CHARM AT CLEO-c

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Introduction

Greetings from C(a)ESR and CLEO!

They have now been together for 28 years. It has been a very productive, exciting, challenging, and happy union as they head into their 30th anniversery.

A short history: CESR/CLEO started in 1979 and have morphed several times. CLEO, for example, went through CLEO I, II, II.V, III, and now CLEO-c.

- CLEO I, II, III were primarily devoted to the physics of **beauty quarks** in the region $\sqrt{s} \approx 10$ GeV, and were the prime source of the physics of bottomonium ($b\bar{b}$) and B mesons ($b\bar{n}$) before the era of the beauty factories at SLAC and KEK.
- CLEO III still has the world's largest samples of $\Upsilon(1S)$ (1.1 fb^{-1}) and $\Upsilon(2S)$ (1.2 fb^{-1}), and several analyses, including **an η_b search**, are in progress.
- In morphing from CLEO to CLEO-c, CESR/CLEO has take up the challenge of the physics of **charm quarks** in the region $\sqrt{s} = 3 - 5$ GeV.

CESR has been modified, and now employs 12 wiggler magnets to maintain good beam quality and luminosity at these lower energies, and CLEO now operates in a lower magnetic field with a new inner drift chamber.

Hidden Flavor Quarkonia ($b\bar{b}$, $c\bar{c}$)

Charmonium ($c\bar{c}$)

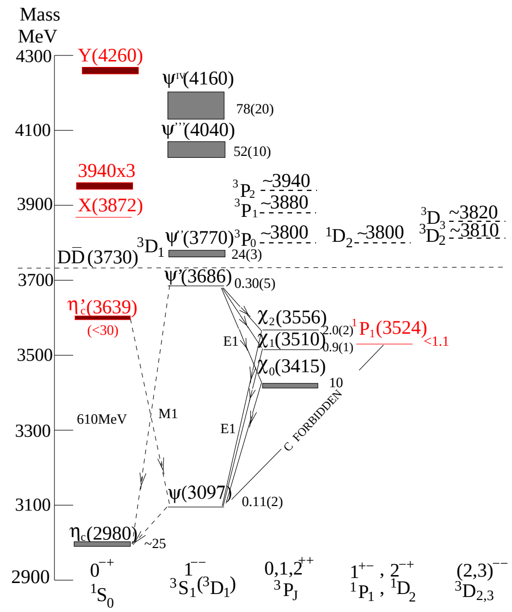
Unlike the bottomonium region in which CLEO no longer runs, CLEO is running in the charmonium region, i.e. $\sqrt{s} = 3 - 5$ GeV, as the name CLEO-c suggests.

- Running in this region makes three different kinds of physics accessible to CLEO-c:
  1. Physics of charmonium, $c\bar{c}$
  2. Physics of charmonium-like exotics, ($c\bar{c}$?)
  3. Physics of open charm or D mesons, $c\bar{n}$ ($n \equiv u, d, s$)
- The luminosities invested at different $\sqrt{s}$ are:

$\sqrt{s}$ (MeV)	$\mathcal{L}$ (pb^{-1})	Physics addressed
3686 (ψ')	51	Bound states of $c\bar{c}$, η'_c, h_c, χ_{cJ}
3671 (off–ψ')	21	Background issues, π, K, p form factors
3770 (ψ'')	540	D spectroscopy, weak decays (more $\mathcal{L}$ to come)
4170	313	D_s spectroscopy, weak decays (more $\mathcal{L}$ to come)
3970–4260	66	coarse scan (hopefully fine scan at 4260)

Charmonium — The Spin–Singlets

After 30 years of charmonium spectroscopy, **a milestone has now been reached** with the discovery of $\eta_c'(2^1S_0)$ at Belle, Babar, and CLEO, and the discovery of $h_c(1^1P_1)$ at CLEO, the long standing gap of missing spin–singlets has been bridged. The spectrum of the bound states of charmonium is now complete!

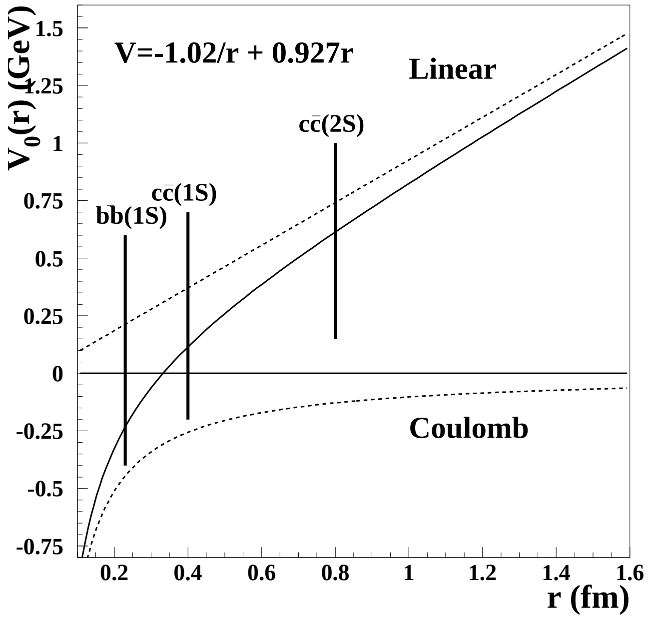


- The spin–singlet states have eluded identification for so long because in e^+e^- annihilations they can only be reached from the produced vectors either by weak M1 radiative transitions ($\eta_c,\ \eta_c'$), or the radiative transition is C-forbidden (h_c).
- The identification of spin–singlets is essential for determining the nature of the spin–spin hyperfine interaction in QCD, its Lorentz character, its variation with mass ($c\bar{c}$ versus $b\bar{b}$), and its variation with n ($1S$ versus $2S$) and L ($1S$ versus $1P$).
- Now we can address these issues.

The Hunt for $\eta_c'(2^1S_0)$

The $1S$ (η_c, J/ψ) region of charmonium:

The $q\bar{q}$ potential which has nearly equal contributions from the Coulomb ($\propto 1/r$) part and the confinement ($\propto r$) part.



The $2S$ (η_c', ψ') region of charmonium:

The confinement part dominates. It is important to know how the hyperfine interaction changes from $1S$ to $2S$.

- The known hyperfine splitting of the $1S$ state is

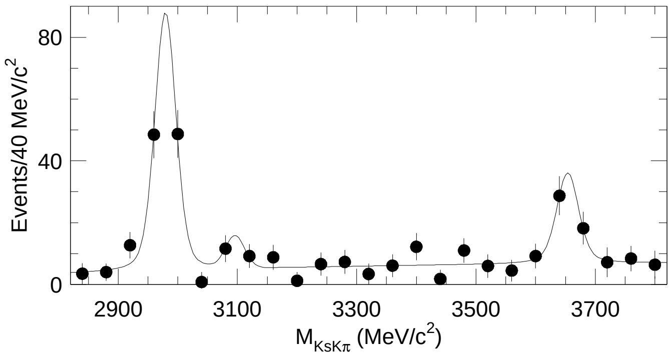
$$\Delta M_{hf}(1S) \equiv M(J/\psi) - M(\eta_c) = 116.5 \pm 1.2 \text{ MeV}$$

A model independent prediction is that

$$\Delta M_{hf}(2S) = \Delta M_{hf}(1S) \times \frac{\Gamma(\psi'(2S) \to e^+e^-)}{\Gamma(J/\psi \to e^+e^-)} \times \frac{M^2(\psi'(2S))}{M^2(J/\psi)} = (62 \pm 5) \text{ MeV}$$

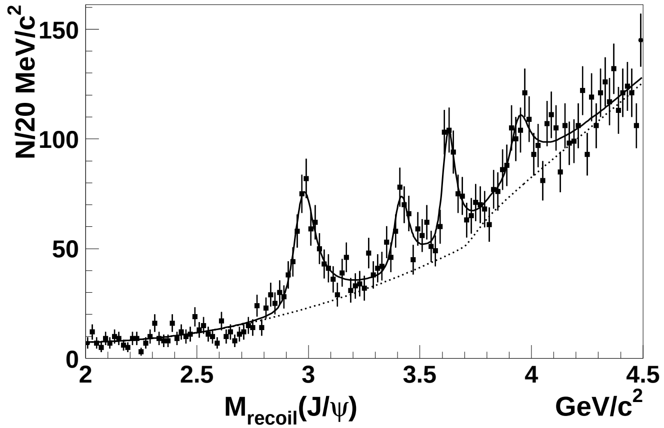
- The 1982 claim by Crystal Ball of $M(\eta_c') = 3594$ MeV, and $\Delta M_{hf}(2S) = 92 \pm 5$ MeV, i.e. 50% larger than predicted, was never confirmed, but never challenged by theory, either.

Attempts by E760/E835, DELPHI, L3, and CLEO failed to find η_c'. Now Belle, BaBar and CLEO have firm identification of η_c', and the challenge is to theory.



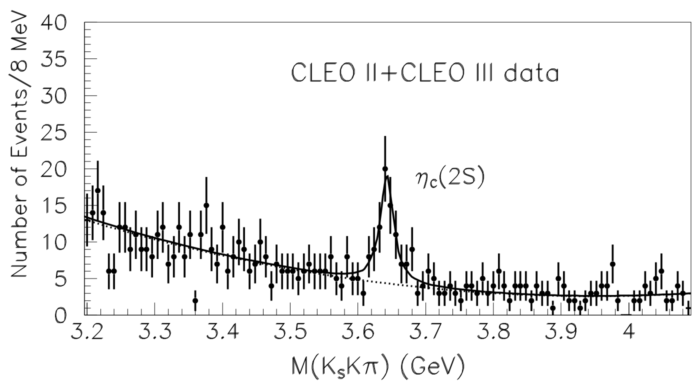
Belle: **42 fb^{-1}** $(B \to K(K_S K\pi))$

PRL **89**, 102001 (2002)



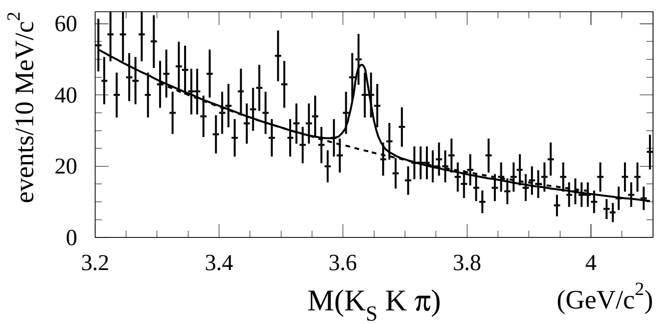
Belle: **350 fb^{-1}** $(e^+e^- \to J/\psi + c\bar{c})$

hep-ex/0507019



CLEO II+III: **27 fb^{-1}** $(\gamma\gamma \to K_S K\pi)$

PRL **92**, 142001 (2004)



BaBar: **86 fb^{-1}** $(\gamma\gamma \to K_S K\pi)$

PRL **92**, 142002 (2004)

The Discovery of $\eta_c'(2^1S_0)$

In all measurements,

- The number of events is small (< 120)
- $M(\eta_c')$ varies from 3631 MeV to 3654 MeV.
- The width of η_c' is essentially unmeasured so far.
- The PDG average is $M(\eta_c') = 3638 \pm 4$ MeV.

  This leads to $\boldsymbol{\Delta M_{hf}(2S) = 3686 - 3638 = 48 \pm 4}$ **MeV.**

  Recall that $\boldsymbol{\Delta M_{hf}(1S) = 3097 - 2980 = 117 \pm 1}$ **MeV.**

  Explaining this large difference is a challenge for theorists. Lattice is not much help so far. $\Delta M_{hf}(2S) = 75 \pm 44$ MeV (Columbia), 26 ± 17 MeV (CP–PACS)
- Width of η_c' is essentially unmeasured so far.
- **LOTS REMAINS TO BE DONE ABOUT $\boldsymbol{\eta_c'(2^1S_0)}$**.
- CLEO has 48 pb^{-1} of new ψ' data, and would love to identify η_c' in $\psi' \to \gamma\eta_c'$. Unfortunately, it is very difficult to identify the 48 MeV weak M1 radiative transition. But efforts are underway.

The Discovery of $h_c(1^1P_1)$

If the confinement potential is Lorentz scalar, there is no long–range spin–spin interaction in $q\bar{q}$. It follows that the hyperfine splitting is zero for $l \neq 0$, or

$$\Delta M_{hf}(1P) = M(\langle^3P_J\rangle) - M(^1P_1)$$

Since $M(\langle^3P_J\rangle)$ is known accuractely, to test this prediction it is necessary to identify $h_c(1^1P_1)$ and measure $M(h_c)$ with precision.

- In 1982 Crystal Ball failed in the search for h_c in the reaction

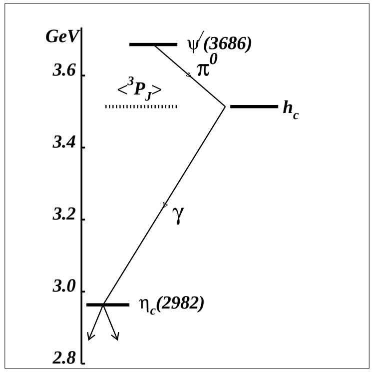
$$\psi(2S) \to \pi^0 h_c,\ h_c \to \gamma\eta_c.$$

- In 1992 Fermilab E760 studied the reaction $p\bar{p} \to h_c \to \pi^0 J/\psi$ and claimed the observation of a signal for h_c. However, higher luminosity runs in 1996 and 2000 have failed to confirm this observation.
- Fermilab E835 has searched for h_c in their 1996/2000 data in the reaction $p\bar{p} \to h_c \to \gamma\eta_c$.
  They report, $\Delta M_{hf}(1P) = -0.4 \pm 0.2 \pm 0.2$ MeV with 13 counts, and a significance of the h_c signal at $\sim 3\sigma$ level.
- Now CLEO has firmly identified h_c, at a significance level $> 6\sigma$.

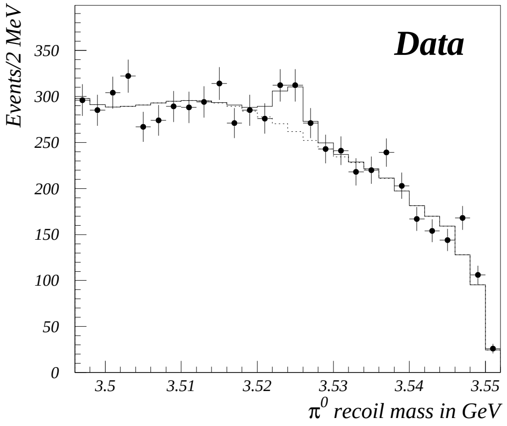
CLEO Observation of $h_c(1^1P_1)$

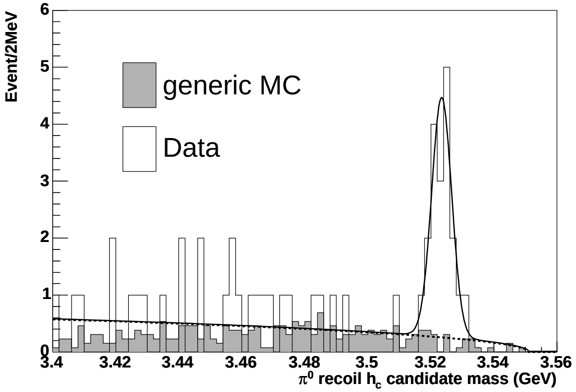
At CLEO-c for 3.08 million $\psi(2S)$ were analyzed for

$$\psi(2S) \to \pi^0 h_c\ ,\ h_c \to \gamma\eta_c$$



Inclusive analyses (constraining either E_γ or $M(\eta_c)$) and exclusive analysis (reconstructing η_c) were done, and accurate determinations of h_c mass were made in recoils against π^0's. Consistent results were obtained (PRL **95**, 102003 (2005)).





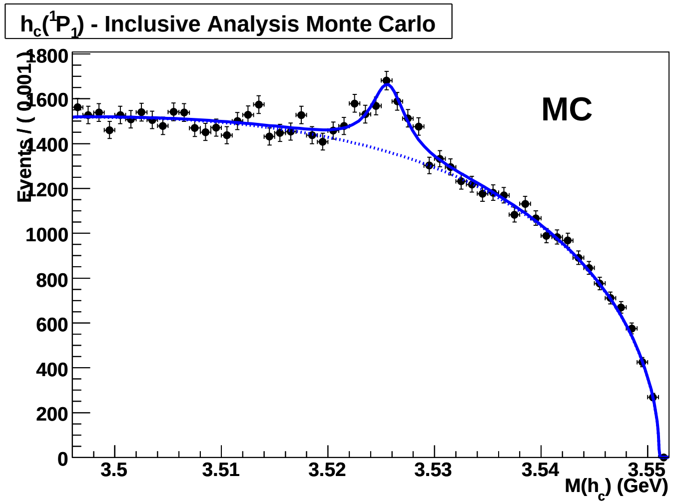
$$M(h_c) = 3524.4 \pm 0.6 \pm 0.4 \text{ MeV},\ \text{or} \qquad \Delta M_{hf}(1P) = +1.0 \pm 0.6 \pm 0.4 \text{ MeV}$$

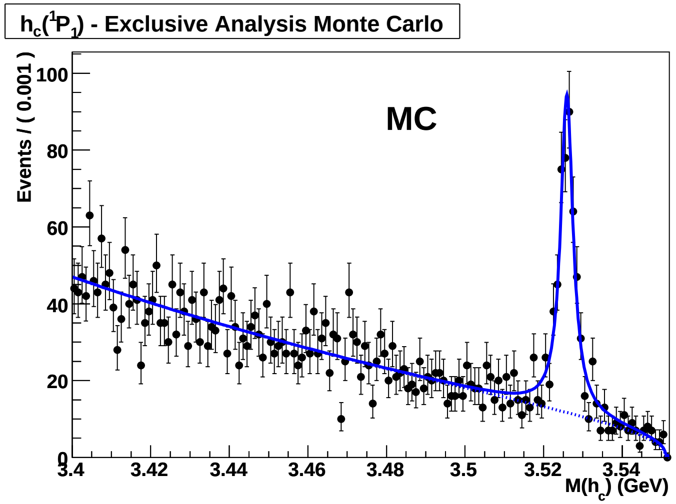
We conclude that the simple pQCD expectation, $\Delta M_{hf}(1P) = 0$ is not strongly violated, and that the magnitude and sign of ΔM_{hf} is not yet well determined.

More on $h_c(^1P_1)$

CLEO-c now has data for 48 pb^{-1}, or 24.5 million ψ', making it the world's largest available sample of ψ'. With these data we expect greatly improved results from both inclusive and exclusive analyses. Preliminary analyses show that these expectations will be fully met, **with ~ 1000 h_c in inclusive analysis and ~ 250 h_c in exclusive analysis**. These should lead to $M(h_c)$ and $\Gamma(h_c)$ determinations with uncertainties at the level of $\sim \pm 0.3$ MeV and $\sim \pm 0.5$ MeV, respectively.

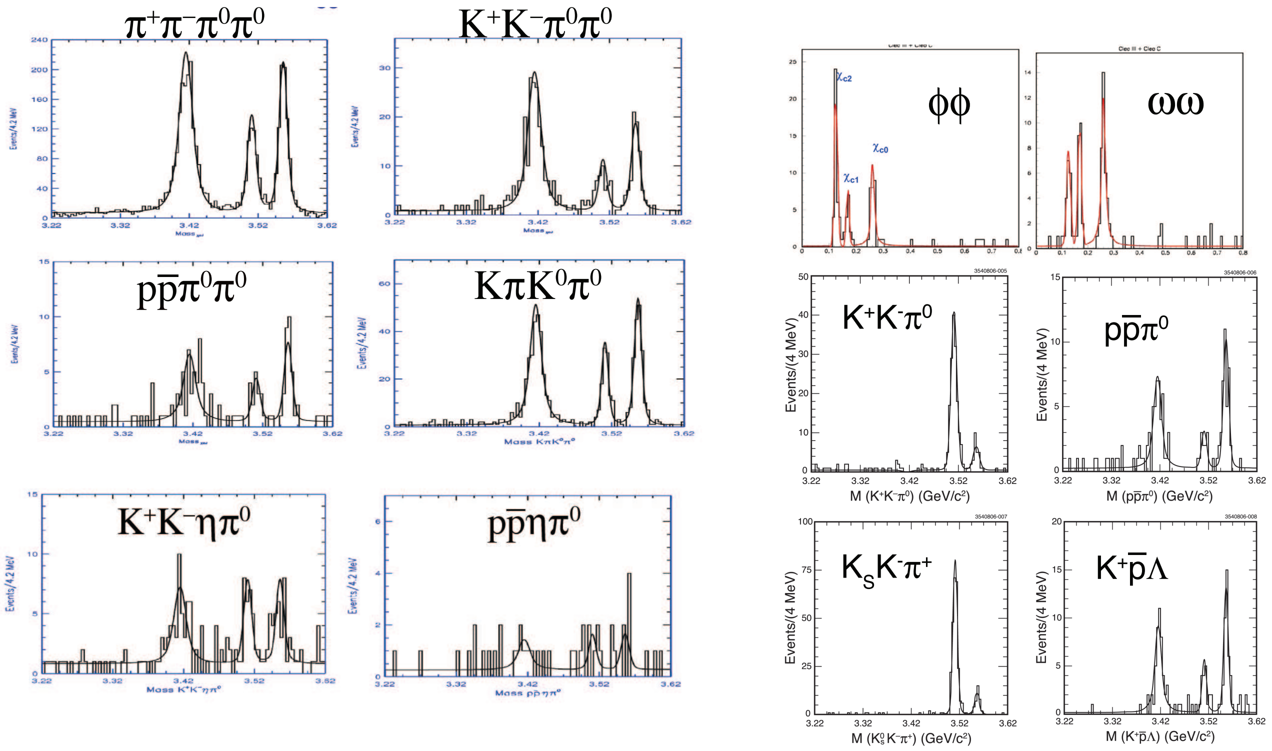
Monte Carlo simulations for 24.5 million ψ' based on our published analysis of 3 million ψ'.





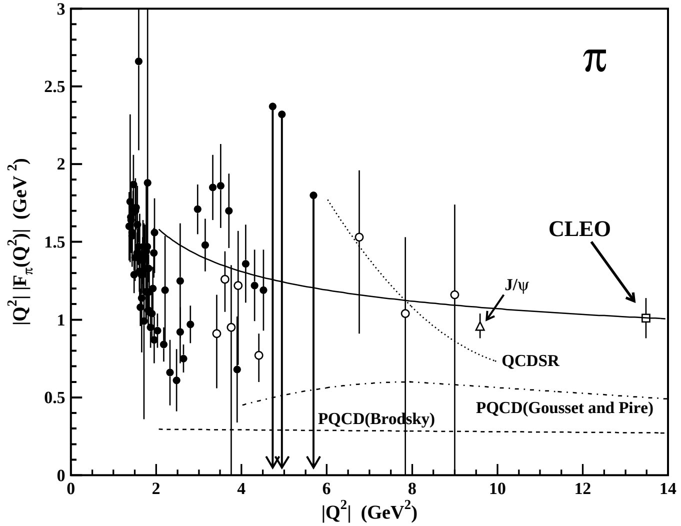
Analyses of 24.5 million in progress

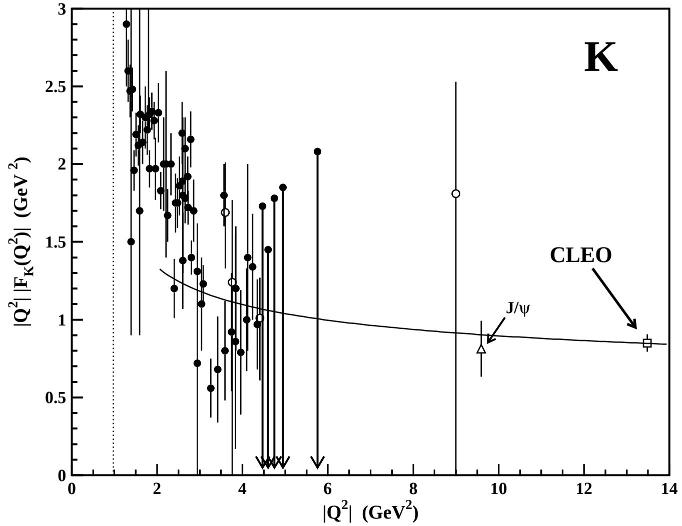
With the new sample of 24.5 million ψ' at our disposal, numerous analyses are just being published or are in progress. To give you a flavor of these I present below a montage of the results for a sample of $\psi' \to \gamma\chi_{cJ}$, $\chi_{cJ} \to$ 2 body, 3 body, 4 body decays with 3 million ψ'. These already increase the χ_{cJ} decays in the PDG severalfold.



Pion and Kaon Timelike Form Factors

It is a surprising fact that we know **very little** about the electromagnetic structure of even the lightest hadrons, pions and kaons, and essentially **nothing** at large momentum transfers. Obviously, the measurement of these form factors is of great importance to QCD and QCD–based models. Using the 21 pb^{-1} data taken off ψ', at 3670 MeV, CLEO-c has been able to make the first precision measurements of pion and kaon form factors via $e^+e^- \to \pi^+\pi^-,\ K^+K^-$ at $Q^2 = 13.5$ GeV^2 (PRL **95**, 261803 (2005)). As the figure illustrates, no satisfactory theoretical prediction exists.





The solid curve (arb. normalization) illustrates variation of α(strong) with $|Q^2|$.

$\psi(3770)$

There is renewed interest in the precision determination of the decays of $\psi(3770)$ because it is the **pure $D\overline{D}$ factory.**

- It is long known that this state decays **dominantly** into $D\overline{D}$. The recent interest has been about the level at which it decays into non–$D\overline{D}$ final states.
- CLEO has made extensive measurements of $\psi(3770)$ decays.
  1. A search for 25 charmless multibody decays of $\psi(3770)$ found evidence for none, and established 90% confidence upper limits, all less than 0.3%. (PRL **96**, 032003 (2006))
  2. Branching fractions for the decays $\pi^+\pi^- J/\psi$, $\pi^0\pi^0 J/\psi$, $\gamma\chi_{c0}$, and $\gamma\chi_{c1}$ were measured at 0.19%, 0.08%, 0.73%, and 0.28% levels, respectively. (PRL **96**, 082004 (2006); PRL **96**, 182002 (2006); PRD **74**, 031106 (2006))
  3. At $\sqrt{s} = 3773$ MeV CLEO has measured $\sigma(e^+e^- \to \mathrm{hadrons}) = (6.38 \pm 0.08^{+0.41}_{-0.30})$ nb, and finds that $\sigma(e^+e^- \to D\overline{D})$ is larger than this by $(0.01 \pm 0.08^{+0.41}_{-0.30})$ nb. This is consistent with non–$D\overline{D}$ hadronic decays of $\psi(3773)$ being of the order of 5%. (PRL **96**, 092002 (2006)). This result is at variance with the recent BES claim that $\mathcal{B}(\psi(3773) \to \mathrm{non} - D\overline{D}) = (16.1 \pm 1.6 \pm 5.7)\%$.

The Charmonium–like Exotics

As most of you know, there has been great excitement recently about what has been called a **"renaissance"** in hadron spectroscopy. This is not just because of the discovery of the long missing singlet states (η_c', h_c) of charmonium, but because of a number of unexpected states with masses in the 3.8 GeV to 4.3 GeV region reported by Belle and BaBar. These are **X(3872), X,Y,Z(3940), and Y(4260).** All these share the following characteristics:

1. They are weakly excited even with hundreds of fb^{-1} e^+e^- annihilation data.
2. They all like to decay into final states containing a c and a $\bar{c}$ quark, hence charmonium-like.
3. But none of them easily fits into the expected spectrum of charmonium states.

CLEO has looked into two of these, X(3872) and Y(4260).

X(3872)

This state has been firmly established in observations by Belle, BaBar, CDF, and DØ, with $M(\mathrm{X}(3872)) = 3971.2 \pm 0.5$ MeV, and $\Gamma(\mathrm{X}(3872)) < 2.3$ MeV

Though not firmly determined, its likely $J^{PC} = 1^{++}$ or 2^{-+}.

- There are numerous theoretical conjectures about the nature of X(3872).

  X(3872) is a a displaced charmonium state $(2\chi_{cJ})$

  X(3872) is a hybrid

  X(3872) is a mixed glueball

  X(3872) is a 4–quark state

  X(3872) is a $D^0\overline{D^{0*}}$

- The most popular and exciting conjecture is that X(3872) is a meson–molecule of weakly bound $D^0\overline{D^{0*}}$. This proposition is mainly based on the fact that $M(D^0) + M(D^{0*})$ is very close to $M(\mathrm{X}(3872))$.

X(3872)

- The PDG06 average mass $M(D^0) = 1864.1 \pm 1.0$ MeV, therefore

$$M(D^0) + M(D^{0*}) = 3870.3 \pm 2.1 \text{ MeV},$$

and the binding energy of the proposed molecule is

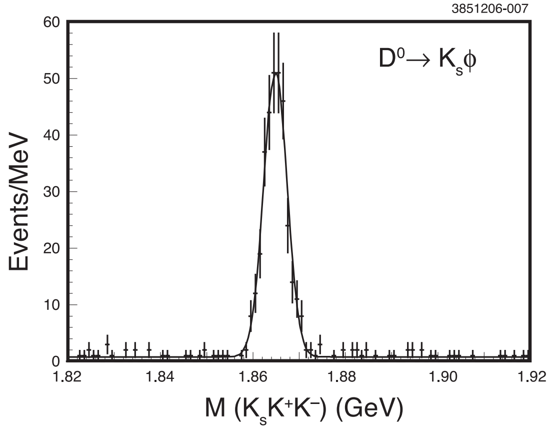
$$E_B(\text{X}(3872)) = -0.9 \pm 2.1 \text{ MeV}$$

- To put the $D^0\overline{D^{0*}}$ molecule model to a more stringent test, CLEO has made a precision measurement of $M(D^0)$. The result (PRL **98**, 092002 (2007)) is

$$M(D^0) = 1864.847 \pm 0.178 \text{ MeV}.$$

$$E_B(\text{X}(3872)) = -0.6 \pm 0.6 \text{ MeV}$$

(The error is now limited by the error in M(X(3872)).



- With the binding energy this small, it is difficult to reconcile Belle's report of $\Gamma(D^0\overline{D^0}\pi^0)/\Gamma(\pi^+\pi^- J/\psi) \approx 10$ (PRL **97**, 16202 (2006)) with Swanson's prediction (PLB **588**, 285 (2004)) of $\sim 1/20$ for the same in the molecular model.

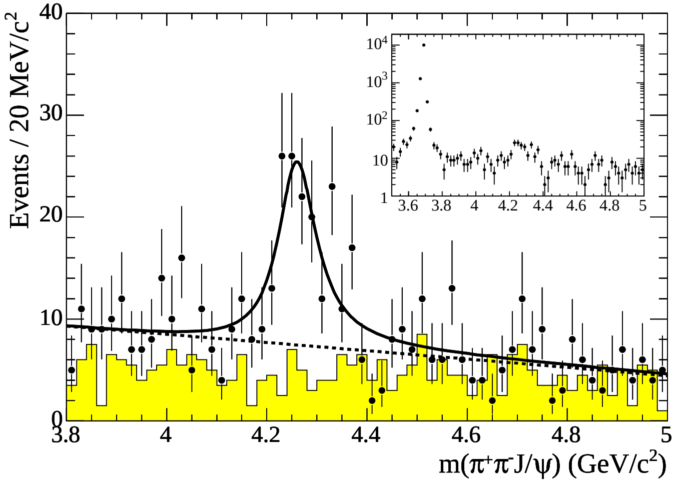
Y(4260)

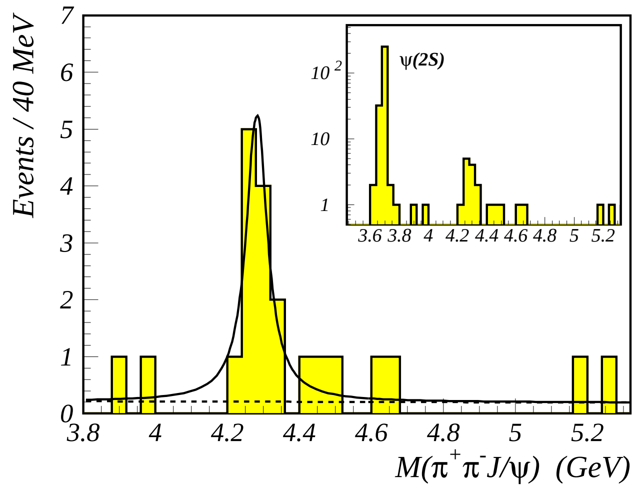
The Y(4260) was originally reported by BaBar in ISR production (PRL **95**, 142001 (2005))

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

which implied that Y(4260) is a **vector**. However, there is no evidence for it in $R \equiv \sigma(\text{hadrons})/\sigma(\mu^+\mu^-)$. In fact there is a deep minimum in R at $\sqrt{s} \approx 4260$ MeV. This would make Y(4260) a very peculiar vector.

- To confirm the vector nature of Y(4260), CLEO made a measurement of the yield of $\pi^+\pi^- J/\psi$ (and several other decays) in its coarse e^+e^- scan. A significant enhancement was observed at $\sqrt{s} = 4260$ MeV (PRL **96**, 162003 (2006)).
- Subsequently, CLEO examined the data for ISR production from its own data in the Υ resonance region. The results convincingly confirmed the Y(4260) production in ISR and decay into $\pi^+\pi^- J/\psi$ (PRD **74**, 091104(R) (2006)).
- Recently, Belle has also confirmed the ISR production of Y(4260) (hep-ex/0612006).
- However, differences in mass remain, and Γ(Y(4260)) is essentially undetermined. A scan of Y(4260) production in direct e^+e^- annihilation is needed to make a precision determination of the mass and width of Y(4260).





$$M(\Upsilon(4260)) = 4259 \pm 8^{+2}_{-6}\ \text{MeV}$$

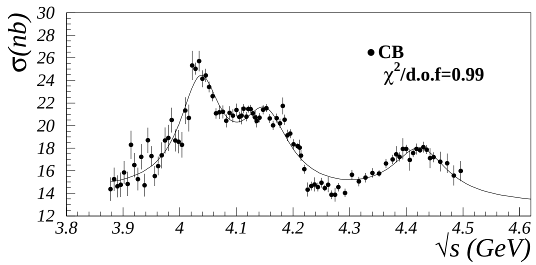
$$\Gamma(\Upsilon(4260)) = 88 \pm 23^{+6}_{-4}\ \text{MeV}$$

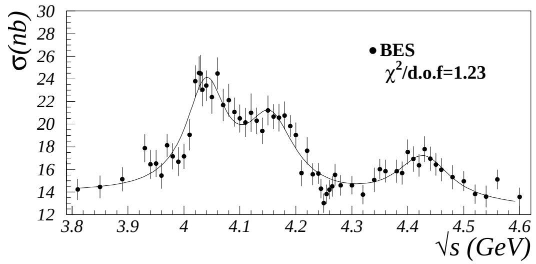
$$\boldsymbol{\mathcal{L} = 233\ \text{fb}^{-1}}$$

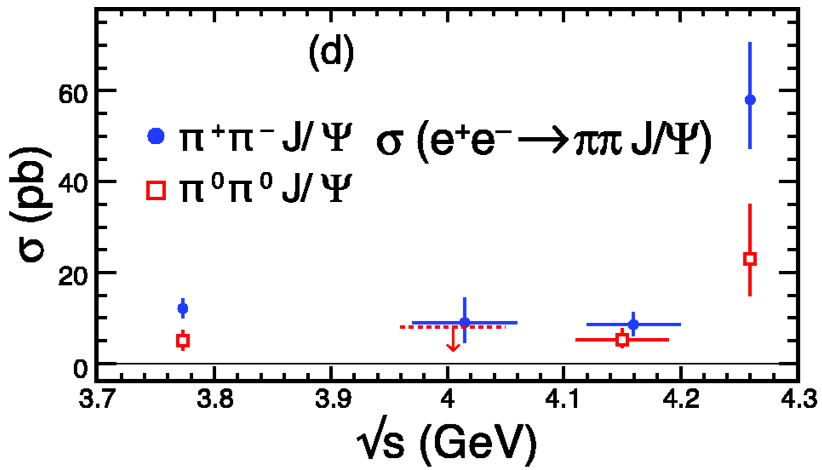
$$M(\Upsilon(4260)) = 4283^{+17}_{-16} \pm 4\ \text{MeV}$$

$$\Gamma(\Upsilon(4260)) = 70^{+2}_{-6} \pm 5\ \text{MeV}$$

$$\boldsymbol{\mathcal{L} = 13.3\ \text{fb}^{-1}}$$







CLEO-c as an Open–Charm Factory

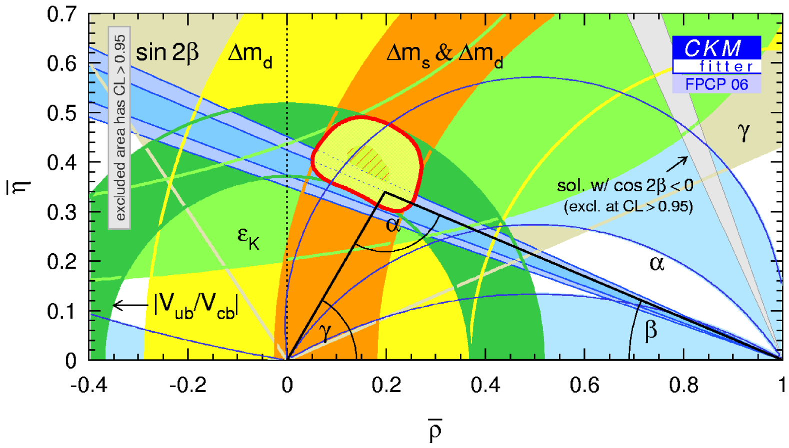
The primary motivation for CLEO to morph into CLEO-c was to become a prodigious factory for the production of open–charm hadrons, the D and D_s, and thereby enable it to make important contributions to D physics, to determine form factors, CKM matrix elements, and to allow peeks into the holy–grail of **"beyond the standard model."**

- As mentioned earlier, 540 pb^{-1} of data at $\psi(3770)$ for near-threshold production of $D\overline{D}$ and ∼313 pb^{-1} of data at $\psi(4170)$ for near-threshold production of $D_s\overline{D_s}$ have already been taken, and more is to come during the one more year of running that is scheduled for CLEO-c.
- There are many advantages of threshold production of D mesons. For example, at $\psi(3770)$, the $D\overline{D}$ are produced without any extraneous particles, the backgrounds are extremely low, and even with much smaller luminosities, results are obtained with precision equal to, or better than, that obtained for D's produced at the B–factories. It might appear surprising, but the number of events in 100 pb^{-1} with two D mesons reconstructed (at CLEO) is the same as the number of events at 10 GeV with 500 fb^{-1} with two B mesons reconstructed (at the B–factories).

The Goals of D–Physics at CLEO-c

The way to contribute to **"physics beyond the Standard Model"**. is by leading to precision determination of CKM matrix elements and test the closure of the unitary triangle. The logical steps in the realization of this goal are the following.

- Make precision measurements of absolute branching ratios for D decays, hadronic, leptonic, and semileptonic are made to determine decay constants for D and D_s and their form factors.
- Compare them to the predictions of the latest unquenched lattice calculations.
- Good agreement would validate the lattice calculations and give confidence in lattice predictions for the B and B_s decay constants, which are needed to determine the parameters of the unitarity triangle.



Hadronic Decays of D Mesons

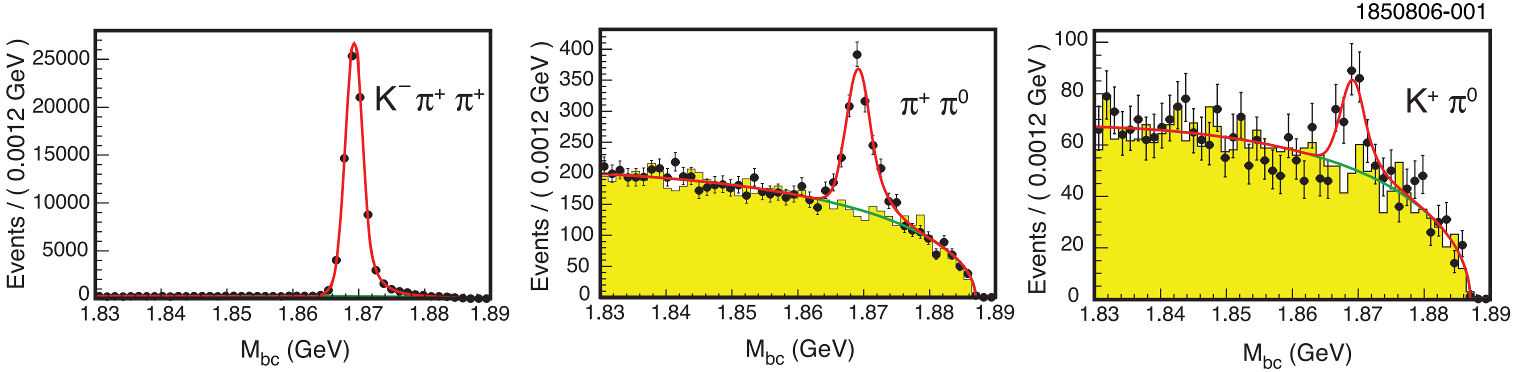
Precision measurements of hadronic decays of D and D_s are required because their absolute branching fractions are needed to normalize all other decays, leptonic and semi-leptonic. Asymmetry measurements between D^0 and $\overline{D^0}$ decays allow studies of CP violation in D decays.

Double tagging (reconstructing both D and $\overline{D}$ mesons) provides essentially background-free spectra of $D\overline{D}$ decays. Double tagging also removes the need to know the number of $D\overline{D}$ produced as well as the tagging efficiency.

- The threshold for $D\overline{D}$ production is at ∼3740 MeV. The $D\overline{D}$ measurements were made near threshold, at the ψ'' peak at $\sqrt{s} = 3770$ MeV.
- The thresholds for $D_s\overline{D_s}$ and $D_s^*\overline{D_s^*}$ production are at ∼3940 MeV and ∼4220 MeV, respectively. A coarse scan in the region $\sqrt{s}$=3.97–4.26 GeV revealed that the optimal energy for all D_s was $\sqrt{s}$=4170 MeV. The D_s data were taken at $\sqrt{s}$=4170 MeV.
- A favourite normalization mode is the Cabbibo favoured decay $D^+ \to K^-\pi^+\pi^+$ for which the CLEO result is the most precise so far. It also leads to the good precision results for the singly Cabbibo suppressed decay $D^+ \to \pi^+\pi^0$ and the doubly Cabbibo suppressed decay $D^+ \to K^+\pi^0$.

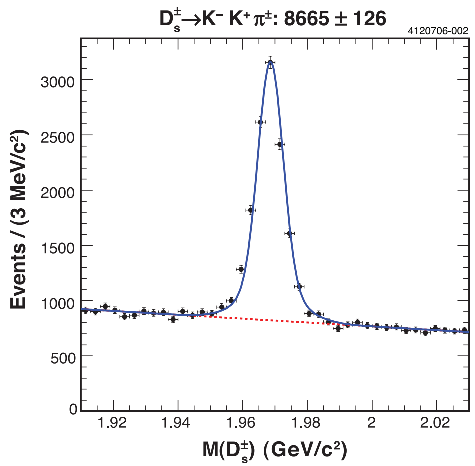
Hadronic Decays of D Mesons

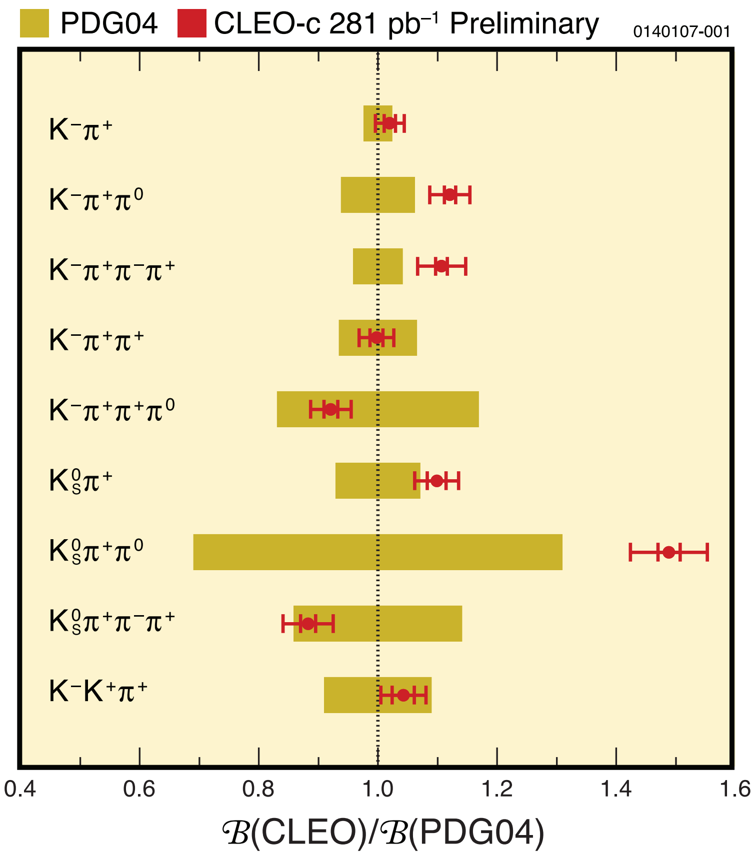
$|V_{ud}| \cdot |V_{cs}|$ $|V_{ud}| \cdot |V_{cd}|$ $|V_{us}| \cdot |V_{cd}|$



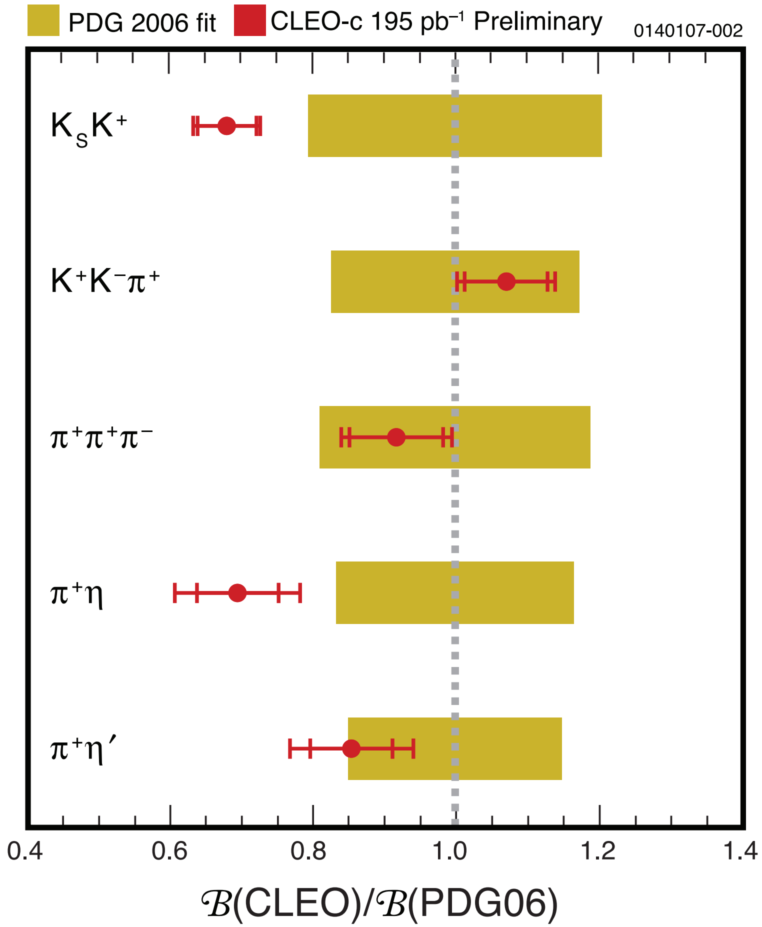
$\mathcal{B}(D^+ \to K^-\pi^+\pi^+)$	$= (9.52 \pm 0.25 \pm 0.27)\%$	HQL 2006
$\mathcal{B}(D^+ \to \pi^+\pi^0)$	$= (12.5 \pm 1.0) \times 10^{-4}$	PRL **96**, 081802 (2006)
$\mathcal{B}(D^+ \to K^+\pi^0)$	$= (2.28 \pm 0.40) \times 10^{-4}$	PRD **74**, 071102 (2006)

$\mathcal{B}(D_s^\pm \to K^-K^+\pi^\pm) =$
$(5.57 \pm 0.36)\%$
(HQL 2006)





D hadronic decays



D_s hadronic decays

Leptonic Decays D Mesons and Decay Constants

The leptonic decays of D mesons provide a measure of the product of form factors and CKM matrix elements

$$\Gamma(D^+_{(d,s)} \to l^+\nu) \propto f^2(D^+_{(d,s)})|V_{c(d,s)}|^2$$

Using $D^+_{(d,s)}$ lifetimes, which have been well measured, and the best known values of the CKM matrix elements, the decay constants can be measured.

- Using 281 pb^{-1} of data taken at $\psi(3770)$, CLEO has measured $\mathcal{B}(D^+ \to \mu^+\nu) = (4.40 \pm 0.66^{+0.08}_{-0.12}) \times 10^{-4}$ and obtained (PRL **95**, 251801 (2005))

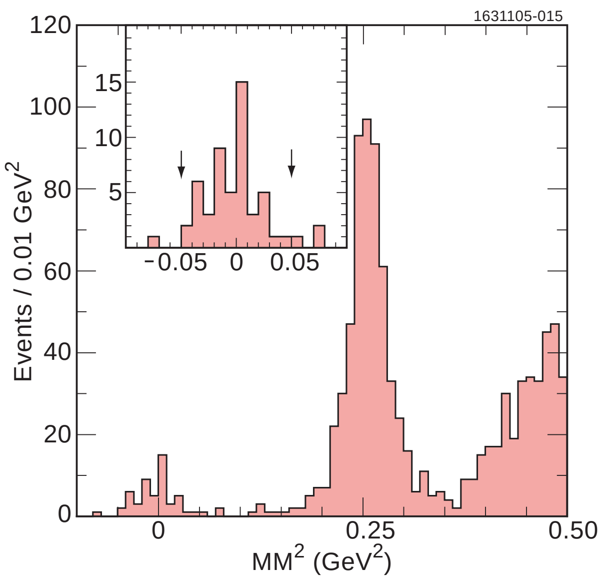
$$f(D^+) = 222.6 \pm 16.7^{+2.8}_{-3.4}\ \mathrm{MeV}$$

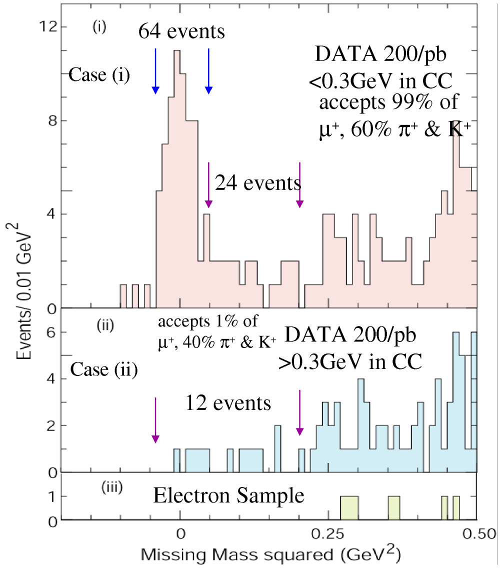
- Using 314 pb^{-1} of data taken at $\sqrt{s} = 4170$ MeV, CLEO has measured
  $\mathcal{B}(D_s^+ \to \mu^+\nu) = (0.664 \pm 0.076 \pm 0.028) \times 10^{-4}$
  $\mathcal{B}(D_s^+ \to \tau^+\nu) = (6.5 \pm 0.8)\%$.
  Using the above results (hep-ex/0702035)

$$f(D_s^+) = 280.1 \pm 11.6 \pm 6.0\ \mathrm{MeV},$$

$$f(D_s^+)/f(D^+) = 1.26 \pm 0.11 \pm 0.03$$

Leptonic of Decays of D Mesons and Decay Constants





To summarize:

	CLEO	Unquenched Lattice
$f(D^+)$	$222.6 \pm 16.7^{+2.8}_{-3.4}$ MeV	$201 \pm 3 \pm 17$ MeV
$f(D_s^+)$	$280.1 \pm 11.6 \pm 6.0$ MeV	$249 \pm 3 \pm 16$ MeV
$f(D_s^+)/f(D^+)$	$1.26 \pm 0.11 \pm 0.03$	$1.24 \pm 0.01 \pm 0.07$

The comparison is presently limited by the statistical error in the CLEO data. These will improve in the near future.

Semi–leptonic Decays of D Mesons and Form Factors

A direct way of determining $|V_{cd}|$ and $|V_{cs}|$ is to measure semileptonic decays of D to the pseudoscalar mesons, π, K, i.e., the branching ratios for $D \to (\pi, K)l\nu$.

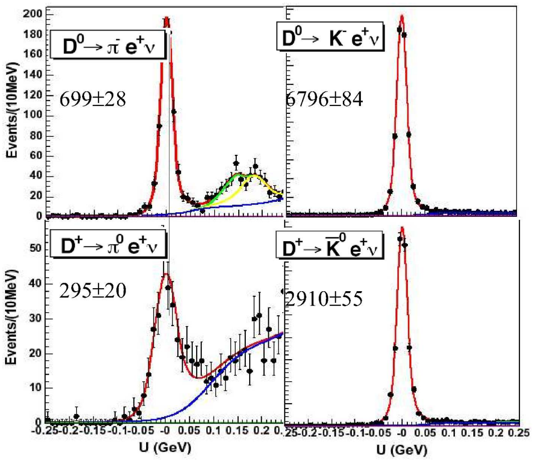
The decay rate as a function of q^2, the squared momentum transfer to the meson is

$$d\Gamma(D \to (\pi, K)l^+\nu)/dq^2 \propto |V_{c(d,s)}|^2 |f^+(q^2)|$$

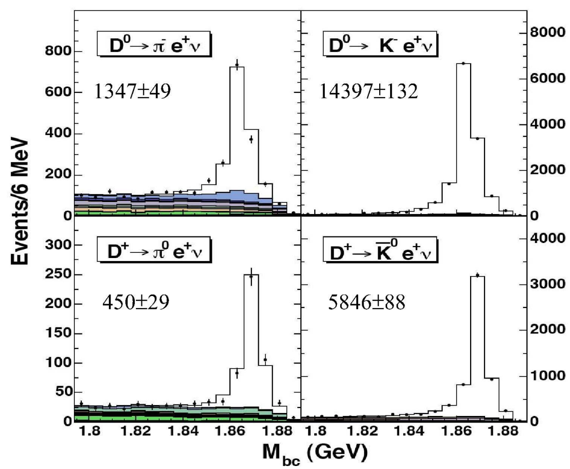
and can therefore be used to determine $|V_{c(d,s)}|^2$.

To determine the D form factors, CLEO has made measurements of $D^0 \to (\pi^-, K^-)e^+\nu$ and $D^+ \to (\pi^0, \overline{K^0})e^+\nu$, shown below. (Note: the events in the tagged and untagged spectra overlap.)

Standard D Tags (Tag)



Neutrino reconstruction (Untagged)



Semi–leptonic Decays of D Mesons and Form Factors

Several different parameterizations of the form factors exist, but they lead to essentially the same results for $f^+(0)$ the form factor at zero momentum transfer. Using the Modified Pole model,

$$f^+(q^2)/f^+(0) = (1 - \frac{q^2}{m^2_{pole}})^{-1}(1 - \frac{\alpha q^2}{m^2_{pole}})^{-1}$$

This quantity is independent of $V_{c(d,s)}$ and can be directly compared to the unquenched lattice calculations. If we use the Unitarity values of V_{cs} and V_{cd}, from the tagged sample we obtain

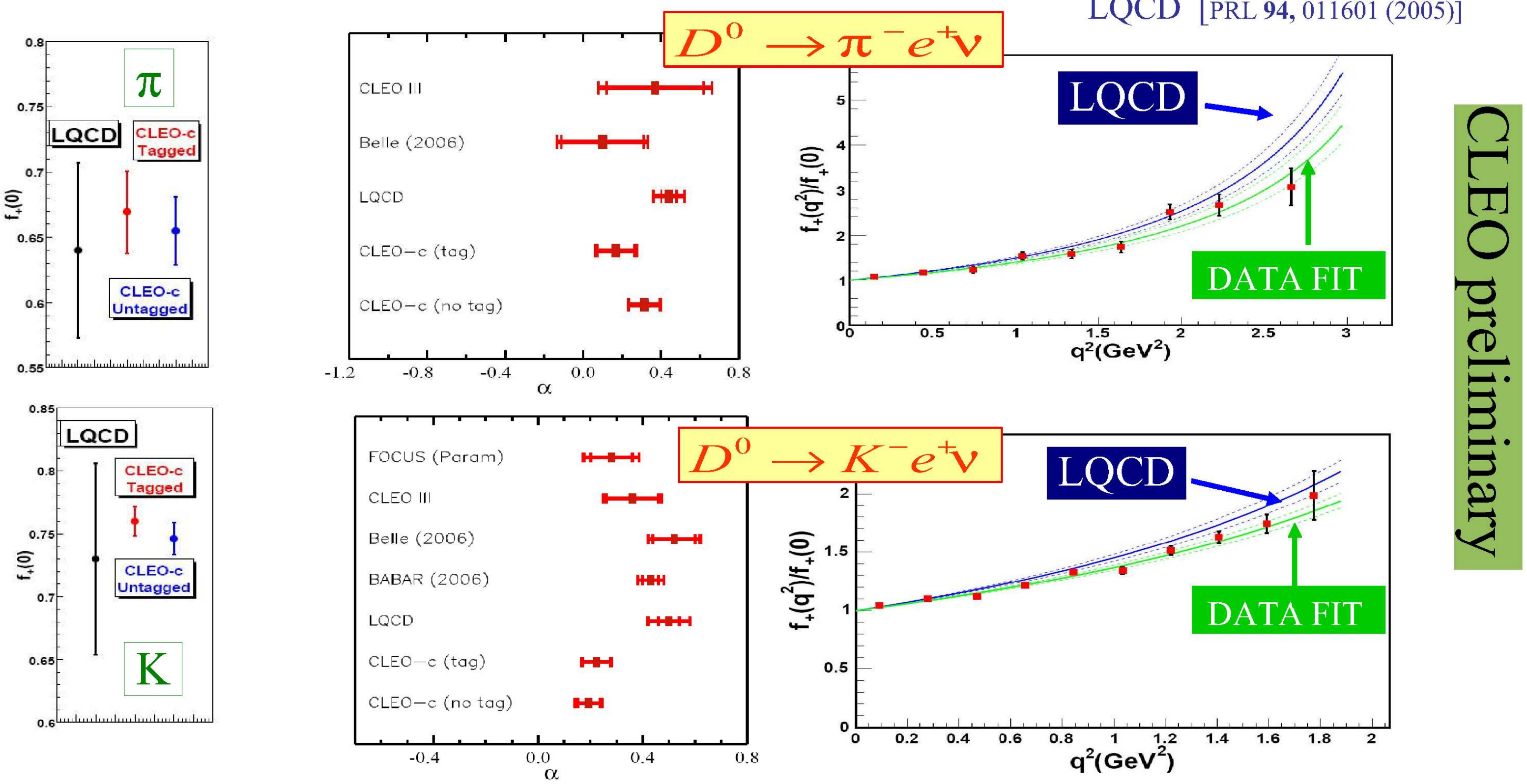
$$f^+_K(0) = 0.761 \pm 10 \pm 7, \qquad \alpha_K = 0.22 \pm 5 \pm 2$$
$$f^+_\pi(0) = 0.660 \pm 28 \pm 11, \qquad \alpha_\pi = 0.17 \pm 10 \pm 5$$

Alternately, by using the $f^+(0)$ values predicted by the unquenched lattice calculations we obtain

$$|V_{cd}| = 0.234(10)(4)(24), \quad |V_{cs}| = 1.014(13)(9)(106) \quad \text{(tagged)}$$
$$|V_{cd}| = 0.229(7)(5)(24), \quad |V_{cs}| = 0.996(8)(15)(104) \quad \text{(untagged)}$$

(The third errors are due to the large uncertainties in lattice predictions for $f^+(0)$.
The tagged and untagged results cannot be avaeraged because they contain common events.)

$f_+(0)$


π
LQCD
CLEO-c Tagged
CLEO-c Untagged
$f_+(0)$
K
CLEO III
Belle (2006)
LQCD
CLEO−c (tag)
CLEO−c (no tag)
α
FOCUS (Param)
BABAR (2006)
$D^0 \rightarrow \pi^- e^+ \nu$
$D^0 \rightarrow K^- e^+ \nu$
LQCD [PRL 94, 011601 (2005)]
DATA FIT
$f_+(q^2)/f_+(0)$
q^2(GeV^2)
CLEO preliminary

To Summarize

- CLEO-c is dedicated to the study of
  - hidden flavor physics of the charmonium region
  - open flavor physics of D–mesons
- In the charmonium region physics
  - CLEO-c has discovered the spin–singlets η_c' and h_c, which lead to new insights into the $q\bar{q}$ hyperfine interaction.
  - With the world's largest sample of ψ', CLEO-c is making a large number of high precision measurements of the decays of charmonium states.
  - In the study of exotics, CLEO-c has confirmed existance of the unexpected vector(?) Y(4260). By making a precision measurement of $M(D^0)$, CLEO-c has provided an important constraint for the $D\overline{D^*}$ molecule model for X(3872).

To Summarize

- CLEO-c has already acquired the largest samples of data at $\psi(3770)$ and $\sqrt{s} = 4170$ MeV, with more to come. These data have been used to make precision measurements of the branching fractions for hadronic, leptonic, and semi–leptonic decays of D and D_s, leading to precision measurements of
  - D and D_s decay constants, and
  - $D \to \pi e^+\nu$, $D \to K e^+\nu$ semi-leptonic form factors
- By comparisons with unquenched LQCD predictions, these measurements are making important contributions to validate LQCD. This in turn lends confidence to the use of LQCD for B–decays, and leads to reliable determinations of CKM matrix elements from their measurements.