Molecular Interpretation of $D_{s0}^{*}(2317)$ and $D_{s1}(2460)$

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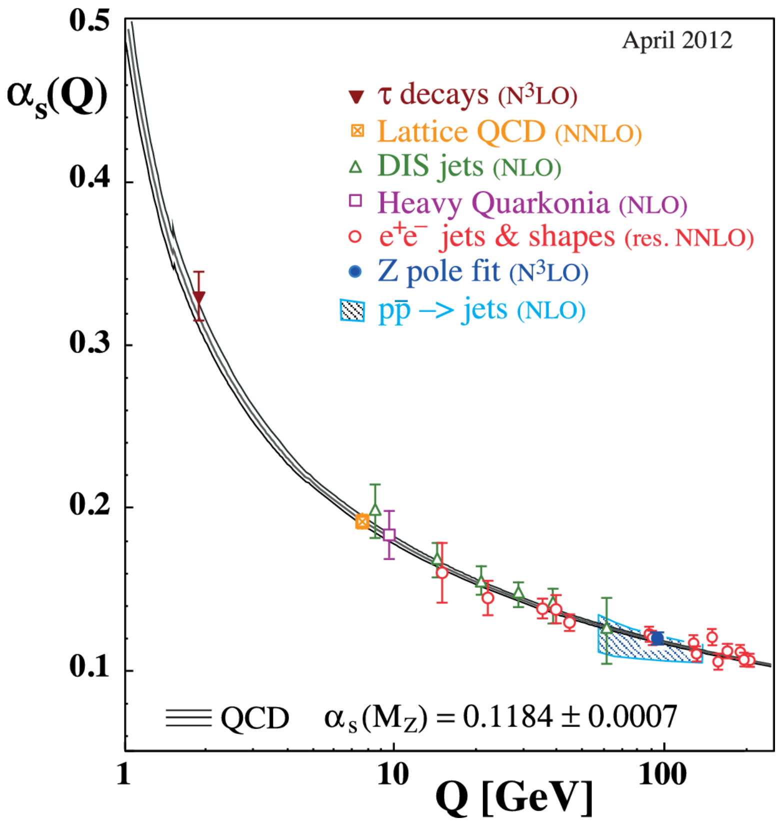
Quantum Chromodynamics (QCD):



- High Energies:

  Asymptotic Freedom, perturbation theory

- Low Energies:

  Lattice, Effective Field Theories

Heavy Meson Chiral Perturbation Theory

- No quarks and gluons
- Mesons as effective d.o.f.: $\pi, K, D^{(*)}, B^{(*)}, \ldots$
- Incorporates Chiral & Heavy Quark Symmetry

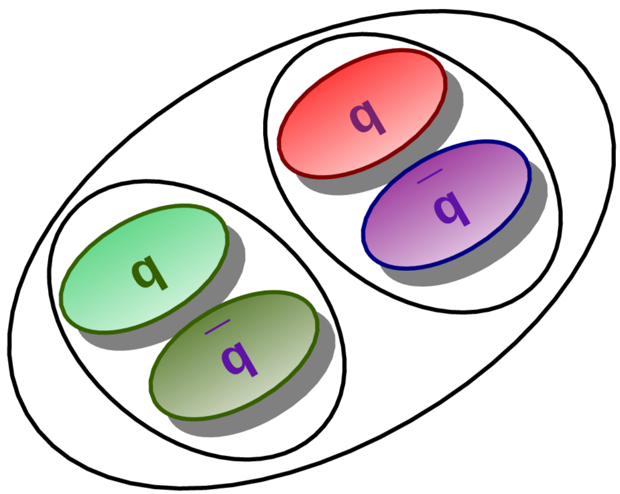
Confinement:

Only color-neutral objects can be observed

Classic Examples →

- Mesons: $q\bar{q}$
- Baryons: qqq

Theory of Strong Interaction: Hadronic Molecules



- Formed from interactions of
- two or more hadrons
- Classic example: Deuteron as Proton-Neutron bound state
- Large number of new candidates in the previous decade

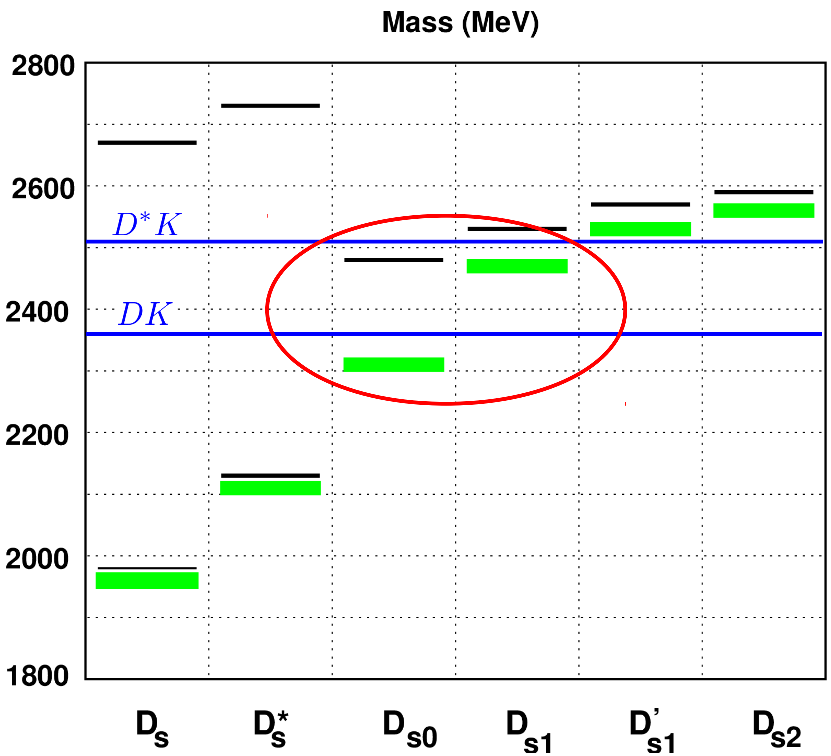
Weinberg's Formula:

Probability λ to find the physical state in the two-hadron state related to coupling to constituents g

$$g^2 = 16\pi\lambda^2 \frac{(m_1+m_2)^2}{\mu}\sqrt{-2\mu(M-m_1-m_2)}$$

$D^*_{s0}(2317)$ and $D_{s1}(2460)$: Experimental Facts

E. Swanson: Physics Reports 429 (2006) 243 – 305}



Experimental Facts

- Discovery by BaBar and Cleo-c in 2003
- Narrow resonances in $D_s^{(*)}\pi$
- $m_{D_{s1}} - m_{D^*_{s0}} \simeq m_{D^*} - m_D$
- Quantum numbers: $\mathrm{I}=0, \quad \mathrm{J}^P = 0^+(1^+)$

→ match S-wave $D^{(*)}K$ pairs

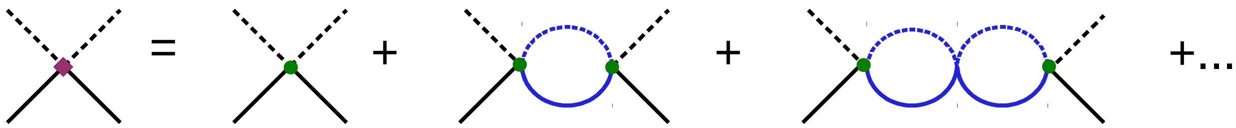
Candidates for DK and D*K molecules!

But: These features can be incorporated in Quark Model

→ Find Quantities that are sensitive to the (molecular) nature!

- Light Quark Mass Dependence of Binding Energy → Lattice
- Radiative & Hadronic Decay Widths

MC, F.-K. Guo, H. Grießhammer, C. Hanhart and U.-G. Meißner, Eur. Phys. J. A50 (2014) 9, 149



T = V + VGV + VGVGV +...

Lippmann Schwinger Eq.:

$$\Rightarrow \quad T = V\,[1 - G\,V]^{-1}$$

- Coupled Channels with I=0 and S=1:

$$V(s) = \begin{pmatrix} V_{DK\to DK}(s) & V_{DK\to D_s\eta}(s) \\ V_{D_s\eta K\to DK}(s) & V_{D_s\eta\to D_s\eta}(s) \end{pmatrix} \qquad G(s) = \begin{pmatrix} G_{DK}(s) & 0 \\ 0 & G_{D_s\eta}(s) \end{pmatrix}$$

- Full LO and NLO Lagrangian for Heavy-Light scattering, LECs from Lattice
- Fix Subtraction Constant to mass of $D^*_{s0}(2317)$

$$m_{D^*_{s0}} = 2317\ \text{MeV} \qquad m_{D_{s1}} = (2457.8 \pm 6.7)\ \text{MeV}$$
$$m^{Exp}_{D^*_{s0}} = (2317.8 \pm 0.6)\ \text{MeV} \qquad m^{Exp}_{D_{s1}} = (2459.5 \pm 0.6)\ \text{MeV}$$

- Extract Coupling

$$g_{DK} = (9.0 \pm 0.5)\ \text{GeV}$$
$$g_{D^*K} = (10.0 \pm 0.3)\ \text{GeV}$$

Weinberg: Molecular Component

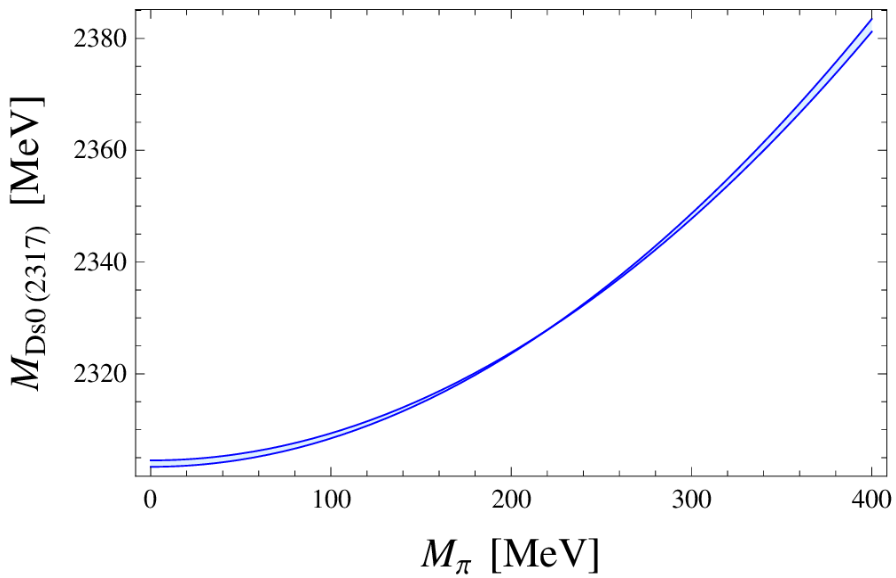
$$P(DK,\ D_{s0}) = (77.8 \pm 4.3) \qquad P(D^*, Ds1) = (81.0 \pm 3.6)$$

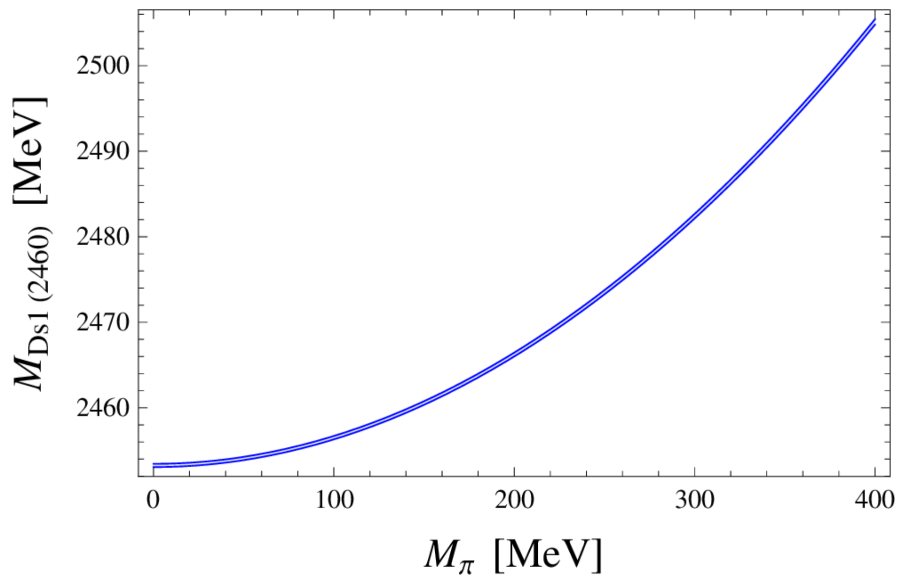
Backed by Lattice Calculation,
See Yesterday"s Talk by Eulogio Oset!

$$P(DK,\ D_{s0}) = (72 \pm 12)$$
$$P(D^*K, Ds1) = (63 \pm 16)$$

A. M. Torres, E. Oset, S. Prelovsek and A. Ramos, arXiv:1412.1706 [hep-lat]

MC, F.-K. Guo, C. Hanhart and U.-G. Meißner, Eur. Phys. J. A 47 (2011) 19



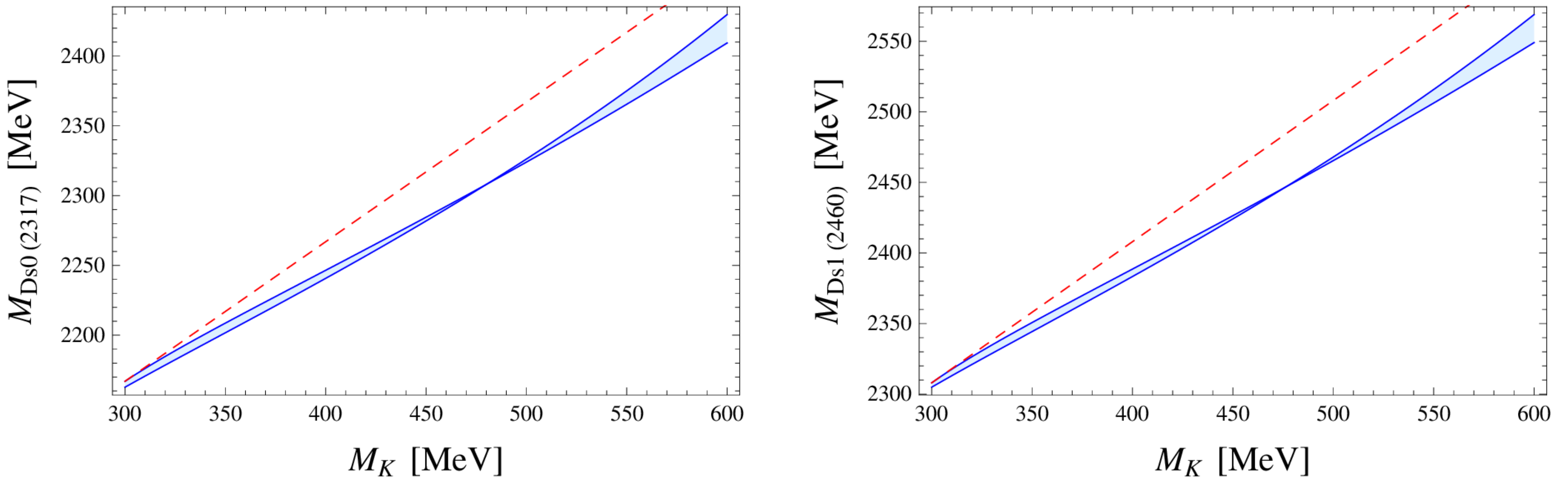


- Pion Mass Dependence enters via DK Loops in both cases, but Weinberg's Formula:
  - Pure $c\bar{s}$ state: g_{DK} small ↔ weak pion mass dependence
  - Molecule $(c\bar{q})(q\bar{s})$: g_{DK} maximal ↔ strong pion mass dependence

Interpretation backed by Lattice Calculation

D. Mohler, C. B. Lang, L. Leskovec, S. Prelovsek and R. M. Woloshyn, Phys. Rev. Lett. **111,** 222001 (2013)

MC, F.-K. Guo, C. Hanhart and U.-G. Meißner, Eur. Phys. J. A 47 (2011) 19



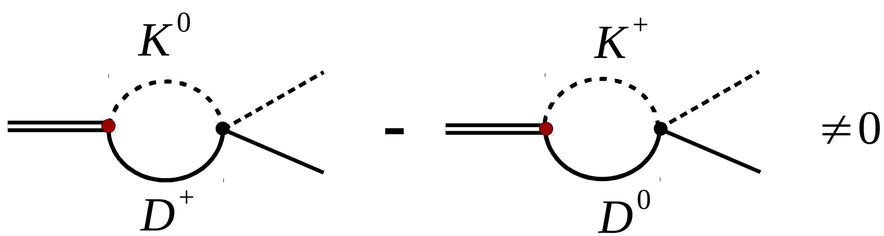
- Bound State of D and K: $M = M_D + M_K - \varepsilon$
  → Kaon mass dependence linear, slope unity
- Compact State $(c\bar{s})$: Compare Kaon $(q\bar{s})$
  → Kaon mass dependence quadratic

$D_{s0}^{*}(2317)$ and $D_{s1}(2460)$: Hadronic Decays

L. Liu, K. Orginos, F.-K. Guo, C. Hanhart and U.-G. Meißner, Phys. Rev. D **87** (2013) 014508

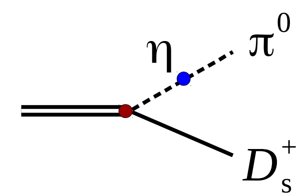
Two contributions shift the stable poles on the complex planes to the second Riemann sheet: $s = M + i\Gamma/2$

- Particle Masses Charged/Neutral



$$m_{K^0} - m_{K^+} = 3.9 \text{ MeV}$$
$$m_{D^+} - m_{D^0} = 4.8 \text{ MeV}$$
$$m_{D^{*+}} - m_{D^{*0}} = 3.3 \text{ MeV}$$

- π–η mixing



$$\begin{pmatrix} \tilde{\pi}^0 \\ \tilde{\eta} \end{pmatrix} = \begin{pmatrix} \cos\epsilon_{\pi^0\eta} & \sin\epsilon_{\pi^0\eta} \\ -\sin\epsilon_{\pi^0\eta} & \cos\epsilon_{\pi^0\eta} \end{pmatrix} \begin{pmatrix} \pi^0 \\ \eta \end{pmatrix}$$

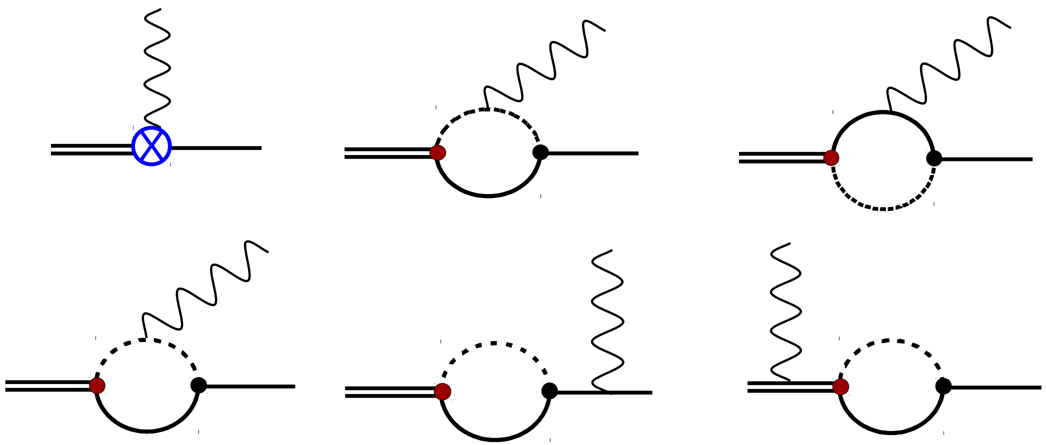
$$\epsilon_{\pi^0\eta} = \frac{1}{2}\arctan\left(\frac{\sqrt{3}}{2}\frac{m_d - m_u}{m_s - \hat{m}}\right) \sim 0.01$$

$$\Gamma(\to D_s^*\pi^0) = (133 \pm 22) \qquad \Gamma(\to D_s^*\pi^0) = (66 \pm 22)$$

1-2 Orders of magnitude larger than for $c\,\bar{s}$ mesons!

$D_{s0}^*(2317)$ and $D_{s1}(2460)$: Radiative Decays

MC, F.-K. Guo, H. Grießhammer, C. Hanhart and U.-G. Meißner, Eur. Phys. J. A50 (2014) 9, 149



- Coupling from Residues
- Sum of all Loops is finite
- Contact Term fixed in $D_{s1} \to D_s\gamma$
- Power Counting: Contact Term and Loop at same order
  → Not dominated by loops

$$\Gamma(D_{s0}^* \to D_s^*\gamma) = (10.1 \pm 4.5)\ \mathrm{keV} \qquad \Gamma(D_{s1} \to D_s\gamma) = (26.2 \pm 12.4)\ \mathrm{keV}$$

$$\Gamma(D_{s1} \to D_s^*\gamma) = (26.5 \pm 11.0)\ \mathrm{keV} \qquad \Gamma(D_{s1} \to D_{s0}^*\gamma) = (1.3 \pm 0.5)\ \mathrm{keV}$$

- Results for ratios Radiative/Hadronic Decays compatible with experiment
- Equal contributions for contact term and loops
  → only loops sensitive to molecular nature
- Values too small even for FAIR

Open Bottom Sector

MC, F.-K. Guo, H. Grießhammer, C. Hanhart and U.-G. Meißner, Eur. Phys. J. A50 (2014) 9, 149
MC, F.-K. Guo, C. Hanhart and U.-G. Meißner, Eur. Phys. J. A 47 (2011) 19

Heavy Quark Flavor Symmetry relates charm and bottom sector! → Predictions for BK and $B^* K$ possible

$$m_{B_{s0}} = (5663 \pm 48)\ \mathrm{MeV} \qquad m_{B_{s1}} = (5712 \pm 48)\ \mathrm{MeV}$$

Smaller Degeneracy between charged and neutral bottom mesons
→ small hadronic width expected:

$$B_{s0} \to B_s \pi^0 = (0.8 \pm 0.8)\ \mathrm{keV}$$
$$B_{s1} \to B_s^* \pi^0 = (1.8 \pm 1.8)\ \mathrm{keV}$$

Radiative Decays more promising discovery channel:

$$B_{s0} \to B_s^* \gamma = (32.6 \pm 20.8)\ \mathrm{keV} \qquad B_{s1} \to B_s \gamma = (4.1 \pm 10.9)\ \mathrm{keV}$$
$$B_{s1} \to B_s^* \gamma = (46.9 \pm 33.6)\ \mathrm{keV} \qquad B_{s1} \to B_{s0} \gamma = (0.02 \pm 0.02)\ \mathrm{keV}$$

Summary

- Interpretation of $D_{s0}(2317)$ and $D_{s1}(2460)$ as $D^{(*)}K$ molecules

  → Explains features that Quark model cannot

- Light Meson Mass Dependence of Binding Energy:

  Linear in m_K, Quadradic in m_π → Lattice

- Two-Body Decays:
  - Hadronic Decays ~ O(100 keV)
  - Radiative Decays ~ O(10 keV)
  - Hadronic Decay Widths distinctive in mol. Picture
- Prediction: Partner States in Open Bottom Sector

  Best chance for Discovery: Radiative Decays $B_s^{(*)}\gamma$

Thank you!

谢谢！