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8-12 July 2024

QCD Chemistry

(Or no place for diquarks of the Qq type)

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Tuesday, July 9

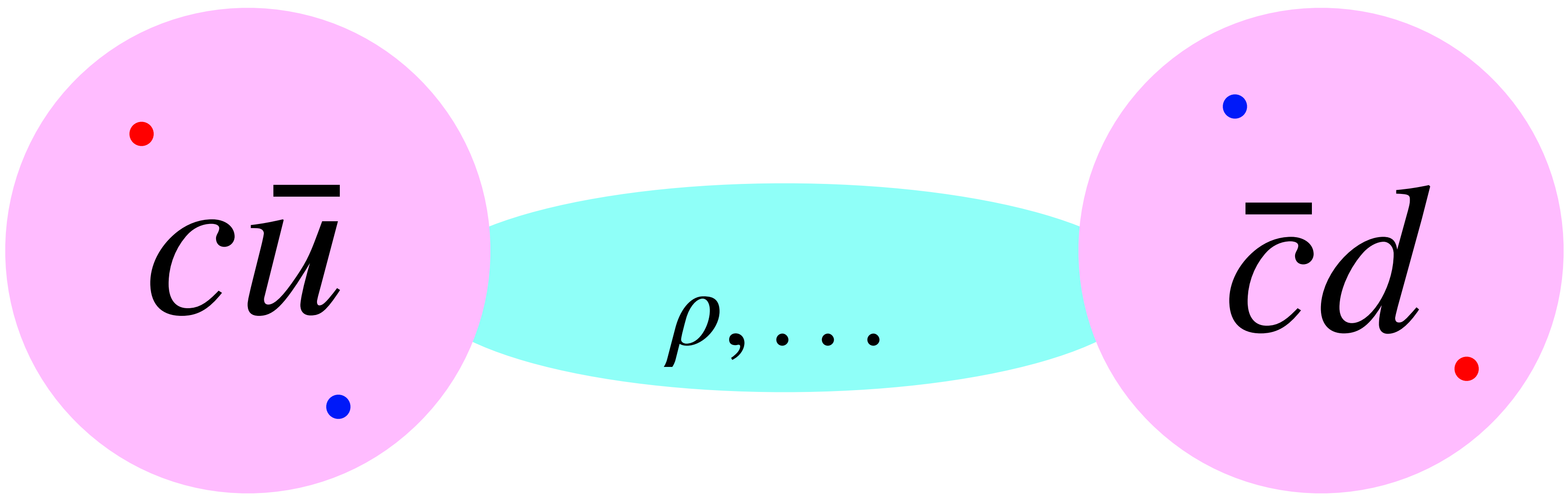
Hydronic molecules and the charmonium atom

M. B. Voloshin and L. B. Okun'

Institute of Theoretical and Experimental Physics

(February 16, 1976)
Pis'ma Zh. Eksp. Teor. Fiz. **23**, No. 6, 369–372 (20 March 1976)

We consider the possible existence of levels in a system consisting of a charmed particle and a charmed antiparticle; these levels result from exchange of ordinary mesons (ω,ρ,ϵ,ϕ, etc.). An interpretation of the resonances in e^+e^- annihilation in the region 3.9–4.8 GeV is proposed.



QM-based chemistry →
Hans Hellmann (of Hellmann–Feynman theorem) and pseudopotentials. The first-ever textbook on quantum chemistry (Vienna, 1937)

Parallel with quasinuclear resonances such as $p\bar{p}$ or $p\bar{n}$

1970's: I.S. Shapiro et al.
many many works

Chemistry vs. QCD Chemistry

"Classical" equations (Schrödinger/ Dirac, expanded), weak coupling (electromagnetic) regime, multielectron configurations create a complex structure of inter-electron and electron-nuclei interactions — so contrived that even numerical calculations are not always fully sufficient.

Strong coupling, relativistic effects may be (are) large, field theory cannot be reduced to an equation. This produces complexity. However, the number of "players" is not so large at moment. This might help.

A tsunami wave of diquarks in the studies of heavy tetra- and penta-quarks after ∼2000

Exotic heavy-light particles

- $\mathbf{\bar{c}du\bar{s}}$: $X(2866)$, $X_1(2904)$
- $\mathbf{c\bar{c}q\bar{q}}$: $\chi_{c1}(3872)$
- $\mathbf{c\bar{c}u\bar{d}}$: $Z_c(3900)$, $Z_c(4020)$, $Z_c(4050)$, $X(4100)$, $Z_c(3985)$, $Z_c(4430)$, $R_{c0}(4240)$
- $\mathbf{c\bar{c}u\bar{s}}$: $Z_{cs}(3985)$, $Z_{cs}(4000)$, $Z_{cs}(4220)$
- $\mathbf{b\bar{b}u\bar{d}}$: $Z_b(10610)$, $Z_b(10650)$
- $\mathbf{\bar{c}c\bar{c}c}$: $X(6900)$ ⟵ Molecular bi-Charmonium
- $\mathbf{cc\bar{u}\bar{d}}$: $T_{cc}^{+}(3875)$, also T_{cc}^{0}, T_{cc}^{++} (preliminary)
- Pentaquarks $\mathbf{c\bar{c}uud}$: $P_c((4380), (4450)$ $\to [(4440), (4457)], (4312)]$
- $\mathbf{c\bar{c}uds}$: $P_{cs}(4459)$
- Heavy-light Chemistry

} Molecular Charmonium, VO

“Good” diquarks, i.e. the $0^{\pm}$ states of two quarks, in color-triplet combination

B. Stech, Phys. Rev. D 36, 975 (1987); ⟵ first significant (in numbers) appearance
H. G. Dosch, M. Jamin, and B. Stech, Z. Phys. C 42, 167 (1989)

F. Wilczek, hep-ph/0409168 (v2: 2018); Alexander Selem, Frank Wilczek, hep-ph/0602128

X-quarks; X=di, tetra, penta → from late 1970s till today

~ 1000 publications (~900 since 2000)

D. Diakonov: 2006, 2007, 2008

WHAT IS “GOOD” DIQUARK?

No diquarks of the Qq type

PHYSICAL REVIEW D **71,** 074010 (2005)

Remarks on diquarks, strong binding, and a large hidden QCD scale

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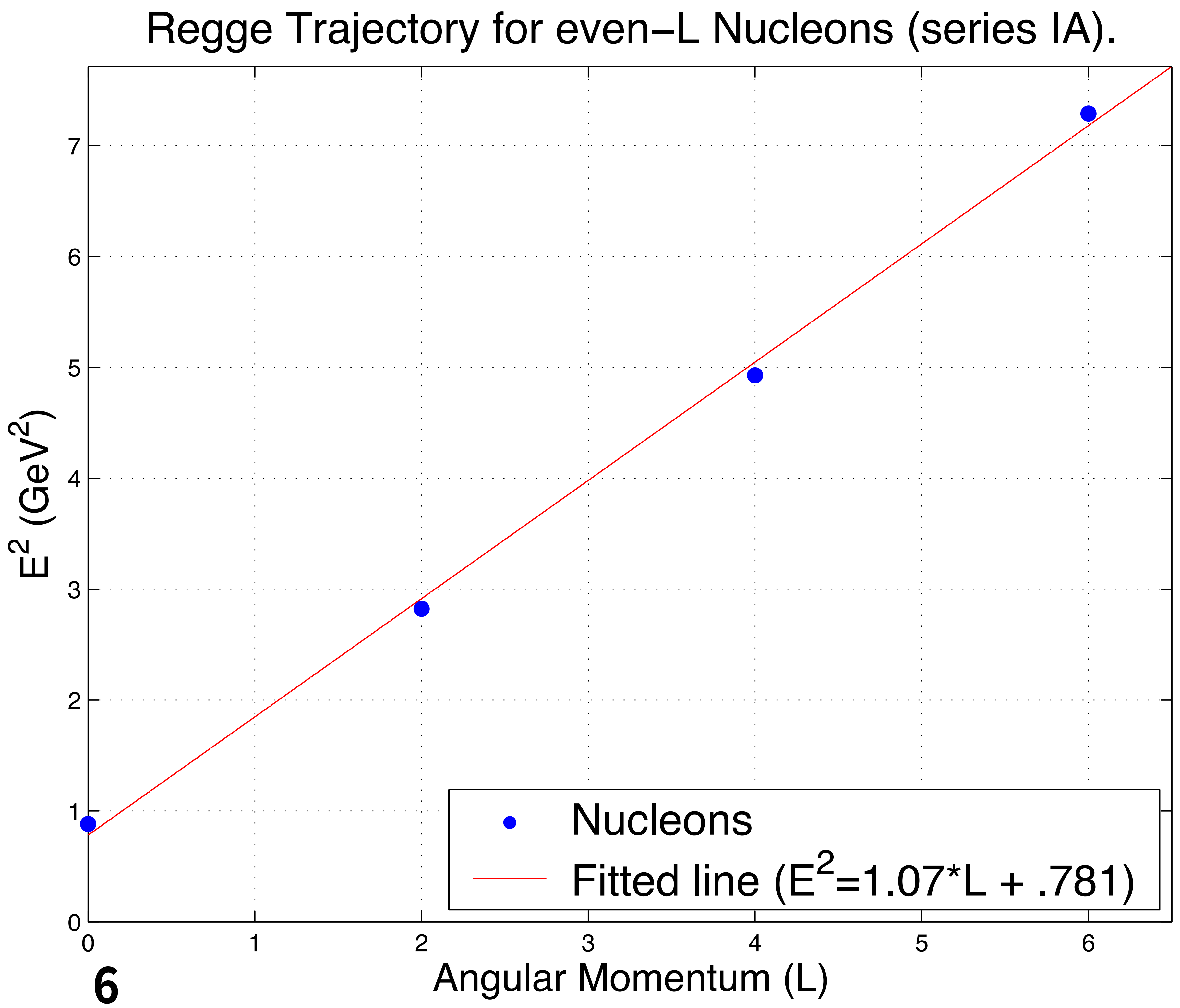
Selem-Wiczek: $M(\Sigma_c) - M(\Lambda_c) \approx 215$ MeV; ; $M(\Sigma_b) - M(\Lambda_b) \approx 180 \pm 10$ MeV

Spin interaction of c is not yet small enough, $\Delta(M(J/\Psi - \eta_c)) \sim 100$ MeV

(ud) spin triplet color $\bar{3}$
"Bad" diquark (flavor symmetric)

Isosinglet → [ud] spin zero color $\bar{3}$
"Good" diquark

$$m_{(ud)} - m_{[ud]} \sim 180 \text{ Mev}$$



1) The lower bound of Selem-Wilczek's analysis (from nucleon Regge trajectories) is 240 MeV

2) At large L, there is a marked convergence between mesons and baryons → near-equality between [ud] and $\bar{u}$ effective masses: $\rho(1690)$, $\omega(1670)$ vs. $N(1680)$

Spin interaction is crucial for good diquarks

Diquarks: pass to

1) Instanton vs OPE studies in 1980s revealed a numerically large scale in the "vacuum" channels i.e. with spin-parity $0^{\pm}$ in which the 't Hooft regularities miserably fail for low-lying mesons (e.g. we have large decay widths, no OZI rule, etc.) Stronger than expected short-range correlations reveal themselves in good diquarks

$$\mathrm{SU}(3)_{\mathrm{color}} \to \mathrm{SU}(2)_{\mathrm{color}} \to \text{Diquarqs} \to \text{well defined mesons (i.e. } \chi\text{SB is } \mathrm{SU}(4) \to \mathrm{SO}(5))$$

5 rather than 3 Goldstones, 3 pions+3 diquarks

Significant dependence of $\mathscr{E}_{m_q}$ on light-quark masses m_q

$$\Lambda_{\mathrm{QCD}} \sim 300\ \mathrm{MeV} \to \Lambda_{0^{\pm}} \sim 2 \text{ to } 3\ \mathrm{GeV}$$

Instanton Liquid Model (E. Shuryak et al.): $(R/\rho)_{\mathrm{inst}} \approx 3$

$R^{-1} \sim \Lambda_{\mathrm{QCD}}$ is conventional hadronic scale

$$\rho^{-1} \sim \sqrt{\Lambda_{\mathrm{QCD}}\,\Lambda_{0^{\pm}}}; \to \qquad \Lambda_{0^{\pm}} \sim 3^2\,\Lambda_{\mathrm{QCD}}$$

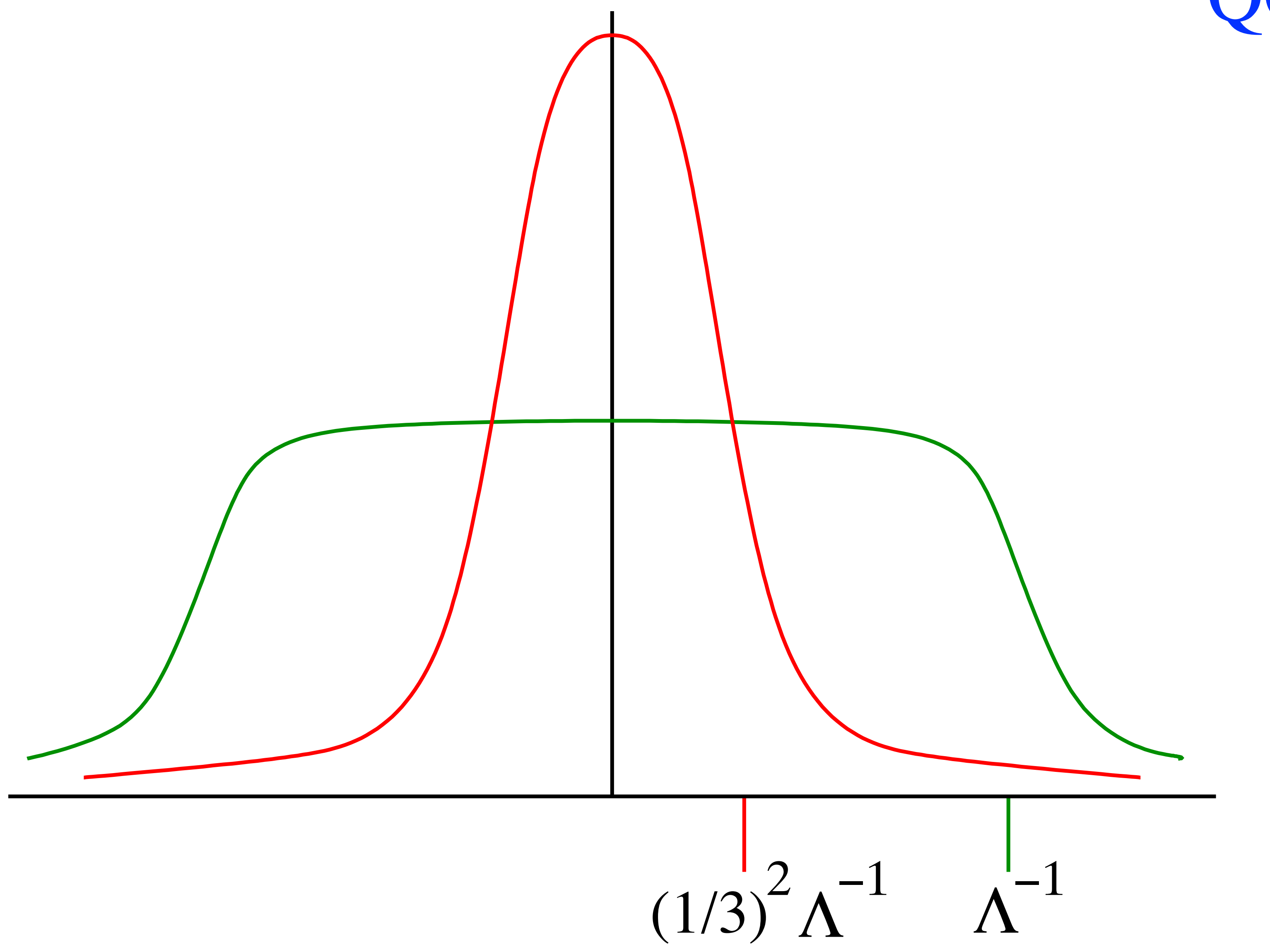


Figure 1: Double-component structure with a core.

In bona fide QCD, with $\mathrm{SU}(3)_{\mathrm{color}}$ in the energy interval between $\sim R_h^{-1}$ and $\sim R_{dq}^{-1}$ good diquarks act as pointlike color-antitriplet objects whose interaction with gluons is determined only by the color representation to which they belong, in much in the same way as color-triplet quarks.

2) The problem of Λ_b : the ratio $\Omega_{\Lambda_b B_d} \equiv \tau(\Lambda_b)/\tau(B_d)$

At $m_b \to \infty$ the ratio $\Omega_{\Lambda_b B_d} \to 1$. If m_b is large but finite, $\Omega_{\Lambda_b B_d} \equiv 1 - \Delta_{\Lambda_b B_d}$ where $\Delta = O(1/m_b^2)$

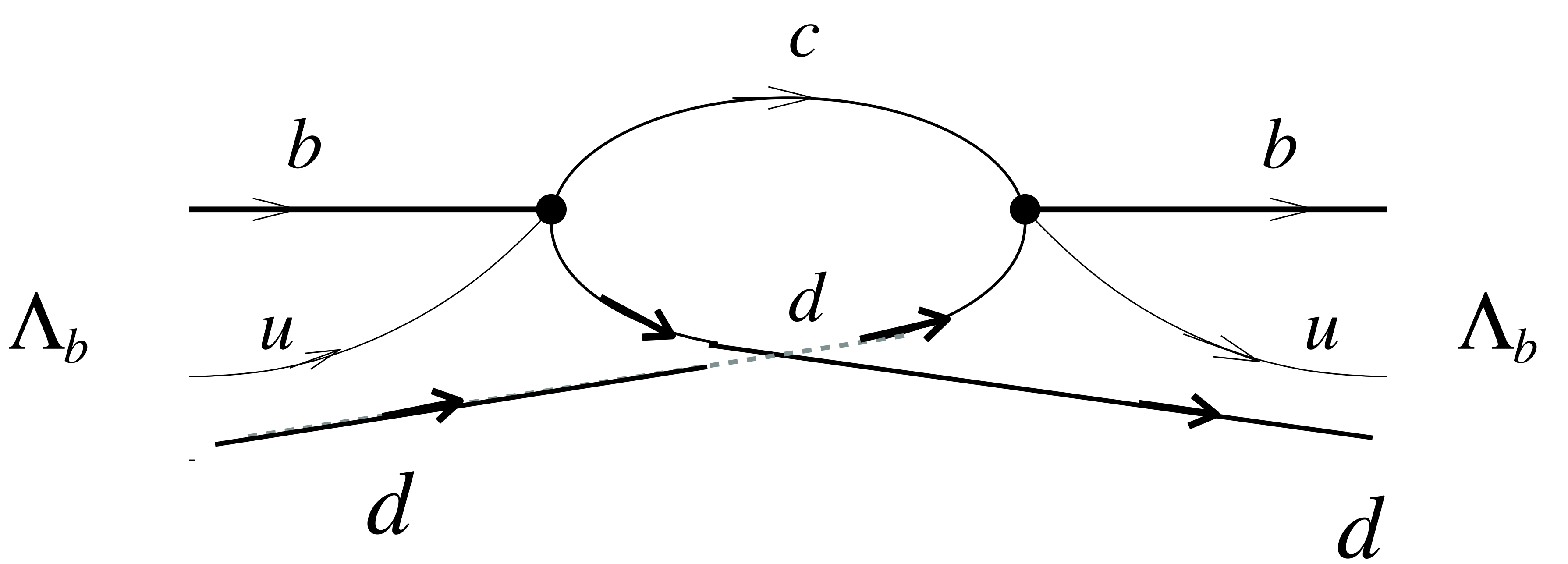
$$\Gamma(H_Q \to f) = G_F^2 |V_{\rm CKM}|^2 m_Q^5 \sum_i \tilde{c}_i^{(f)}(\mu) \frac{\langle H_Q|O_i|H_Q\rangle_\mu}{2M_{H_Q}}$$

$$\propto \Big[c_3^{(f)}(\mu) \frac{\langle H_Q|\bar{Q}Q|H_Q\rangle_{(\mu)}}{2M_{H_Q}}$$

$$+ c_5^{(f)}(\mu) m_Q^{-2} \frac{\langle H_Q|\bar{Q}\frac{i}{2}\sigma G Q|H_Q\rangle_{(\mu)}}{2M_{H_Q}}$$

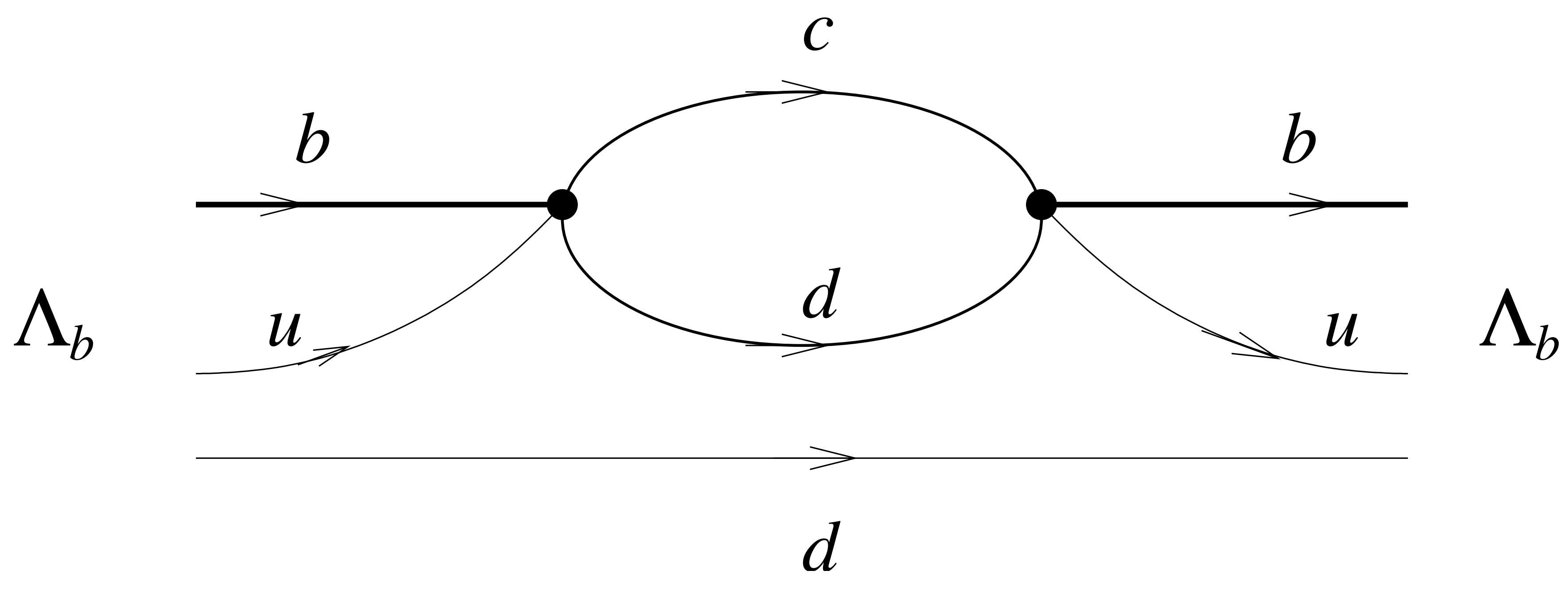
$$+ \sum_i c_{6,i}^{(f)}(\mu) m_Q^{-3} \frac{\langle H_Q|(\bar{Q}\Gamma_i q)(\bar{q}\Gamma_i Q)|H_Q\rangle_{(\mu)}}{2M_{H_Q}}$$

$$+ \mathcal{O}(1/m_Q^4) + \ldots \Big] ,$$



PI

m_Q^{-6} ↗



Qq weak scatter

Preasymptotic m_b^{-3} corrections

Flavor-dependent are dimension-6 four-quark operator whose contribution is suppressed by $\sim m^{-3}$ and dimension-6 weak scattering $\sim m^{-6}$

Experimental measurements of $\tau(\Lambda_b)/\tau(B_d)$ conducted in the 1990's indicated that the ratio $\tau(\Lambda_b)/\tau(B_d)$ was 0.77 ± 0.05

Pauli interference works in the "unfavorable" direction, increasing the ratio $\tau(\Lambda_b)/\tau(B_d)$, while weak scattering tends to decrease it

One typically gets ~ 0.03 to 0.04 for Pauli interference and ~ - 0.08 to - 0.10 for weak scattering, with a recent revaluation

$$\tau(\Lambda_b)/\tau(B_d)_{\rm theor} = 0.93^{-0.05}_{+0.01}$$ (Bigi et al.)

and a relatively recent (in the 2010s) remeasurement

$$\tau(\Lambda_b)/\tau(B_d)_{\rm exp} = 0.93 \pm 0.04$$

Conclusions

For weak scattering we deal with $O_- = 2j_k^\dagger\, j_k$ where $j_k = \varepsilon_{kji}\, b^j C \dfrac{1-\gamma^5}{2} u^i$

If bu good diquark (à la Wilczek) existed, then the contribution of O_- in weak scattering would significantly encrease, shifting $\tau(\Lambda_b)/\tau(B_d)_{\rm theor}$ back to its 1990s measurement away from the more precise 2020 measurement. NO bu **good diquark!**