Charm Physics at CLEO-c

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CLEO Collaboration

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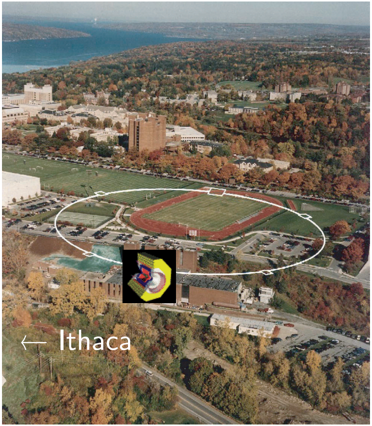
CLEO-c Physics

- CLEO-c probes the **strong force**: how are charm quarks bound in mesons?
  - How do we obtain the "low-energy" degrees of freedom of QCD?
  - Need to understand strong force to extract weak interactions of quarks from observables
- The charm quark is:
  - *heavy*, so the same theory can be used as for bottom quarks;
  - *lighter* than the b, so effects of non-infinite mass are larger.
- CLEO-c probes both *heavy-light* (D^0 $[c\bar{u}]$, D^+ $[c\bar{d}]$, D_s^+ $[c\bar{s}]$) and *heavy-heavy* $[c\bar{c}]$ mesons
- This talk: just a flavor of the broad range of CLEO-c physics!

CESR-c Accelerator

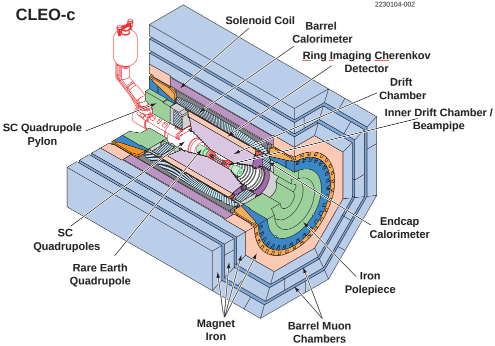


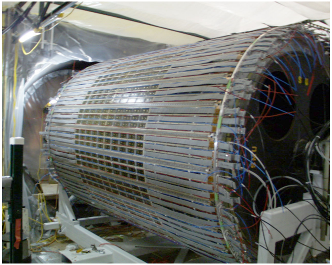
- CESR is a 768 m circumference symmetric e^+e^- storage ring
- Provides collisions for **CLEO** and beams for the **C**ornell **H**igh **E**nergy **S**ynchrotron **S**ource
- Originally designed for $E_{cm} =$ 16 GeV, ran mostly at Υ resonances
- Now provides collisions down to $E_{cm} = 3.7$ GeV

CLEO-c Experiment

- General-purpose symmetric detector
- Particle ID (dE/dx, Ring Imaging Cherenkov) excellent in our momentum region

- Tracking: $\delta p/p = 0.6\%$ at 1 GeV
- CsI calorimeter: $\delta E/E \sim 5\%$ at 100 MeV



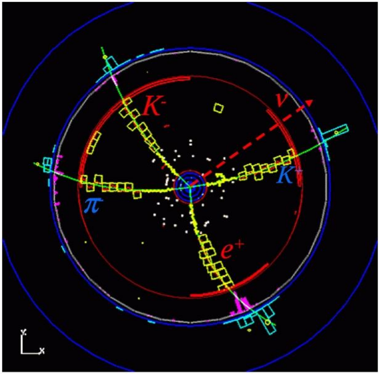


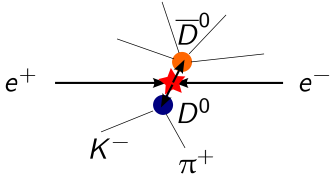
Ring-Imaging Cherenkov detector

Heavy-Light Mesons

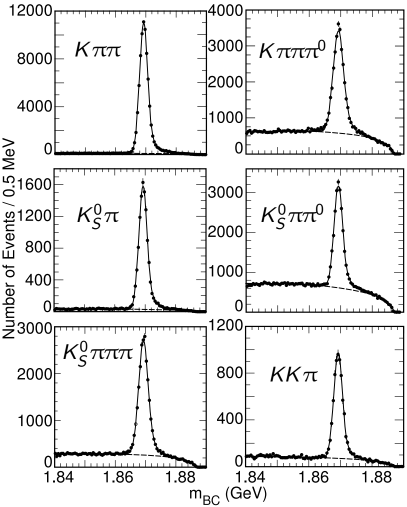
$$e^+e^- \to c\bar{c} \to D^0\bar{D}^0$$

$$\bar{D}^0 \to K^+\pi^-, D^0 \to K^- e^+ \bar{\nu}$$





- Open charm threshold: only $D^0\overline{D}^0$, D^+D^- possible
- Fully reconstruct 10–15% of D decays in clean hadronic "tagging" modes
  - Reduces combinatoric background, constrains recoil momentum
  - Tags provide a D sample of a known size for absolute branching fraction measurements

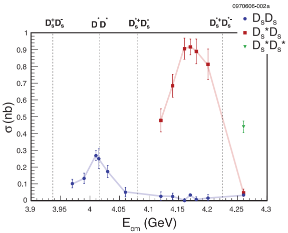


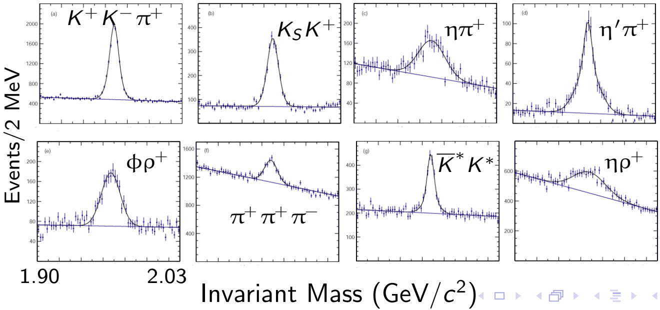
$$m_{BC} \equiv \sqrt{E^2_{beam} - \vec{p}^{\,2}_D}$$

1.6×10^5 D^+ tags in 6 modes, 281 pb^{-1}

- 4.17 GeV data is used for its large sample of $D_s D_s^*$ events
- A $D_s^\pm$ tag implies $D_s^\mp$ on the other side; γ (or π^0) from the $D_s^* \to D_s$ transition is also present
- Tagging efficiency for D_s is $\sim 6\%$; 200 pb^{-1}: $\sim$ 20,000 tags

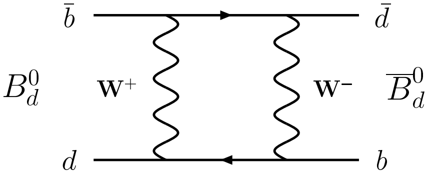
CLEO-c scan Preliminary





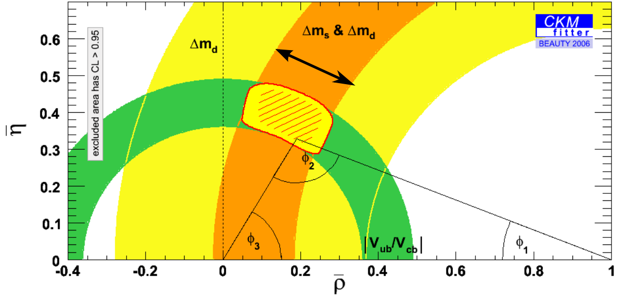
QCD in CKM — B mixing

- $B^0_{d,s}$ mixing proceeds through box diagrams
- Interaction is *short-distance*; quarks need to approach within $\sim 1/m_W$



- $B^0_{d,s}$ mixing proceeds through box diagrams
- Interaction is *short-distance*; quarks need to approach within $\sim 1/m_W$
- Rate depends on wave function near zero separation f_B:

$$\Delta m_{d,s} \propto f^2_{B_{d,s}} |V_{t(d,s)} V^*_{tb}|^2$$



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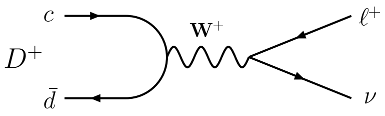
- Analogous quantity appears in D leptonic decays:



$$\Gamma(P \to \ell\nu) = f_P^2 |V_{Qq}|^2 \frac{G_F^2}{8\pi} m_P m_\ell^2 \left(1 - \frac{m_\ell^2}{m_P^2}\right)^2$$

- Tests of $f_{D_{(s)}}$, f_{D_s}/f_D, etc. $\Rightarrow$ more confidence in results for B systems

D Leptonic Decays

- Measure f_D and f_{D_s} using leptonic decays
  - Constrain $|V_{cd}|$ and $|V_{cs}|$ by demanding unitarity
- Measurement modes are
  - $D^+ \to \mu^+\nu$
  - $D_s^+ \to \mu^+\nu$
  - $D_s^+ \to \tau^+\nu$ $(\tau^+ \to \pi^+\nu)$
  - $D_s^+ \to \tau^+\nu$ $(\tau^+ \to e^+\nu\bar{\nu})$.
- Relative branching ratios for $D_{(s)}^+ \to \ell^+\nu$ set by lepton mass

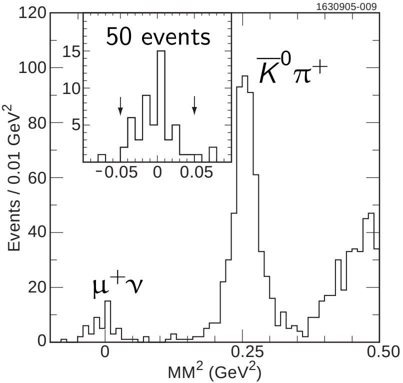
	$\mathcal{B}_e$	$\mathcal{B}_\mu$	$\mathcal{B}_\tau$
D^+	2.4×10^{-5}	1	2.6
D_s^+	2.4×10^{-5}	1	9.7

  - Combine the D_s^+ results for a single f_{D_s}

Quoted form factor lattice QCD results: Aubin et al., PRL **95**, 122002 (2005) [Fermilab-MILC-HPQCD]

$D^+ \to \mu^+\nu$

- Find D^- tag and muon candidate (< 300 MeV in calorimeter, not a kaon candidate)
- Veto extra tracks and extra calorimeter energy
- Compute missing mass $MM^2 = (p^\mu_{CM} - p^\mu_{D^-} - p^\mu_{\mu^+})^2$
- Backgrounds: $D^+ \to \pi^+\pi^0$ and $\tau^+\nu \approx 2$ events



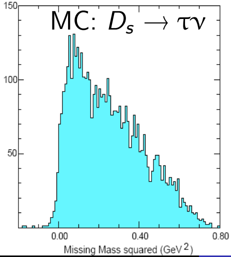
$$\mathcal{B}(D^+ \to \mu^+\nu) = (4.40 \pm 0.66\ ^{+0.09}_{-0.12}) \times 10^{-4}$$
$$f_D = 222.6 \pm 16.7\ ^{+2.8}_{-2.4}\ \text{MeV}$$

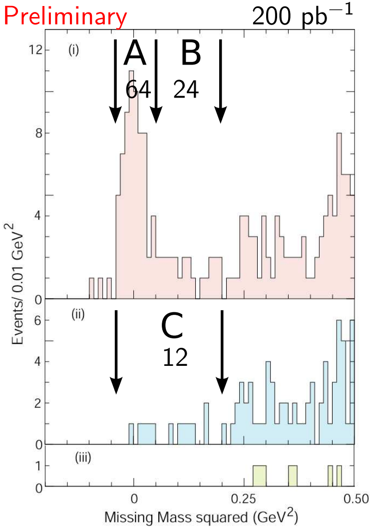
PRL **95** 251801 (2005) (281 pb^{-1})

Lattice: $f_D = 201 \pm 3 \pm 17$ MeV

$D_s^+ \to \mu^+\nu,\ \tau^+\nu\ (\tau^+ \to \pi^+\bar{\nu})$

- Find D_s^- tag, transition photon, and additional track candidate
- Veto extra tracks and extra calorimeter energy
- Three types of event based on track:
  - (i) $E_{cal} < 300$ MeV: μ-like tracks
  - (iii) Pass electron ID: e-like tracks
  - (ii) Other: π-like tracks

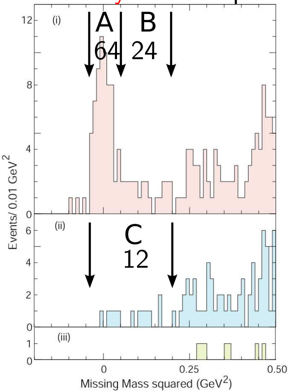




$$MM^2 = (p^\mu_{CM} - p^\mu_{D_s^-} - p^\mu_\gamma - p^\mu_{\mu^+})^2$$

$D_s^+ \to \mu^+\nu,\ \tau^+\nu\ (\tau^+ \to \pi^+\bar{\nu})$

- $\mathcal{B}(\mu^+\nu)$ from A, correct for feedthrough from $\tau^+\nu$
- $\mathcal{B}(\tau^+\nu)$ from B and C
  - 6.8 bkg events in $A + B + C$
- No evidence of $e\nu$



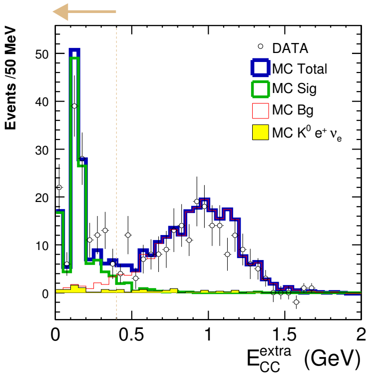
Preliminary

$$\mathcal{B}(D_s^+ \to \mu^+\nu) = (6.57 \pm 0.90 \pm 0.28) \times 10^{-3}$$
$$\mathcal{B}(D_s^+ \to \tau^+\nu) = (7.1 \pm 1.4 \pm 0.3)\%$$
$$f_{D_s} = 282 \pm 16 \pm 7 \text{ MeV}$$
$$\mathcal{B}(D_s^+ \to e^+\nu) < 3.1 \times 10^{-4}$$

Lattice: $f_{D_s} = 249 \pm 3 \pm 16$ MeV

$D_s^+ \to \tau^+\nu$ ($\tau^+ \to e^+\nu\bar{\nu}$)

- Find hadronic D_s tag and electron candidate
- Veto extra tracks
- Signal candidates have extra calorimeter energy < 400 MeV
- Major backgrounds are semileptonic decays (e.g. Cabibbo-suppressed $D_s^+ \to K_L^0 e^+\nu$)



Preliminary

$$\mathcal{B}(D_s^+ \to \tau^+\nu) = (6.29 \pm 0.78 \pm 0.52)\%$$

[$\tau \to \pi\nu$ result: $(7.1 \pm 1.4 \pm 0.3)\%$]

$$f_{D_s} = 278 \pm 17 \pm 12 \text{ MeV}$$

Lattice: $f_{D_s} = 249 \pm 3 \pm 16$ MeV

$D_s^+ \to \mu^+\nu$ and two $D_s^+ \to \tau^+\nu$ measurements statistically independent: combine

Average:

$f_{D_s} = 280.1 \pm 11.6 \pm 6.0$ MeV*

Lattice: $f_{D_s} = 249 \pm 3 \pm 16$ MeV

Recall

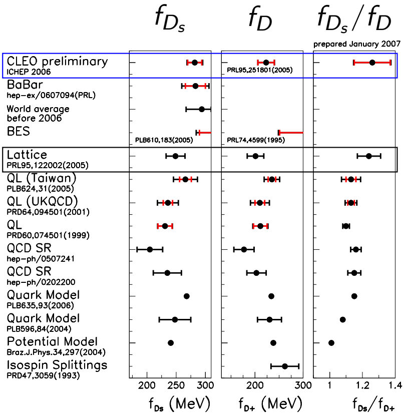
$f_D = 222.6 \pm 16.7^{+2.3}_{-3.4}$ MeV

Lattice: $f_D = 201 \pm 3 \pm 17$ MeV

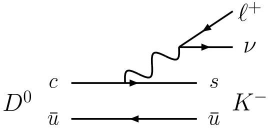
So

$f_{D_s}/f_D = 1.26 \pm 0.11 \pm 0.03$*

Lattice: $1.24 \pm 0.01 \pm 0.07$

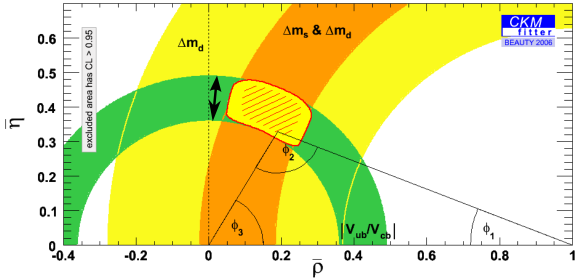


* Preliminary



$$\frac{d\Gamma(P \to P'\ell\nu)}{dq^2} = f_+(q^2)^2|V_{Qq}|^2 \frac{G_F^2}{24\pi^3} p_{P'}^3$$

- Rate depends on a form factor $f_+(q^2 = (p_{W^\pm}^\mu)^2)$ times a CKM matrix element $|V_{Qq}|$.
- Γ from experiment and $f_+(q^2)$ from theory $\Rightarrow |V_{Qq}|$
  - Need precision $f_+(q^2)$!

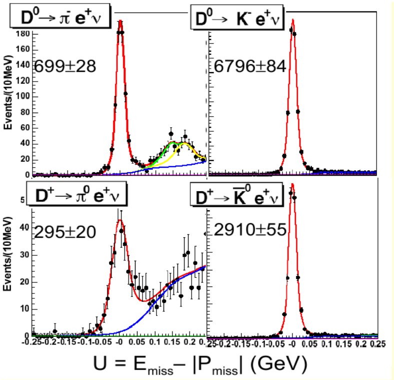


Exclusive D Semileptonic Decays

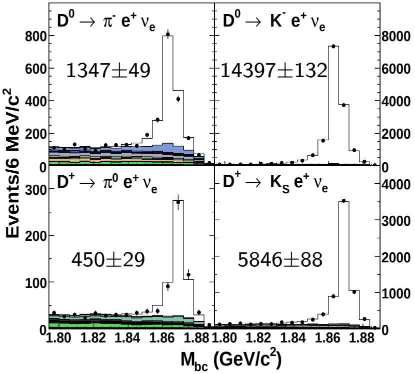
- Only electrons used ($\pi \to \mu$ fake rate too high)
- Results for:
  - $D^0 \to K^- e^+ \nu$
  - $D^+ \to \overline{K}^0 e^+ \nu$
  - $D^0 \to \pi^- e^+ \nu$
  - $D^+ \to \pi^0 e^+ \nu$
- Two methods:
  - Reconstruct hadronic $\overline{D}$ tag + hadron + lepton, see if missing four-momentum is consistent with neutrino ("tagged analysis")
  - Use detector hermeticity to reconstruct neutrino four-momentum with no tag, then combine with hadron and lepton to make a D candidate ("ν reconstruction")
- Tagged analysis has better systematics
- ν reconstruction has better statistics

281 pb^{-1} Preliminary

Tagged

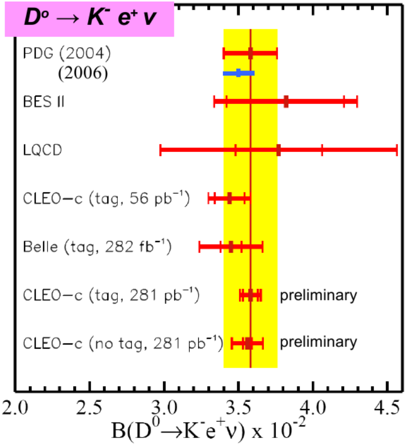


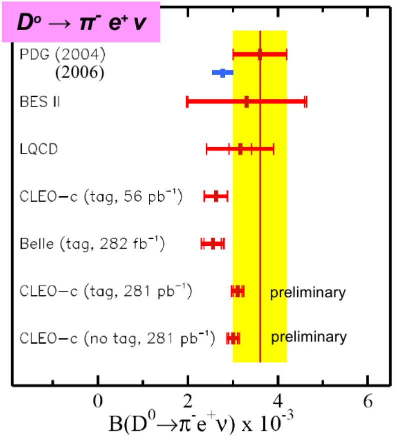
ν reconstruction



Results not statistically independent!

D Semileptonics: Absolute Branching Fractions





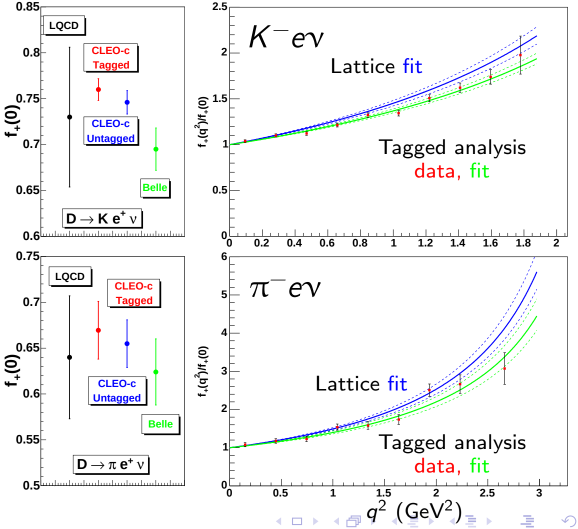
PDG 2006 fits include CLEO-c 56 pb^{-1} results

Fits shown are to Modified Pole Model: $f_+(q^2) = \frac{f_+(0)}{(1-q^2/m_{pole}^2)(1-\alpha q^2/m_{pole}^2)}$

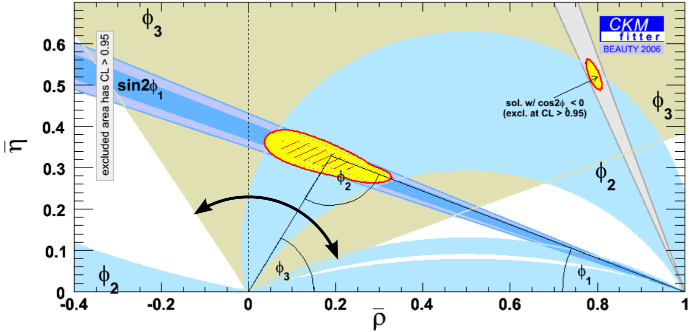
Lattice:
PRL **94**, 011601 (2005)

Belle:
PRL **97**, 061804 (2006)

CLEO-c:
281 pb^{-1} Preliminary

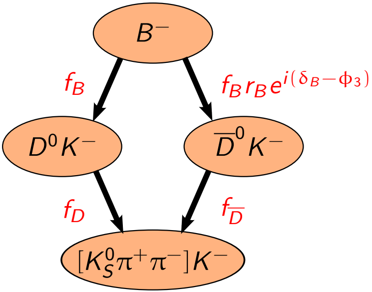


QCD in CKM — ϕ_3/γ Extraction



QCD in CKM — ϕ_3/γ Extraction

- Interference between $b \to c(\bar{u}s)$ and $b \to u(\bar{c}s)$ involves ϕ_3/γ
- "Dalitz Method" uses $D \to K_S \pi^+\pi^-$
  (Giri *et. al.* PRD **68**, 054018 (2003))
- Need to know interference between D^0 and $\overline{D}^0$ amplitudes for same final state
  - Phase δ_D comes from intermediate resonances: nonpeturbative QCD!
  - δ_D depends on daughter momenta (Dalitz variables)



- r_B, δ_B from B-factories. How to get δ_D?
  - At B-factories, mesons tagged as definitely D^0 or $\overline{D}^0$ ("flavor tag"); phase information lost, δ_D from Dalitz plot modeling
  - At CLEO-c, can interfere D^0 and $\overline{D}^0$ $\Rightarrow$ δ_D directly from data

CP Tagging at CLEO-c

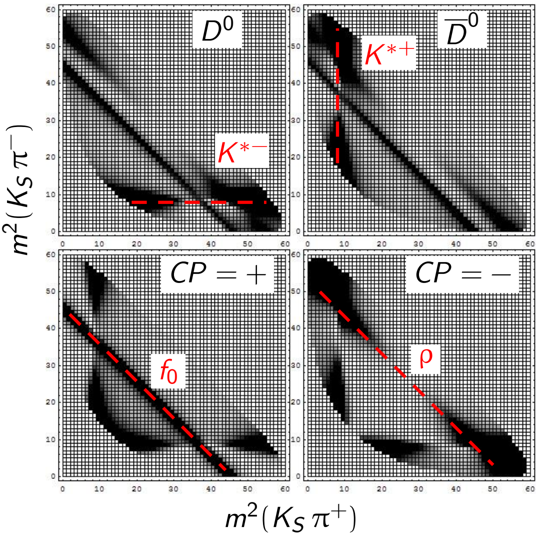
- The $\psi(3770)$ has $CP = +$; daughter D^0 mesons have opposite CP to each other (P-wave decay)
- Tag modes like $D^0 \to K_S\,\pi^0$ $(CP = -)$ or $\pi^+\pi^-$ $(CP = +)$ fix CP content of the other side decay:

$$D^0_{CP=\pm} = \frac{D^0 \mp \overline{D}^0}{\sqrt{2}}$$

- Tag modes like $K^-\pi^+$ determine if the other side is D^0 or $\overline{D}^0$

Decay:	D^0	$\overline{D}^0$	$CP = +$	$CP = -$
Measures	$\lvert f_D\rvert^2$	$\lvert f_{\overline{D}}\rvert^2$	$\frac{1}{2}(\lvert f_D\rvert^2 + \lvert f_{\overline{D}}\rvert^2)$ $-\lvert f_D\rvert\lvert f_{\overline{D}}\rvert \cos\delta_D$	$\frac{1}{2}(\lvert f_D\rvert^2 + \lvert f_{\overline{D}}\rvert^2)$ $+\lvert f_D\rvert\lvert f_{\overline{D}}\rvert \cos\delta_D$

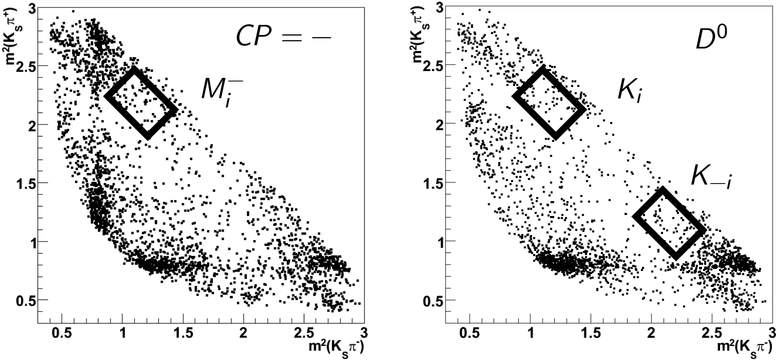
$D^0 \to K_S \pi^+ \pi^-$ Dalitz Plot (MC)



Dalitz plots for toy MC with $K^*\pi$, $K_S\,\rho$, $K_S\,f_0$ components

Clear difference in flavor-tagged (top) and *CP*-tagged (bottom) plots

$D^0 \to K_S \pi^+\pi^-$ Dalitz Plot (MC)



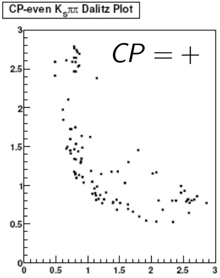
Can compute (average) strong phase difference in each bin i:

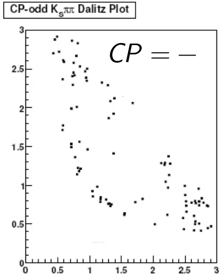
$$\langle \cos \delta \rangle_i = \frac{1}{2} \times \frac{M_i^- - M_i^+}{M_i^- + M_i^+} \times \frac{K_i + K_{-i}}{\sqrt{K_i K_{-i}}}$$

from various efficiency-corrected yields.

$D^0 \to K_S \pi^+ \pi^-$ Dalitz Plot: Prospects

- Statistics-limited: need as many *CP* tags as possible
  - Can use K_L^0 as well as K_S^0 (reconstruct using missing mass)
- δ_D uncertainty in ϕ_3/γ:
  $\sim 10^\circ$ (current) $\Rightarrow$ $\sim 4^\circ$ (CLEO-c 750 pb^{-1})



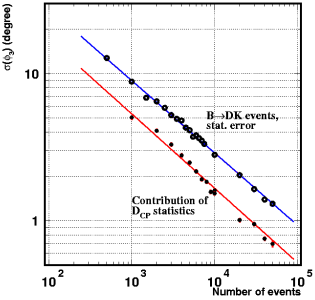


281 pb^{-1} Preliminary

ϕ_3/γ status:

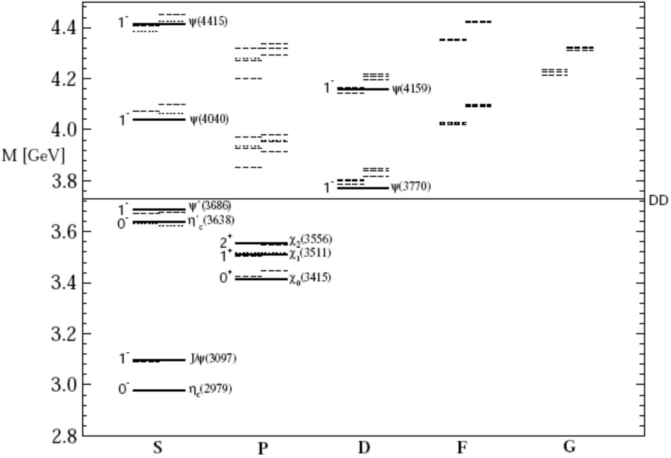
Belle: $(53\ ^{+15}_{-18} \pm 3 \pm 9)^\circ$
PRD **73** 112009 (2006)

BaBar: $(92 \pm 41 \pm 11 \pm 12)^\circ$
ICHEP 06, hep-ex/0607104



Bondar and Poluektov, EPJ C**47** 347 (2006)

Heavy-Heavy Mesons



PRD **72** (2005) 054026

QCD in Charmonia

- Charm quarks have $m_c \gg \Lambda_{QCD}$ so $c\bar{c}$ states act analogously to positronium, etc.
- Can *predict* properties of charmonium states using models for the forms of the interquark interactions, e.g.

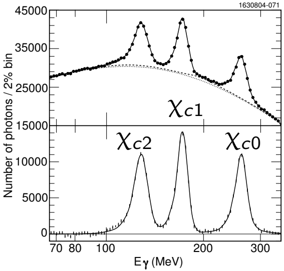
$$V_0 = -\frac{4}{3}\frac{\alpha_s}{r} + br + \frac{32\pi\alpha_s}{9m_c^2}\delta^3(\mathbf{r})\mathbf{S}_c\cdot\mathbf{S}_{\bar{c}} + \frac{1}{m_c^2}\left[\left(\frac{2\alpha_s}{r^3} - \frac{b}{2r}\right)\mathbf{L}\cdot\mathbf{S} + \frac{4\alpha_s}{r^3}T\right] + \ldots$$

(Barnes, Godfrey, Swanson NR potential, PRD **72** (2005) 054026)

- (Electromagnetic) radiative transitions probe wave function overlap between different states
- *Hadronic* transitions (e.g. $\psi(2S) \to \pi^+\pi^- J/\psi(1S)$) still far from fully understood!

The decays $\psi(2S) \to \gamma\chi_{cJ}(1P)$ can be reconstructed by fitting the inclusive photon spectrum in $\psi(2S)$ decays

3 million $\psi(2S)$



(PRD **70** (2004) 112002)

- In naive non-relativistic limit, $\Gamma \propto (2J+1)E_\gamma^3$ (radial wavefunctions the same for the χ_{cJ})

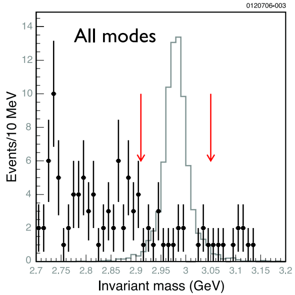
	$\mathcal{B}/E_\gamma^3$		
	χ_{c0}	χ_{c1}	χ_{c2}
Non-relativistic	1	3	5
Godfrey-Isgur (rel)†	1	3.9	7.9
Data	1	3.5 ± 0.2	8.7 ± 0.7

Better agreement with "relativized" prediction
(†Barnes, Godfrey, Swanson PRD **72** (2005) 054026)

Hadronic Decays: $\psi(2S) \to \eta_c 3\pi$

- $\psi(2S)$ and J/ψ have different patters of decays to light hadrons ("$\rho\pi$ puzzle")
- Assume same decay mechanism for $\psi(2S)$ and J/ψ. Is that right?
  - Model: $\psi(2S) \not\to ggg$; instead the $c\bar{c}$ pair survives soft gluon emission (Artoisenet *et al.*, PL B**628**, 211 (2005))
  - Estimate $\mathcal{B}(\psi(2S) \to \eta_c \pi^+\pi^-\pi^0) \sim \mathcal{O}(1\%)$ ($> \mathcal{B}(\psi(2S) \to \gamma\eta_c)$!)
- Use 6 exclusive η_c decays
- 90% upper limit: $\mathcal{B} < 1.0 \times 10^{-3}$

3 million $\psi(2S)$



Histogram: MC expectation if $\mathcal{B}(\psi(2S) \to \eta_c 3\pi) = 1\%$

hep-ex/0611027, submitted to PRD RC

Summary

- The CLEO-c program provides precision measurements that probe meson structure
- Tests of theory promise to improve theory uncertainties for CKM element extraction
  - Experiment ahead of theory at this point
- Expected final dataset $\sim$ 2–3 times what has been presented

Stay tuned!

The End