

Recent Results from CLEO-c

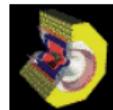
Peter Onyisi

*Enrico Fermi Institute, University of Chicago
CLEO Collaboration*

Moriond Electroweak, 8 March 2010



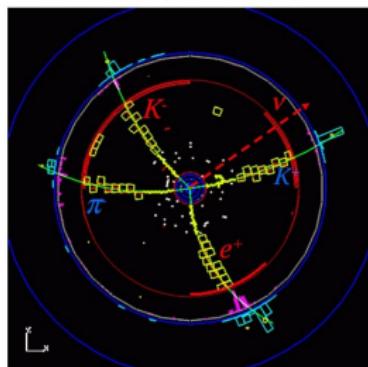
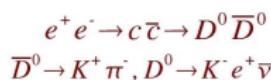
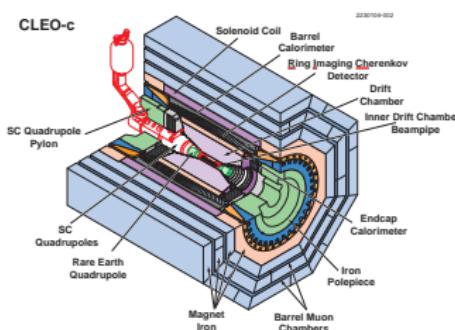
THE UNIVERSITY OF
CHICAGO



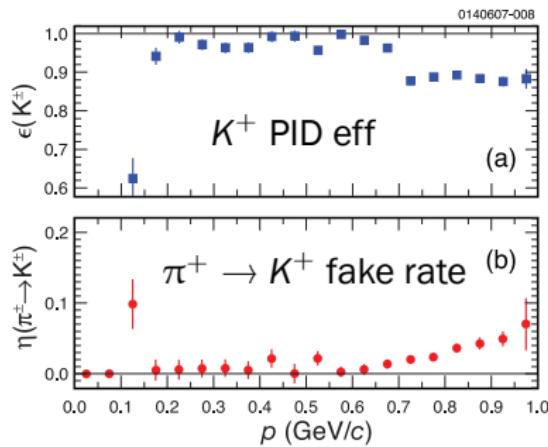
Hadronic Impact on EW Physics

- Most CKM information comes from meson decays and properties. Non-perturbative QCD is unavoidable.
- Leptonic/semileptonic decays and mixing requires knowing hadronic currents
 - $\langle 0 | \bar{q} \gamma_\mu \gamma_5 c | D \rangle$ for leptonic decays
 - $\langle X | \bar{q} \gamma_\mu (1 - \gamma_5) c | D \rangle$ for semileptonic decays
- Hadronic physics can introduce extra phases on top of weak angles we are trying to measure
- These topics are addressed by CLEO-c
 - Validate theoretical understanding of QCD in the hadronic regime, in particular heavy-light mesons
 - Exploit coherence of mesons produced at threshold to measure phases

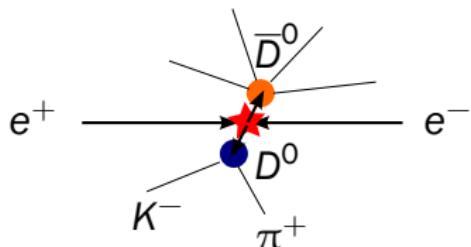
CLEO-c physics run ended in March 2008



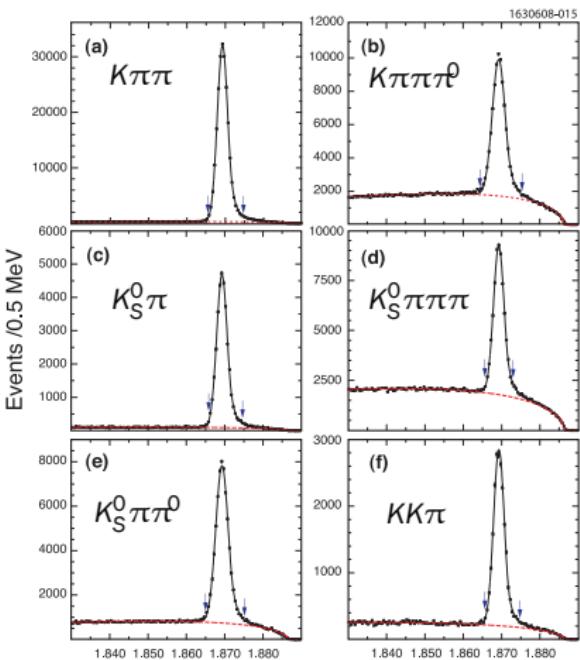
Great tracking, calorimetry, particle ID



Reconstruction – 3.77 GeV



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



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

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

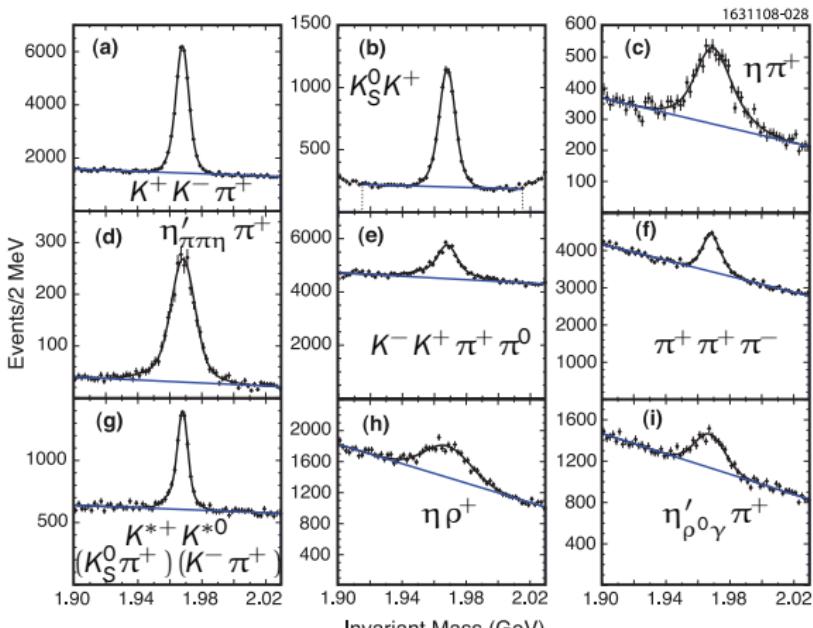
Reconstruction – 4.17 GeV

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 $D_s^* \rightarrow D_s$ transition is also present

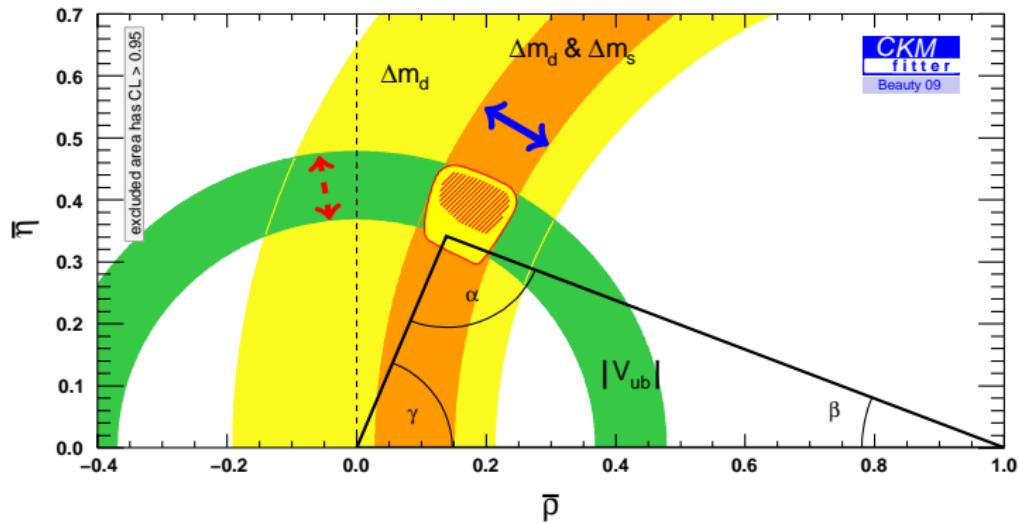
Tagging efficiency for D_s
~ 6%

Transition γ finding eff
~ 60%

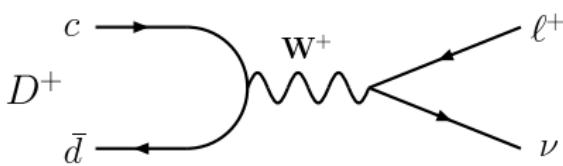
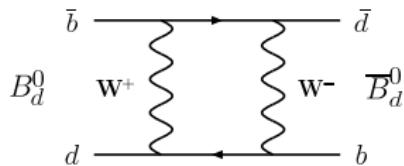


70.5k tags in 9 modes, 600 pb^{-1}

Decay Constant Measurements



QCD in CKM – B mixing



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

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

- Analogous quantity appears in D leptonic decays (and $B^+ \rightarrow \tau\nu$):

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

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

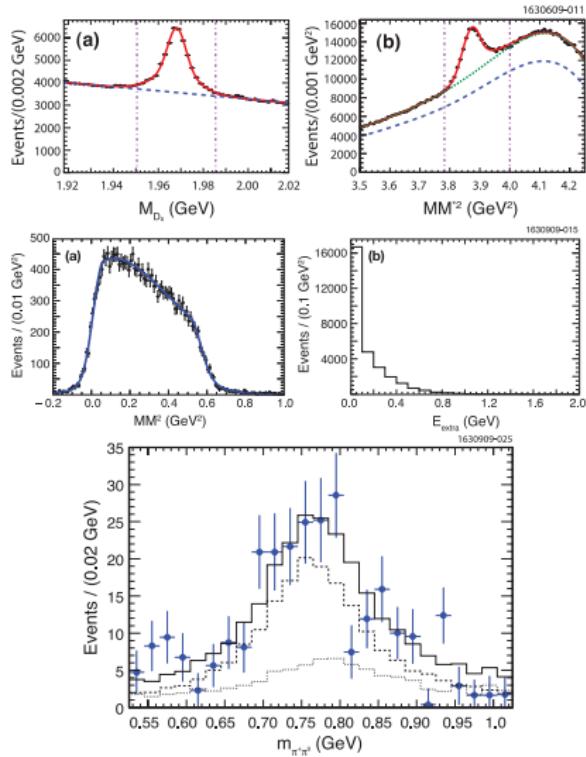
D Leptonic Decays

- Measure f_D and f_{D_s} using leptonic decays
 - Constrain $|V_{cd}|$ and $|V_{cs}|$ with CKM unitarity
- $D_s^+ \rightarrow \ell^+\nu$ not Cabibbo-suppressed so \mathcal{B} much larger
- Measurement modes are
 - $D^+ \rightarrow \mu^+\nu$ PRD **78** 052003 (2008)
 - $D_s^+ \rightarrow \mu^+\nu$ PRD **79** 052001 (2009)
 - $D_s^+ \rightarrow \tau^+\nu (\tau^+ \rightarrow \pi^+\bar{\nu})$ PRD **79** 052001 (2009)
 - $D_s^+ \rightarrow \tau^+\nu (\tau^+ \rightarrow e^+\nu\bar{\nu})$ PRD **79** 052002 (2009)
 - $D_s^+ \rightarrow \tau^+\nu (\tau^+ \rightarrow \rho^+\bar{\nu})$ PRD **80** 112004 (2009) [NEW]
- Relative branching ratios for $D_{(s)}^+ \rightarrow \ell^+\nu$ set by lepton mass (at least in SM!)

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

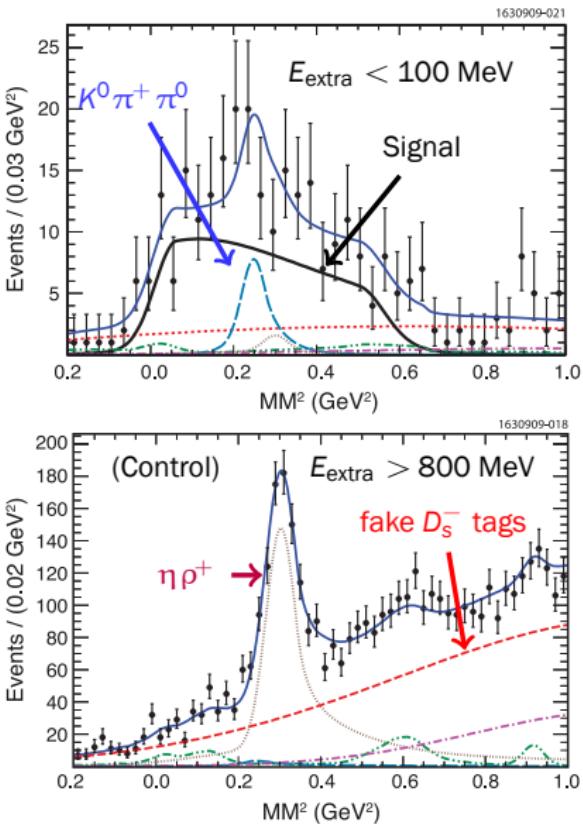
$$D_s^+ \rightarrow \tau^+ \nu, \tau^+ \rightarrow \rho^+ \bar{\nu}$$

- $\mathcal{B}(\tau^+ \rightarrow \pi^+ \pi^0 \bar{\nu}) = 26\%$: large!
- Only two neutrinos to deal with: enough kinematic separation to extract signal
- From sample of D_s^- tag events, find ρ^+ , veto extra tracks and compute missing mass squared
 - for signal, is a plateau from 0 to 0.5 GeV^2
- For signal, extra calorimeter energy E_{extra} is small



$$D_s^+ \rightarrow \tau^+ \nu, \tau^+ \rightarrow \rho^+ \bar{\nu}$$

- Large peaking backgrounds ($K^0 \rho^+$, $\eta \rho^+$, $\pi^0 \pi^+ \pi^0$) are measured in CLEO-c data
- Fake tag background from tag mass sidebands
- Resolutions checked with data
- Not shown: additional fit for $E_{\text{extra}} \in [100, 200] \text{ MeV}$



Combined Leptonic Results

$D_s^+ \rightarrow \mu^+\nu$ and three $D_s^+ \rightarrow \tau^+\nu$
measurements statistically
independent: combine

Average:

$$f_{D_s} = 259.0 \pm 6.2 \pm 3.0 \text{ MeV}$$

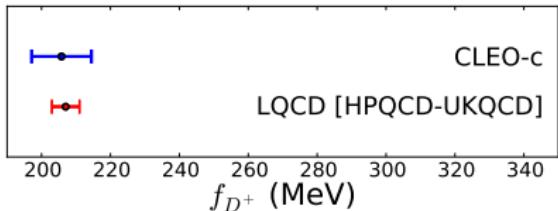
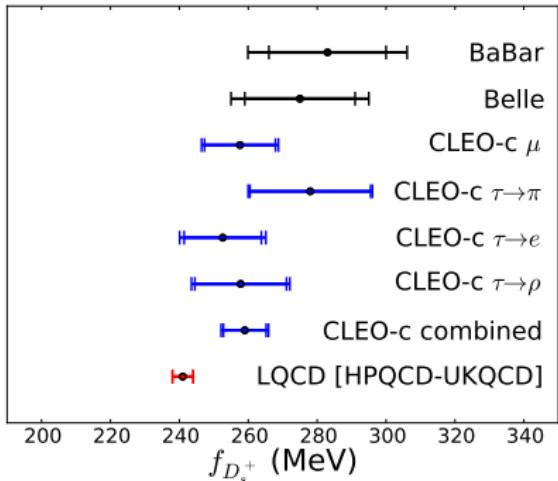
Lattice: $241 \pm 3 \text{ MeV}$

Also from CLEO-c:

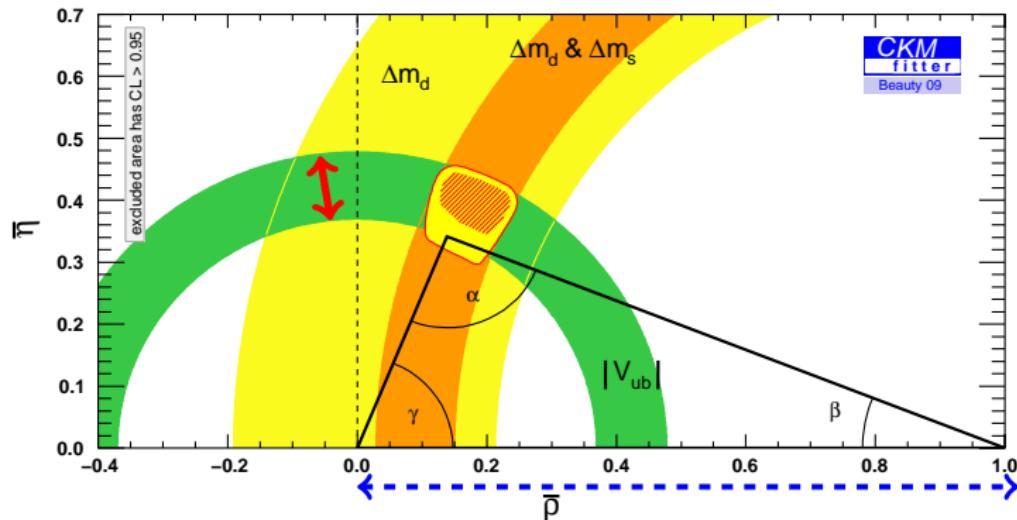
PRD 78 052003 (2008)

$$f_D = 205.8 \pm 8.5 \pm 2.5 \text{ MeV}$$

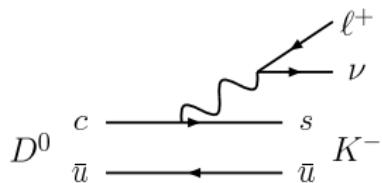
Lattice: $201 \pm 3 \pm 17 \text{ MeV}$



Semileptonic Form Factor Measurements



QCD in CKM – Semileptonic Decays



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

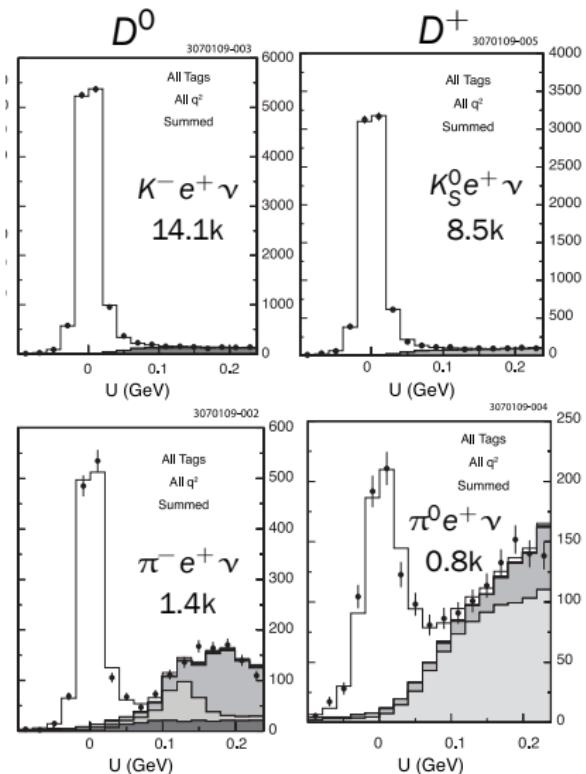
(X' a pseudoscalar)

- Rate depends on a form factor $f_+(q^2 = m_{\ell\nu}^2)$ 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 at CLEO-c

- Only electrons used in this analysis ($\pi \rightarrow \mu$ fake rate too high)
- Results for:
 - $D^0 \rightarrow K^- e^+ \nu$, $D^+ \rightarrow \bar{K}^0 e^+ \nu$
 - $D^0 \rightarrow \pi^- e^+ \nu$, $D^+ \rightarrow \pi^0 e^+ \nu$
- Reconstruct hadronic \bar{D} tag + hadron + lepton, see if missing four-momentum is consistent with neutrino
- Following results use full dataset (PRD 80 032005)

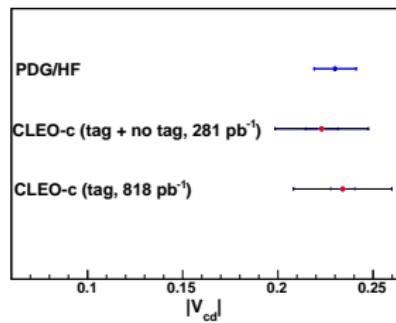
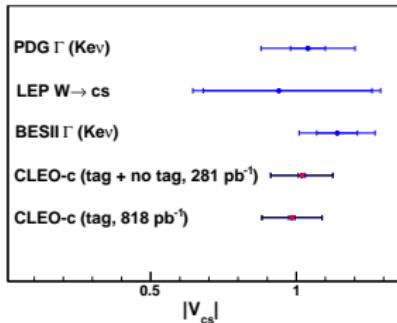
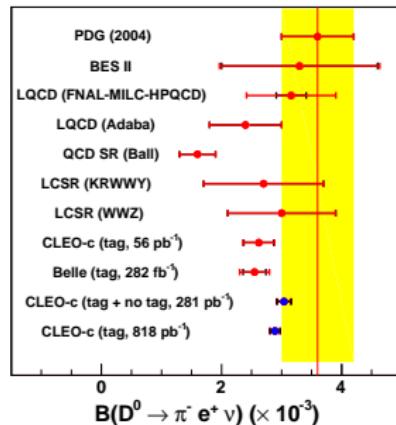
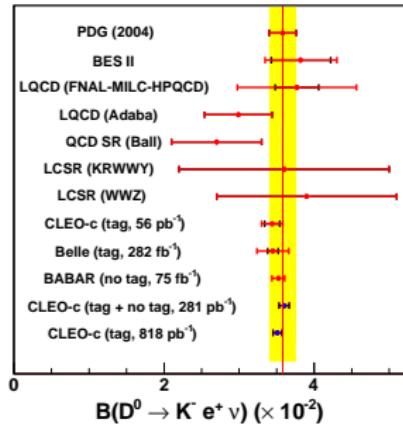
D Semileptonics: Reconstruction



$$U \equiv E_{\text{miss}} - |\vec{p}_{\text{miss}}|$$

- Very good signal/background separation
- Fits done in bins of q^2 , careful treatment of migration

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



D Semileptonics: Form Factors

$$\text{Simple pole: } f_+(q^2) = \frac{f_+(0)}{1 - \frac{q^2}{M_{pole}^2}}$$

Modified pole (PLB **478** 417 (2000)):

$$f_+(q^2) = \frac{f_+(0)}{\left(1 - \frac{q^2}{M_{pole}^2}\right) \left(1 - \alpha \frac{q^2}{M_{pole}^2}\right)}$$

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

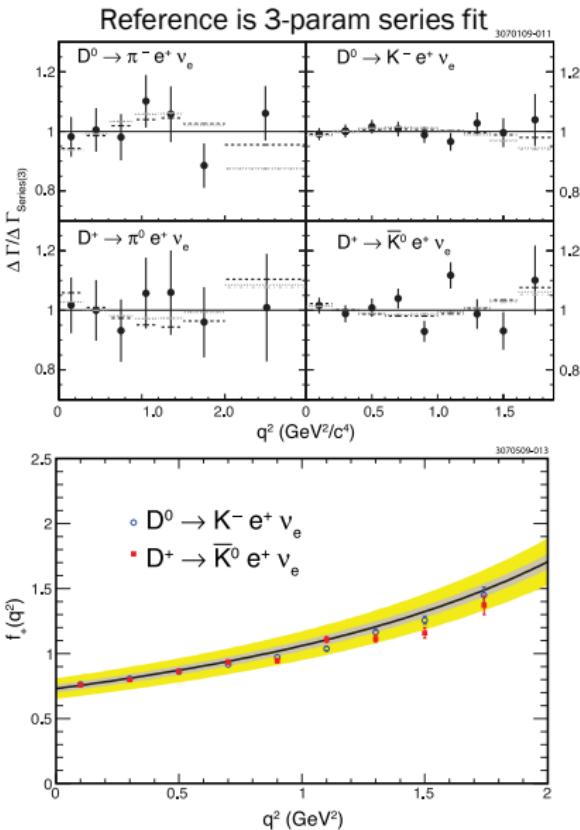
$$f_+(q^2) = \frac{a_0}{P(q^2)\phi(q^2, t_0)} \left(1 + \sum_{k=1}^{\infty} a_k(t_0) z(q^2, t^0)^k\right)$$

All shapes fit data if parameters allowed to float

“Physical” pole masses highly disfavored

LQCD: FNAL-MILC-HPQCD, PRL **94** 011601 (2005)

Visualization: PRD **80** 034026 (2009)



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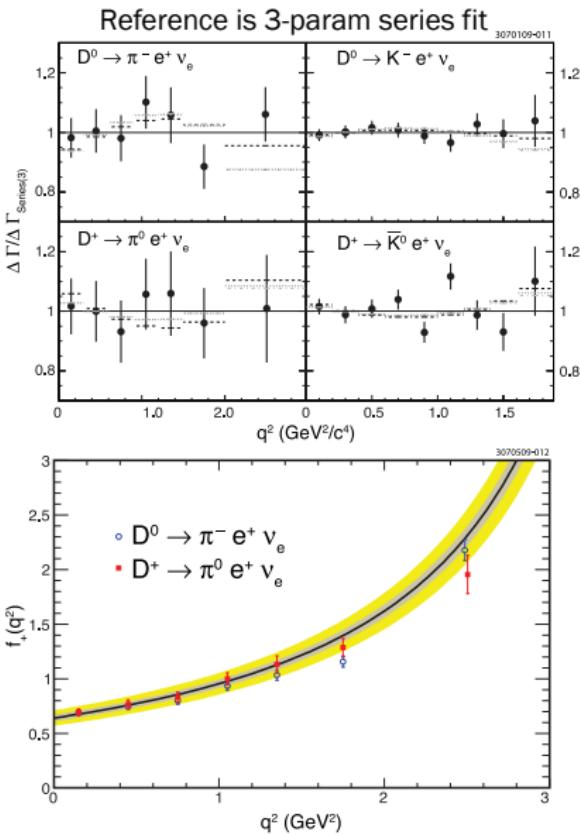
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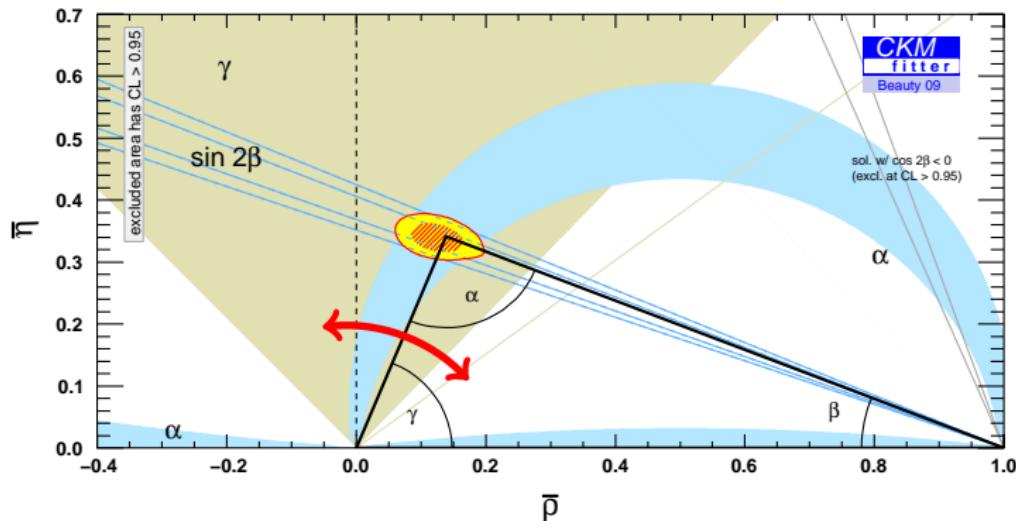
LQCD: FNAL-MILC-HPQCD, PRL **94** 011601 (2005)

Visualization: PRD **80** 034026 (2009)



D^0 Decay Strong Phases for γ

QCD in CKM – γ Extraction



CKMFitter, Beauty 2009

Direct measurements, in $^\circ$

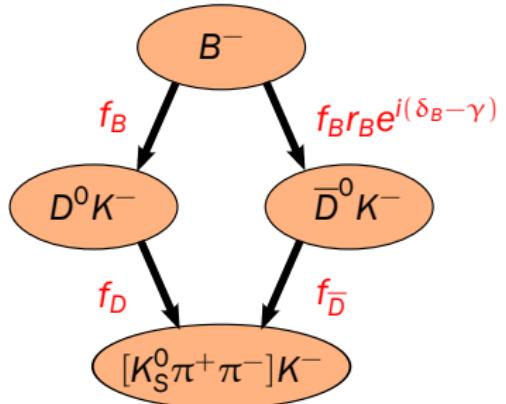
α	$89.0^{+4.4}_{-4.2}$
β	$21.15^{+0.90}_{-0.88}$
γ	73^{+22}_{-25}

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

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

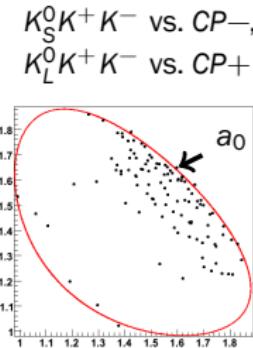
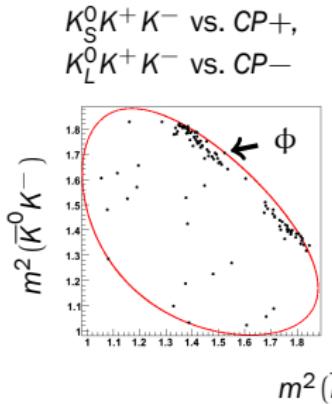
QCD in CKM – γ Extraction

- Can obtain γ from interference between $b \rightarrow c(\bar{u}s)$ and $b \rightarrow u(\bar{c}s)$
- Use final states common to D^0 and \bar{D}^0
- Must know relative phase of D^0 and \bar{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 $D^0\bar{D}^0$ pairs: get δ_D from data
 - $CP = +$ decay of one $D \Rightarrow$ other D decay **must** be $CP = -$



Studying:

- δ_D for $D^0 \rightarrow K^-\pi^+$
PRL **100** 221801 (2008): 281 pb^{-1}
- Dalitz plot-dependent phases
for $D^0 \rightarrow K_{S,L}^0 \pi^+ \pi^-$
PRD **80** 032002 (2009)
and $K_{S,L}^0 K^+ K^-$
- Coherence factor and average
strong phase for
 $D^0 \rightarrow K^-\pi^+\pi^0$ and
 $K^-\pi^+\pi^+\pi^-$
PRD **80** 031105 (2009)



818 pb^{-1} Preliminary

Statistically limited by CP tag yields

Impact on γ

Dalitz modes:

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

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

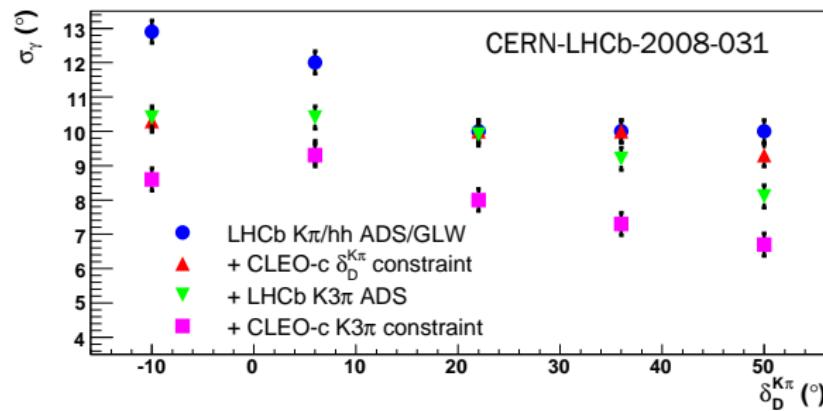
Belle: $(76^{+12}_{-13} \pm 4 \pm 9)^\circ$
(arxiv:0803.3375)

$7^\circ - 9^\circ$ model uncertainty

$\Rightarrow 2^\circ$ CLEO-c statistical uncertainty
(PRD 80 032002)

Important since LHCb statistical error is $\approx 5.5\%$ with 10 fb^{-1}

Projected CLEO-c $K\pi, K\pi\pi\pi$ impact on LHCb



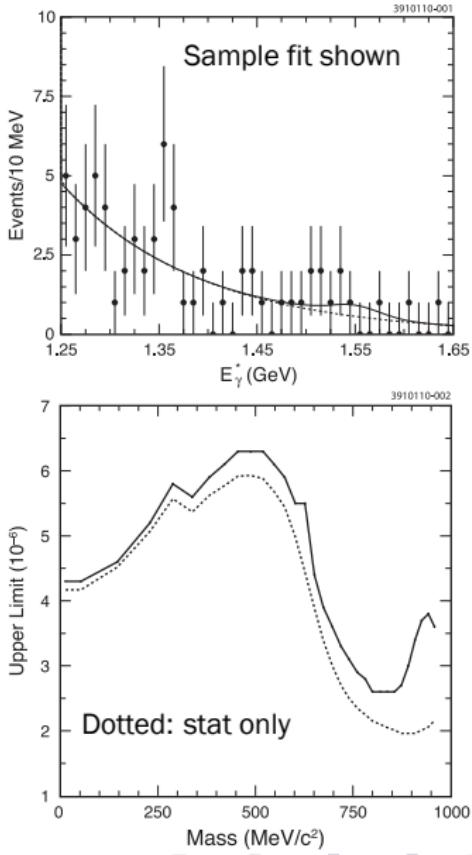
- CKM measurements are a key focus area for CLEO-c
- D^+ and D_s^+ leptonic decays test lattice predictions
- D^0 and D^+ semileptonic decays test the lattice, probe $|V_{cs}|$ and $|V_{cd}|$
 - Results shown here use full CLEO-c dataset
- Strong phase measurements in various D decays have a large impact on the systematic uncertainty in γ
 - Technique unique to charm threshold
 - Multiple modes being studied
 - Great symbiosis with LHCb and B -factory programs

And now for something completely different

Limits on Light Weakly-Interacting Neutrals

- Search for $J/\psi \rightarrow \gamma + X$, where X is invisible
- Use $\psi(2S)$ data
- Reconstruct
 $\psi(2S) \rightarrow \pi^+ \pi^- J/\psi$
 $J/\psi \rightarrow \gamma + \text{nothing}$
- 2-body decay \Rightarrow narrow peak in E_γ
- Sensitive for $m_X < 960$ MeV
- Complements Υ searches as c is up-type
- $\mathcal{B}(J/\psi \rightarrow \gamma X) < 6.3 \times 10^{-6}$

arxiv:1003.0417, submitted to PRD



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

$$D_{CP=\pm}^0 = \frac{D^0 \mp \bar{D}^0}{\sqrt{2}}$$

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

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

- 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

Dalitz Model Limitations

TABLE II: CA, DCS, and CP eigenstates complex amplitudes $a_r e^{i\phi_r}$, $\pi\pi$ S-wave P-vector parameters, $K\pi$ S-wave parameters, and fit fractions, as obtained from the fit of the $D^0 \rightarrow K_0^0 \pi^+ \pi^-$ Dalitz plot distribution from $D^{*+} \rightarrow D^0 \pi^+$. P-vector parameters f_{1v}^{prod} , for $v \neq 1$, are defined as $f_{1v}^{\text{prod}}/f_{11}^{\text{prod}}$. Errors for amplitudes are statistical only, while fit fractions include statistical and systematic uncertainties, largely dominated by the latter. Upper limits on fit fractions are quoted at 95% confidence level.

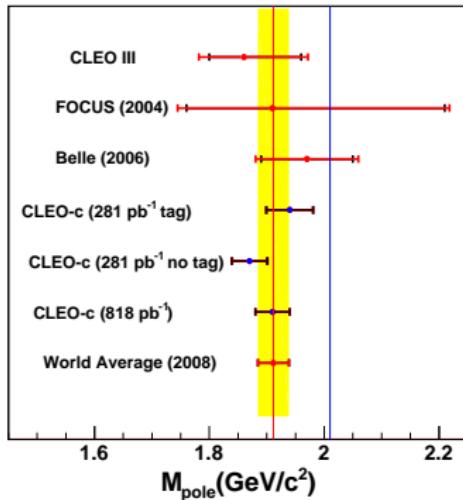
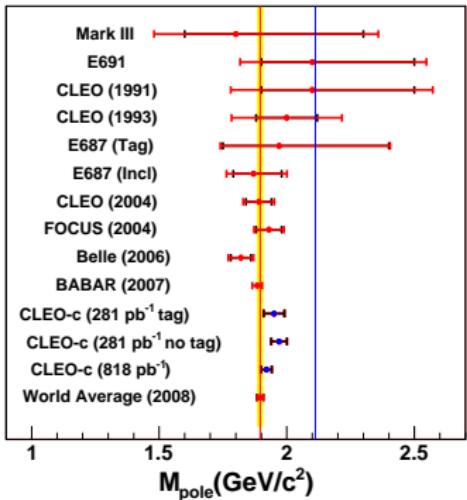
Component	a_r	ϕ_r (deg)	Fraction (%)
$K^*(892)^-$	1.740 ± 0.010	139.0 ± 0.3	55.7 ± 2.8
$K_0^*(1430)^-$	8.2 ± 0.7	153 ± 8	10.2 ± 1.5
$K_2^*(1430)^-$	1.410 ± 0.022	138.4 ± 1.0	2.2 ± 1.6
$K^*(1680)^-$	1.46 ± 0.10	-174 ± 4	0.7 ± 1.9
$K^*(892)^+$	0.158 ± 0.003	-42.7 ± 1.2	0.46 ± 0.23
$K_0^*(1430)^+$	0.32 ± 0.06	143 ± 11	< 0.05
$K_2^*(1430)^+$	0.091 ± 0.016	85 ± 11	< 0.12
$\rho(770)^0$	1	0	21.0 ± 1.6
$\omega(782)$	0.0527 ± 0.0007	126.5 ± 0.9	0.9 ± 1.0
$f_2(1270)$	0.606 ± 0.026	157.4 ± 2.2	0.6 ± 0.7
β_1	9.3 ± 0.4	-78.7 ± 1.6	
β_2	10.89 ± 0.26	-159.1 ± 2.6	
β_3	24.2 ± 2.0	168 ± 4	
β_4	9.16 ± 0.24	90.5 ± 2.6	
f_{11}^{prod}	7.94 ± 0.26	73.9 ± 1.1	
f_{12}^{prod}	2.0 ± 0.3	-18 ± 9	
f_{13}^{prod}	5.1 ± 0.3	33 ± 3	
f_{14}^{prod}	3.23 ± 0.18	4.8 ± 2.5	
s_0^{prod}		-0.07 ± 0.03	
$\pi\pi$ S-wave			11.9 ± 2.6
M (GeV/c^2)	1.463 ± 0.002		
Γ (GeV/c^2)	0.233 ± 0.005		
F	0.80 ± 0.09		
ϕ_F	2.33 ± 0.13		
R	1		
ϕ_R	-5.31 ± 0.04		
a	1.07 ± 0.11		
r	-1.8 ± 0.3		

B -factories have a lot of data and can make very nice Dalitz fits, but...

- Have to assume parametrizations
- (Badly understood) scalar contributions are important!
- It's not enough to reproduce the Dalitz distribution; must get the CP structure right

CLEO-c can measure the CP content directly

Modified Pole Fits



Modified Pole Fits

