Heavy Flavor at CLEO-c

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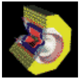
La Thuile, 4 March 2009



CLEO-c Scope

CLEO-c's extensive program in charm and light flavor physics:

- Leptonic and semileptonic decays for CKM magnitudes
- Strong phase measurements for CKM angles and *D* mixing
- Precise normalization branching fraction measurements
- *D* hadronic decay dynamics
- Charmonia and light hadrons
- Rare decay + new physics searches

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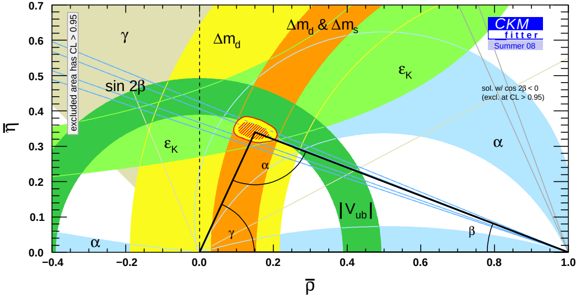
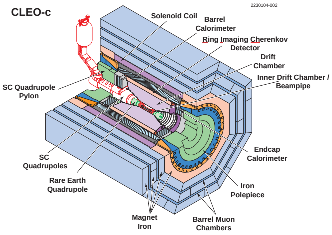
Only have time for first two topics — can't do justice to full range of work...

Unitarity Triangle Constraints

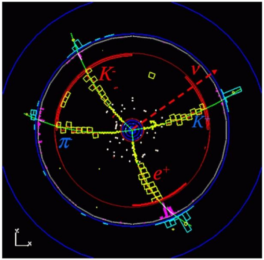


- Overconstrain unitarity triangle to validate Standard Model/find new physics in *CP* violation
- Weak physics must be extracted from strongly-interacting objects
- Theoretical understanding of nonperturbative QCD can limit precision
- CLEO-c aims to validate theoretical tools in the charm system



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

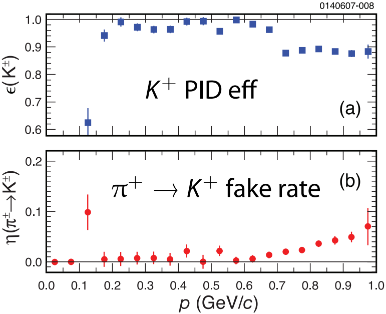
$\overline{D}^0 \to K^+\pi^-,\ D^0 \to K^- e^+\overline{\nu}$



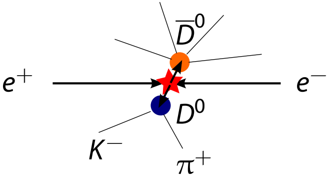
CLEO-c physics run ended in March 2008

- 818 pb^{-1} at $\psi(3770)$ (for D^0, D^+)
- 600 pb^{-1} near $E_{cm} = 4.17$ GeV (for D_s^+)
- 26 million $\psi(2S)$
- + small runs for $Y(4260)$, charm component of R, continuum, etc.

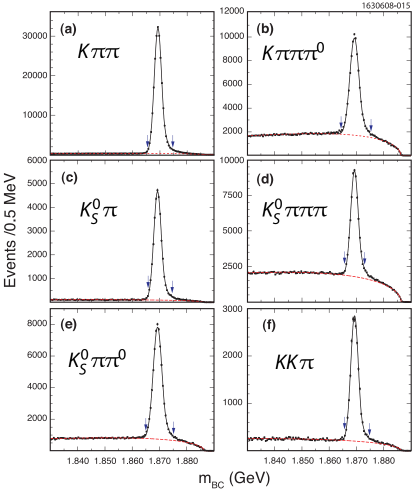
Great tracking, calorimetry, particle ID



Reconstruction — 3.77 GeV



- Open charm threshold: only $D^0\overline{D}^0$, D^+D^- possible
- Fully reconstruct 10–15% of D decays in clean hadronic "tagging" modes



$$m_{BC} \equiv \sqrt{E_{beam}^2 - \vec{p}_D^2}$$

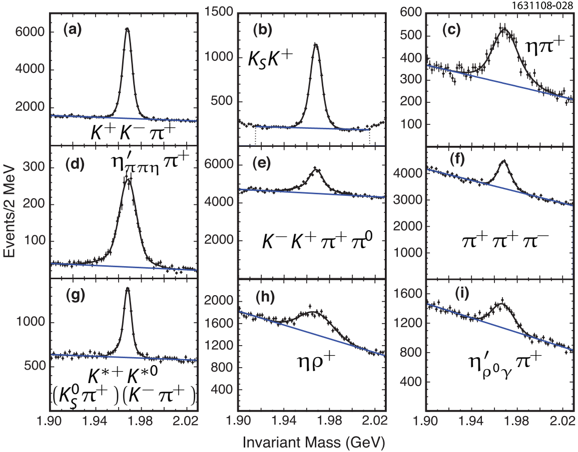
4.6×10^5 D^+ tags in 6 modes, 818 pb^{-1}

Reconstruction — 4.17 GeV

4.17 GeV data is used for its large sample of $D_s D_s^*$ events

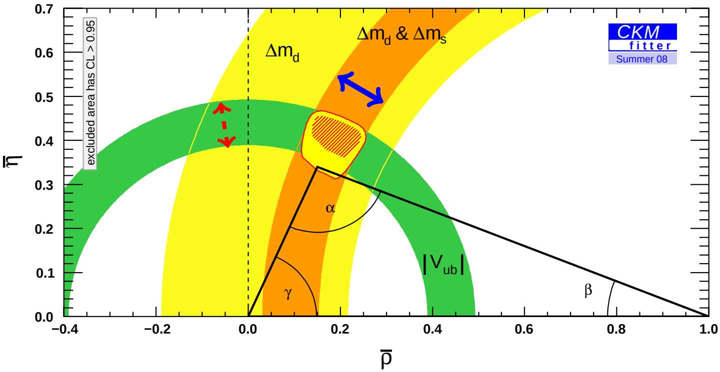
A $D_s^\pm$ tag implies $D_s^\mp$ on the other side; γ (or π^0) from the $D_s^* \to D_s$ transition is also present

Tagging efficiency for D_s is $\sim 6\%$



70.5k tags in 9 modes, 600 pb^{-1}

Decay Constant Measurements



QCD in CKM — *B* mixing

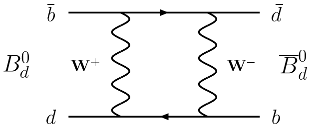
- $B^0_{d,s}$ mixing proceeds through box diagrams (short distance interactions)
- Rate depends on wave function near zero separation f_B:

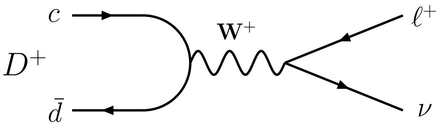
$$\Delta m_{d,s} \propto f^2_{B_{d,s}} |V_{t(d,s)} V^*_{tb}|^2$$

- Analogous quantity appears in *D* leptonic decays:

$$\Gamma(D_{(s)} \to \ell\nu) = f^2_{D_{(s)}} |V_{cq}|^2 \frac{G_F^2}{8\pi} m_{D_{(s)}} m_\ell^2 \left(1 - \frac{m_\ell^2}{m^2_{D_{(s)}}}\right)^2$$

- Precision test of lattice predictions of $f_{D_{(s)}}$, $f_{D_s}/f_D \Rightarrow$ more confidence in predictions for *B* systems





(Also affects $B^+ \to \tau\nu$...)

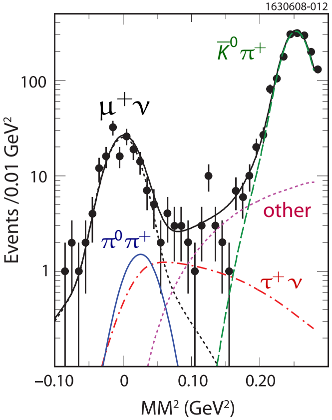
D Leptonic Decays

- Measure f_D and f_{D_s} using leptonic decays
  - Constrain $|V_{cd}|$ and $|V_{cs}|$ with CKM unitarity
- $D_s^+ \to \ell\nu$ not Cabibbo-suppressed so $\mathcal{B}$ much larger
- 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
  - Competing effects of helicity suppression and phase space
- Combine the D_s^+ results for a single f_{D_s}

Quoted lattice QCD results: PRL **100**, 062002 (2008) [HPQCD-UKQCD]

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

- Find D^- tag and muon candidate ($<$ 300 MeV in calorimeter, not a kaon candidate)
- Veto extra tracks and extra calorimeter energy
- Compute missing mass from four-vectors $MM^2 = (p_{CM} - p_{D^-} - p_{\mu^+})^2$ and fit distribution



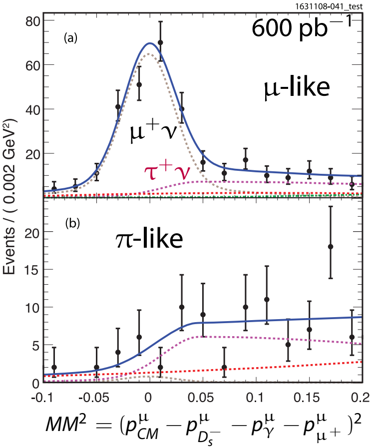
$$f_{D^+} = (205.8 \pm 8.5 \pm 2.5)\ \text{MeV}$$

PRD **78** 052003 (2008) (818 pb^{-1})

Lattice: $f_{D^+} = 207 \pm 4$ 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
- Two types of event:
  - (i) $E_{cal} < 300$ MeV: μ-like tracks
  - (ii) $E_{cal} > 300$ MeV, fail electron ID: π-like tracks

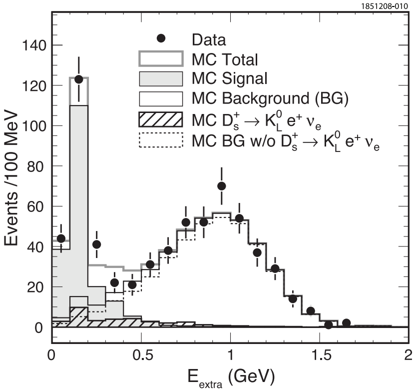


$$\mathcal{B}(D_s^+ \to \mu^+\nu) = (5.65 \pm 0.45 \pm 0.17) \times 10^{-3}$$
$$\mathcal{B}(D_s^+ \to \tau^+\nu) = (6.42 \pm 0.81 \pm 0.18)\%$$

arxiv:0901.1216, accepted by PRD

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

- Find hadronic D_s tag and electron candidate
- Veto extra tracks
- Signal candidates have extra calorimeter energy < 400 MeV
  - Peaks above zero due to $D_s^* \to \gamma D_s$ photon
- Dominant systematic uncertainty is $\mathcal{B}(D_s^+ \to K_L^0 e^+\nu)$



$$\mathcal{B}(D_s^+ \to \tau^+\nu) = (5.30 \pm 0.47 \pm 0.22)\%$$

arxiv:0901.1147, accepted by PRD

[$\tau \to \pi\nu$ result: $(6.42 \pm 0.81 \pm 0.18)\%$]

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

Average:

$$f_{D_s} = 259.5 \pm 6.6 \pm 3.1 \text{ MeV}$$
Lattice: 241 ± 3 MeV

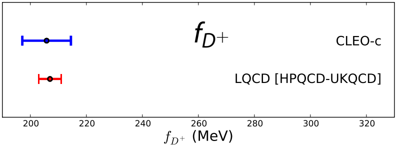
Recall

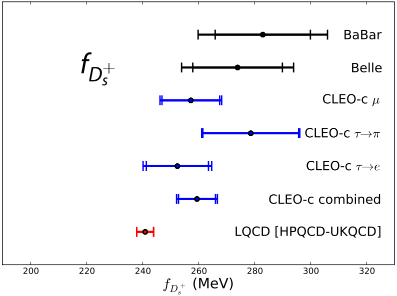
$$f_D = 205.8 \pm 8.5 \pm 2.5 \text{ MeV}$$
Lattice: $201 \pm 3 \pm 17$ MeV

So

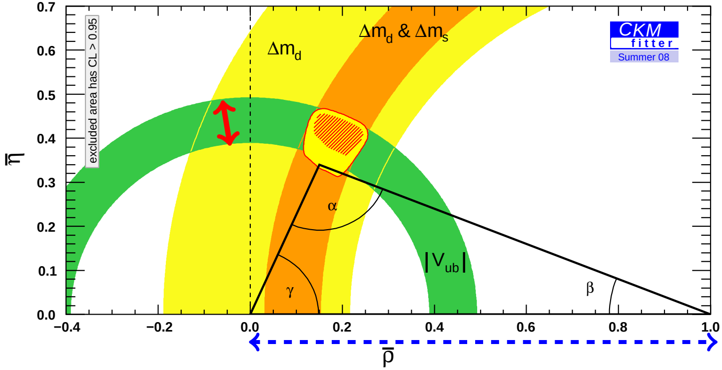
$$f_{D_s}/f_D = 1.26 \pm 0.06 \pm 0.02$$
Lattice: 1.162 ± 0.009

arxiv:0901.1216

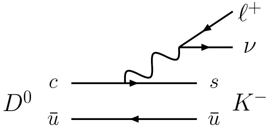




Semileptonic Form Factor Measurements



QCD in CKM — Semileptonic Decays



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

- Rate depends on a form factor $f_+(q^2 = m^2_{\ell\nu})$ times a CKM matrix element $|V_{Qq}|$.
- Γ from experiment and $f_+(q^2)$ from theory $\Rightarrow |V_{Qq}|$
  - CLEO-c: test lattice $f_+(q^2)$, or extract $|V_{cs}|$, $|V_{cd}|$

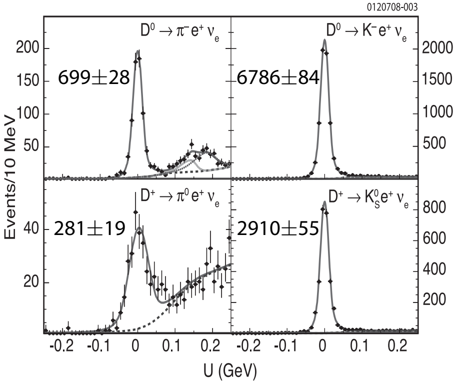
Exclusive D Semileptonic Decays

- 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
- Following results use 281 pb^{-1}

D Semileptonics: Reconstruction

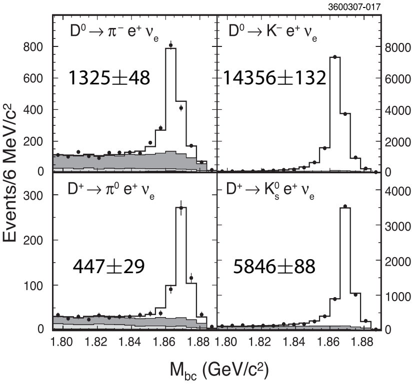
Tagged

(arXiv:0810.3878, accepted by PRD)



ν reconstruction

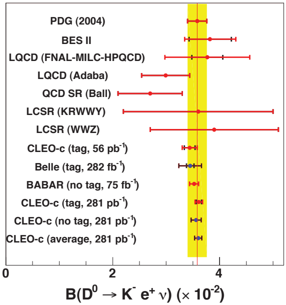
(PRL 100, 251802 (2008))

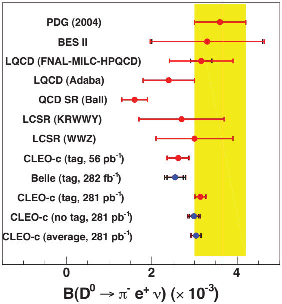


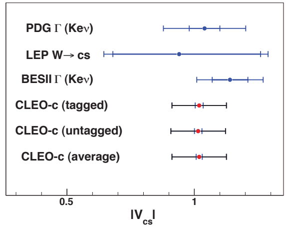
Not statistically independent!

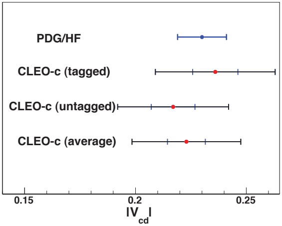
Results combined with proper correlations in arXiv:0810.3878

D Semileptonics: Absolute $\mathcal{B}$s, CKM Magnitudes









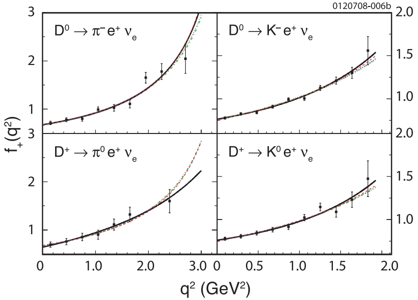
D Semileptonics: Form Factors

Simple pole: $f_+(q^2) = \dfrac{f_+(0)}{1 - \frac{q^2}{M^2_{pole}}}$

Modified pole: $f_+(q^2) = \dfrac{f_+(0)}{\left(1 - \frac{q^2}{M^2_{pole}}\right)\left(1 - \alpha \frac{q^2}{M^2_{pole}}\right)}$

Series expansion (PLB **633**, 61 (2006)):

$$f_+(q^2) = \frac{a_0}{P(q^2)\phi(q^2, t_0)} \left(1 + \sum_{k=1}^{\infty} a_k(t_0) z(q^2, t^0)^k\right)$$

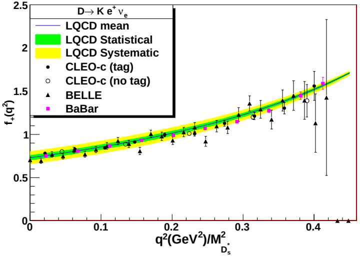


All shapes fit data if parameters allowed to float

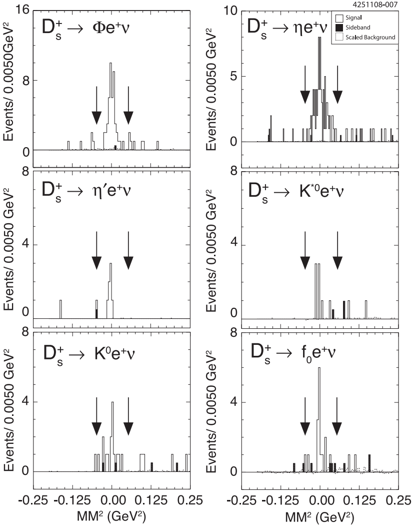
“Physical” pole masses highly disfavored

(LQCD: FNAL-MILC-HPQCD

PRL **94** 011601 (2005))



D_s^+ Semileptonic Decays



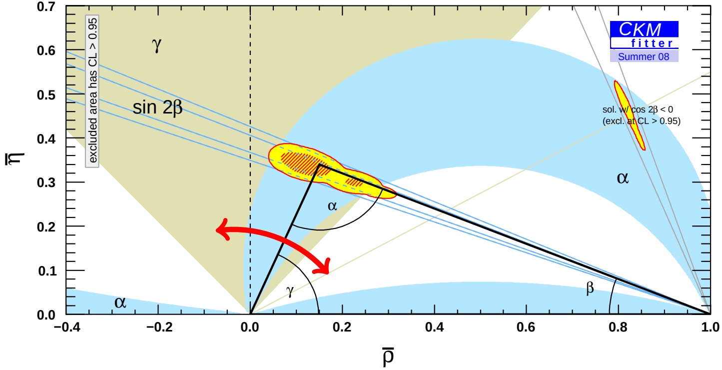
310 pb^{-1} Preliminary

$D_s^+ \to Xe^+\nu$:

X	$\mathcal{B}(\%)$
ϕ	$2.29 \pm 0.37 \pm 0.11$
η	$2.48 \pm 0.29 \pm 0.13$
η'	$0.91 \pm 0.33 \pm 0.05$
K^0	$0.37 \pm 0.10 \pm 0.02$
K^{*0}	$0.18 \pm 0.07 \pm 0.01$
$f_0 \to \pi^+\pi^-$	$0.13 \pm 0.04 \pm 0.01$

- Absolute branching fractions
- First observation of Cabibbo-suppressed and $f_0(980)$ modes
- Gives information on $\eta/\eta'/$glueball mixing angles

D^0 Decay Strong Phases for γ



CKMFitter, Summer 2008

Direct measurements

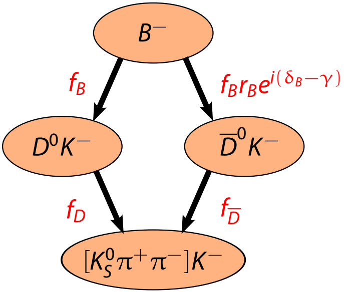
α	$88.2^{+6.1}_{-4.8}$
β	$21.11^{+0.94}_{-0.92}$
γ	70^{+27}_{-29}

γ/ϕ_3 is the poorest directly measured angle of the unitarity triangle

Tree measurements of γ complement loop measurements of $|V_{td}|$

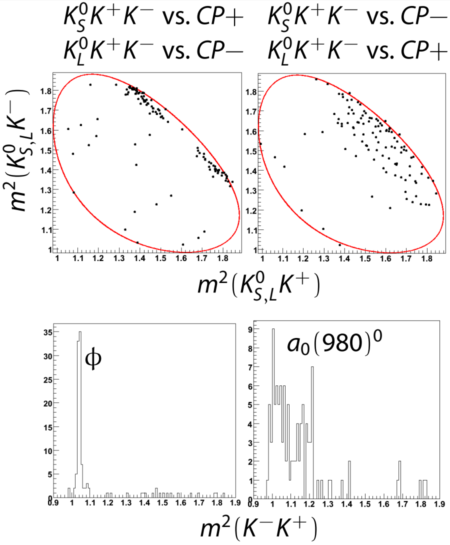
QCD in CKM — γ Extraction

- Can obtain γ from interference between $b \to c(\bar{u}s)$ and $b \to u(\bar{c}s)$
- Use final states common to D^0 and $\overline{D}^0$
- Must know relative phase of D^0 and $\overline{D}^0$ amplitudes to same final state
  - This strong phase δ_D comes from intermediate resonances
  - δ_D depends on daughter momenta (hence resonant structure)



- r_B, δ_B from B-factories, δ_D from CLEO-c
  - Charm threshold gives unique access to CP-coherent $D^0\overline{D}^0$ pairs, giving δ_D from from data
  - Elsewhere, mesons tagged as definitely D^0 or $\overline{D}^0$ (“flavor tag”); phase information lost, δ_D only from Dalitz plot modeling

CP Correlation Studies



818 pb^{-1} Preliminary

Studying:

- δ_D for $D^0 \to K^-\pi^+$ (PRL **100** 221801 (2008))
- Dalitz plot-dependent phases for $D^0 \to K^0_{S,L}\pi^+\pi^-$ and $K^0_{S,L}K^+K^-$ (arxiv:0810.3666)
- Coherence factor and average strong phase for $D^0 \to K^-\pi^+\pi^0$ and $K^-\pi^+\pi^+\pi^-$ (arXiv:0805.1722)

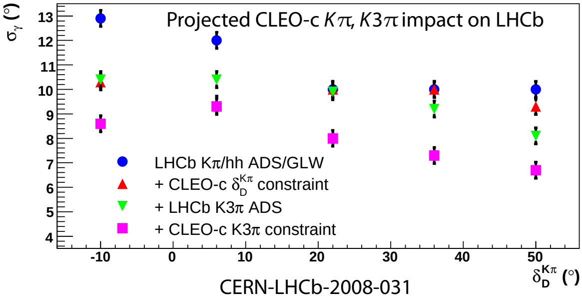
Statistically limited by *CP* tag yields

$K^0_{S,L}\pi^+\pi^-$ only:

BaBar: $(63^{+30}_{-28} \pm 8 \pm 7)^\circ$
(PRD **78** 034023 (2008))

Belle: $(76^{+12}_{-13} \pm 4 \pm 9)^\circ$
(arxiv:0803.3375)

model uncertainty $\Rightarrow \approx 2^\circ$ CLEO-c statistical uncertainty (Preliminary)



CERN-LHCb-2008-031

Summary and Outlook

- CLEO-c has had a significant impact across a broad range of topics, only a few of which are covered here
  - CKM measurements are a key focus area
- D^+ and D_s^+ leptonic decays test lattice predictions
  - Results shown here use full CLEO-c dataset
- D^0 and D^+ semileptonic decays test the lattice, probe $|V_{cs}|$ and $|V_{cd}|$
  - Update to full CLEO-c dataset ($3\times$ data shown here) nearing completion
- D_s^+ semileptonic decays are a new frontier
- Strong phase measurements in various D decays have a large impact on the systematic uncertainty in γ
  - Technique unique to charm threshold
  - Multiple modes being studied
  - Great symbiosis with LHCb and B-factory programs

The End

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 $D^0 \to K_S^0\pi^0$ ($CP = -$) or $\pi^+\pi^-$ ($CP = +$) fix CP content of the other side decay:

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

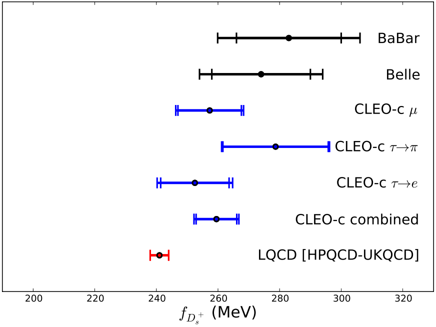
- Tag modes like $K^-\pi^+$ determine if the other side is D^0 or $\overline{D}^0$

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

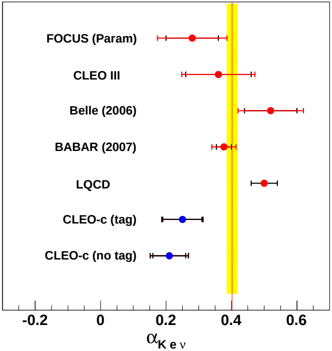
- For 2-body decays (e.g. $K^-\pi^+$) there's only one δ_D, otherwise it varies over the Dalitz plot
- Can also measure a weighted average phase whose effect is diluted by a "coherence factor" R

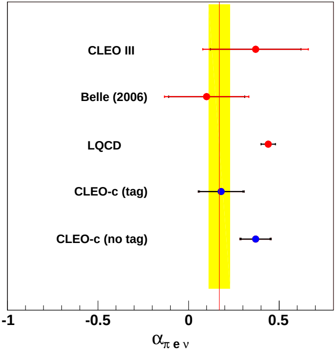
A Note On $f_{D_s^+}$

- CLEO-c discrepancy from HPQCD-UKQCD prediction is 2.3σ
  - rises to 2.6σ when combined with Belle measurement
- Not particularly significant
- From new physics perspective: theoretically unpleasant to modify $f_{D_s^+}$ but not f_{D^+}
- We leave it to our colleagues on BES-III to constrain $f_{D_s^+}$ more tightly...



Modified Pole Fits





Modified Pole Fits