Hadron Physics -
Spectroscopy and QCD

Ulrich Wiedner
(Ruhr-University Bochum)
Fundamental Particles and Interactions

The Standard Model is a theoretical framework that describes the fundamental interactions of subatomic particles. It includes the electromagnetic, weak, and strong forces, and it predicts the existence of quarks and leptons, which are the building blocks of all matter.

**Fermions**
- **Leptons**: Matter constituents with spin 1/2, including the electron, muon, and tau, which interact via the weak force and gravity.
- **Quarks**: Matter constituents with spin 1/2, including up, down, charm, strange, top, and bottom, which interact via all four forces.

**Bosons**
- **Electroweak Bosons**: Charged leptons and quarks that mediate the weak force, including the $W^+/-$, $Z^0$, and photons.
- **Strong (Color) Bosons**: Gluons that mediate the strong force, and gluons and photons that mediate the electromagnetic force.

**Properties of the Interactions**

- **Gravitational Interaction**: Acts on all matter.
- **Electromagnetic Interaction**: Acts on charged particles.
- **Weak Interaction**: Acts on charged and neutral particles.
- **Strong Interaction**: Acts on quarks and gluons.

**Baryons and Mesons**
- **Baryons** are particles with half-integer spin (1/2 or 3/2).
- **Mesons** are particles with integer spin (0 or 1).

**Matter and Antimatter**
- Matter and antimatter are identical in all respects except for their charge.

**Standard Model of Fundamental Particles and Interactions**

The Standard Model summarizes the current knowledge in Particle Physics. It is the quantum theory that includes the theory of weak and electromagnetic interactions (electroweak). Gravity is included on this chart because it is one of the fundamental interactions even though not part of the "Standard Model."
Level of complexity

Hadron Physics

Ulrich Wiedner
We learned about the nature of the atom due to the periodic system

![Periodic Table](image)

Ulrich Wiedner
How to study hadrons?

• All particles except the proton are unstable and have to be produced

• Build them together in a controlled manner
  ∷ $e^+e^-$ collider can produce vector mesons (other particles in decays)
  ∷ hadron beams have high production cross sections but little control (except for antiprotons)

• Observe them in a spectroscopic way
  ∷ study their properties (mass, spin, lifetime, ...)
  ∷ study their decay patterns
  ∷ study their production modes
**Standard Model of FUNDAMENTAL PARTICLES AND INTERACTIONS**

The Standard Model summarizes the current knowledge in Particle Physics. It is the quantum theory that includes the theory of strong interactions (quantum chromodynamics or QCD) and the unified theory of weak and electromagnetic interactions (electroweak). Gravity is included on this chart because it is one of the fundamental interactions even though not part of the "Standard Model."

### FERMIONS

<table>
<thead>
<tr>
<th>Flavor</th>
<th>Mass GeV/c²</th>
<th>Electric Charge</th>
</tr>
</thead>
<tbody>
<tr>
<td>ν_e</td>
<td>&lt;1×10⁻³</td>
<td>0</td>
</tr>
<tr>
<td>e</td>
<td>0.000511</td>
<td>-1</td>
</tr>
<tr>
<td>ν_μ</td>
<td>&lt;0.0002</td>
<td>0</td>
</tr>
<tr>
<td>μ</td>
<td>0.106</td>
<td>-1</td>
</tr>
<tr>
<td>ν_τ</td>
<td>&lt;0.02</td>
<td>0</td>
</tr>
<tr>
<td>τ</td>
<td>1.7771</td>
<td>-1</td>
</tr>
</tbody>
</table>

Spin is the intrinsic angular momentum of particles. Spin is given in units of ℏ, which is the quantum unit of angular momentum, where ℏ = h/2π, E = 6.626×10⁻³⁴ GeV·s = 1.986×10⁻³⁷ J·s.

Electric charges are given in units of the proton's charge. In SI units the electric charge of the proton is 1.602×10⁻¹⁹ coulombs.

The energy unit of particle physics is the electronvolt (eV), the energy gained by one electron in crossing a potential difference of one volt. Masses are given in GeV/c² (Gev/c2) and are 1.602×10⁻³⁴ joule. The mass of the proton is 938.2720 MeV/c² = 1.672×10⁻²⁷ kg.

### BOSONS

<table>
<thead>
<tr>
<th>Flavor</th>
<th>Mass GeV/c²</th>
<th>Electric Charge</th>
</tr>
</thead>
<tbody>
<tr>
<td>γ photon</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>W⁺</td>
<td>80.4</td>
<td>-1</td>
</tr>
<tr>
<td>W⁻</td>
<td>80.4</td>
<td>+1</td>
</tr>
<tr>
<td>Z⁰</td>
<td>91.187</td>
<td>0</td>
</tr>
</tbody>
</table>

Color Charge: Each quark carries one of three types of "quark charge," also called "color charge." These colors have nothing to do with the colors of visible light. There are eight possible types of color charge for gluons, just as electrically charged particles interact by exchanging photons, in strong interactions color-charged particles interact by exchanging gluons.

Quarks Confined in Mesons and Baryons

One cannot isolate single quarks and gluons, they are confined in color-neutral particles called hadrons. This confinement (binding) results from multiple exchanges of gluons among the color-charged constituents. As color-charged particles (quarks and gluons) move apart, the energy in the color-force field between them increases. This energy eventually converts into additional quark-antiquark pairs (see figure below). The quarks and antiquarks then combine into hadrons; these are the particles seen to emerge. Two types of hadrons have been observed in nature: mesons (qq) and baryons (qqq).

Residual Strong Interaction

The strong binding of color-neutral protons and neutrons to form nuclei is due to residual strong interactions between their color-charged constituents. It is similar to the residual electrical interaction that binds electrically neutral atoms into larger molecules. It can also be viewed as the exchange of mesons between the hadrons.

### PROPERTIES OF THE INTERACTIONS

<table>
<thead>
<tr>
<th>Property</th>
<th>Interaction</th>
<th>Gravitational</th>
<th>Weak</th>
<th>Electromagnetic</th>
<th>Strong</th>
</tr>
</thead>
<tbody>
<tr>
<td>Particles experiencing:</td>
<td></td>
<td></td>
<td>All</td>
<td>Quarks, Leptons</td>
<td>Electrically charged</td>
</tr>
<tr>
<td></td>
<td></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>Strength relative to electrons</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>for two quarks at:</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>for two protons in nucleus</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Matter and Antimatter**

For every particle type there is a corresponding antiparticle type, denoted by a bar over the particle symbol (unless e + e⁻ charge is shown). Particle and antiparticle have identical mass and spin but opposite charge. Some electrically neutral bosons (e.g., Z, γ, and η, η', η''), but not η'′, are their own antiparticles.

**Figures**

These diagrams are an artist's conception of physical processes. They are not exact and have no meaningful scale. Green shaded areas represent the cloud of gluons or the gluon field, and red lines the quark paths.

### Baryons qqq and Antibaryons qqq

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Name</th>
<th>Quark content</th>
<th>Electric charge</th>
<th>Mass GeV/c²</th>
<th>Spin</th>
</tr>
</thead>
<tbody>
<tr>
<td>p</td>
<td>proton</td>
<td>uud</td>
<td>1/2</td>
<td>0.938</td>
<td>1/2</td>
</tr>
<tr>
<td>p</td>
<td>antiproton</td>
<td>uud</td>
<td>-1/2</td>
<td>-0.938</td>
<td>1/2</td>
</tr>
<tr>
<td>n</td>
<td>neutron</td>
<td>udd</td>
<td>0</td>
<td>0.940</td>
<td>0</td>
</tr>
<tr>
<td>Λ</td>
<td>lambda</td>
<td>uds</td>
<td>0</td>
<td>1.116</td>
<td>1/2</td>
</tr>
<tr>
<td>Ω⁻</td>
<td>omega</td>
<td>sss</td>
<td>-1/2</td>
<td>-1.672</td>
<td>3/2</td>
</tr>
</tbody>
</table>

**Mesons qqq**

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Name</th>
<th>Quark content</th>
<th>Electric charge</th>
<th>Mass GeV/c²</th>
<th>Spin</th>
</tr>
</thead>
<tbody>
<tr>
<td>π⁺</td>
<td>K⁺</td>
<td>ud</td>
<td>+1</td>
<td>0.166</td>
<td>0</td>
</tr>
<tr>
<td>K⁻</td>
<td>ρ⁺</td>
<td>ud</td>
<td>+1</td>
<td>0.270</td>
<td>0</td>
</tr>
<tr>
<td>B⁺</td>
<td>d⁻</td>
<td>db</td>
<td>0</td>
<td>5.279</td>
<td>0</td>
</tr>
<tr>
<td>η</td>
<td>η'</td>
<td>e⁺e⁻</td>
<td>0</td>
<td>0.548</td>
<td>0</td>
</tr>
<tr>
<td>η'</td>
<td>η'</td>
<td>e⁺e⁻</td>
<td>0</td>
<td>0.548</td>
<td>0</td>
</tr>
</tbody>
</table>

The Particle Adventure

Visit the award-winning web feature The Particle Adventure at http://ParticleAdventure.com

This chart has been made possible by the generous support of:

- U.S. Department of Energy
- U.S. National Science Foundation
- Lawrence Berkeley National Laboratory
- Stanford Linear Accelerator Center
- American Physical Society, Division of Particles and Fields

BURLINGTON, VERMONT 05401

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There are certain rules for building hadrons:

- Even though quarks and gluons carry color, hadrons are colorless.
- The total angular momentum $J = S(\text{spin}) + L(\text{angular momentum})$.

- There are rules for parity and $C$ parity.
Two examples of success for spectroscopy

1) How to interpret strange particles

In 1962 the baryon decuplet had 9 known members and the theoretical possibility existed that it contains 27 members. Gell-Mann predicted at a conference in a comment that he believes that baryons form a decuplet and the 10th member is a baryon with

\[ S = -3, \ I = 0 \text{ and } J^P = (3/2)^+ \] with a mass of 1680 MeV

The mass prediction came out of the known mass spectrum:

\[ 1385 - 1232 = 153 \text{ und } 1530 - 1385 = 145 \Rightarrow 1530 + 150 = 1680 \]

\[ \Rightarrow M_{\Sigma} - M_{\Delta} \text{ und } M_{\Xi} - M_{\Sigma} \]
The $\Omega^-$ was discovered two years later at Brookhaven:

\[
K^- p \rightarrow \Omega^- K^+ K^0
\]

\[
\Omega^- \rightarrow \Xi^0 \pi^-
\]

\[
\Xi^0 \rightarrow \Lambda \pi^0
\]

\[
\Lambda \rightarrow p \pi^-
\]
2) Striking evidence for quarks: The Charmonium Spectrum

![Graph showing the spectrum of charmonium states with labels J=2, J=1, J=0, Crystal Ball, and various peaks and transitions](image)
BESIII data quality

\[ \psi' \rightarrow \gamma X \]
**Standard Model of FUNDAMENTAL PARTICLES AND INTERACTIONS**

The Standard Model summarizes the current knowledge in Particle Physics. It is the quantum theory that includes the theory of strong interactions (quantum chromodynamics QCD) and the unified theory of weak and electromagnetic interactions (electroweak). Gravity is included on this chart because it is one of the fundamental interactions even though not part of the “Standard Model.”

### FERMIONS

<table>
<thead>
<tr>
<th>Flavor</th>
<th>Mass (GeV/c²)</th>
<th>Electric Charge</th>
</tr>
</thead>
<tbody>
<tr>
<td>$u$ electron neutrino</td>
<td>$&lt;10^{-6}$</td>
<td>0</td>
</tr>
<tr>
<td>$d$ electron</td>
<td>0.000511</td>
<td>-1</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>175</td>
<td>2/3</td>
</tr>
<tr>
<td>$b$ bottom</td>
<td>4.3</td>
<td>-1/3</td>
</tr>
</tbody>
</table>

**Spin** is the intrinsic angular momentum of particles. Spin is given in units of $\hbar$, which is the quantum unit of angular momentum, where $\hbar = h/2\pi = 6.58 \times 10^{-34}$ GeV s = 1.94 \times 10^{-29}$ J s.

Electric charges are given in units of the proton's charge. In SI units the electric charge of the proton is 1.602176634 \times 10^{-19}$ Coulombs.

The energy unit of particle physics is the electron volt (eV), the energy gained by one electron in crossing a potential difference of one volt. Masses are given in GeV/c², where 1 GeV = 10^9 eV = 1.60 \times 10^{-19}$ J. The mass of the proton is 0.938 GeV/c² = 1.67 \times 10^{-27}$ kg.

**Leptons** spin = 1/2, 3/2, 5/2, ...

### QUARKS

<table>
<thead>
<tr>
<th>Flavor</th>
<th>Mass (GeV/c²)</th>
<th>Electric Charge</th>
</tr>
</thead>
<tbody>
<tr>
<td>$u$ up</td>
<td>0.003</td>
<td>2/3</td>
</tr>
<tr>
<td>$d$ down</td>
<td>0.006</td>
<td>-1/3</td>
</tr>
<tr>
<td>$s$ strange</td>
<td>0.1</td>
<td>-1/3</td>
</tr>
<tr>
<td>$c$ charm</td>
<td>1.3</td>
<td>2/3</td>
</tr>
<tr>
<td>$t$ top</td>
<td>175</td>
<td>2/3</td>
</tr>
<tr>
<td>$b$ bottom</td>
<td>4.3</td>
<td>-1/3</td>
</tr>
</tbody>
</table>

**Structure within the Atom**

If the protons and neutrons in this picture were 10 cm across, then the quarks and electrons would be less than 0.1 nm in size and the entire atom would be about 10 km across.

### BOSONS

**Electromagnetic**

<table>
<thead>
<tr>
<th>Name</th>
<th>Mass (GeV/c²)</th>
<th>Electric Charge</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\gamma$ photon</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>$g$ gluon</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

**Color Charge**

Each quark carries one of three types of “color charge,” also called “flavor charge.” These charges have nothing to do with the color of visible light. There are eight possible types of color charge for gluons. As in electricity, bosons are color-neutral particles; instead of exchanging photons, strong interactions color-charged particles interact by exchanging gluons. Leptons, photons, and $W$ and $Z$ bosons have no strong interactions and hence no color charge.

### MESONS

**Strong (color)** spin = 0, 1, 2, ...

<table>
<thead>
<tr>
<th>Name</th>
<th>Mass (GeV/c²)</th>
<th>Electric Charge</th>
</tr>
</thead>
<tbody>
<tr>
<td>$W^+$</td>
<td>80.4</td>
<td>+1</td>
</tr>
<tr>
<td>$W^-$</td>
<td>80.4</td>
<td>-1</td>
</tr>
<tr>
<td>$Z^0$</td>
<td>91.18</td>
<td>0</td>
</tr>
</tbody>
</table>

**Residual Strong Interaction**

The residual coupling of color-neutral protons and neutrons to form nuclei is due to residual strong interactions between their color-charged constituents. It is similar to the residual electrical interaction that binds electrically neutral atoms in their molecules. It can also be viewed as the exchange of mesons between the hadrons.

### PROPERTIES OF THE INTERACTIONS

#### Gravity, strong, weak, electromagnetic

- **Gravitational**
- **Strong**
- **Weak**
- **Electromagnetic**

### Matter and Antimatter

For every particle type there is a corresponding antiparticle type, denoted by a bar over the particle symbol (unless $e$ ~ charge is shown). Particles and antiparticles have identical mass and spin but opposite electric charge. Some electically neutral bosons (e.g., $Z^0$, $\gamma$, and $\eta$, $\eta'$) are not their own antiparticles.

#### Figures

These diagrams are an artist's conception of physical processes. They are not exact and have no meaningful scale. Green shaded areas represent the cloud of gluons or the gluon field, and red lines the quark’s paths.

- **$n \rightarrow p + e^- + \bar{\nu}_e$**
- **$e^- + e^- \rightarrow g + g$**
- **$p + p \rightarrow Z^0 +$ assorted hadrons**

**The Particle Adventure**

This diagram was created by the Particle Adventure team at the University of Washington and is available for streaming via The Particle Adventure at http://ParticleAdventure.org.

The Particle Adventure has been made possible by the generous support of:

- U.S. Department of Energy
- National Science Foundation
- University of Washington
- Fermi National Accelerator Center
- American Physical Society: Division of Particles and Fields
- Particle Physics and Astrophysics Program of the National Science Foundation
- APS Division of Particle Physics
- APS Division of Nuclear Physics
- APS Division of High Energy Physics
- APS Division of Elementary Particle Physics
- APS Division of Biological Physics
- APS Division of Condensed Matter Physics
- APS Division of Plasma Physics
- APS Division of Atomic Molecular and Optical Physics
- APS Division of Quantum Information Science
- APS Division of Chemical Physics
- APS Division of Fluid Dynamics
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http://CPEWeb.org
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FERMIONS

matter constituents

Leptons spin = 1/2

Quarks spin = 1/2

<table>
<thead>
<tr>
<th>Flavor</th>
<th>Mass GeV/c^2</th>
<th>Electric charge</th>
</tr>
</thead>
<tbody>
<tr>
<td>e^+</td>
<td>&lt;1 x 10^-3</td>
<td>0</td>
</tr>
<tr>
<td>e^-</td>
<td>0.005511</td>
<td>-1</td>
</tr>
<tr>
<td>μ^+</td>
<td>&lt;0.0002</td>
<td>0</td>
</tr>
<tr>
<td>μ^-</td>
<td>0.106</td>
<td>-0.5</td>
</tr>
<tr>
<td>τ^+</td>
<td>&lt;0.0</td>
<td>0</td>
</tr>
<tr>
<td>τ^-</td>
<td>1.77</td>
<td>-1</td>
</tr>
</tbody>
</table>

BOSONS

force carriers

Unified Electroweak spin = 1

Strong (color) spin = 1

<table>
<thead>
<tr>
<th>Name</th>
<th>Mass GeV/c^2</th>
<th>Electric charge</th>
</tr>
</thead>
<tbody>
<tr>
<td>γ photon</td>
<td></td>
<td>0</td>
</tr>
<tr>
<td>g gluon</td>
<td></td>
<td>0</td>
</tr>
</tbody>
</table>

Quarks Confined in Mesons and Baryons

One cannot isolate quarks and gluons; they are confined in color-neutral particles called hadrons. This confinement (binding) results from multiple exchanges of gluons among the color-charged constituents. As color-charged particles (quarks and gluons) move apart, the energy in the color-force field between them increases. This energy eventually is converted into additional quark-antiquark pairs (see figure below). The quarks and antiquarks then combine into hadrons; these are the particles seen to emerge. Two types of hadrons have been observed in nature: mesons g̅q̅ and baryons qqq.

Matter and Antimatter

For every particle type there is a corresponding antiparticle type, denoted by a bar over the particle symbol (unless ¯e = e− charge is shown). Particle and antiparticle have identical mass and spin but opposite charge. Some electrically neutral bosons (e.g., Z^0, γ, and η, c = c̅, but not K^0 = K̅) are their own antiparticles.

Figures

These diagrams are an artist's conception of physical processes. They are not exact and have no meaningful scale. Green shaded areas represent the cloud of gluons or the quark field, and red lines the quark paths.
There are hundreds of particles ... however most of them are so short-lived that we'll never see them directly in our detectors.

Track length: $l_{\text{track}} = v\tau = c\beta\gamma\tau_0$ with $\tau_0$ being the lifetime at rest.

Only if $l_{\text{track}}$ (at GeV scale) $\geq$ 1 mm, we have a chance to measure them.

We usually have to reconstruct them from “stable” particles.

Which are left then? These 8 particles (and their antiparticles).

<table>
<thead>
<tr>
<th>Particle</th>
<th>$\tau_0$</th>
<th>$l_{\text{track}}$ (p=1GeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\tau$</td>
<td>$\infty$</td>
<td>$\infty$</td>
</tr>
<tr>
<td>$\mu^+$</td>
<td>$\infty$</td>
<td>$\infty$</td>
</tr>
<tr>
<td>$\mu^-$</td>
<td>$\infty$</td>
<td>$\infty$</td>
</tr>
<tr>
<td>$\nu_e$</td>
<td>$\infty$</td>
<td>$6.1$ km</td>
</tr>
<tr>
<td>$\nu_\mu$</td>
<td>$\infty$</td>
<td>$5.5$ m</td>
</tr>
<tr>
<td>$\nu_\tau$</td>
<td>$\infty$</td>
<td>$6.4$ m</td>
</tr>
<tr>
<td>$K_0$ (Ks/KL)</td>
<td>$89$ ps / $51$ ns</td>
<td>$5$ cm / $27.5$ m</td>
</tr>
</tbody>
</table>

Ulrich Wiedner
The determination of contributing particles and their properties requires refined analysis methods.

The interpretation of the states’ nature requires refined theory.

\[ p\bar{p} \rightarrow \pi^0\pi^0\pi^0 \] Dalitz plot

700000 events = 6×700000 entries
Statistics is important!

100,000 events

Ulrich Wiedner
How to access the beautiful, clean charmonium spectrum?
Hadron production (e.g. charmonium) in $e^+e^-$ annihilations

- **Direct formation**
  - $J^{PC}=1^{--}$
  - $e^-$ to $c$, $e^+$ to $\bar{c}$

- **Double charmonium**
  - $J^{PC}=1^{--}$
  - $e^-$ to $J/\psi$, $e^+$ to $c\bar{c}$

- **Initial State Radiation**
  - $J^{PC}=1^{--}$
  - $e^-$ to $c$, $e^+$ to $\bar{c}$

- **Two-Photon Production**
  - $J^{PC}=0^{++}$ or $2^{++}$
  - but strong limitations on cross section and mass range

Ulrich Wiedner
Charmonium production in $e^+e^-$ at B-factories (BELLE)

Direct formation provides kinematical constraints

Typical b.f. for decays into charmonia $\leq 10^{-4}$

q.n. limited to low spins
Hadroproduction of charmonium-like states (e.g. LHCb, CDF, D0) mostly via B decays as in $e^+e^-$ colliders

$\Rightarrow$ limited $J^{PC}$ for charmonium-like states
Selection

- Trigger on detached vertex and high-$p_T$ hadrons and muons
- Good quality tracks
- $\mu$, K, $\pi$, $\gamma$ identification (Muon, RICH, CALO)
- Vertex quality
- PV and SV separation
- Daughter particles not from PV
- B-candidate from the PV
- Decay structure consistent
- Rectangular cuts or Boosted Decision Trees (BDT)

Efficiencies:
- Efficiencies from simulation
- when possible from data – for PID, trigger

+ higher cross section for B production

– missing kinematical constraints lead to reduced resolution
Surprises
X and Y mesons

X(3872)

$\psi'$

$B \to K \pi^+ \pi^- J/\psi$

$M(\pi^+ \pi^- J/\psi) - M(J/\psi)$

Y(3940)

$B \to K \omega J/\psi$

$M(\omega J/\psi)$

Y(4008)

$e^+ e^- \to \gamma_{ISR} \pi^+ \pi^- J/\psi$

$M(\pi^+ \pi^- J/\psi)$

Y(4260)

$Y(4008)$?

$e^+ e^- \to \gamma_{ISR} \pi^+ \pi^- \psi'$

$Y(4350)$ & $Y(4660)$

X (3940)

$e^+ e^- \to D D^* J/\psi$

$M(D D^*)$

X (3940)

$e^+ e^- \to D^* D J/\psi$

$M(D^* D)$

X (4160)

$e^+ e^- \to D^* D^* J/\psi$

$M(D^* D^*)$

Y (4140)

$Y(4140)$

$B \to K \phi J/\psi$

$M(\phi J/\psi)$

Y (4630)

$e^+ e^- \to \gamma_{ISR} \Lambda_c \Lambda_c$

$M(\Lambda_c \Lambda_c)$

Ulrich Wiedner
The $X$ $Y$ particles

- $X(3872) - B \rightarrow K\pi^+\pi^- J/\psi$
- $Y(3940) - B \rightarrow K\omega J/\psi$
- $X(3940) - e^+e^- \rightarrow J/\psi X \& e^+e^- \rightarrow J/\psi DD^*$
- $Y(4260) - e^+e^- \rightarrow \gamma \pi^+\pi^- J/\psi$
- $Y(4320) - e^+e^- \rightarrow \gamma \pi^+\pi^- \psi'$

Unusual strong decay into hidden charm.

Charmonium states?
Z_{c}(3900) at BESIII

Even more exotic: \( Z^{\pm} \)

The first one: \( Z^{+} (4430) \rightarrow \pi^{+}\psi' \)

\( e^{+}e^{-} \rightarrow \pi Z_{c}(4020) \rightarrow \pi^{+}\pi^{-}h_{c} \)

\( e^{+}e^{-} \rightarrow \pi Z_{c}(4025) \rightarrow \pi^{-}(D^{*} \overline{D}^{*})^{+} \)

~ 1 month data

~ 10 years data

Ulrich Wiedner
Charmonium
$B \to K X; \ p\bar{p}$

$X \to \pi^+ \pi^- J/\psi$

$X \to \pi^+ \pi^- \pi^0 J/\psi$

$X \to \gamma J/\psi; \ X \to \gamma \psi(2S)$

$X(3875) \to D^0 \bar{D}^0 \pi^0$

$J^{PC} = 1^{++}$

$M = 3871.68 \pm 0.17 \text{ MeV}$

$\Gamma < 1.2 \text{ MeV}$

$> 10 \sigma$

DD* molecule

threshold effect

tetraquark

Ulrich Wiedner
CONCLUSION:

New unexpected and exotic form of matter exist and has to be understood.
Discovery vs. Formation
Production of $\chi_{1,2}$

$$e^+e^- \rightarrow \psi'$$

$$\gamma (J/\psi)$$

$$\gamma \gamma (e^+e^-)$$

Reconstruction of invariant mass:
detector resolution dependent

Formation of $\chi_{1,2}$

$$\bar{p}p \rightarrow \chi_{1,2}$$

$$\gamma J/\psi$$

$$\gamma (e^+e^-)$$

Rate measurement (beam energy dependent):
detector resolution "independent"

$J^{PC} = 1^{--}$

$J = 0, 2, \ldots$
$C = +$

$J = 1$
$C = -$
It is difficult to determine the width of narrow XYZ states in decays (limited detector resolution) but in scanning experiments it should be possible.
Resonance scan

Measure rate of final state under study:

$$R_i = L_0 \cdot \sigma(p_i) \cdot K (\Delta p/p, |p_i - p_R|)$$

(K takes overlap between beam and resonance into account)
It is important to determine the resonance curve precisely ...

Analysis of $J/\psi \pi^+\pi^-$ and $D^0 \bar{D}^0 \pi^0$ Decays of the $X(3872)$

Eric Braaten and James Stapleton

Physics Department, Ohio State University, Columbus, Ohio 43210, USA
(Dated: July 17, 2009)

arXiv: 0907.3167
E. Swanson

charmonium vector states
### Thresholds in the Charmonium Spectrum

<table>
<thead>
<tr>
<th>Associated Pair</th>
<th>m/MeV/c²</th>
<th>J⁺</th>
<th>Channel (+cc)</th>
<th>Final State</th>
</tr>
</thead>
<tbody>
<tr>
<td>D_s(1968.5) D_s(1968.5)</td>
<td>3937.0</td>
<td>0⁺,1⁺,2⁺,3⁺,4⁺</td>
<td>D_s⁺D_s⁻</td>
<td>2K⁺2K⁺π⁺π⁻</td>
</tr>
<tr>
<td>D_s(1968.5) D_s⁺(2112.4)</td>
<td>4080.9</td>
<td>0⁺,1⁺,2⁺,3⁺,4⁺</td>
<td>D_s⁺(D_s⁺γ)</td>
<td>2K⁺2K⁺π⁺πγ</td>
</tr>
<tr>
<td>D_s⁺(2112.4) D_s⁺(2112.4)</td>
<td>4224.8</td>
<td>0⁺,0⁺,1⁺,2⁺,3⁺,4⁺</td>
<td>(D_s⁺γ)(D_s⁺γ)</td>
<td>2K⁺2K⁺π⁺πγγ</td>
</tr>
<tr>
<td>D_s(1968.5) D_s⁺⁺(2317.5)</td>
<td>4286.0</td>
<td>0⁺,1⁺,2⁺,3⁺,4⁺</td>
<td>D_s⁺⁺(D_s⁺⁺γ)</td>
<td>2K⁺2K⁺π⁺π⁺0</td>
</tr>
<tr>
<td>D_s(2317.5) D_s⁺⁺(2317.5)</td>
<td>4427.0</td>
<td>0⁺,1⁺,2⁺,3⁺,4⁺</td>
<td>D_s⁺⁺(D_s⁺⁺γ)</td>
<td>2K⁺2K⁺π⁺π⁺γ</td>
</tr>
<tr>
<td>D_s⁺⁺(2112.4) D_s⁺⁺(2112.4)</td>
<td>4429.9</td>
<td>0⁺,1⁺,2⁺,3⁺,4⁺</td>
<td>(D_s⁺⁺γ)(D_s⁺⁺γ)</td>
<td>2K⁺2K⁺π⁺π⁺γ</td>
</tr>
<tr>
<td>D_s⁺⁺(2112.4) D_s⁺⁺(2112.4)</td>
<td>4503.9</td>
<td>0⁺,1⁺,2⁺,3⁺,4⁺</td>
<td>D_s⁺⁺(D_s⁺⁺K⁺)</td>
<td>2K⁺K⁺K⁺π⁺2π⁺(π⁺0)</td>
</tr>
<tr>
<td>D_s⁺⁺(2112.4) D_s⁺⁺(2112.4)</td>
<td>4540.9</td>
<td>0⁺,1⁺,2⁺,3⁺,4⁺</td>
<td>D_s⁺⁺(D_s⁺⁺K⁻)</td>
<td>2K⁺K⁺K⁺π⁺(π⁻0)</td>
</tr>
<tr>
<td>D_s⁺⁺(2112.4) D_s⁺⁺(2112.4)</td>
<td>4579.9</td>
<td>0⁺,1⁺,2⁺,3⁺,4⁺</td>
<td>(D_s⁺⁺γ)(D_s⁺⁺γ)</td>
<td>2K⁺2K⁺π⁺π⁺γγ</td>
</tr>
<tr>
<td>D_s⁺⁺(2112.4) D_s⁺⁺(2112.4)</td>
<td>4635.0</td>
<td>0⁺,1⁺,2⁺,3⁺,4⁺</td>
<td>D_s⁺⁺(D_s⁺⁺π⁺0)</td>
<td>2K⁺2K⁺π⁺2π⁺0</td>
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<tr>
<td>D_s⁺⁺(2112.4) D_s⁺⁺(2112.4)</td>
<td>4647.9</td>
<td>0⁺,1⁺,2⁺,3⁺,4⁺</td>
<td>(D_s⁺⁺γ)(D_s⁺⁺K⁺0)</td>
<td>2K⁺K⁺K⁺π⁺2π⁺(π⁺0)</td>
</tr>
<tr>
<td>D_s⁺⁺(2112.4) D_s⁺⁺(2112.4)</td>
<td>4683.4</td>
<td>0⁺,1⁺,2⁺,3⁺,4⁺</td>
<td>(D_s⁺⁺γ)(D_s⁺⁺K⁻)</td>
<td>2K⁺K⁺K⁺π⁺2π⁻0</td>
</tr>
<tr>
<td>D_s⁺⁺(2112.4) D_s⁺⁺(2112.4)</td>
<td>4738.5</td>
<td>0⁺,1⁺,2⁺,3⁺,4⁺</td>
<td>D_s⁺⁺(D_s⁺⁺π⁺π)</td>
<td>2K⁺2K⁺π⁺2π⁺π⁺</td>
</tr>
<tr>
<td>D_s⁺⁺(2112.4) D_s⁺⁺(2112.4)</td>
<td>4776.0</td>
<td>0⁺,1⁺,2⁺,3⁺,4⁺</td>
<td>(D_s⁺⁺π⁺0)(D_s⁺⁺γ)</td>
<td>2K⁺2K⁺π⁺2π⁺0γ</td>
</tr>
<tr>
<td>D_s⁺⁺(2112.4) D_s⁺⁺(2112.4)</td>
<td>4838.5</td>
<td>0⁺,1⁺,2⁺,3⁺,4⁺</td>
<td>D_s⁺⁺((D_s⁺⁺γ)π⁺π⁺)</td>
<td>2K⁺2K⁺2π⁺2π⁺γ</td>
</tr>
<tr>
<td>D_s⁺⁺(2112.4) D_s⁺⁺(2112.4)</td>
<td>4852.9</td>
<td>0⁺,1⁺,2⁺,3⁺,4⁺</td>
<td>(D_s⁺⁺π⁺0)(D_s⁺⁺K⁺⁻)</td>
<td>2K⁺K⁺K⁺π⁺π⁺(1⁻2)⁺π⁻0</td>
</tr>
<tr>
<td>D_s⁺⁺(2112.4) D_s⁺⁺(2112.4)</td>
<td>4882.4</td>
<td>0⁺,1⁺,2⁺,3⁺,4⁺</td>
<td>(D_s⁺⁺γ)(D_s⁺⁺π⁺π⁺)</td>
<td>2K⁺2K⁺2π⁺2π⁺γ</td>
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<tr>
<td>D_s⁺⁺(2112.4) D_s⁺⁺(2112.4)</td>
<td>4889.9</td>
<td>0⁺,1⁺,2⁺,3⁺,4⁺</td>
<td>(D_s⁺⁺π⁺0)(D_s⁺⁺K⁺⁻)</td>
<td>2K⁺K⁺K⁺π⁺π⁺(1⁻2)⁺π⁻0</td>
</tr>
<tr>
<td>D_s⁺⁺(2112.4) D_s⁺⁺(2112.4)</td>
<td>4917.0</td>
<td>0⁺,1⁺,2⁺,3⁺,4⁺</td>
<td>((D_s⁺⁺γ)π⁺0)((D_s⁺⁺γ)π⁺0)</td>
<td>2K⁺2K⁺π⁺2π⁺0γγ</td>
</tr>
<tr>
<td>D_s⁺⁺(2112.4) D_s⁺⁺(2112.4)</td>
<td>4982.4</td>
<td>0⁺,1⁺,2⁺,3⁺,4⁺</td>
<td>(D_s⁺⁺γ)(D_s⁺⁺γ)π⁺π⁺</td>
<td>2K⁺2K⁺2π⁺2π⁺γγ</td>
</tr>
<tr>
<td>D_s⁺⁺(2112.4) D_s⁺⁺(2112.4)</td>
<td>4993.9</td>
<td>0⁺,1⁺,2⁺,3⁺,4⁺</td>
<td>(D_s⁺⁺π⁺0)(D_s⁺⁺K⁺⁻)</td>
<td>2K⁺K⁺K⁺π⁺π⁺(1⁻2)⁺π⁻0</td>
</tr>
<tr>
<td>D_s⁺⁺(2112.4) D_s⁺⁺(2112.4)</td>
<td>5030.9</td>
<td>0⁺,1⁺,2⁺,3⁺,4⁺</td>
<td>((D_s⁺⁺γ)π⁺0)(D_s⁺⁺K⁺⁻)</td>
<td>2K⁺2K⁺2π⁺2π⁺γγ</td>
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<tr>
<td>D_s⁺⁺(2112.4) D_s⁺⁺(2112.4)</td>
<td>5070.8</td>
<td>0⁺,1⁺,2⁺,3⁺,4⁺</td>
<td>(D⁺⁺K⁺)(D⁺⁺K⁻)</td>
<td>K⁺K⁺2K⁺2π⁺2π⁺(0⁻2)⁺π⁻0</td>
</tr>
</tbody>
</table>
If we understand the nature of these states better ...

4-quark state

\[ \bar{u} \quad c \quad \bar{d} \quad d \]

D\bar{D}-“molecule”

\[ \bar{u} \quad c \quad \pi \quad u \quad c \]

Transition from color forces to colorless nuclear forces?
Glueballs → Creation of Mass

A few % of a hadron (proton) mass is generated due to the Higgs mechanism.

Most of the proton mass is created by the strong interaction.

Glueballs gain their mass solely by the strong interaction and are therefore an unique approach to the mass creation by the strong interaction.
Glueballs

A possible glueball spectrum
Are glueballs configurations of twisted or knotted colored flux?

GLUEBALLS, FLUXTUBES AND η(1440).
L. Fadeev, A. Niemi and U. Wiedner
Phys.Rev.D70:114033, 2004
Glueballs on Regge trajectories like mesons?

Marco Bochicchio; arXiv:1308.2925


G. S. Bali et al.; arXiv:1302.1502
Gluons contribute to the quantum numbers of the particle.

Mesons are fermion-antifermion systems, which follow rules:

$$\bar{J} = \bar{L} + \bar{S}$$  \hspace{1cm} \text{possible from } q\bar{q}

$$P = (-1)^{L+1}$$

$$C = (-1)^{L+S}$$  \hspace{1cm} \text{not possible from } q\bar{q}

$$J^{PC} = 0^{--}, 0^{+-}, 1^{--}, 1^{+-}, 2^{++}, ...$$

$$J^{PC} = 0^{--}, 0^{+-}, 1^{--}, 2^{+-}, ...$$
Production vs. Formation

Produktion experiments:

all quantum numbers possible

Formation experiments:

identical quantum numbers

\[ \hat{J} = \hat{L} + \hat{S} \]

\[ P = (-)^{L+1} \]

\[ C = (-)^{L+S} \]
Formation experiments cannot produce exotic $J^{PC}$.

Production experiments can produce exotic $J^{PC}$.

Signal in production but no signal in formation

new physics

Expect early results without partial wave analysis necessary
Crystal Barrel

\[ \bar{p}d \rightarrow \pi^- \pi^0 \eta + p \]

spectator

\(<100 \text{ MeV}/c\)

![Graph showing the relationship between various masses and momentum squares.](image)

- \(a_2(1320)\)
- \(\rho^*(770)\)

Ulrich Wiedner
\( J^{PC}=1^{-+} \) – Pb vs H Target

- Peak at 1.67 GeV/c² for both targets
- Phase motion indicates resonant behavior
- Structure at 1.2 GeV/c² unstable w.r.t. fit model
- No fit to spin-density matrix yet for H target
- Production of \( M=1 \) states enhanced for heavy target
- Non-resonant background to be understood

\[ \pi^- \text{Pb} \rightarrow \pi^- \pi^- \pi^+ \text{Pb} \]
\[ \pi^- \text{p} \rightarrow \pi^- \pi^- \pi^+ \text{p} \]

[Ulrich Wiedner]


\[[\text{F. Haas, arXiv:1109.1789 (2011)}]\]
Gluonic Excitations – Hybrids at JLAB 12 GeV

Gluonic Excitations provide an experimental measurement of the excited QCD potential.

... at Hall D
Hybrids?

What we know:

\( \pi_1(1400) \)

Mass: 1400 ± 30 MeV
Width: 310 ± 70 MeV
Decay: (\( \eta \pi \))
\( J^{PC} = 1^{+} \)

\( \rho (1660) \)

Mass: 1660 ± 10 MeV
Width: 369 ± 42 MeV
Decay: (\( \rho \pi \))
\( J^{PC} = 1^{+} \)

M.G. Alekseev et al.,
PRL 104 (2010) 241803

BROAD (~300 MeV)
likely unmixed

light quarks

ss hybrids

Y(4260)

charm quarks
much more
narrow (~80 MeV)

Belle

JLAB@12 GeV

PANDA

Ulrich Wiedner
I hope I could show you that the spectroscopic investigation of hadrons can tell us a lot of fundamental results about nature.

Thank you!