CLEO-c: Physics Implications

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Two Themes

1. Flavor Physics
2. Nonperturbative QCD

Flavor Physics

- CKM matrix elements:
  - Fundamental parameters of nature
  - Large uncertainties:

			B decays ↓
	0.1 %	1.0 %	25 %
D decays →	7 %	12 %	5 %
Mixing →	36 %	39 %	29 %

- Beyond the Standard Model:
  - Unitarity tests
  - CP violation
  - Non-standard processes

- Theoretical errors becoming dominant.
  - Nonperturbative QCD effects.
  - HQET parameterizes ignorance.
    - D decays 1/M corr'ns, SU(3) violations …

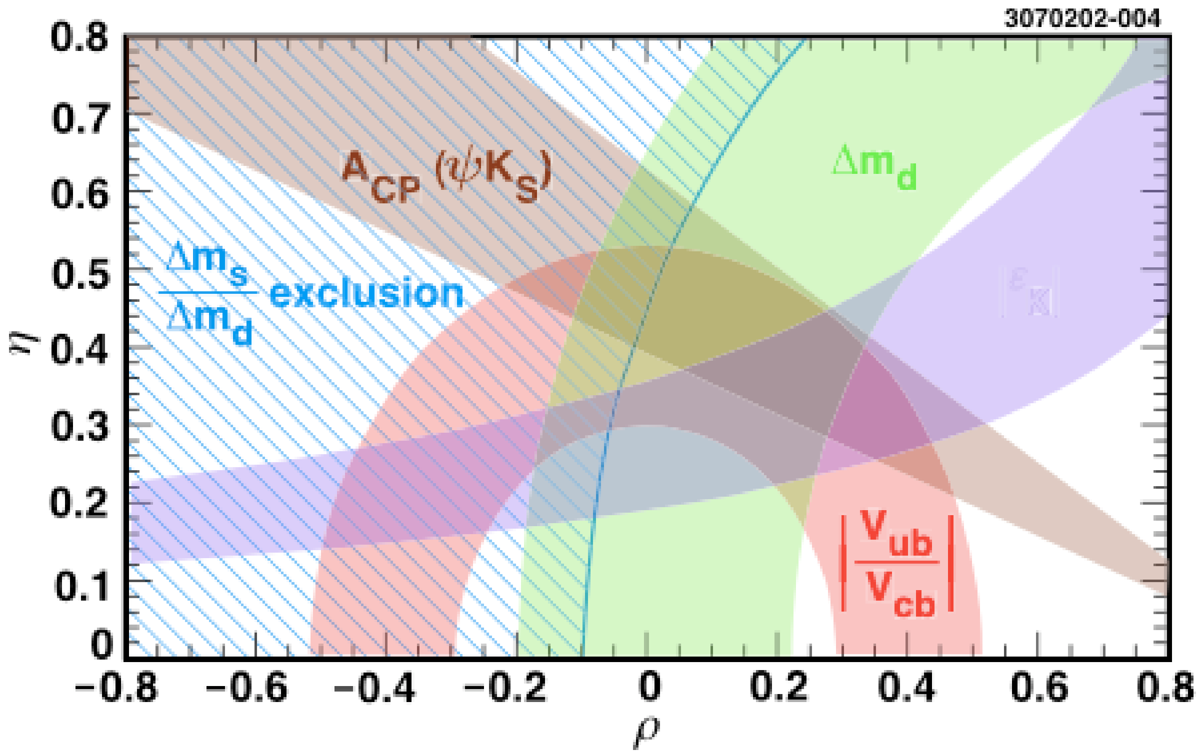
Nonperturbative QCD & Strong Coupling

- Nonperturbative, strongly-coupled field theory is an outstanding challenge to all theoretical physics
  - No general techniques.
  - Field theory is generic; weak coupling is not.

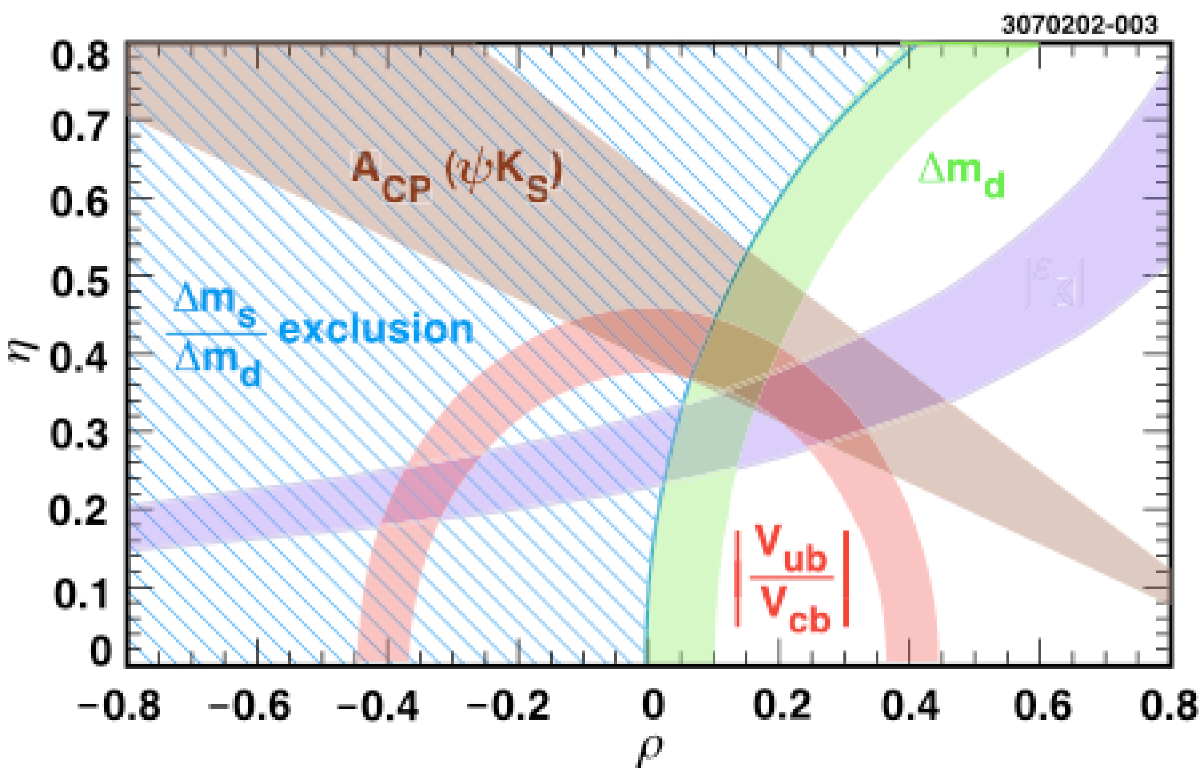
- 2 of the 3 known interactions are strongly coupled: QCD, gravity (string theory)
  - Strong coupling □ asymptotic freedom, dynamical symmetry breaking.
  - Strong coupling at LHC and beyond?
    - SUSY (hierarchy problem)
    - Technicolor
    - …

- Critical long-term need for:
  - Detailed experimental data about all sectors of QCD — our best example/analogy for understanding new theories (e.g., technicolor).
  - Reliable theoretical techniques for analyzing strongly-coupled theories.

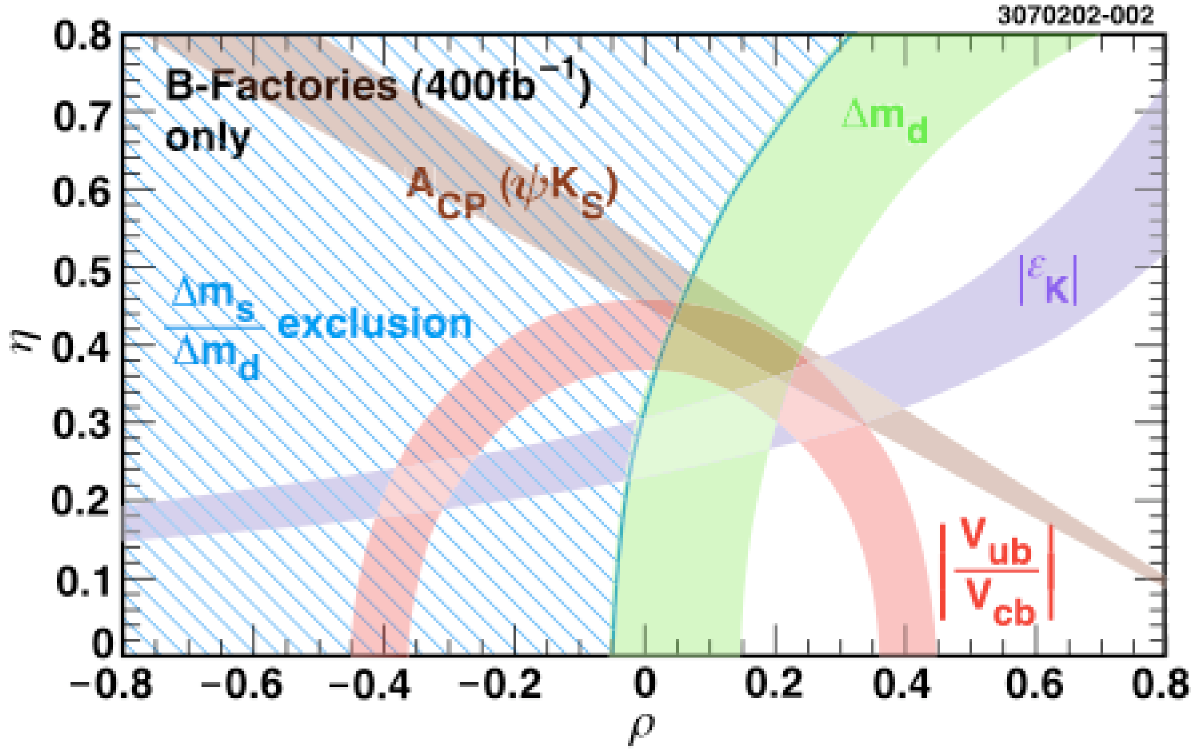
- Important for flavor physics: e.g., CKM now



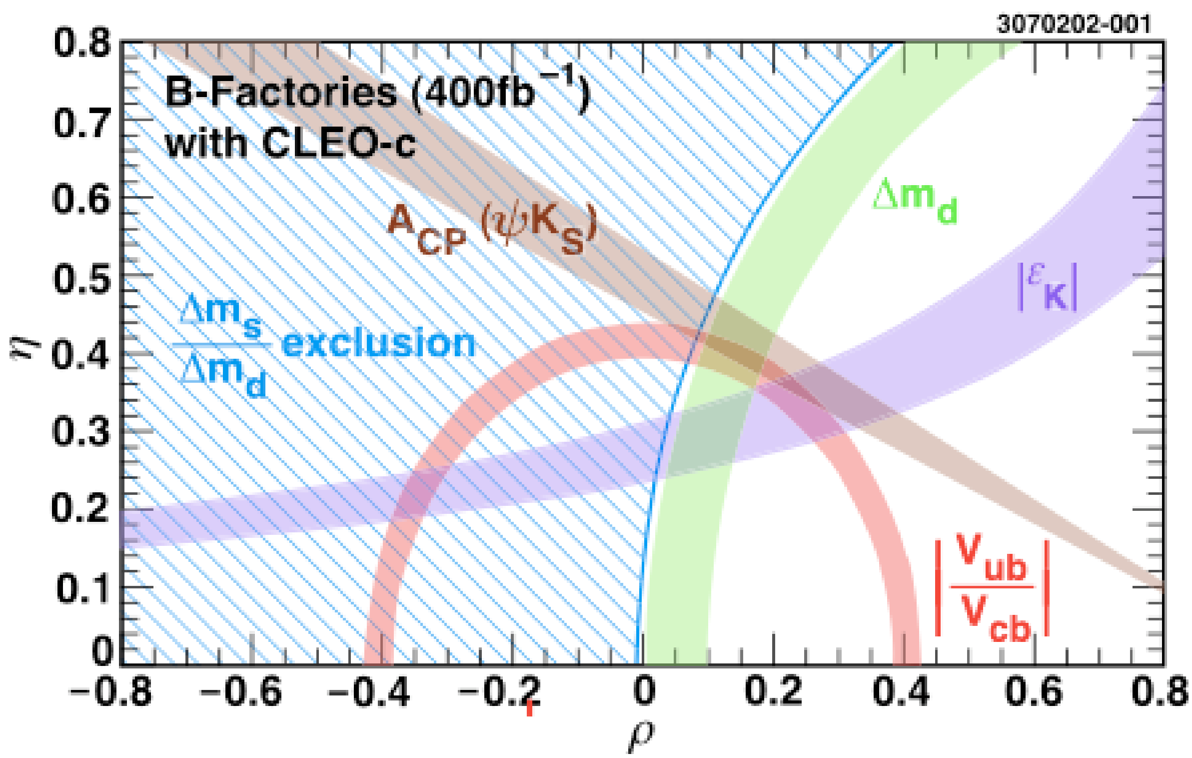
And with 2-3% theory errors:



B-Factories + 10% theory errors (ie, no CLEO-c):



B-Factories + 2-3% theory errors (with CLEO-c):



What is needed to achieve this precision?

Lattice QCD Revolution

- Lattice QCD is the only complete definition of QCD: includes both perturbative and nonperturbative aspects.

- Lattice QCD is not a model.
  - Single formalism relates B/D physics to □/ physics to glueball physics to ...
  - Systematically improvable (beyond 10%)
  - Only parameters are α_s and the quark masses; no fudge factors!

- Lattice QCD has been transformed in the last decade, particularly since 1995.

- History: “Fall and Rise of Lattice QCD”
  - Invented 1974; “explains” confinement.
  - Stalls for almost 20 years.
    - Ken Wilson declares it dead (1989).
  - Renaissance in 1990’s:
    - Lattice perturbation theory fixed.
    - Effective field theories for heavy quarks (NRQCD, HQET…).
    - Improved discretizations (larger lattice spacings); affordable unquenching.
  - First high-precision nonperturbative results in history of strong interactions:
    - $\alpha_s(M_Z)$ to 2-3%.
    - M_b to 2-4%.
    - Ken Wilson retracts (circa 1995).

- Current situation (last 5 years):
  - 10-20% accurate results for a wide range of masses, form factors, … for B’s, D’s, □’s, ’s, □’s, K’s …

- Future (Cornell Workshop, Jan 2001)
  - Few % accuracy for dozens of "gold-plated" calculations possible now:
    - Masses, decay constants, semileptonic form factors, and mixing amplitudes for D, D_s, D*, D_s*, B, B_s, B*, B_s*, and corresponding baryons.
    - Masses, leptonic widths, electromagnetic form factors, and mixing amplitudes for any meson in □ and families below D and B threshold.
    - Masses, decay constants, electroweak form factors, charge radii, magnetic moments, and mixing angles for low-lying light-quark hadrons.
    - Gold-plated processes for *every off-diagonal CKM matrix element.*
    - High-precision lattice QCD collaboration (Cornell, Fermilab, SFU, Illinois, OSU, SMU, Cambridge, Glasgow …)
  - Uses current (1985-1999) techniques; new types of data (e.g., glueballs) will drive development of new techniques.
  - Progress driven by improved algorithms (theoretical physics). Future pace will be much faster than pace of computer hardware evolution.

- HPLQCD case study: f_D systematic errors
  - Perturbation theory
    - Connects lattice to continuum (fills in gaps): for f_D use

      $$J_{cont} = Z\, J_{latt} + a^2 \quad J + \ldots$$

      where

      $$Z = 1 + c_1 \square_s(\square) + c_2 \square_s^2 + \ldots$$

      $\square\ \square\ 2/a$ is typical (for $\square_V$ and n_f=3).

    - Current work uses 1st-order results; relative error is $O(\square_s^2)$.
      - $a = 0.1$fm $\square$ $\square_s^2 \ \square\ 7\%$.
      - Typically the largest systematic error.

    - Next generation will use 2nd-order results; relative error is $O(\square_s^3)$ $\square$ 1.6% at a = 0.1 fm.

  - Finite-lattice-spacing errors
    - E.g., on lattice

      $p^2 \ \square \ (\sin(pa)/a)^2 \ \square\ p^2\,(1 - (pa)^2/3 + \ldots)$

    - Remove a^2, a^4… errors by adding correction terms (improved discretizations).

    - Current work uses a = 0.1fm.
      - $(pa)^2/3$ $\square$ 0.7 % for p$\square$300MeV; smaller with improved discretizations now in use.
      - Improved discretizations important for high-momentum form factors (p larger), and flavor-symmetry restoration in staggered quarks (biggest errors?).

- 1/M errors
  - Effective field theory (e.g., NRQCD) essential for heavy quarks □ 1/M expansion.
  - Current work accurate through O(1/M); errors:
    - $O(1/M^2)$ □ 2% or less for f_D
    - $O(\alpha_s/M)$ □ 3.6% for f_D
    - 3-10 times smaller for B mesons.
  - Future work accurate through $O(\alpha_s/M, 1/M^2)$; relative error is $O(\alpha_s^2/M)$ □ 0.9 %.

- Unquenching
  - Most current work is quenched: $m_{u,d,s}$ □ for sea quarks (ie, no vacuum polarization).
    - Decay constant errors are 10-20%.
  - Current simulations running with realistic m_s and $m_{u,d} = m_s/2, m_s/4$ …
    - Use chiral perturbation theory to estimate and correct errors.
    - Expect relative error of $O(15\%$□$(m_{u,d}/m_s)^2)$ □ 1% for $m_{u,d} = m_s/4$.
  - Simulations with a=0.1fm, $m_{u,d}=m_s/4$ require □ 3 months on 200-node PC cluster for 1% statistical errors (e.g., Fermilab cluster).
    - Use improved staggered quarks.
    - No more quenched analyses!
    - Already happening.

- Challenge for lattice QCD: Demonstrate reliability at the level of few% errors, given past history of 10-20% errors.

  - Requires comparison with wide variety of highly accurate experimental data.
    - High precision (few %) essential to differentiate QCD from models.
    - Wide variety essential for independent tests of all components.
    - C.f., 1950's.

  - Test:
    - Heavy-quark actions (NRQCD, etc)
    - Light-quark actions (improved stagg. quarks)
    - Gluon action
    - High-precision perturbation theory
    - Techniques for computing spectra, decay constants, form factors …

CLEO-c Impact

- □ and Physics
  - >30 gold-plated (few%) lattice calculations possible now (more than □).
    - Masses, spin fine structure for S, P, D states.
    - Leptonic widths for S-states.
    - Electromagnetic transition form factors for P->S states, S->P states ….
    - S-D mixing.
  - Richest, most efficient calibration/ testing ground for lattice techniques.
    - *Independent* calibration of c and b quark actions used in B/D physics.
      - Exactly same action and parameters in both onia and B/D simulations (c.f. models)
    - *Independent* calibration of techniques for decay constants, form factors and mixing used in B/D physics.
      - Tests high-order perturbation theory.
    - Essential for credibility/viability of high-precision B, D experiments at BaBar, CLEO …
    - Detailed verification of a major <u>new</u> theoretical technique.
  - Precursor to heavy-hybrid searches.

CLEO-c Impact

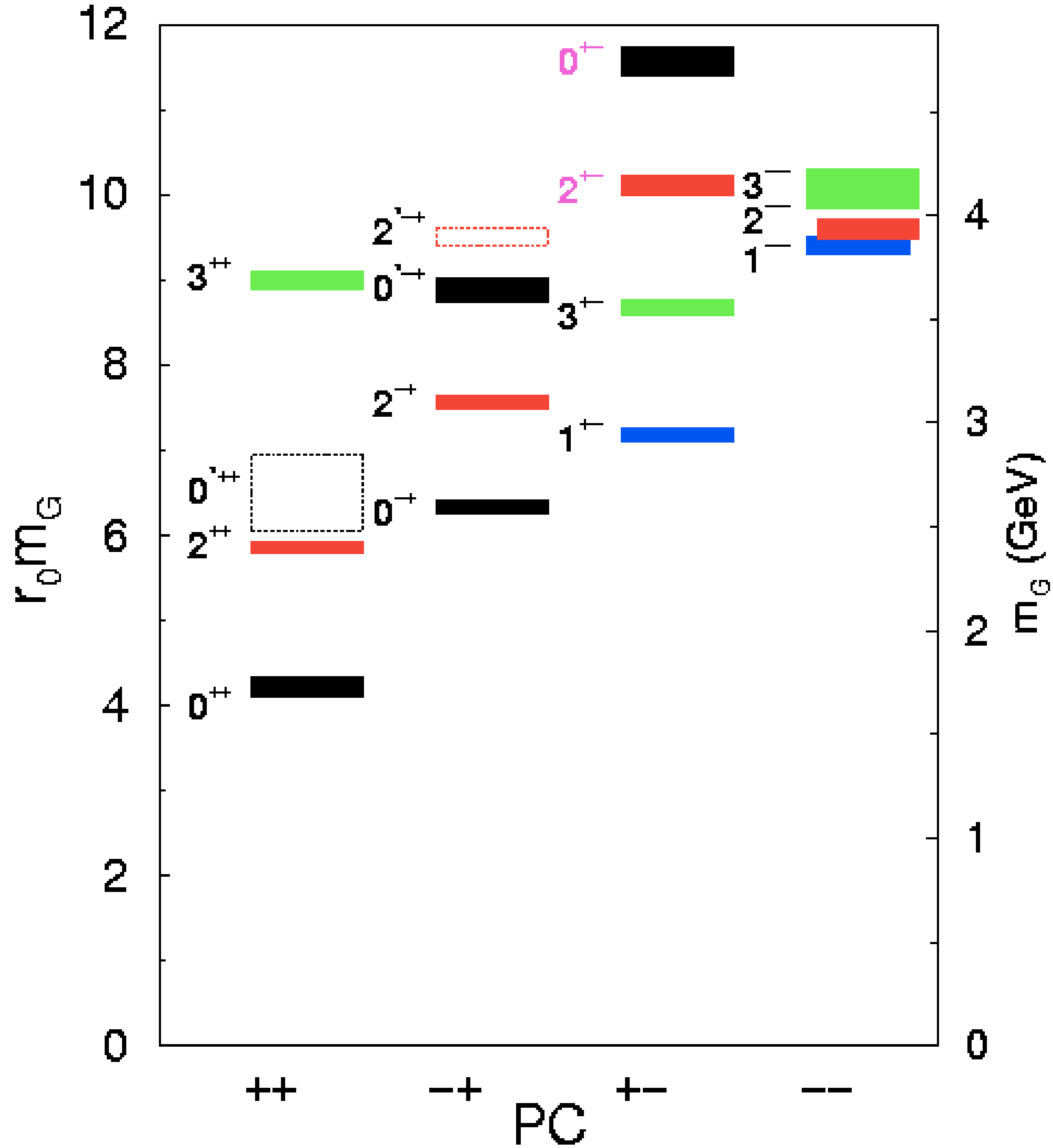
- CKM Matrix and New Physics
  - CLEO-c semileptonic decay rates for D and D_s plus gold-plated lattice QCD give
    - V_{cd} to few% (currently 7%)
    - V_{cs} to few% (currently 12%)
    - New few% tests of CKM unitarity; all 6 triangles worth examining.
    - Q dependence is a test of lattice QCD.
  - CLEO-c leptonic decay rates for D and D_s plus gold-plated lattice QCD give few% cross check on previous results.
    - Stringent calibration of lattice QCD.
    - Provides credibility for final results.
  - Theory and exp't disagree $\to$ new physics?
    - E.g., D $\to$ higgs $\to$ leptons contaminates helicity-suppressed D$\to$ W$\to$ leptons.
    - Any observable D mixing is new physics.
  - Leverage B-physics from D-physics
    - E.g., CLEO-C f_D plus lattice (f_B/f_D) gives 1% accurate prediction for f_B.

CLEO-c Impact

- Glueball, Hybrid States
  - Fascinating states: only known theory in nature where gauge particle is also a constituent.
  - Previous theoretical work frustrated by ambiguous and/or highly incomplete data.
  - Dramatic improvement in data will provide a major incentive for lattice QCD, string theory(!), … to develop rigorous analyses.
    - Lattice QCD needs its □$^-$.
  - Glueballs certainly exist. Two possibilities:
    - Glueballs narrow □ a major discovery in particle physics; highly nontrivial test of lattice QCD; need gluon-rich source.
    - Glueballs broad □ detailed information about the gluonic content of hadrons — beyond the quark model.

Approx. Glueball Spectrum

Morningstar and Peardon



Summary

- CLEO-c contribution:
  - Flavor physics
    - Precise determinations of V_{cd} and V_{cs}.
    - Precise measurements of D analogues of critical B decay rates (semileptonic …).
      - Important for HQET and lattice QCD.
    - Precise measurements of D decays used to tag D's in B studies.
    - Limits (discovery?) on non-standard decays and mixing.
  - Fill out last known sector of QCD spectrum: glueballs, hybrids… — new forms of matter.
  - First high-precision calibration/tests of lattice methods — *landmark* in history of quantum field theory.
    - High-precision and broad range essential to differentiate from models.

- Superb opportunity:
  - Detector and collider capable of 100 fold or better improvement in data.
  - Lattice QCD revolution of the late 1990's means theorists are ready to engage new data. Theorists racing with CLEO/CLEO-c.