton is 2 ups + 1 down; the neutron is 1 up + 2 downs.
- A quiz: How much does the proton weigh?

\[ m_p = 2m_{up} + m_{down} = 2(0.002 \text{ GeV/c}^2) + 0.005 \text{ GeV/c}^2 \]
\[ = 0.009 \text{ GeV/c}^2 \]
Where does mass come from? - **UH-OH!**

- The proton is 2 ups + 1 down; the neutron is 1 up + 2 downs.
- A quiz: How much does the proton weigh?

$$m_p = 2m_{up} + m_{down} = 2(0.002 \text{ GeV}/c^2) + 0.005 \text{ GeV}/c^2$$

$$= 0.009 \text{ GeV}/c^2$$

$$= 0.939 \text{ GeV}/c^2 \quad \text{OOOPS}!!!???
How do we get out of this?

- The color charge of a quark produces a strong field, e.g., a charged particle.
How do we get out of this?

- The color charge of a quark produces a strong field, e.g. a charged particle.
- Between and around bound quarks the energy density is high.
How do we get out of this?

- The color charge of a quark produces a strong field, e.g. a charged particle.
- Between and around bound quarks the energy density is high.
How do we get out of this?

- The color charge of a quark produces a strong field, e.g. a charged particle.
- Between and around bound quarks the energy density is high.
- Most of the mass we see comes from the quark color fields → gluon cloud!
How do we get out of this?

- The color charge of a quark produces a strong field, e.g. a charged particle.
- Between and around bound quarks the energy density is high.
- Most of the mass we see comes from the quark color fields → gluon cloud!
How do we get out of this?

- The color charge of a quark produces a strong field, e.g. a charged particle.
- Between and around bound quarks the energy density is high.
- Most of the mass we see comes from the quark color fields → gluon cloud!

- At JLab we probe the nucleon interior with high-momentum electrons.
- The momentum/wavelength (\(\lambda\)) of the electrons sample different sizes.
How do we get out of this?

- The color charge of a quark produces a strong field, e.g. a charged particle.
- Between and around bound quarks the energy density is high.
- Most of the mass we see comes from the quark color fields → gluon cloud!

- At JLab we probe the nucleon interior with high-momentum electrons.
- The momentum/wavelength (\(\lambda\)) of the electrons sample different sizes.
- At high momentum you probe close to the quarks → bare quark mass.

\[ E = mc^2 \]
How do we get out of this?

- The color charge of a quark produces a strong field, e.g. a charged particle.
- Between and around bound quarks the energy density is high.
- Most of the mass we see comes from the quark color fields → gluon cloud!

- At JLab we probe the nucleon interior with high-momentum electrons.
- The momentum/wavelength ($\lambda$) of the electrons sample different sizes.
- At high momentum you probe close to the quarks → bare quark mass.
- At low momentum you probe the whole cloud.
But is it real?

- The cross section reflects the effective size of the target in a scattering experiment.
- The form factors $G_E$ and $G_M$ are two components of the cross sections we measure.

Jerry Gilfoyle
The cross section reflects the effective size of the target in a scattering experiment.

The form factors $G_E$ and $G_M$ are two components of the cross sections we measure.

The ratio of the form factors $G_E/G_M$ for the proton is sensitive to the shape of the mass function.

But is it real?
But is it real?

- The cross section reflects the effective size of the target in a scattering experiment.
- The form factors $G_E$ and $G_M$ are two components of the cross sections we measure.
- The ratio of the form factors $G_E/G_M$ for the proton is sensitive to the shape of the mass function.

We are probing how mass emerges from QCD color fields.
A Connection With Ted

History of the Universe

Key:
- W, Z bosons
- photon
- quark
- meson
- galaxy
- gluon
- baryon
- star
- electron
- ion
- black hole
- neutrino

Particle Data Group, LBNL, © 2008. Supported by DOE and NSF
A Connection With Ted

History of the Universe

Key:
- W, Z bosons
- photon
- q quark
- g gluon
- e electron
- μ muon
- τ tau
- ν neutrino
- γ photon
- meson
- galaxy
- atom
- black hole

Particle Data Group, LBNL, © 2008. Supported by DOE and NSF
The usual suspects: Keegan Sherman, Omair Alam, Alexander Balsamo, David Brakman, Peter Davies, old gray-haired guy.

Software is important! We are writing code for:
- methods to align the 33,792 elements of the silicon vertex tracker to within $40 - 50 \mu m$.
- extracting the magnetic form factor $G_M^n$ from the $eD \rightarrow e'p(n)$ and $eD \rightarrow e'n(p)$ reactions.
- measuring the neutron detection efficiency needed for $eD \rightarrow e'n(p)$ with $ep \rightarrow e'\pi^+ n$.
- monitoring and operating a cryogenic LD$_2$ – LH$_2$ target.

Rely now on simulation of CLAS12 and cosmic ray data until 2017.
Four student posters in Vancouver in October.
JLab is at the frontier of our understanding of the basic properties of matter including most of the known mass.

First measurement of the nucleon mass curve?

CLAS12 is a large, complex particle detector about to see first beam.

Our group is preparing feverishly to understand the deluge of data that is coming - first beams in April!
What is the force that holds us together?

- The color force binds quarks together via gluon exchange.
- The quarks are never alone. → confinement
- At high energy the force is weak. → asymptotic freedom
What is the force that holds us together?

- The color force binds quarks together via gluon exchange.
- The quarks are never alone.
  → confinement
- At high energy the force is weak.
  → asymptotic freedom
- Quantum Chromodynamics - QCD nails it.
  → Only at high energy where the color force is weak.
What is the force that holds us together?

- The color force binds quarks together via gluon exchange.
- The quarks are never alone.
  → confinement
- At high energy the force is weak.
  → asymptotic freedom
- Quantum Chromodynamics - QCD nails it.
  → Only at high energy where the color force is weak.

QCD is wildly successful!

Jerry Gilfoyle

Research Introduction
What is the force that holds us together?

- The color force binds quarks together via gluon exchange.
- The quarks are never alone. → confinement
- At high energy the force is weak. → asymptotic freedom
- Quantum Chromodynamics - QCD nails it. → 2005 Nobel to Gross, Wilczek, and Politzer. → Only at high energy where the color force is weak.

QCD is wildly successful! But can’t be solved at nucleon energies. Yet!
But is it real?

- The cross section reflects the effective size of the target in a scattering experiment.
But is it real?

- The cross section reflects the effective size of the target in a scattering experiment.
- This cross section can be expressed here in electric and magnetic form factors $G_E$ and $G_M$.

\[ \frac{d\sigma}{d\Omega} = \frac{\sigma_{\text{Mott}}}{\epsilon(1+\tau)} \left( \epsilon G_E^2 + \tau G_M^2 \right) \]
But is it real?

- The cross section reflects the effective size of the target in a scattering experiment.
- This cross section can be expressed here in electric and magnetic form factors $G_E$ and $G_M$.
- The ratio $G_E/G_M$ for the proton has a zero crossing sensitive to the shape of the mass function.

$$\frac{d\sigma}{d\Omega} = \frac{\sigma_{\text{Mott}}}{\epsilon(1+\tau)} \left( \epsilon G_E^2 + \tau G_M^2 \right)$$

But is it real?

- The cross section reflects the effective size of the target in a scattering experiment.
- This cross section can be expressed here in electric and magnetic form factors $G_E$ and $G_M$.
- The ratio $G_E / G_M$ for the proton has a zero crossing sensitive to the shape of the mass function.
- So does $G_E / G_M$ for the neutron.

$$\frac{d\sigma}{d\Omega} = \frac{\sigma_{\text{Mott}}}{\epsilon(1+\tau)} \left( \epsilon G_E^2 + \tau G_M^2 \right)$$