# EHM and the Meson Spectrum

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# **Background**: EHM



## **EHM = Emergence of Hadron Mass**

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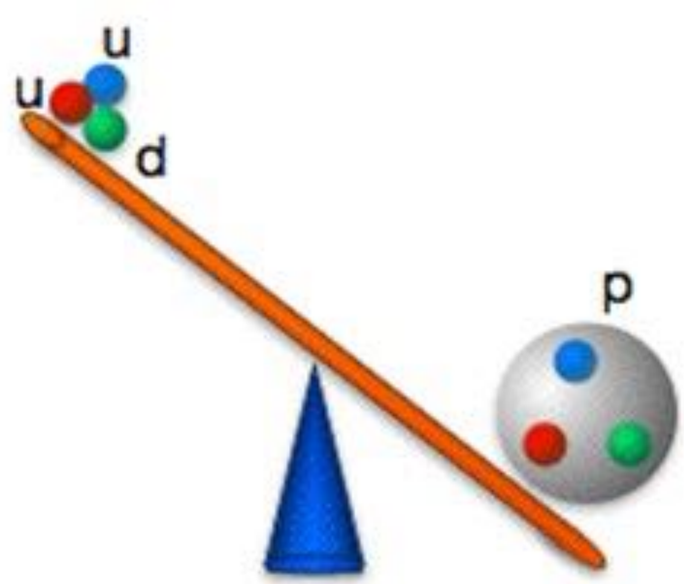
The Free Encyclopedia

In particle physics, a **hadron** /ˈhædrɒn/ (Greek: ἁδρός, *hadrós;* "stout, thick") is a subatomic composite particle made of two or more quarks held together by the strong force in a similar way as molecules are held together by the electromagnetic force.

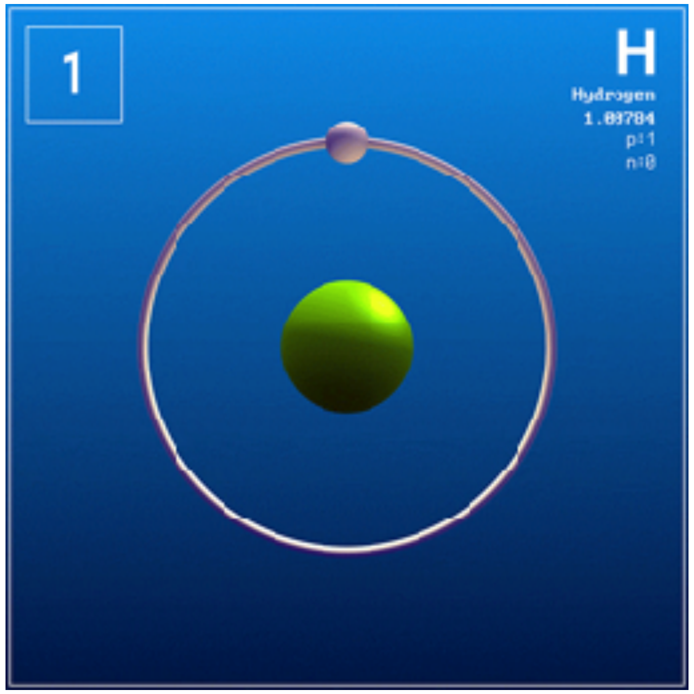
In philosophy, systems theory, science, and art, **emergence** occurs when an entity is observed to have properties its parts do not have on their own, properties or behaviors which emerge only when the parts **interact** in a wider whole.

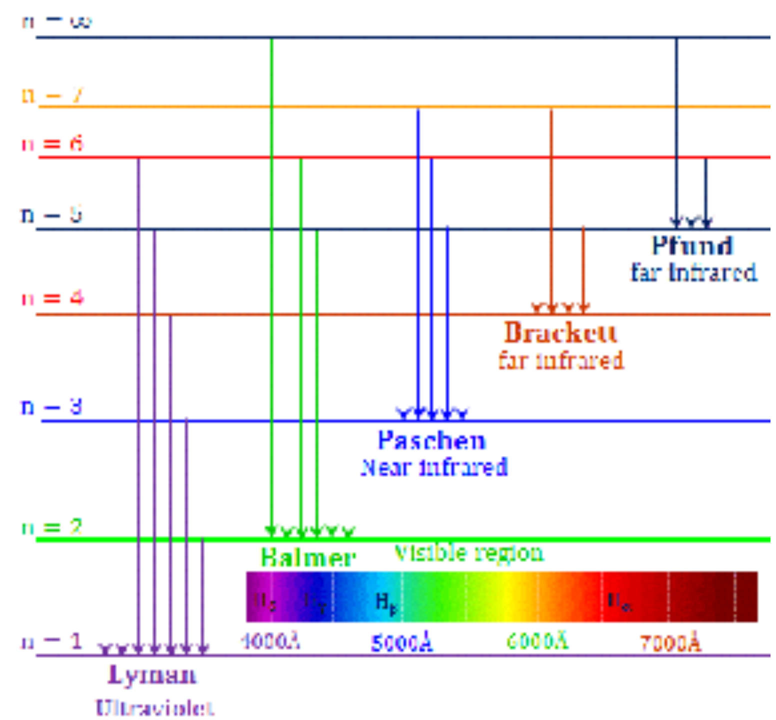
**Massless quarks**




**Massive hadrons**

# **Background**: Hydrogen atom — The simplest element

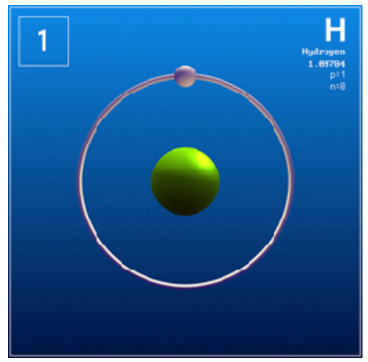


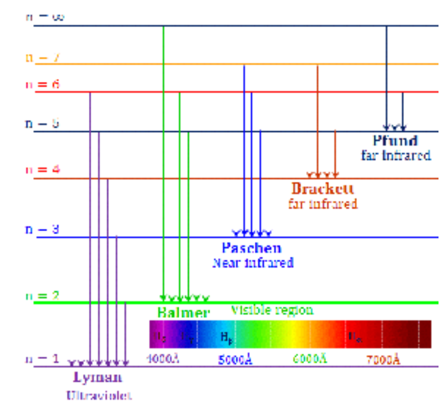



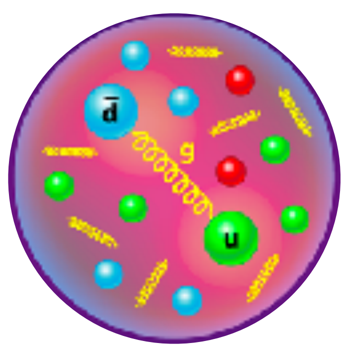

$$H|\psi_n\rangle = E_n|\psi_n\rangle$$

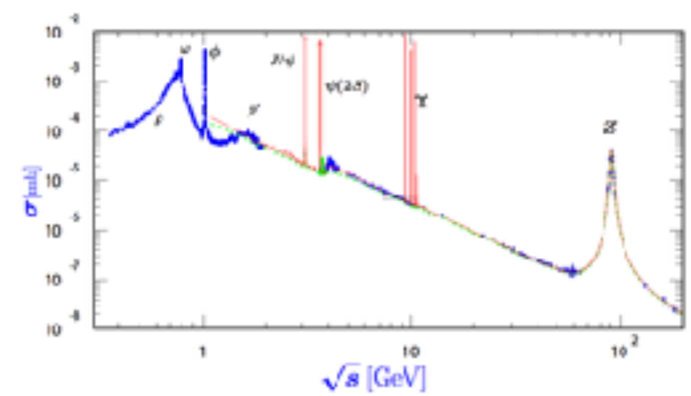
$$H = H_{\text{kinetic}} + H_{\text{Coulomb}} + H_{\text{spin-orbit}} + H_{\text{relativistic}} + H_{\text{QED}}$$

# **Background**: Meson — The simplest hadron




✦ **Theories**: Simple (two-body) objects could involve surprisingly rich physics.

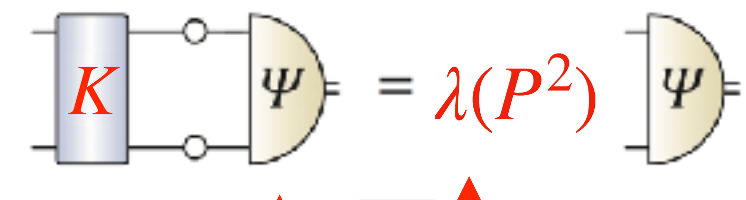
✦ **Experiments**: High-Energy, High-Luminosity Facilities can change the game.

# **Background**: Meson — The simplest hadron

**Quantum Mechanics** → **Quantum Field Theory**

Schrödinger equation → Bethe-Salpeter equation

$$H|\psi\rangle = E|\psi\rangle$$

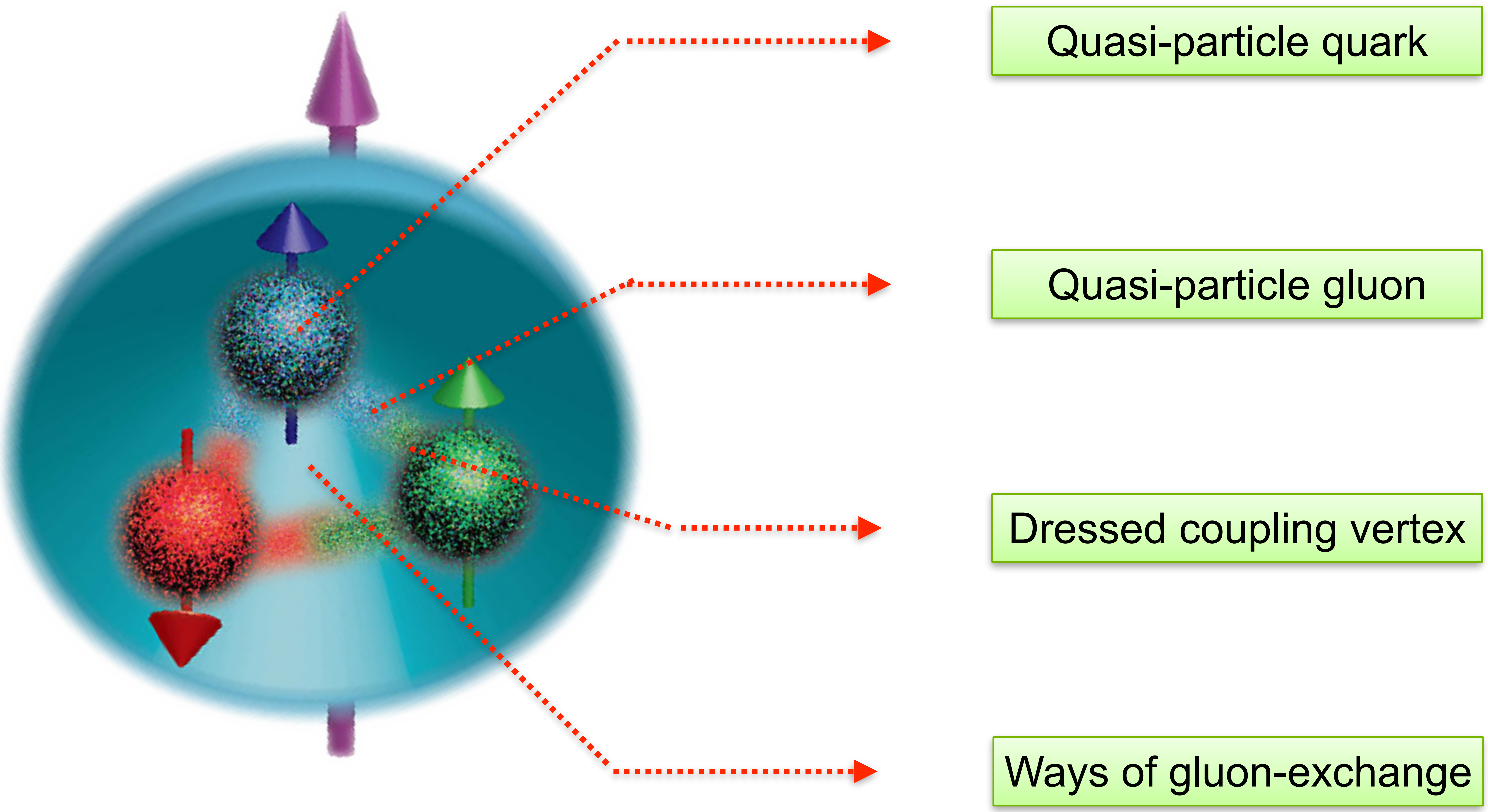



✦ **Question 1**: What physics is involved in the bound-state equation (BSE)?

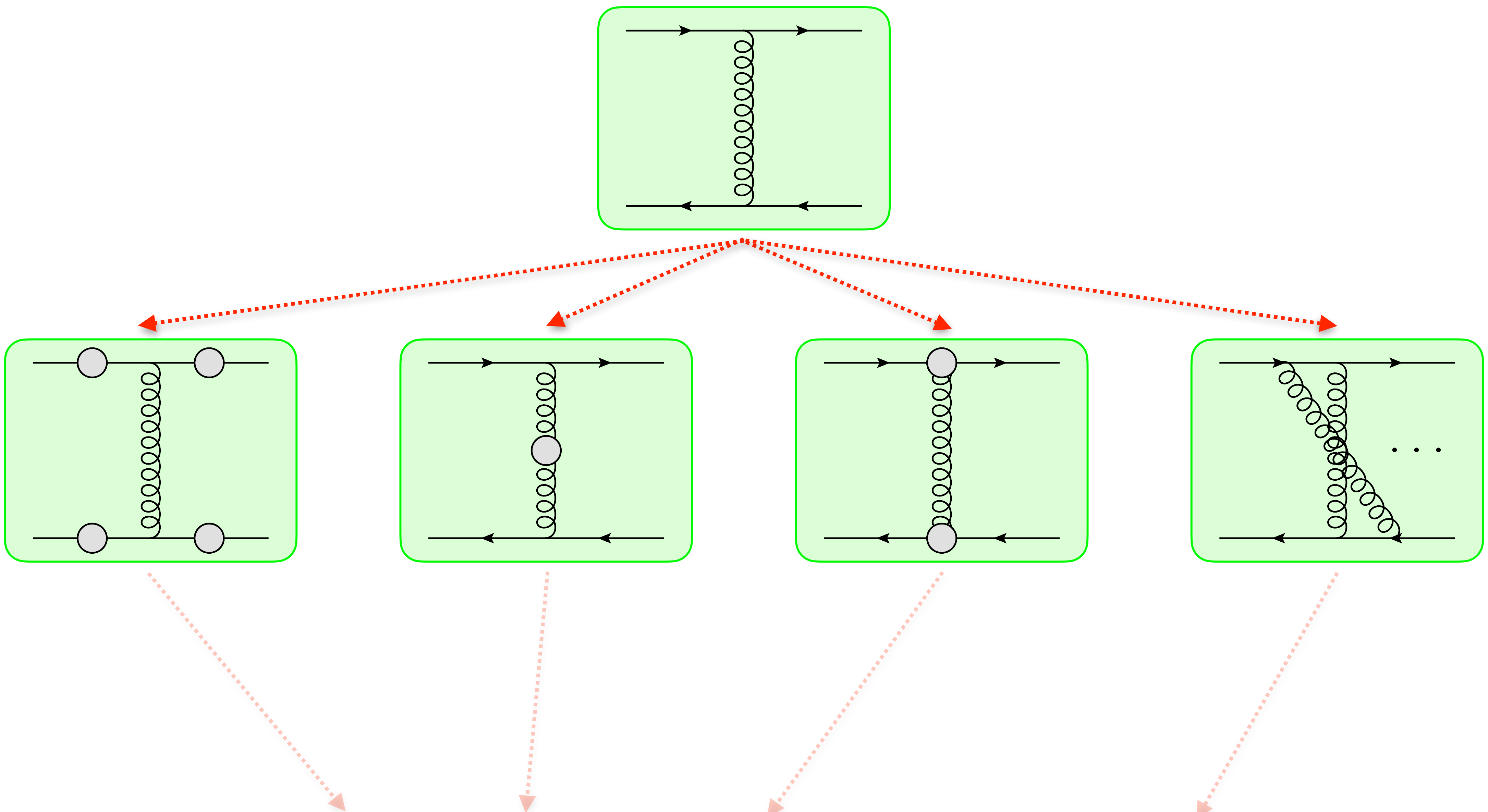
✦ **Question 2**: How physics manifests itself from the outcomes of the BSE?

✦ **Question 1**: What physics is included in the bound-state equation (BSE)?

# **Continuum QCD**: Interaction between quarks

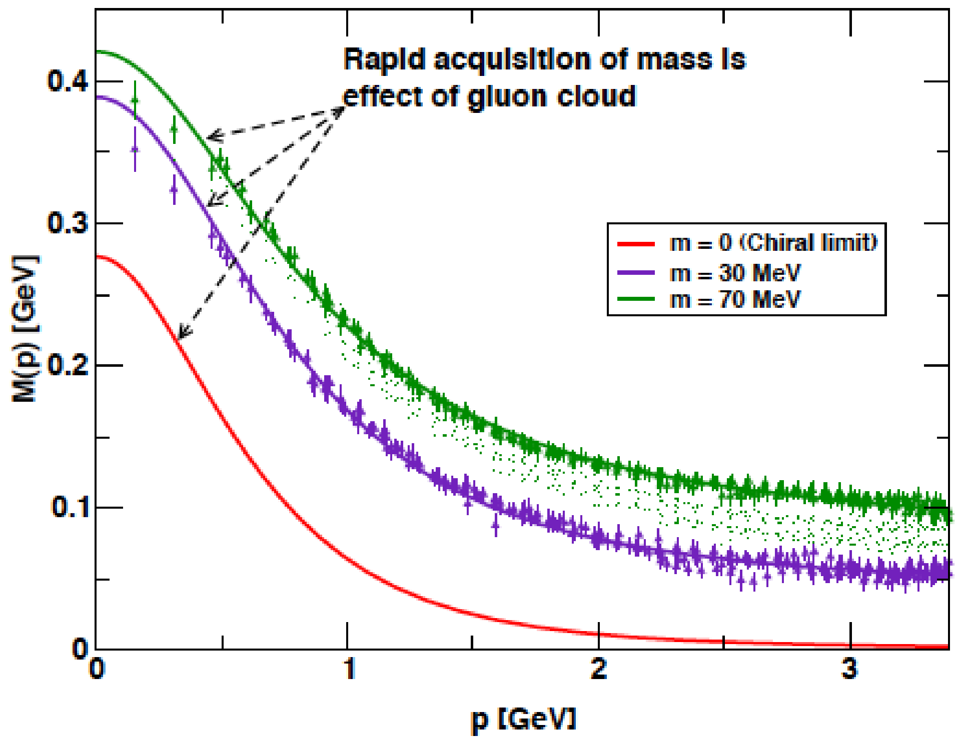


# **Continuum QCD**: Interaction between quarks



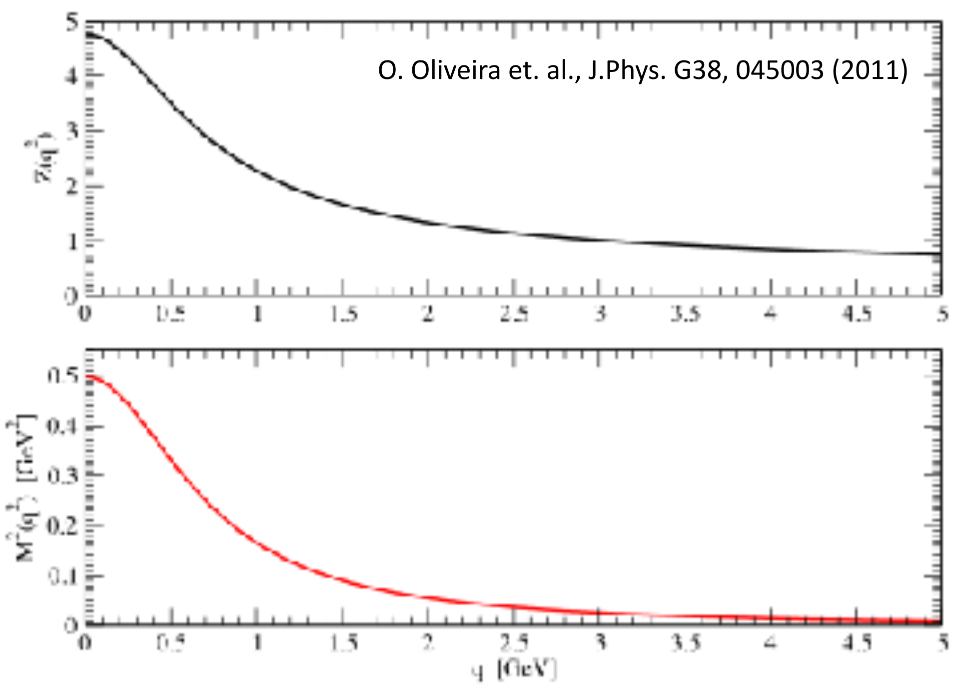

$$\color{red}{H} = H_{\color{red}{\text{kinetic}}} + H_{\color{red}{\text{Coulomb}}} + H_{\color{red}{\text{spin-orbit}}} + H_{\color{red}{\text{relativistic}}} + H_{\color{red}{\text{QED}}}$$

# **Continuum QCD**: Quasi quarks and gluons




✦ Quasi-quark: The most **constituent mass** of a light quark comes from a cloud of gluons

$$S(p) = \frac{Z(p^2)}{i\gamma \cdot p + M(p^2)}$$



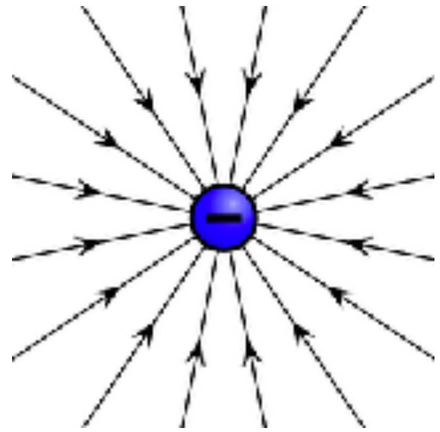

✦ Quasi-gluon: The dressed gluon has a running mass, and can be well parameterized by a **mass scale**

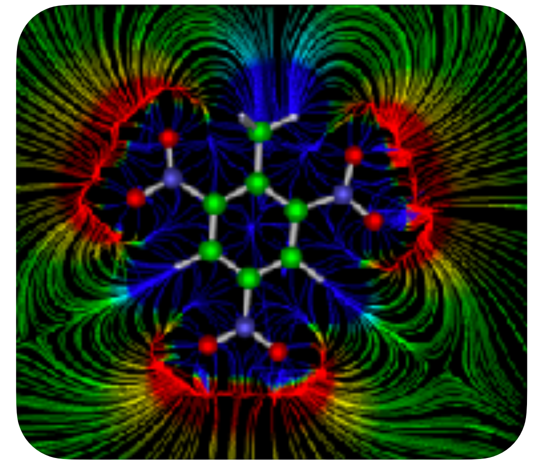
$$m_g^2(k^2) = \frac{M_g^4}{M_g^2 + k^2}$$

**See, e.g., QIN et al, PRC 84, 042202 (2011)**

# **Continuum QCD**: Dressed structures of vertex

point charge





distributed charge

- The **Dirac** and **Pauli** terms: for an on-shell fermion, the vertex can be decomposed by two form factors:

$$\Gamma^{\mu}(P', P) = \gamma^{\mu} F_1(Q^2) + \frac{i\sigma_{\mu\nu}}{2M_f} Q^{\nu} F_2(Q^2)$$

- The form factors express (color-)**charge** and (color-)**magnetization** densities. And the so-called **anomalous magnetic moment** is proportional to the Pauli term.

**Equation of Motion (DSEs)**

$$\boxed{S = \frac{1}{i\gamma \cdot p A(p^2) \; + \; B(p^2)}}$$

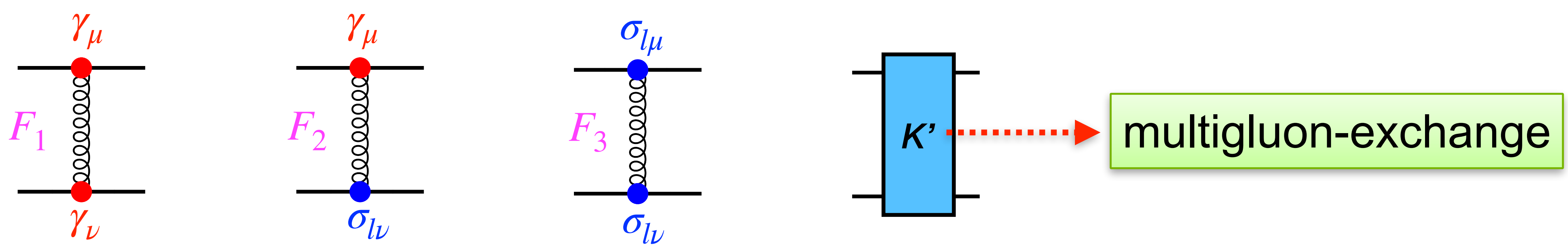
$$\boxed{\gamma^{\mu}\Sigma_A \; + \; i\sigma_{\mu\nu}Q^{\nu}\Delta_B \; + \; \text{etc.} \sim \Gamma^{\mu}}$$

**Ward identities (Symmetries)**

See, e.g., QIN et al, PLB722, 384 (2013)

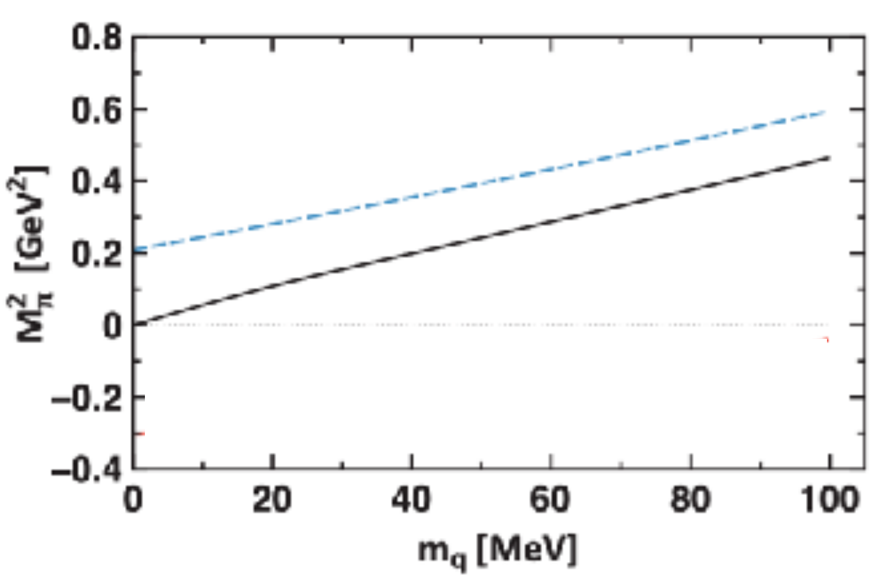
# **Continuum QCD**: Subtle structures of kernel

✦ A realistic kernel must involves the Dirac and Pauli structures:




✦ The discrete and continuous symmetries strongly constrain the kernel:

| **Poincaré symmetry** |  | **Gauge symmetry** |
|---|---|---|
| **C-, P-, T-symmetry** |  | **Chiral symmetry** |




**Bound state:** massive quark and anti-quark bind in an abnormally light system

$$M_\pi \ll M_u + M_{\bar{d}}$$

**Goldstone boson:** If a generic continuous symmetry is spontaneously broken, then new massless scalar particles appear in the spectrum of possible excitations.

**See, e.g., QIN et al, CPL 38 (2021) 7, 071201**

✦ **Question 2**: How physics manifests itself from the outcomes of the BSE?

# **Solution:** Partial-wave-mixing wavefunction

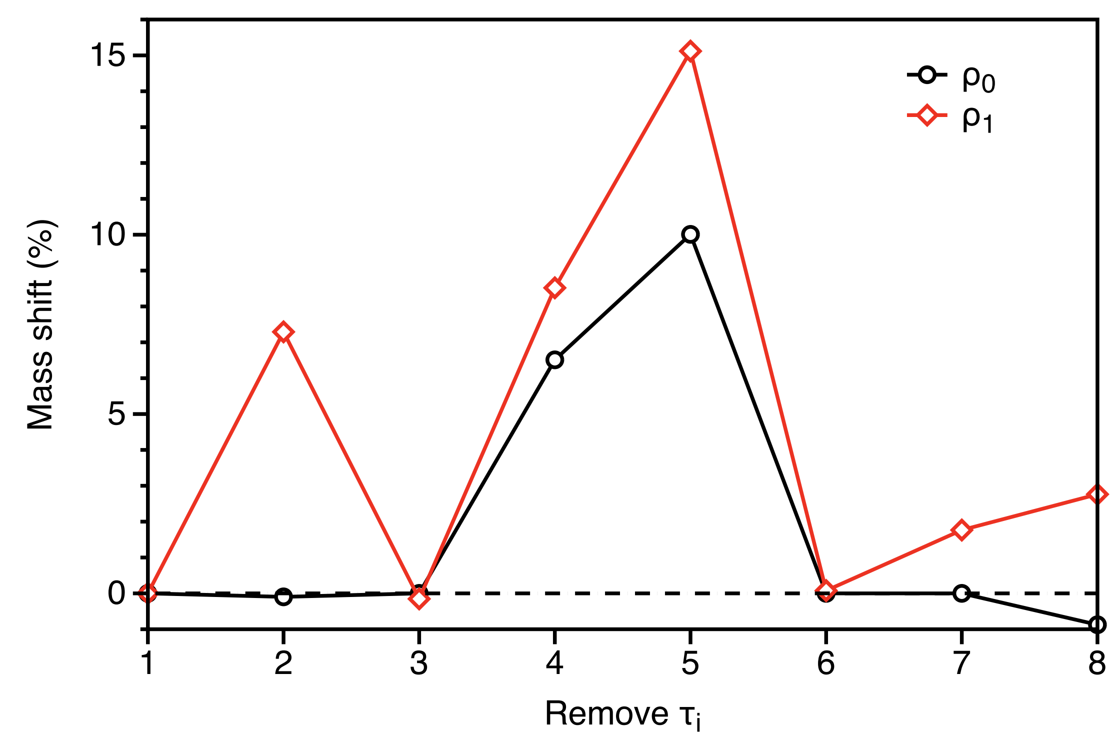
✦ Structure of wave function, e.g. $\rho$ meson:

$$
\begin{aligned}
\tau_{1^-}^{1} &= i\gamma_\mu^T, \\
\tau_{1^-}^{2} &= i\left[3k_\mu^T \gamma\cdot k^T - \gamma_\mu^T k^T\cdot k^T\right], \\
\tau_{1^-}^{3} &= i k_\mu^T\, k\cdot P\, \gamma\cdot P, \\
\tau_{1^-}^{4} &= i\left[\gamma_\mu^T \gamma\cdot P\, \gamma\cdot k^T + k_\mu^T \gamma\cdot P\right], \\
\tau_{1^-}^{5} &= k_\mu^T, \\
\tau_{1^-}^{6} &= k\cdot P\left[\gamma_\mu^T \gamma^T\cdot k - \gamma\cdot k^T \gamma_\mu^T\right], \\
\tau_{1^-}^{7} &= (k^T)^2\left(\gamma_\mu^T \gamma\cdot P - \gamma\cdot P\gamma_\mu^T\right) - 2k_\mu^T \gamma\cdot k^T \gamma\cdot P, \\
\tau_{1^-}^{8} &= k_\mu^T \gamma\cdot k^T \gamma\cdot P.
\end{aligned}
$$

$$
\mathbf{J = 1}\ \begin{cases} \mathbf{S = 0,\ L = 1} \\ \mathbf{S = 1,\ L = 0} \\ \mathbf{S = 1,\ L = 1} \\ \mathbf{S = 1,\ L = 2} \end{cases}
$$

✦ Total angular momentum **J** is a good quantum number, but **S** and **L** are not. The partial waves mix together.

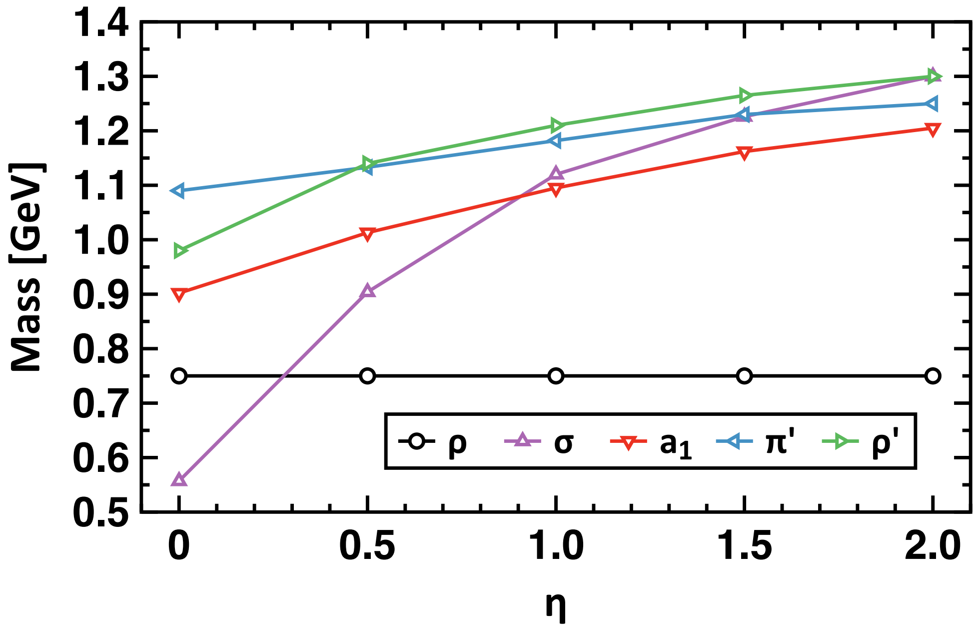
✦ Partial waves missing could shift the mass, especially of excitation states.



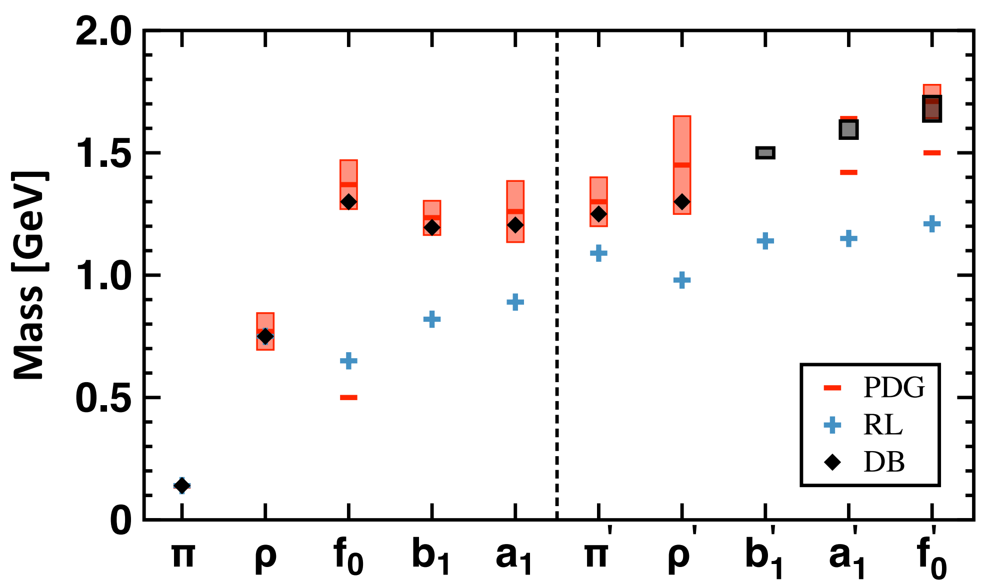

**See, e.g., QIN et al, PRC 85, 035202 (2012)**

# **Solution:** DCSB-rendered mass spectra

✦ Impact of the Pauli structure:




✦ Light-flavor meson spectrum:




✓ With increasing the Pauli strength, the $a_1$−ρ mass-splitting rises very rapidly. The DCSB-rendered kernel increases spin-orbit repulsion.

✓ The spin-orbit boosted quark-core mass of the scalar meson $f_0$ is much greater than the empirical value.

✓ The magnitude and ordering of low-lying excitation states can be fixed with the DCSB-rendered kernel.

**See, e.g., QIN et al, CPL 38 (2021) 7, 071201**

# Summary

✦ The **Continuum QCD** for describing meson properties has made important progress by analyzing QCD's **fundamental features** (quark, gluon, vertex, and kernel).

✦ **Meson spectra** play a key role for revealing QCD mysteries. The future **High-Energy, High-Luminosity Facilities** can be critical for understanding them.

# Outlook

◆ With the **sophisticated** approach, we can further iterate with future experiments on **light** and **heavy** mesons and baryons, from spectra to structures.

◆ Hopefully, based on more and more **successful applications**, we may provide a **faithful path** to understand QCD.