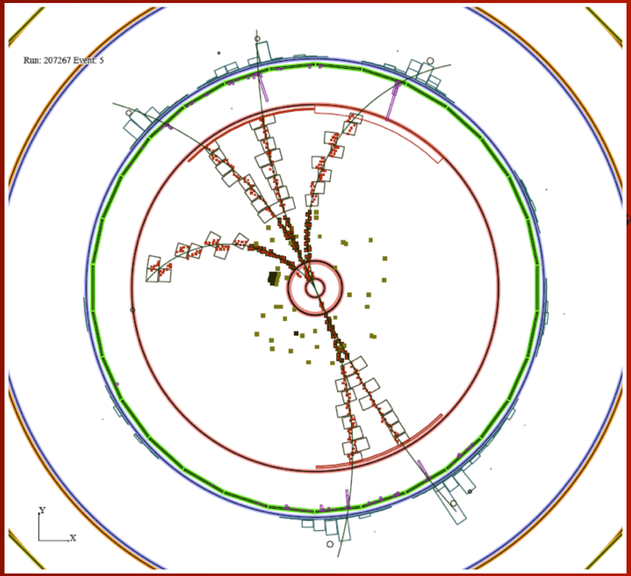
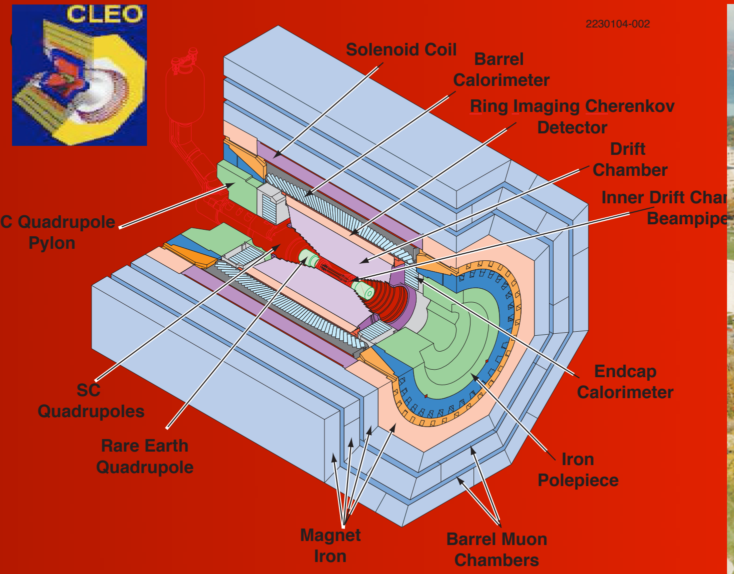
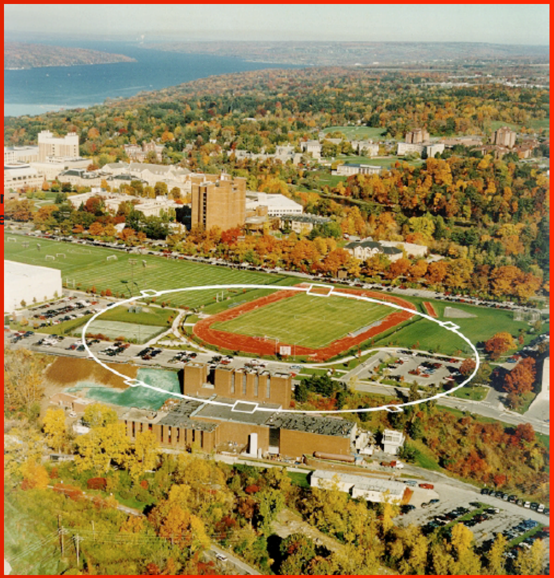
Advances in Open Charm Physics at CLEO-c

Paras Naik

University of BRISTOL







Goals of Open Charm studies at CLEO-c

Charm Impact on CKM

- CKM Phase γ/ϕ_3
- Tests of LQCD
- V_{cd}, V_{cs}
- $\sin 2\beta_s$

Important Ingredient
CP tagged D's from
Quantum Correlated
Charm at Threshold

Rare Charm Processes

- Rare Decays
- Charm Mixing
- CP Violation

Hadronic D/D_s Decays

- Symmetry Tests
- Dalitz Plots

Branching Ratios: Absolute | Inclusive vs Exclusive | Baryonic

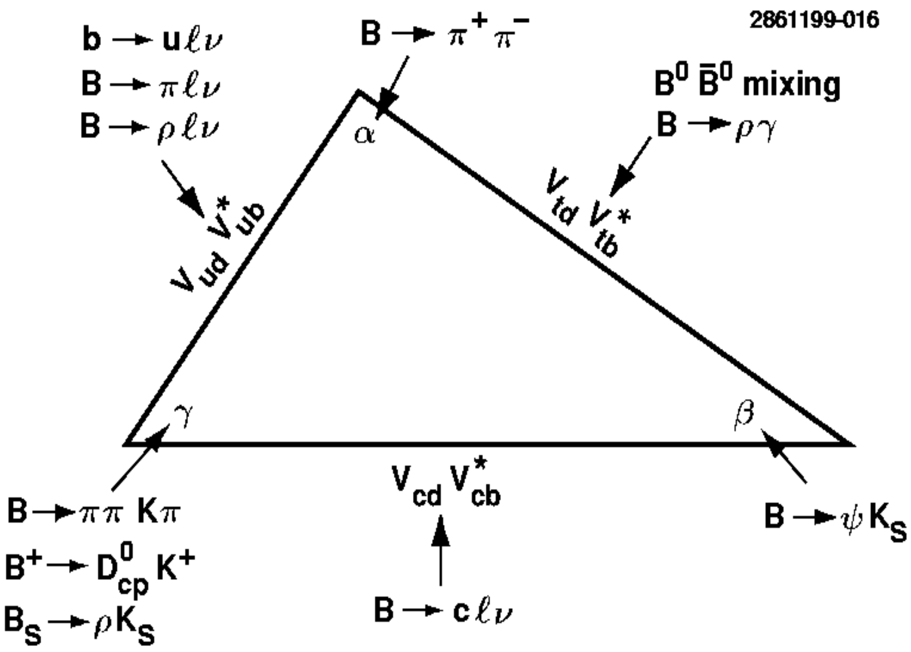
Other CLEO-c Studies: Charmonium | XYZ States | D* Spectroscopy

CKM

CKM Matrix

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

CKM Unitarity Triangle

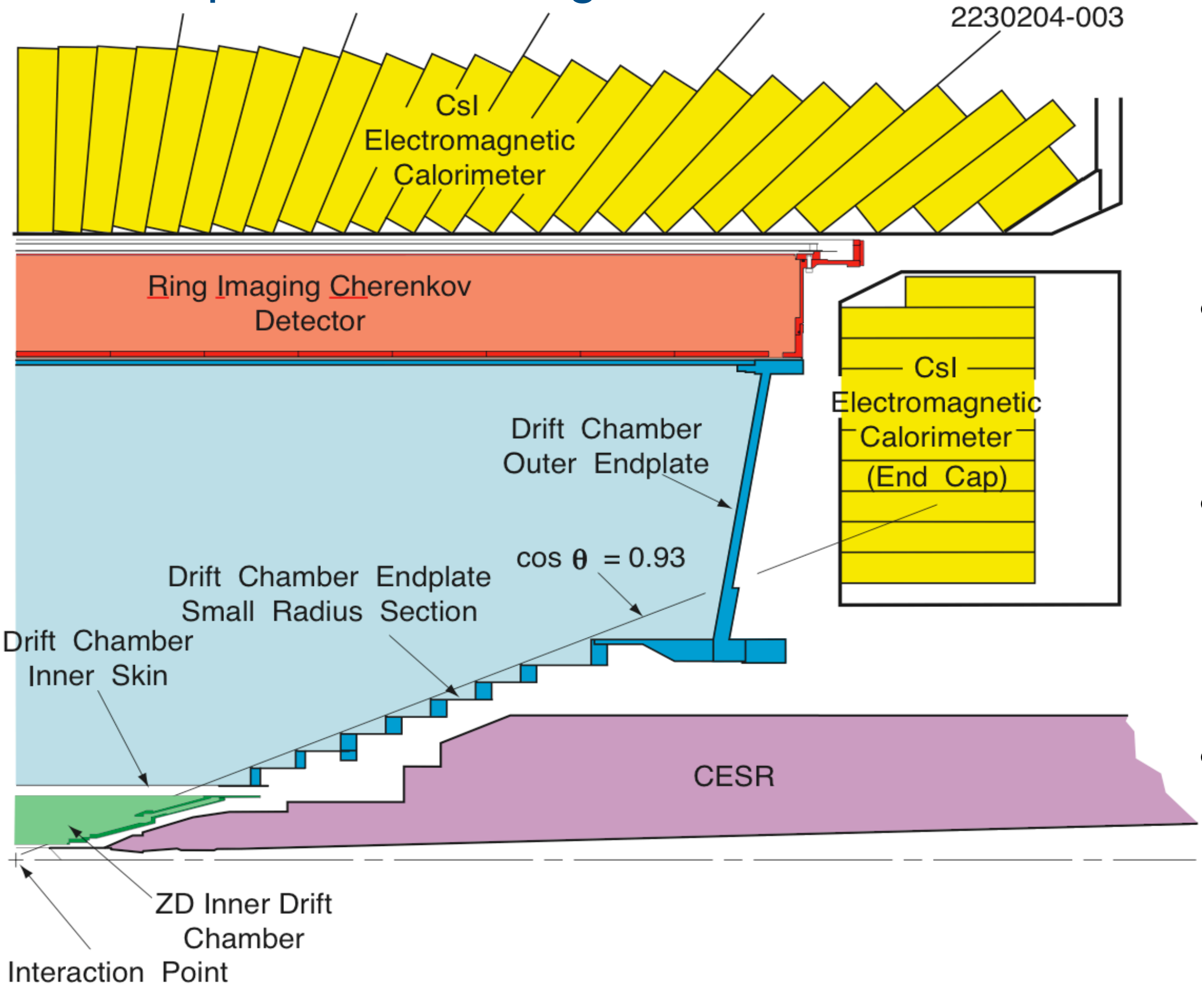


Charm impact on measurements of γ/ϕ_3 with B→DK

Lattice QCD tests in Charm sector

CLEO-c Detector (December 2003 - March 2008)

- Hermetic detector based at CESR (the Cornell Electron Storage Ring)
- Operated at energies around $c\bar{c}$ threshold



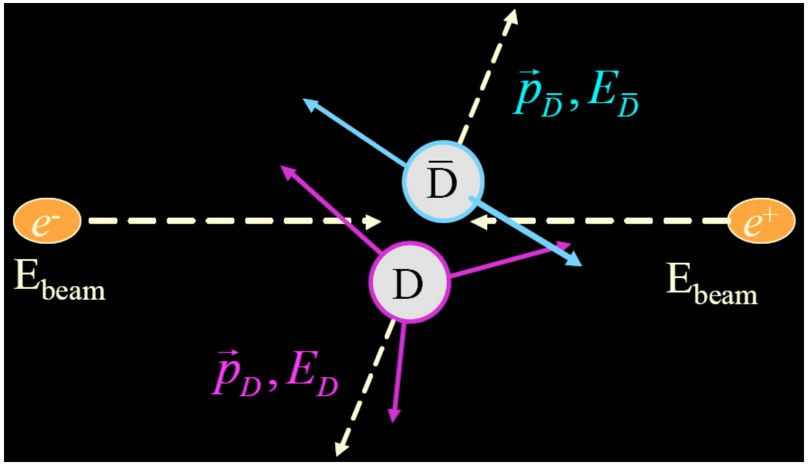
Open Charm Samples

$\psi(3770)$	4170 GeV
818 pb^{-1}	600 pb^{-1}
5.1M DD	0.57M $D_sD_s^*$

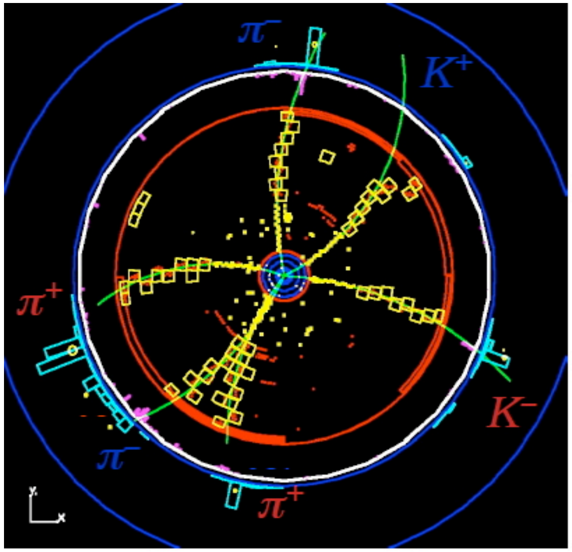
Covered 93% of Solid Angle

- Tracking
  - $\sigma_p/p = 0.6\%$ @ 1 GeV
- Calorimetry
  - $\sigma_E/E = 5\%$ @ 0.1 GeV
    $= 2.2\%$ @ 1 GeV
- Charged PID (RICH+dE/dx)
  - Good K/π separation over entire momentum range ($p < 2.5$ GeV/c)

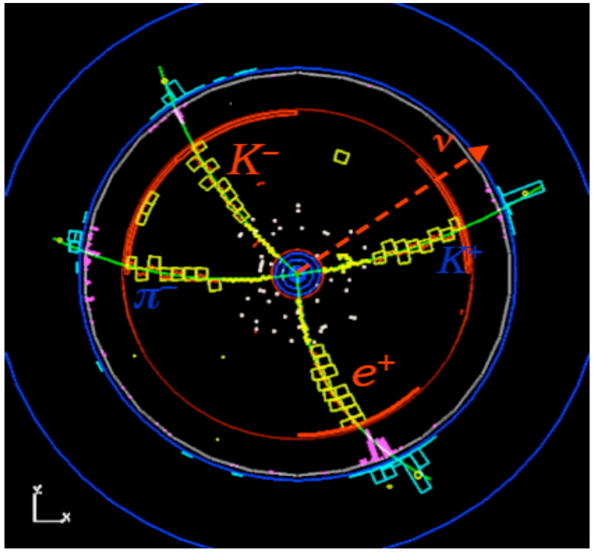
D Physics with Tags



- ψ(3770) provides large σ(DD̄)
- Reconstruct 1 D: "single tag"
- Reconstruct 2 D's: "double tag"
- High efficiency tagging of hadronic decays defines "beam" of D's on other side of event



$K^- \pi^+ \pi^+$ vs. $K^+ \pi^- \pi^-$



$K^- e^+ \nu$ vs. $K^+ \pi^-$

Key Analysis Variables

$$M_{bc} = \sqrt{E_{beam}^2 - p_D^2}$$

$$\Delta E = E_{beam} - E_D$$

$$U = E_{miss} - |P_{miss}|$$

$$MM^2 = E_{miss}{}^2 - P_{miss}{}^2$$

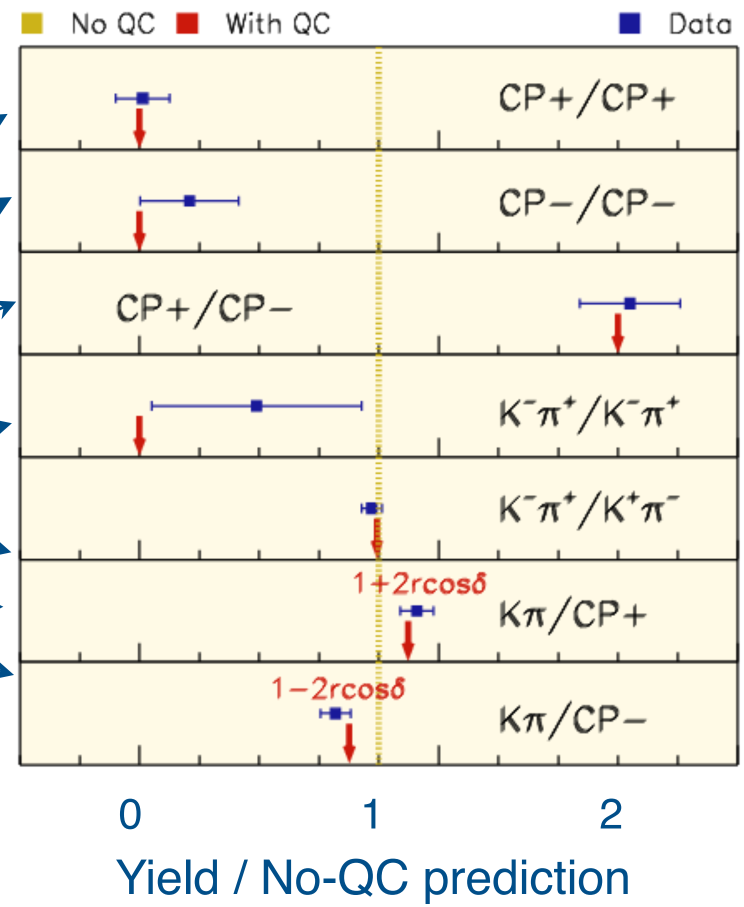
Coherent vs. Incoherent Decay

D. Asner and W. Sun,
Phys. Rev. D73, 034024 (2006)
Phys. Rev. D77, 019901(E) (2008)

$C = -1$

$$e^+e^- \to \gamma^* \xrightarrow{\psi(3770)} D^0\bar{D}^0$$

Forbidden by CP conservation	*CP*+	*CP*+
	CP–	*CP*–
Maximal enhancement	*CP*+	*CP*–
Forbidden if no mixing	$K^-\pi^+$	$K^-\pi^+$
Interference of CF with DCS	$K^-\pi^+$	*CP*±
	CP±	$K^-\pi^+$
Single Tags Unaffected	*CP*± $K^-\pi^+$ *SL*	X



Enable strong phase measurements

- Reduce sys. err. on CKM phase γ
- Interpret charm mixing results

Quantum Correlations
Clearly visible in data!

Measuring $\delta_D^{K\pi}$ and D-Mixing parameters with Quantum Correlated D's

PRL 100, 221801 (2008)
PRD 78, 012001 (2008)

Take advantage of $\psi(3770)$
281 pb^{-1} = 10^6 *C*-odd $D^0\bar{D}^0$
and calculate mixing parameters via interference of two D decays

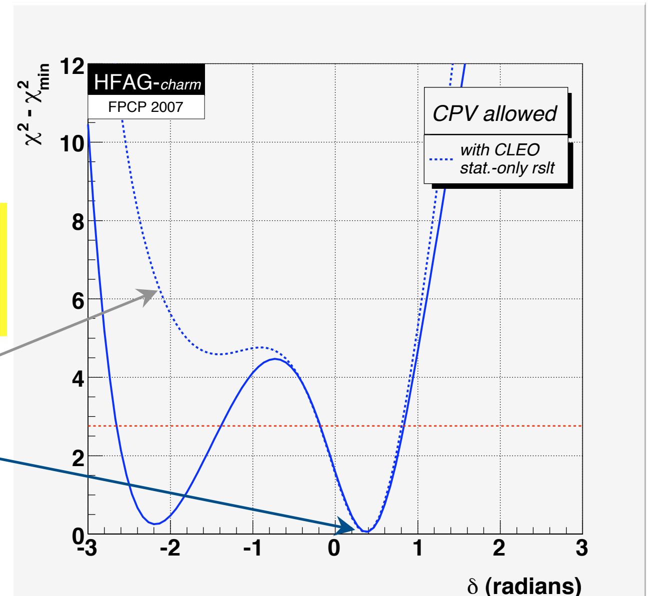
Parameter	Standard Fit	Extended Fit
$y\ (10^{-3})$	$-45 \pm 59 \pm 15$	$6.5 \pm 0.2 \pm 2.1$
$r^2\ (10^{-3})$	$8.0 \pm 6.8 \pm 1.9$	$3.44 \pm 0.01 \pm 0.09$
$\cos\delta$	$1.03 \pm 0.19 \pm 0.06$	$1.10 \pm 0.35 \pm 0.07$
$x^2\ (10^{-3})$	$-1.5 \pm 3.6 \pm 4.2$	$0.06 \pm 0.01 \pm 0.05$
$x\sin\delta\ (10^{-3})$	0 (fixed)	$4.4 \pm 2.4 \pm 2.9$
$\chi^2_{\rm fit}/{\rm ndof}$	$30.1/46$	$55.3/57$

First determination (281 pb^{-1})

- Extended fit with a likelihood scan of the physically allowed region leads to a measurement of:

$$\delta = \left(22^{+11+9}_{-12-11}\right)^\circ$$

- Fit result important component average of charm mixing
  - Selects one of two possible solutions for δ
- Future
  - We need to control non-linearities in the fit
  - Adding many additional modes
  - Will use full 818 pb^{-1} sample ($3*10^6$ C-odd pairs)

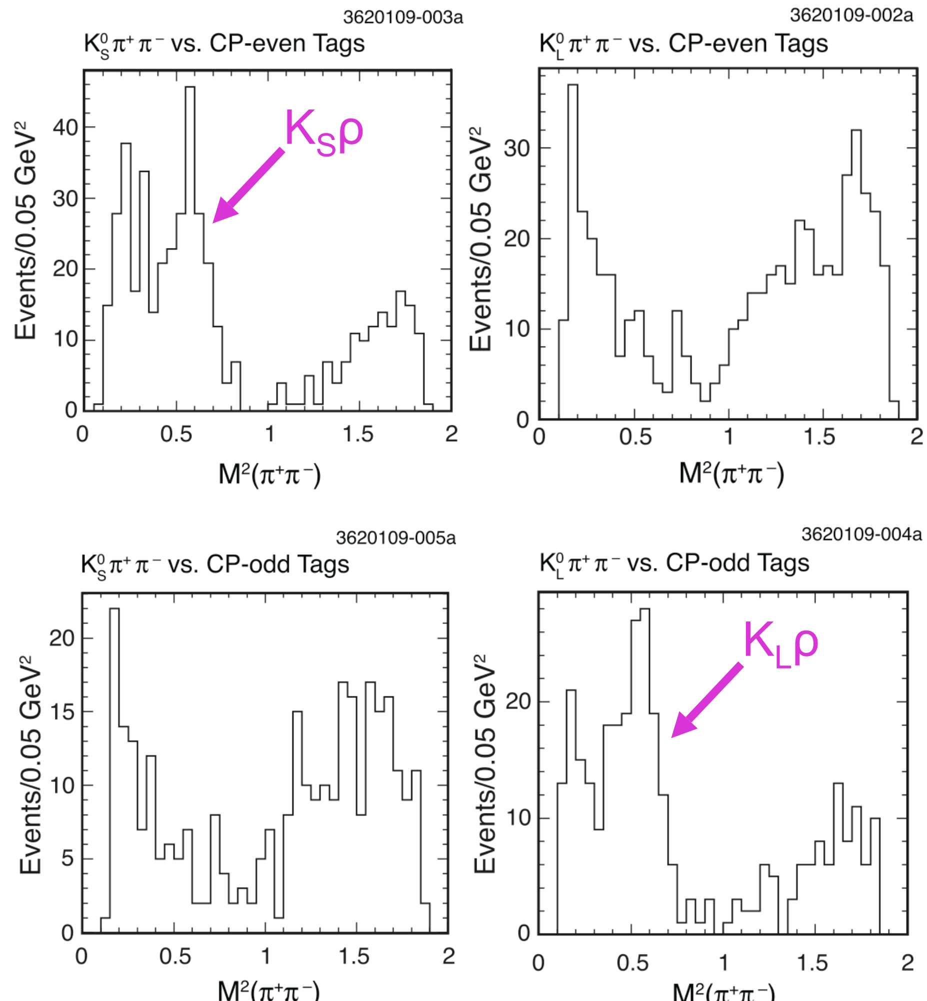


E. Barberio et al., "Averages of b-hadron and c-hadron Properties at the End of 2007," arXiv:0808.1297 and online update at http://www.slac.stanford.edu/xorg/hfag

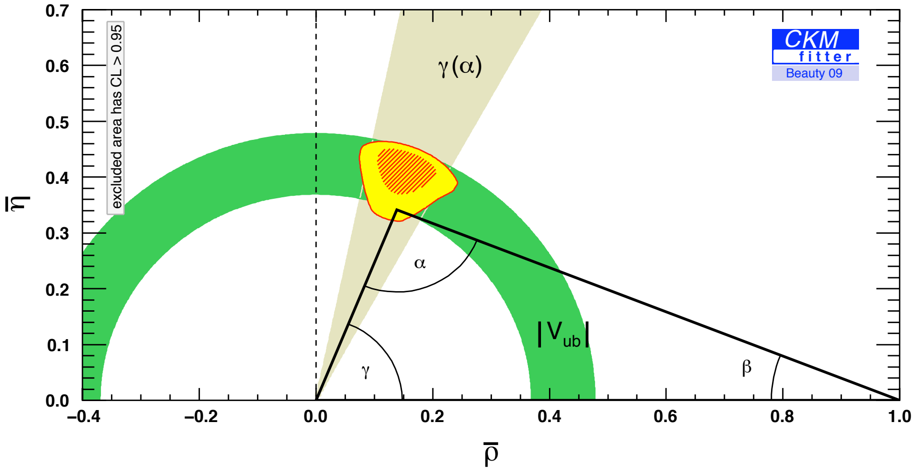
Example: CP-tagged $K_{S/L}\pi^+\pi^-$ Dalitz plots

Phys. Rev. D 80, 032002 (2009)

Clear differences seen between CP-odd and CP-even:



CKM phase γ/ϕ_3



Constraints from tree quantities

$$\gamma : (73^{+22}_{-25})^{\circ}$$

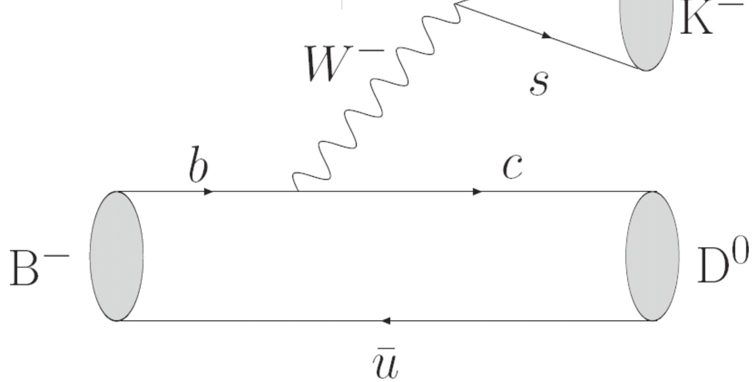
Fit from direct measurements only (CKM Fitter, Beauty 2009)

CKMfitter Group (J. Charles et al.), Eur. Phys. J. C41, 1-131 (2005) [hep-ph/0406184], updated results and plots available at: http://ckmfitter.in2p3.fr

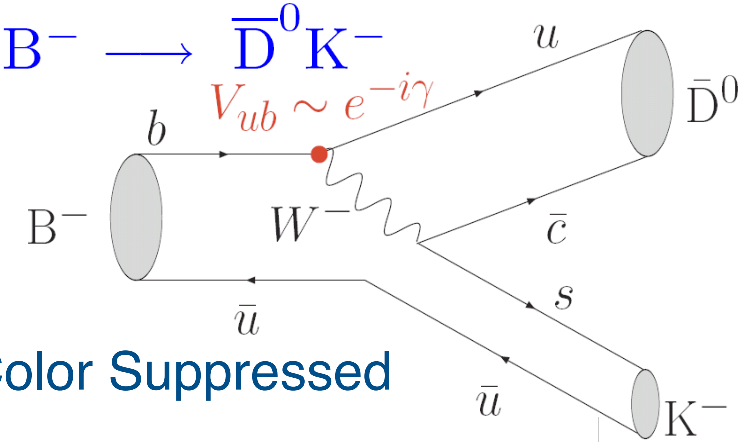
- Of the three CKM phases, γ is the least constrained.
- A precision measurement of γ is essential in order to test the internal consistency of the CKM unitarity triangle.
- In addition, tree measurements of γ compared to loop measurements may provide a first indication of New Physics in the flavor sector.
- The precision measurement of γ is one of the most important measurements of LHCb and e^+e^- flavor factories

Measuring the CKM phase γ/ϕ_3 via $B \to DK$

$B^- \longrightarrow D^0 K^-$

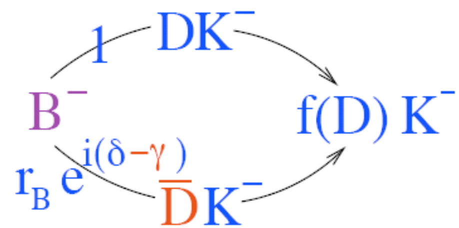


$B^- \longrightarrow \overline{D}^0 K^-$



$$\frac{< B^- \longrightarrow \overline{D}^0 K^- >}{< B^- \longrightarrow D^0 K^- >} = r_B e^{i(\delta_B - \gamma)}$$

$r_B \sim 0.1$



- The CKM phase γ can be determined through the *interference* between the $b \to c$ and $b \to u$ transitions
- Require the neutral D mesons to decay to the same final state f(D)
- This method is theoretically clean
- **Success of this method requires that the D decay is well understood**

$K^0_S\ \pi^+\pi^-$ 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)

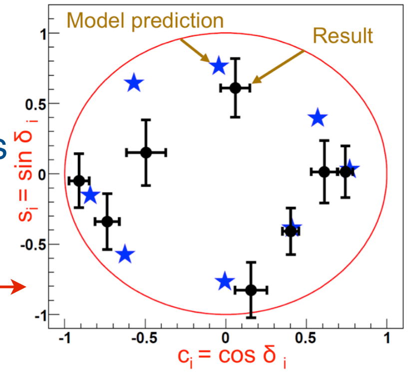
D decay studies for γ/ϕ_3 at CLEO-c

- CLEO-c takes advantage of the Quantum Correlations in our $(D^0\overline{D}^0)_{\psi(3770)}$ sample

δ_D for $D^0 \to K^-\pi^+$ (discussed earlier)

PRL 100, 221801 (2008)

- Expect update with all data and more modes



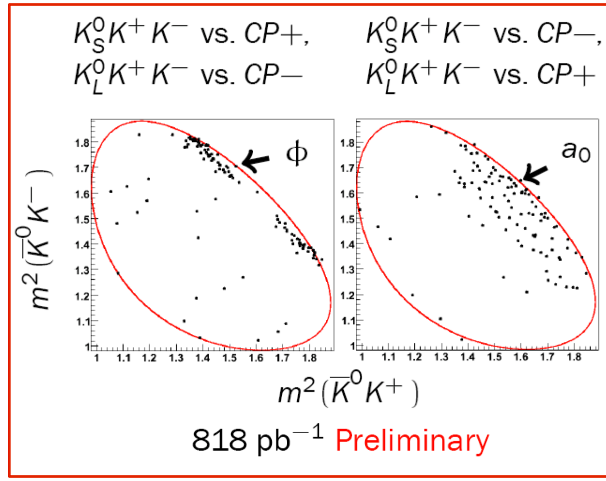
Impact: ~7° $D \to K_S\pi^+\pi^-$ model systematic uncertainty replaced by 1.7° statistical error on c_i & s_i

(model = BaBar PRL 95 (2005) 121802)

Dalitz plot bin-integrated phases for $D^0 \to K_{S,L}\pi^+\pi^-$

PRD 80, 032002 (2009)

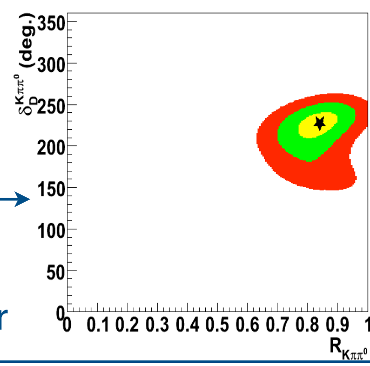
and $D^0 \to K_{S,L}K^+K^-$ (Preliminary)

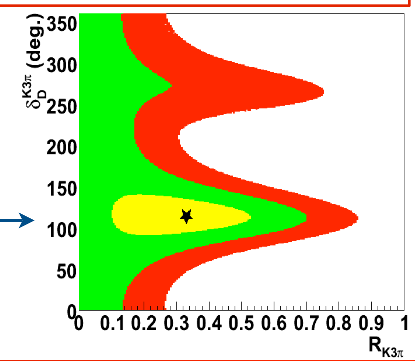


Coherence factor and average strong phase for $D^0 \to K^-\pi^+\pi^0$ and $D^0 \to K^-\pi^+\pi^+\pi^-$

PRD 80, 031105 (2009)

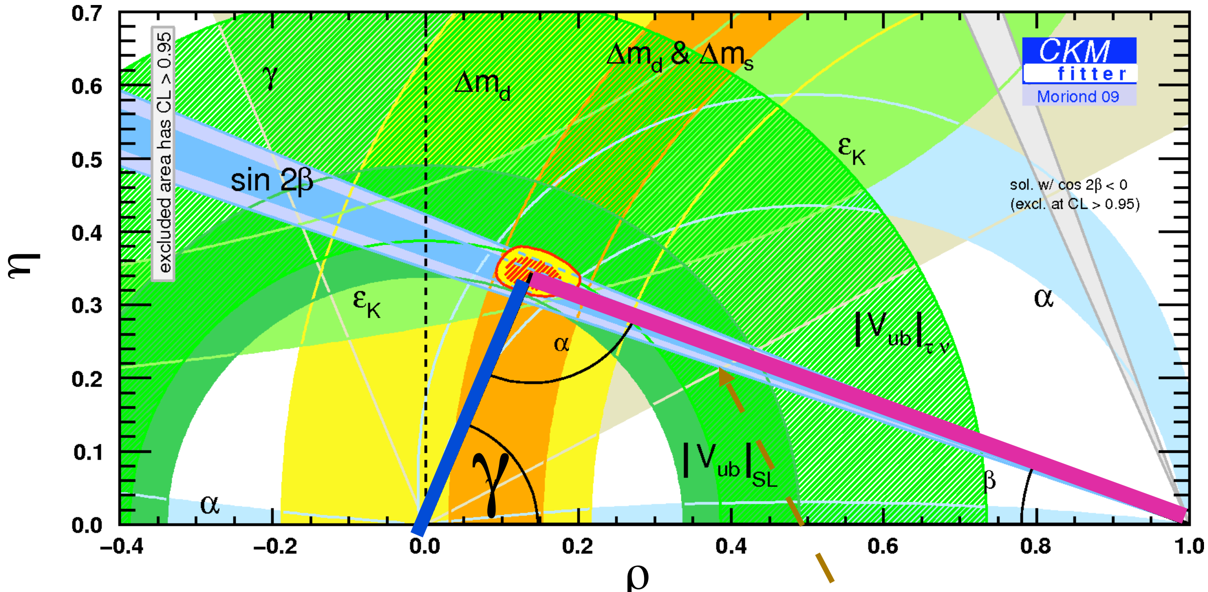
- $D^0 \to K^-\pi^+\pi^0$ is very coherent (almost at two body limit!)
- $D^0 \to K^-\pi^+\pi^+\pi^-$ is not very coherent (this is good in its own way, enables better better future measurements of r_B)





Coherence factor analyses enable 2-3° γ determination (overall) at LHCb
(Also sensitive to D mixing)

Tests of Lattice QCD using Charm



CKM unitarity triangle is constrained by over 50 independent measurements in B decays

TeV scale revealed by inconsistencies - not seen.

But uncertainty on *key* measurements have high dependence (direct & indirect) on D decays:

- 'Vub side' - LQCD errors dominate

  $D \to \pi$ form factors (normalization & q^2 dependence) test/develop LQCD

- 'Mixing' side - Depends on LQCD calculation of $(f_{Bs}\sqrt{B_{Bs}}) / (f_{Bd}\sqrt{B_{Bd}})$

  Measure f_{Ds}/f_D to test LQCD

'Mixing Side' of unitarity triangle determined by B_d/B_s oscillation rates – box diagrams sensitive to new physics – and QCD corrections

Calculated on lattice – present *assigned* uncertainty ~5% (and will decrease)

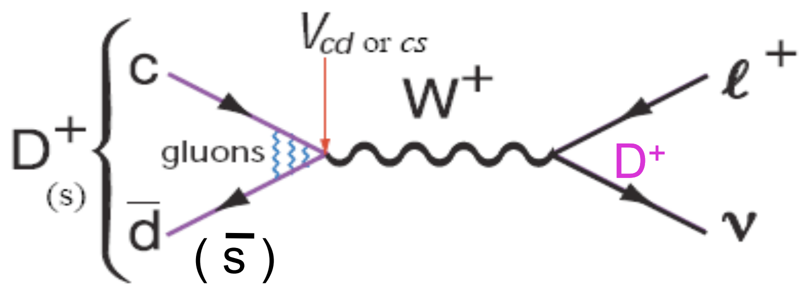
Very well known (~0.3%), since observation of B_s mixing

$$\text{Length} = (f_{B_s}\sqrt{B_{B_s}}) / (f_{B_d}\sqrt{B_{B_d}}) \sqrt{(\Delta m_d\, m_{B_d} / \Delta m_s\, m_{B_s})} = |V_{td}/V_{ts}|$$

Highly desirable to cross-check lattice against experiment in the D system!

Leptonic D Decays and Decay Constants

In D^+ and D_s c and spectator quark can annihilate to produce leptonic final state:



In general, for all pseudoscalars:

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

Since V_{cd} and V_{cs} well known, can extract f_D & f_{Ds} and compare with lattice calculation

Measurement modes are

- $D^+ \to \mu^+\nu$ PRD **78** 052003 (2008)
- $D_s^+ \to \mu^+\nu$ PRD **79** 052001 (2009)
- $D_s^+ \to \tau^+\nu$ $(\tau^+ \to \pi^+\bar{\nu})$ PRD **79** 052001 (2009)
- $D_s^+ \to \tau^+\nu$ $(\tau^+ \to e^+\nu\bar{\nu})$ PRD **79** 052002 (2009)
- $D_s^+ \to \tau^+\nu$ $(\tau^+ \to \rho^+\bar{\nu})$ PRD **80** 112004 (2009) [NEW]

$D_s \to \mu^+\nu$

Best Measured at Threshold

$D \to \mu^+\nu$, $D \to \tau^+\nu$ & $D_s \to \tau^+\nu$

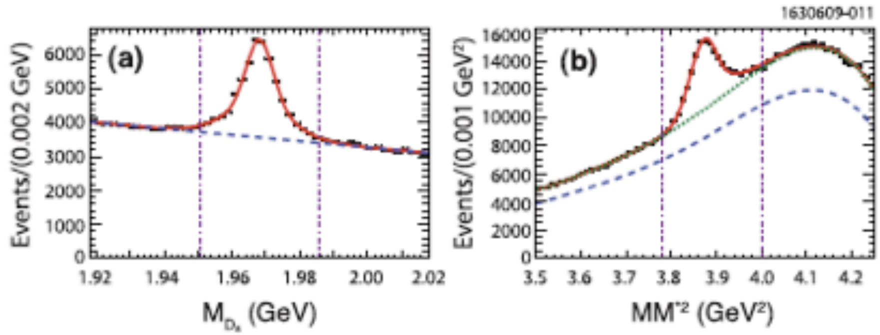
Only Measured at Threshold

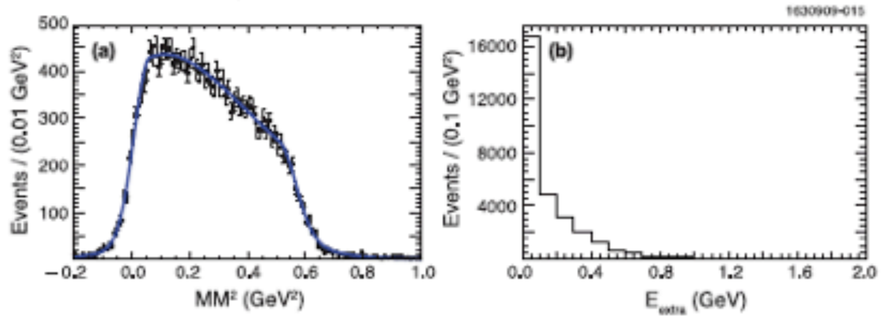
Also interested in ratios

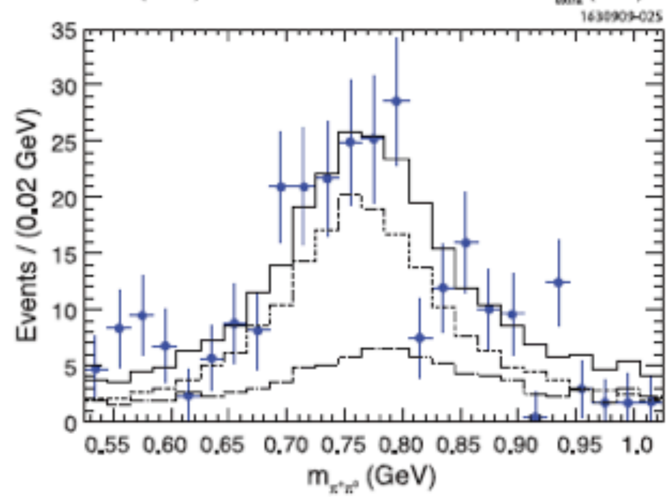
$D_{(s)} \to \mu^+\nu / D_{(s)} \to \tau^+\nu$

CLEO-c $D_s^+ \to \tau^+\nu \to (\rho^+\nu)_{\tau^+}\nu$

- $\mathcal{B}(\tau^+ \to \pi^+\pi^0\bar{\nu}) = 26\%$: 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

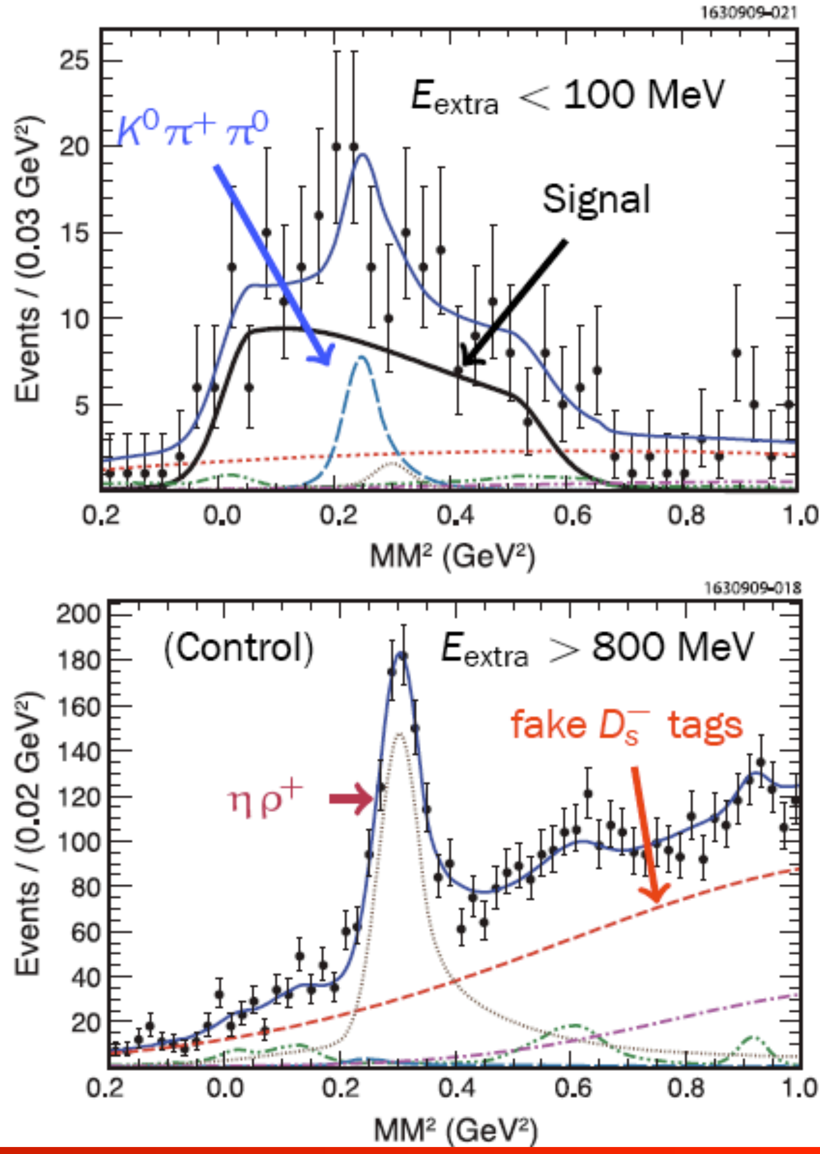






CLEO-c $D_s^+ \to \tau^+\nu \to (\rho^+\nu)_{\tau^+}\nu$

- 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 $E_{\text{extra}} \in [100, 200]$ MeV



Test of Lattice: CLEO-c Combined Leptonic Results

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

Average:

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

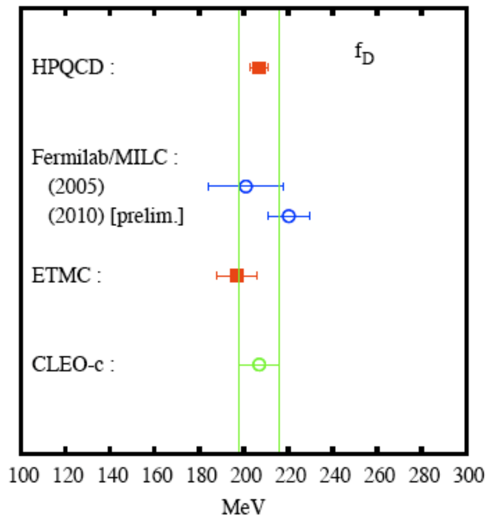
Also from CLEO-c:

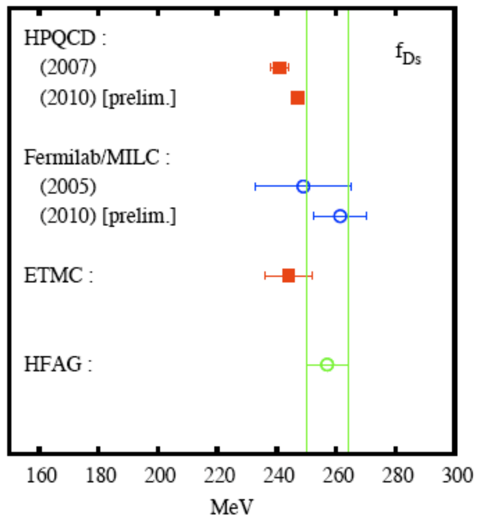
PRD **78** 052003 (2008)

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

Latest Theory

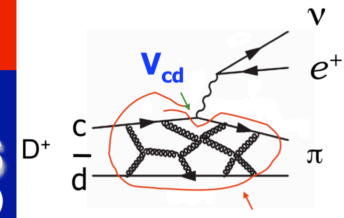
	Fermi-Milc (2005)	Fermi-Milc (2010)	HPQCD (2007)	HPQCD (2010)	ETMC (2 flavors of sea q)
f_{D^+}	207±3±17	220.3±8.0±4.8	207±4		197±9
f_{Ds}	249±3±16	261.4±7.7±5.0	241±3	247±2	244±8





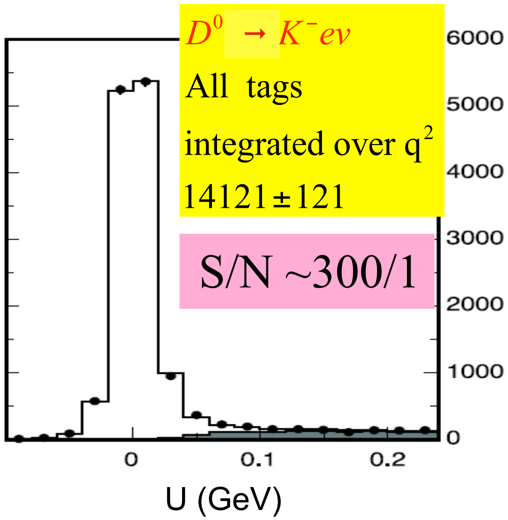
Test of Lattice: $D^0 \rightarrow \{K/\pi\}^- e^+ \nu$ Form Factors

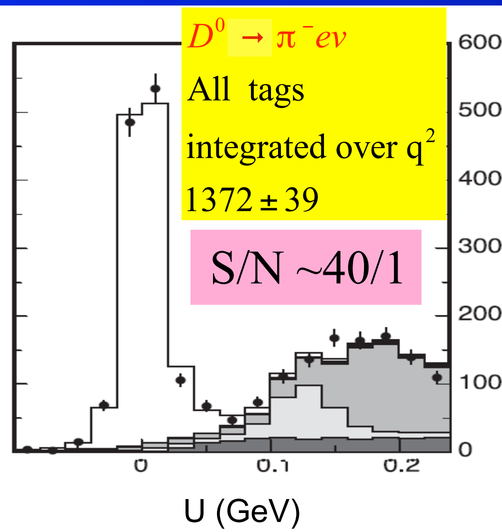
Phys. Rev. D 80, 032005 (2009)

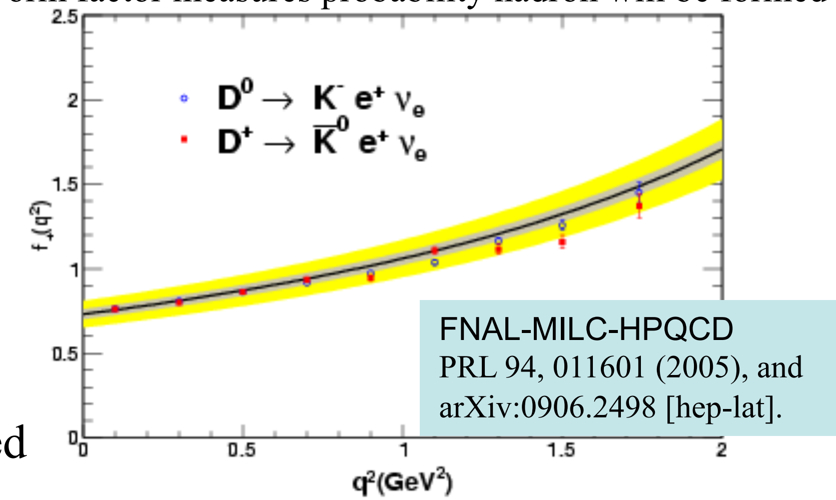


$$\frac{d\Gamma}{dq^2} = \frac{G_F^2}{24\pi^3} P_K^3 \left| f_+(q^2) \right|^2 \left| V_{cs} \right|^2$$

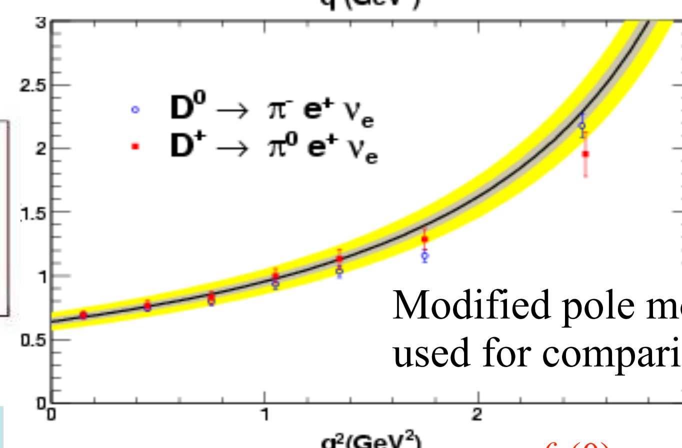
Form factor measures probability hadron will be formed







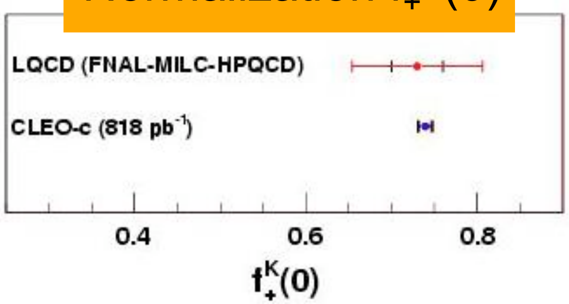
- Binned likelihood fits to U distributions are performed in each q^2 bin and each tag mode $q^2 = m_W^2 = (P_e + P_\nu)^2$



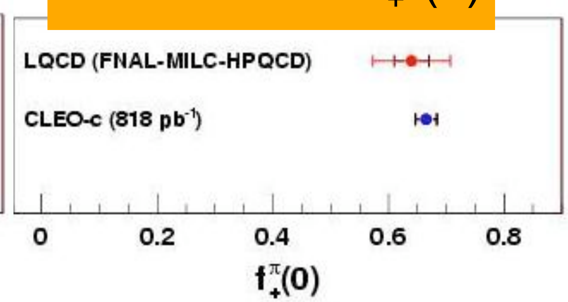
Modified pole model used for comparison

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

Normalization $f_+^K(0)$



Normalization $f_+^\pi(0)$



Shape: experiments compatible with LQCD.
Normalization: experiments (1.2% for $K^- e\nu$ and 2.0% for $\pi^- e\nu$) consistent with LQCD (10%).

|V_{cs}| & |V_{cd}| Results

Phys. Rev. D 80, 032005 (2009)

500th CLEO Publication: 100 authors, 21 Institutions

CLEO-c: the most precise *direct* determination of V_{cs}

$$\sigma(|V_{cs}|)/|V_{cs}| \sim 1.1\%(\text{expt}) \oplus 10\%(\text{theory})$$

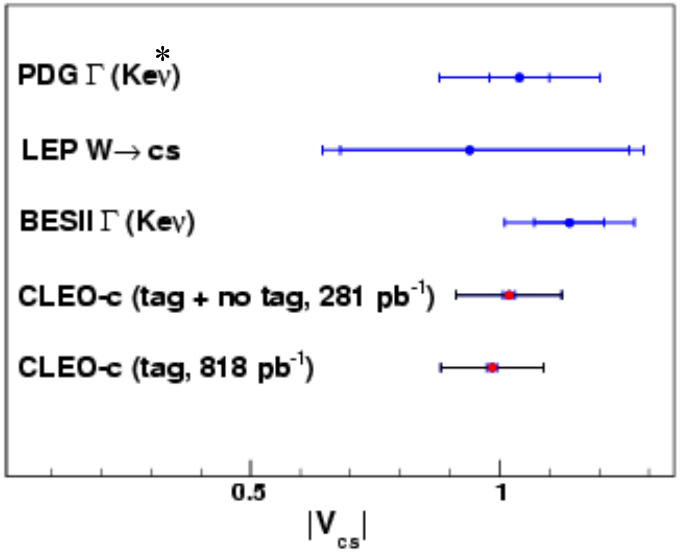
$CLEO-c$	$\lvert V_{cs} \rvert$
$(818\ \text{pb}^{-1})$	$0.985 \pm 0.009 \pm 0.006 \pm 0.103$
	stat syst theory

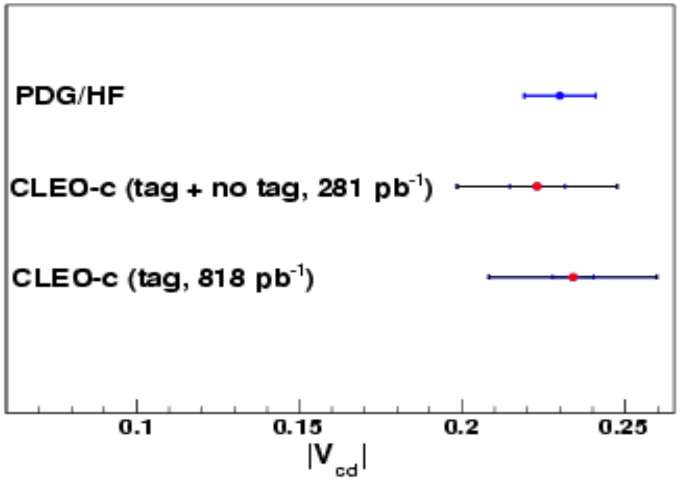
CLEO-c: $\sigma(|V_{cd}|)/|V_{cd}| \sim 3.1\%(\text{expt}) \oplus 10\%(\text{theory})$

$CLEO-c$	$\lvert V_{cd} \rvert$
$(818\ \text{pb}^{-1})$	$0.234 \pm 0.007 \pm 0.002 \pm 0.025$
	stat syst theory

* PDG2000

LQCD form factors with improved precision are eagerly awaited!





Fits use Becher-Hill z-expansion

Summary

Hadronic Decays: Absolute branching fractions, inclusive yields from D_s, exclusive $D^0/D^+/D_s \to PP$, exclusive $D_s \to \omega$, Dalitz plots, DCS decays, symmetry tests

CP Violation: Experiments entering interesting territory due to data driven estimates of systematic uncertainties. CLEO D decays will have an impact.

Charm Mixing: Discovery of D^0-$\bar{D}^0$ oscillation points way forward to searches for CPV & New Physics.

Rare Charm Decays: Experiments entering interesting territory - expect more results soon from CLEO, BESIII, B-factories & Tevatron that provide constraints on New Physics.

Precision CKM Tests: Success of the B-factories and the Tevatron has meant that unitarity triangle tests are entering a new, precision era. Charm input is a vital ingredient.

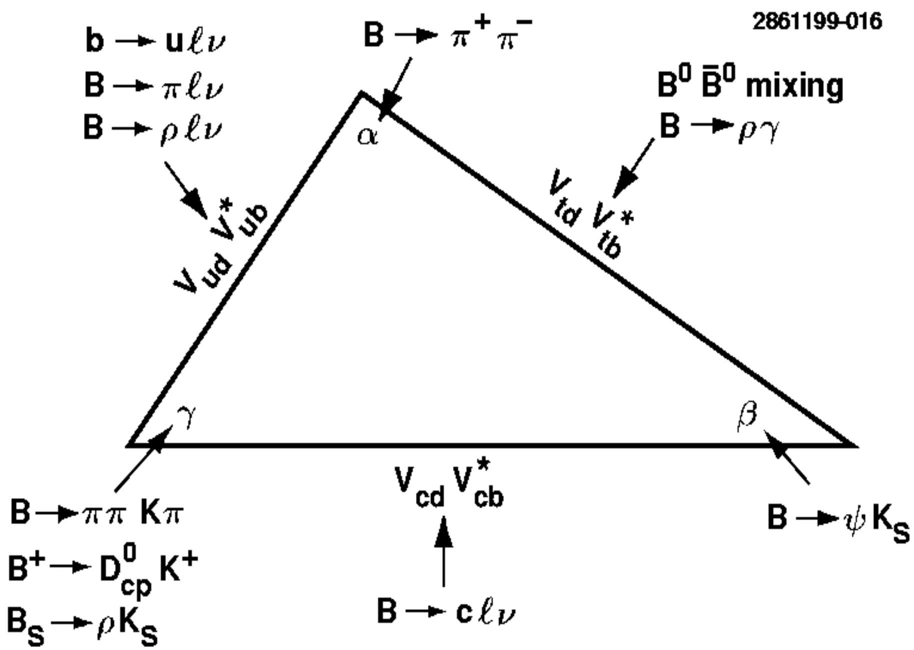
CLEO-c has made many advances in Open Charm physics.
More physics results from us in 2010 and 2011!

Additional slides

Charm Impact on CKM

- Charm impact on measurements of γ/ϕ_3 with $B\to DK$
- Lattice QCD tests in Charm sector

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$



Rare Charm Processes

- Charm provides constraints on beyond SM physics that are distinct from B and K sectors
- Only now are experiments reaching “interesting” sensitivity

- Rare Decays = Search for New Physics
- **Charm Mixing → Constraints on New Physics**
- **CP Violation = Search for New Physics**

CPV Searches in CLEO study of $D^+ \rightarrow K^+K^-\pi^+$

Singly Cabibbo Suppressed (SCS) decays

Interference between tree & penguin can generate direct CP asymmetries which:

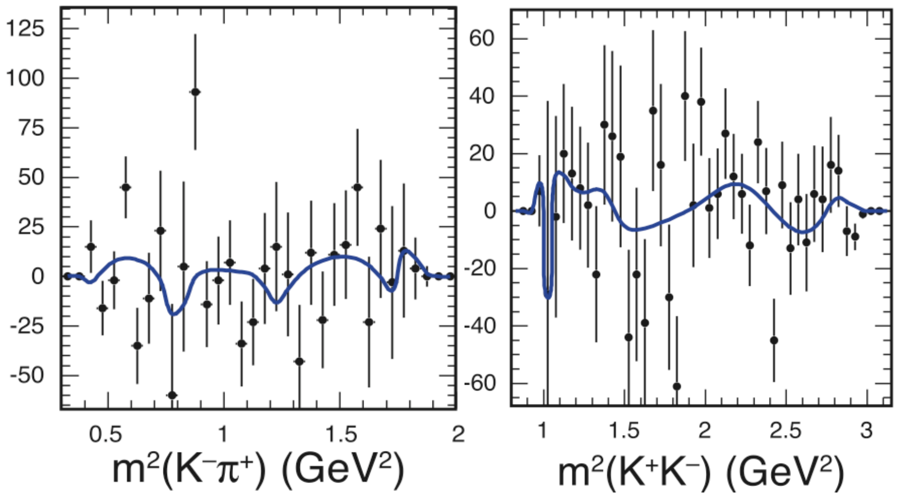
- Could reach $\sim 10^{-3}$ in SM - may be observable!
  - In NP models effects of $\sim 10^{-2}$ possible

    (Grossman, Kagan, Nir, PRD 75 (2007) 036008)

Analysis with high sensitivity:

- Compare amplitude fits of D^+ & D^- Dalitz plot (model dependent)

CLEO-c 818 pb^{-1} PRD78:072003,2008



Hadronic D/D_s Decays

- Absolute Branching Fractions
  - $D^0 \to K\pi$, $D^+ \to K\pi\pi$, $D_s \to KK\pi$
- **"Complete Set" of PP**
  - **$D^0/D^+/D_s \to PP$ with $P = K^\pm, K_S, K_L, \pi^\pm, \pi^0, \eta, \eta'$**
- **Inclusive D_s Rates**
- **Exclusive $D_s \to \omega$**
- Baryonic D_s Decay
- Dalitz plots

Already discussed
CP Violation
CKM phase γ
Charm Mixing

Comprehensive Analysis of $D^0/D^+/D_s \to PP$

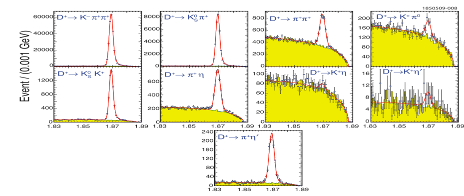
with $P = K^\pm, K_S, \pi^\pm, \pi^0, \eta, \eta'$ – not K_L

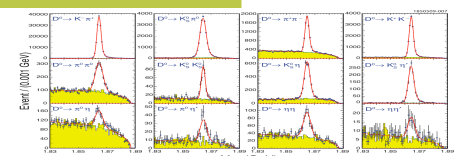
$\pi^0 \to \gamma\gamma$, $K_S \to \pi^+\pi^-$, $\eta \to \gamma\gamma$, $\eta' \to \pi\pi\eta$

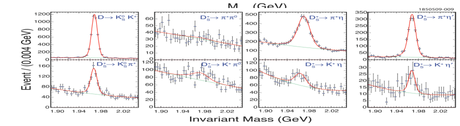
3 Normalization modes
3 Upper limits
23 Branching Fractions

9 D^+ modes
12 D^0 modes
8 D_s modes

Subm. to PRD ArXiV:0906.3198





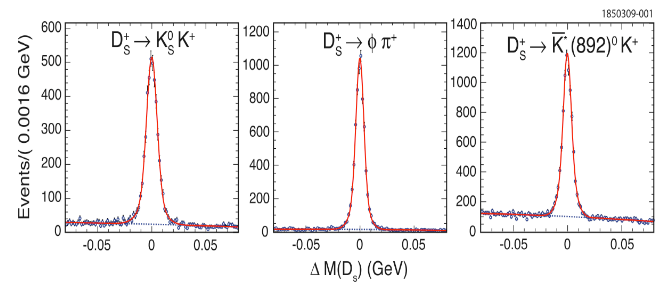


Inclusive D_s Rates

Mode	Yield(%)	K_L^0 Mode	Yield(%)	$\mathcal{B}$(PDG)(%)	prediction based on summing excl. rates [1]
$D_s^+ \to \pi^+ X$	$119.3 \pm 1.2 \pm 0.7$				125.5 ±11.1
$D_s^+ \to \pi^- X$	$43.2 \pm 0.9 \pm 0.3$				46.6±6.8
$D_s^+ \to \pi^0 X$	$123.4 \pm 3.8 \pm 5.3$				112.5±8.0
$D_s^+ \to K^+ X$	$28.9 \pm 0.6 \pm 0.3$			$20\ ^{+18}_{-14}$	27.3 ± 1.4
$D_s^+ \to K^- X$	$18.7 \pm 0.5 \pm 0.2$			$13\ ^{+14}_{-12}$	18.4±0.7
$D_s^+ \to \eta X$	$29.9 \pm 2.2 \pm 1.7$				32.7 ± 2.9
$D_s^+ \to \eta' X$	$11.7 \pm 1.7 \pm 0.7$				18.2±2.1
$D_s^+ \to \phi X$	$15.7 \pm 0.8 \pm 0.6$				19.2±2.4
$D_s^+ \to \omega X$	$6.1 \pm 1.4 \pm 0.3$				0.8±0.1
$D_s^+ \to f_0(980)X, f_0(980) \to \pi^+\pi^-$	$< 1.3\%$ (90% CL)				
$D_s^+ \to K_S^0 X$	$19.0 \pm 1.0 \pm 0.4$	$D_s^+ \to K_L^0 X$	15.6 ± 2.0	20 ± 14	
$D_s^+ \to K_S^0 K_S^0 X$	$1.7 \pm 0.3 \pm 0.1$	$D_s^+ \to K_L^0 K_S^0 X$	5.0 ± 1.0		
$D_s^+ \to K_S^0 K^+ X$	$5.8 \pm 0.5 \pm 0.1$	$D_s^+ \to K_L^0 K^+ X$	5.2 ± 0.7		
$D_s^+ \to K_S^0 K^- X$	$1.9 \pm 0.4 \pm 0.1$	$D_s^+ \to K_L^0 K^- X$	1.9 ± 0.3		
$D_s^+ \to K^+ K^- X$	$15.8 \pm 0.6 \pm 0.3$				
$D_s^+ \to K^+ K^+ X$	$< 0.26\%$ (90% CL)				
$D_s^+ \to K^- K^- X$	$< 0.06\%$ (90% CL)				

K^o: 18.4±2.0, $\bar{K}^o$ 22.7± 2.2

Phys. Rev. D. 79, 112008 (2009)

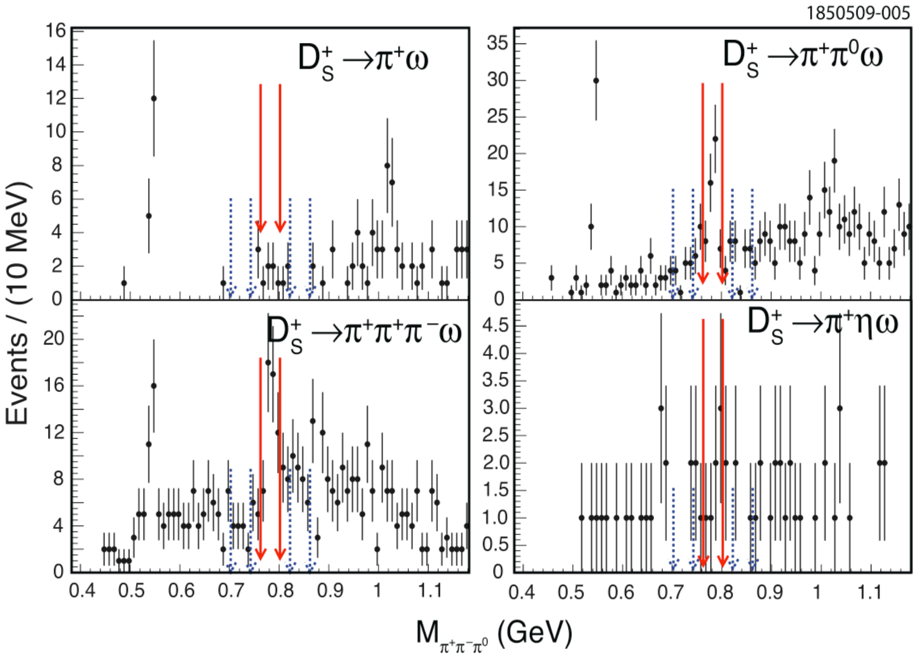


[1] Gronau,Rosner
arXiv:0903.2287
PRD79:074022,2009

$D_s \to \omega X$ Measured Inclusive (6.1±1.4±1.3)% Incl.Estimate from Excl. (0.8±0.1)%

D_s Exclusive Decays with an ω

- Inclusive Branching Fraction $D_s \to \omega X$ is (6.1±1.4)%
  - unexpectedly large
- Previously only excl. mode observed $D_s \to \pi^+\omega$ (0.25±0.09)%
- Use 18,586±163 D_s tags
  - $D_s \to K_S K$, $\phi\pi$, K^*K
- Sum of exclusive rates consistent with inclusive
  - (5.4±1.0)%
  - Expect $D_s \to \pi^+\pi^0\pi^0\omega$ O(1%)
- Phys.Rev.D80:051102,2009 arXiv:0906.2138



Mode	$\mathcal{B}_{\rm mode}(\%)$
$D_s^+ \to \pi^+\omega$	$0.21 \pm 0.09 \pm 0.01$
$D_s^+ \to \pi^+\pi^0\omega$	$2.78 \pm 0.65 \pm 0.25$
$D_s^+ \to \pi^+\pi^+\pi^-\omega$	$1.58 \pm 0.45 \pm 0.09$
$D_s^+ \to \pi^+\eta\omega$	$0.85 \pm 0.54 \pm 0.06$
	< 2.13 (90% CL)
$D_s^+ \to K^+\omega$	< 0.24 (90% CL)
$D_s^+ \to K^+\pi^0\omega$	< 0.82 (90% CL)
$D_s^+ \to K^+\pi^+\pi^-\omega$	< 0.54 (90% CL)
$D_s^+ \to K^+\eta\omega$	< 0.79 (90% CL)