Physics at Charm Threshold: Recent Results from CLEO-c & CESR-c & Prospects for BESIII

David Asner, *Carleton University*

9 Oct 2006, presented at the
4th meeting of
FLAVOUR IN THE ERA OF THE LHC

What We Hope to Learn - I

- Precision CKM
    - Over constrain CKM with results from B-sector
    - Inconsistencies indicate New Physics
    - Precision charm measurements required for precision CKM results in B sector
  - Leptonic Charm Decays $D\to\ell^+\nu$: Check QCD calculations including Lattice (LQCD)
    - Measure decay constants fD, fDs
    - Improved f_B possible from f_D measurement + LQCD
    - Important for $|V_{td}|$ and $|V_{ts}|$
  - Semileptonic decay rates & form-factors: Check QCD calculations
    - Measurements of $|V_{cs}|$ and $|V_{cd}|$
    - Test theoretical form factor models in D meson decays
    - Impacts prediction of form factors for B meson decays
    - Important for $|V_{ub}|$ and $|V_{cb}|$
  - Hadronic Charm Decays
    - Important for $|V_{cb}|$
    - Engineering numbers useful for other studies
      - B→Charm is dominant, so knowing lots about charm is useful, e.g. absolute $\mathcal{B}$'s, resonant substructure, phases on Dalitz plots, especially versus CP eigenstates
    - Important for β and γ
    - Learn about Strong Interactions, esp. final state interactions
- Lots of new CLEO-c results. Only time for the high-lights

What We Hope to Learn - II

- Search for New Physics in Charm Sector
    - Very low SM rates for loop processes provide unique window to observe NP in rare charm processes (rare decays, CPV & mixing)
        - NP can introduce new particles into loop
    - Different sensitivity to NP than B and K sectors
        - Particles & couplings in rare charm processes are NOT the same as in rare B, K
    - Rare Charm Decays
        - FCNC decays only occur in loop diagrams in SM: heavily GIM suppressed: BF($c \to ull$)~10^{-8}
    - Charm Mixing
        - Mixing is Double Cabibbo suppressed & GIM mechanism suppressed
        - In SM $x \equiv \Delta m/\Gamma \leq y \equiv \Delta\Gamma/2\Gamma$
        - Short distance 10^{-6} - 10^{-3}, Long distance 10^{-3} - 10^{-2}
        - New physics in loops implies $x >> y$; long range effects complicate predictions.
        - Large CPV in mixing indicates NP
    - CP Violation - Direct
        - CF & DCS decay: Direct CPV requires New Physics
            - Exception: interference between CF & DCS amplitudes to $D^{\pm} \to K_{S,L}\pi^{\pm}$
            - SM contribution due to K^0 mixing is $A_S=[+]_S-[-]_S \sim -3.3\times10^{-3}; A_S = -A_L$
            - New Physics could be ~%
        - SCS decay
            - expect $O(\lambda^4) \sim 10^{-3}$ from CKM matrix
            - New Physics could be ~%
- No new CLEO-c results. I'll mention prospects for BESIII in conclusion

Absolute Charm Branching Fractions

- $D\bar{D}$ production at threshold: used by Mark III, & more recently by CLEO-c & BESII.
  - Unique event properties
    - ➢Only $D\bar{D}$ not $D\bar{D}x$ produced
  - Large cross sections:

$\sigma(D^0\bar{D}^0)$ = 3.72±0.09 nb

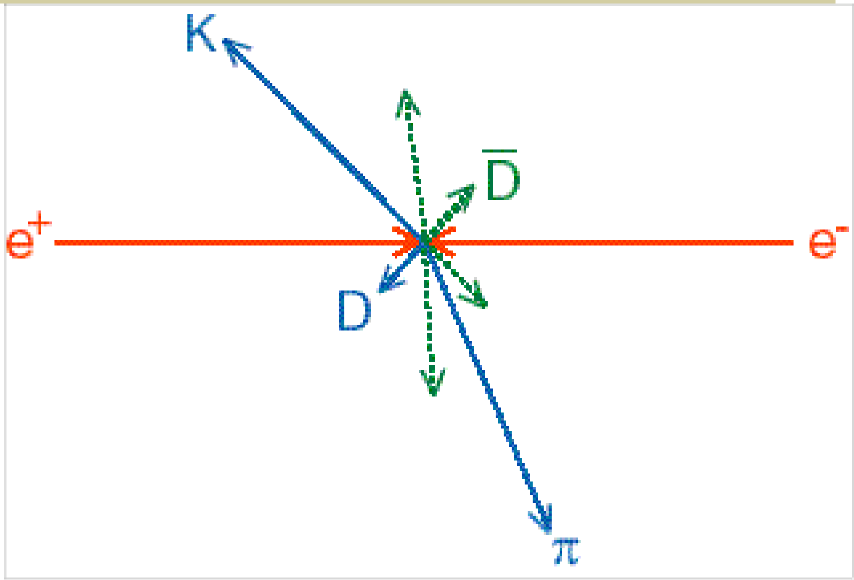
$\sigma(D^+D^-)$ = 2.82±0.09 nb

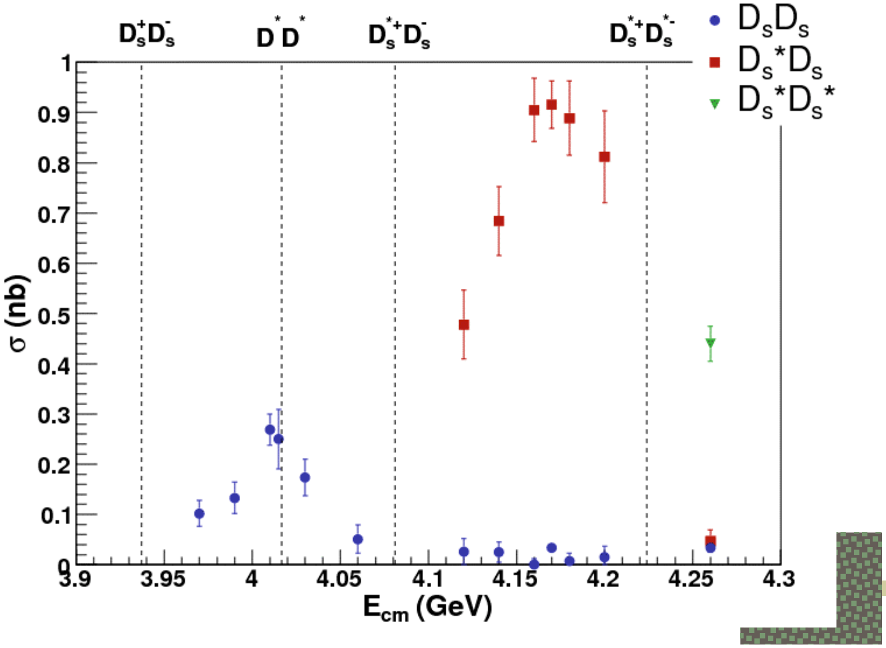
} World Ave

$\sigma(D_sD_s^*)$ = 0.9 nb

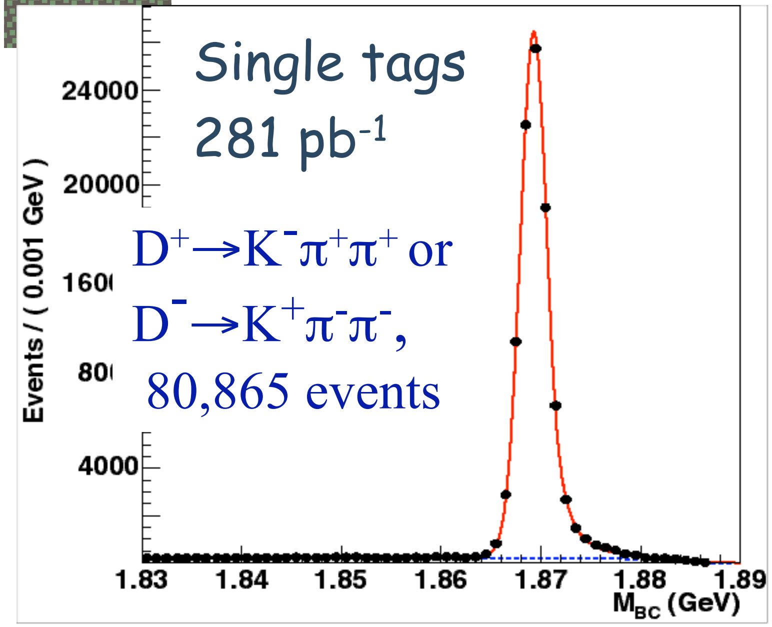
Continuum ~14 nb

- Ease of $\mathcal{B}$ measurements using "double tags"
- $\mathcal{B}_A$ = # of A/# of D's





D+→K-π+π+ at the ψ" (CLEO-c)



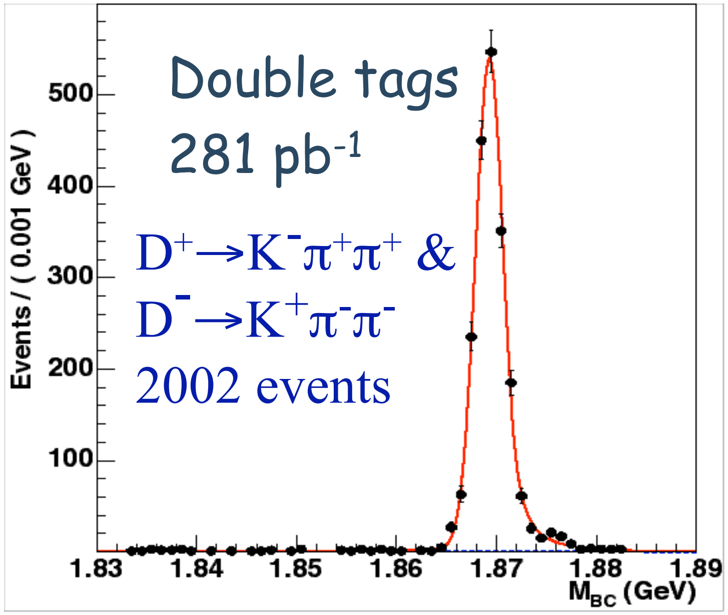
Single tags

281 pb^{-1}

$D^+ \to K^-\pi^+\pi^+$ or

$D^- \to K^+\pi^-\pi^-$,

80,865 events



Double tags

281 pb^{-1}

$D^+ \to K^-\pi^+\pi^+$ &

$D^- \to K^+\pi^-\pi^-$

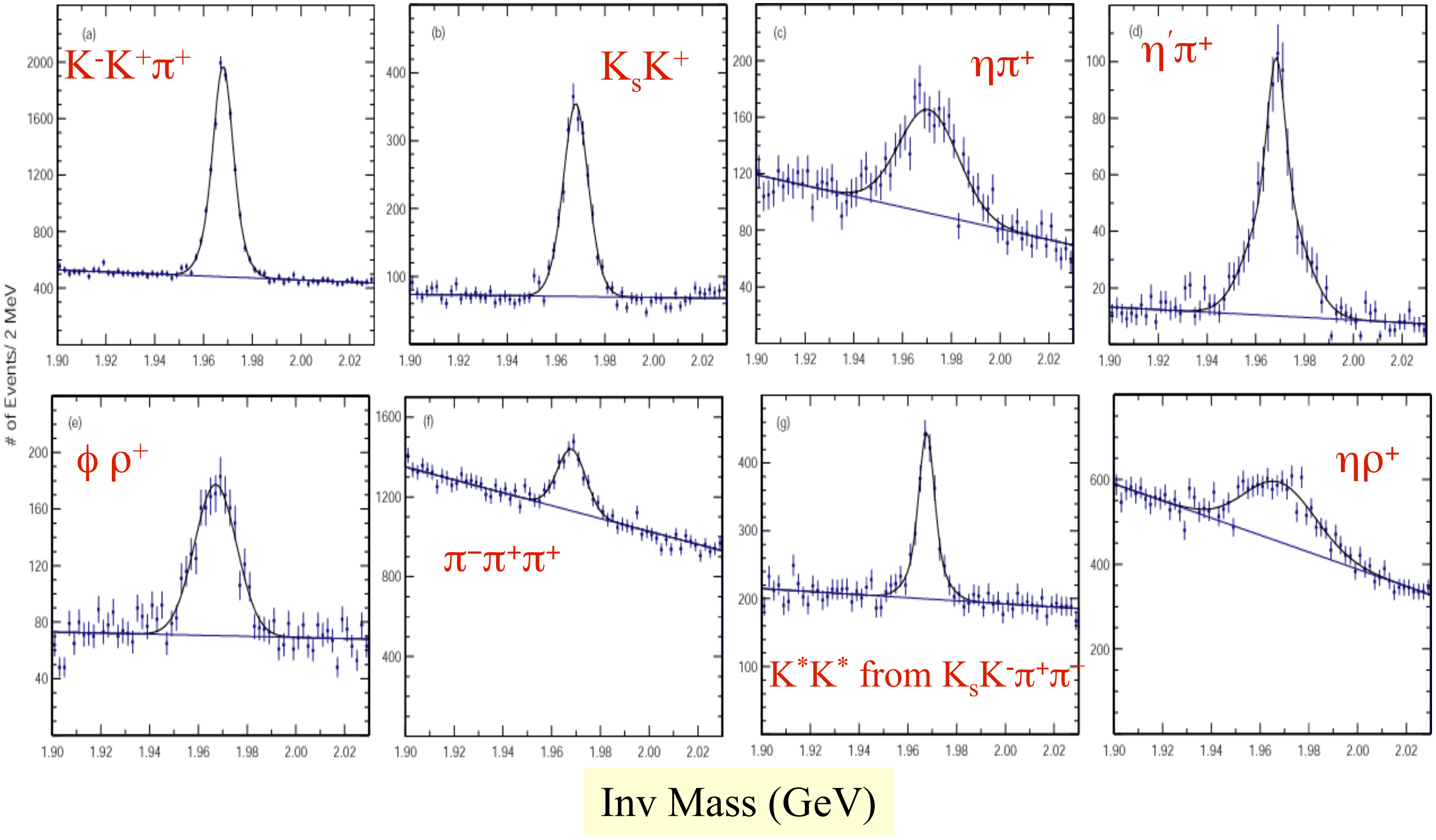
2002 events

$\mathcal{B}$ (%)	Error(%)	Source
9.52 ±0.25±0.27	3.9	CLEO-c (57 pb^{-1})
9.2±0.6	6.5	PDG04
9.51 ±0.34	3.6	PDG06

$\mathcal{B}$ (%)	Error(%)	Source
3.91±0.08 ±0.09	3.1	CLEO-c (57 pb^{-1})
3.81±0.09	2.4	PDG04
3.80 ±0.07	1.8	PDG06

For 281pb^{-1} (systematics limited):
2.2% projected error 1.8% projected error

CLEO-c D_s^+ Results at 4170 MeV



Total # of Tags = 19185 ± 325 (stat)

Single & Double D_S^+ Tags in 200 pb^{-1}

Single tags

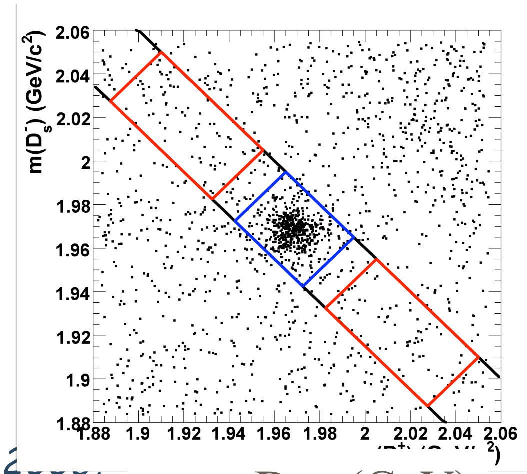
	$K_S K^+$	$K^- K^+ \pi^+$	$K^- K^+ \pi^+ \pi^0$	$\pi^+ \pi^+ \pi^-$	$\pi^+ \eta$	$\pi^+ \eta'$
D_s^+	1054.8 ± 39.4	4315.8 ± 88.8	1159.7 ± 84.5	969.5 ± 79.5	547.0 ± 49.8	361.8 ± 23.4
D_s^-	927.8 ± 37.3	4349.7 ± 88.7	1250.6 ± 84.4	946.7 ± 77.7	569.8 ± 49.7	371.5 ± 23.6

Double tags

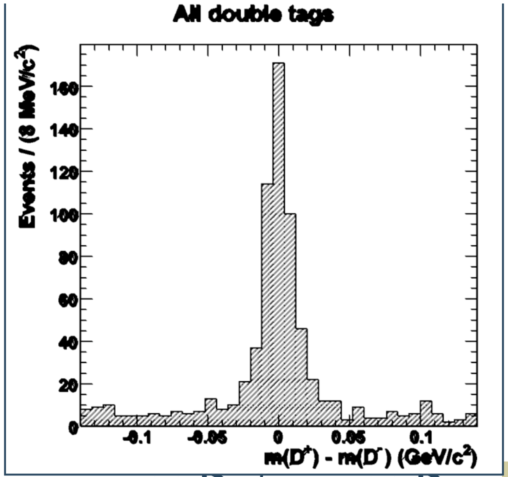
	$K_S K^-$	$K^+ K^- \pi^-$	$K^+ K^- \pi^- \pi^0$	$\pi^- \pi^- \pi^+$	$\pi^- \eta$	$\pi^- \eta'$
$K_S K^+$	7.7	27.0	18.7	7.3	4.0	5.0
$K^- K^+ \pi^+$	18.0	104.7	43.7	30.7	12.0	8.0
$K^- K^+ \pi^+ \pi^0$	8.7	35.7	14.0	13.3	1.0	5.7
$\pi^+ \pi^+ \pi^-$	3.3	22.7	16.0	13.3	4.7	4.0
$\pi^+ \eta$	0.0	10.0	2.7	6.0	1.0	1.7
$\pi^+ \eta'$	3.0	10.0	3.0	3.7	1.0	0.0

Clean double tag signal

mass D_S^- (GeV)



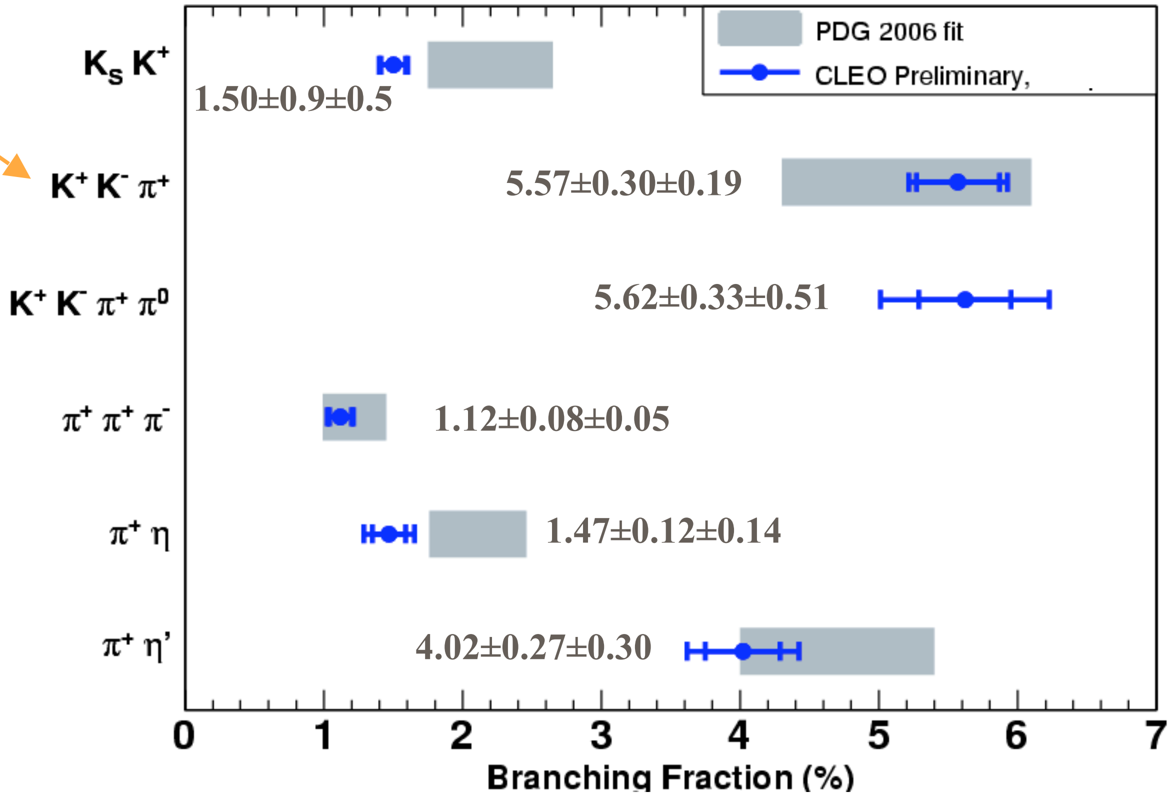
mass D_S+ (GeV)

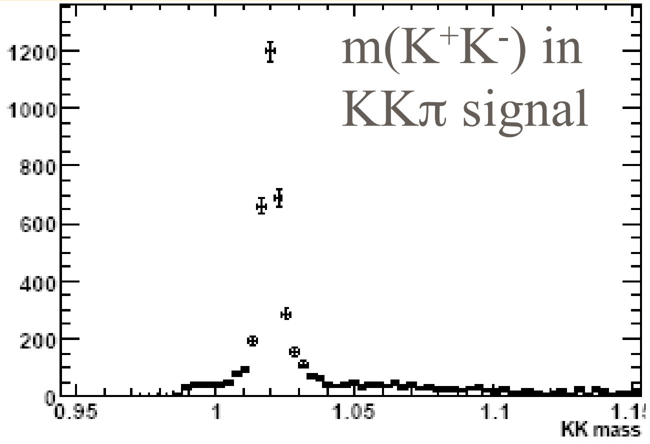


mass D_S^+-mass D_S^-

Absolute $\mathcal{B}$ Results for D_s^+ 200 pb^{-1}

- About ±6% error
- $D_s \rightarrow \phi\pi^+$ is difficult to quote because of interferences in KKπ Dalitz plot – K*K, f_0 π, etc…





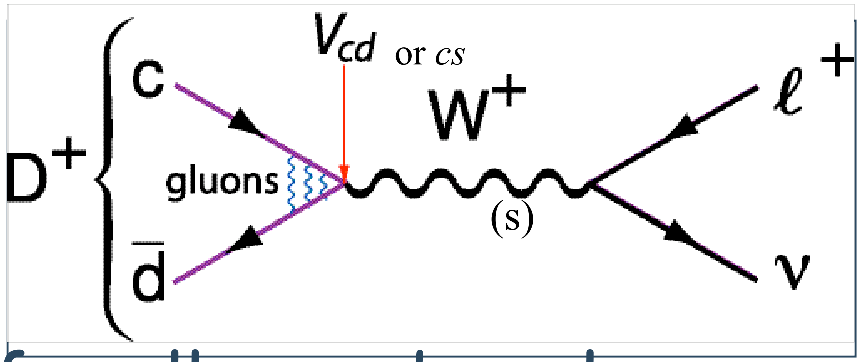
- Partial branching fraction ±10 MeV around m(φ): **1.98±0.12±0.09 %**
  ±20 MeV around m(φ): **2.25±0.13±0.12 %** (need x2 for $\phi \rightarrow K^+K^-$)

Leptonic Decays: $D_{(s)} \rightarrow \ell^+\nu$

Introduction: Pseudoscalar decay constants

c and q can annihilate, probability is ∝ to wave function overlap

Example :



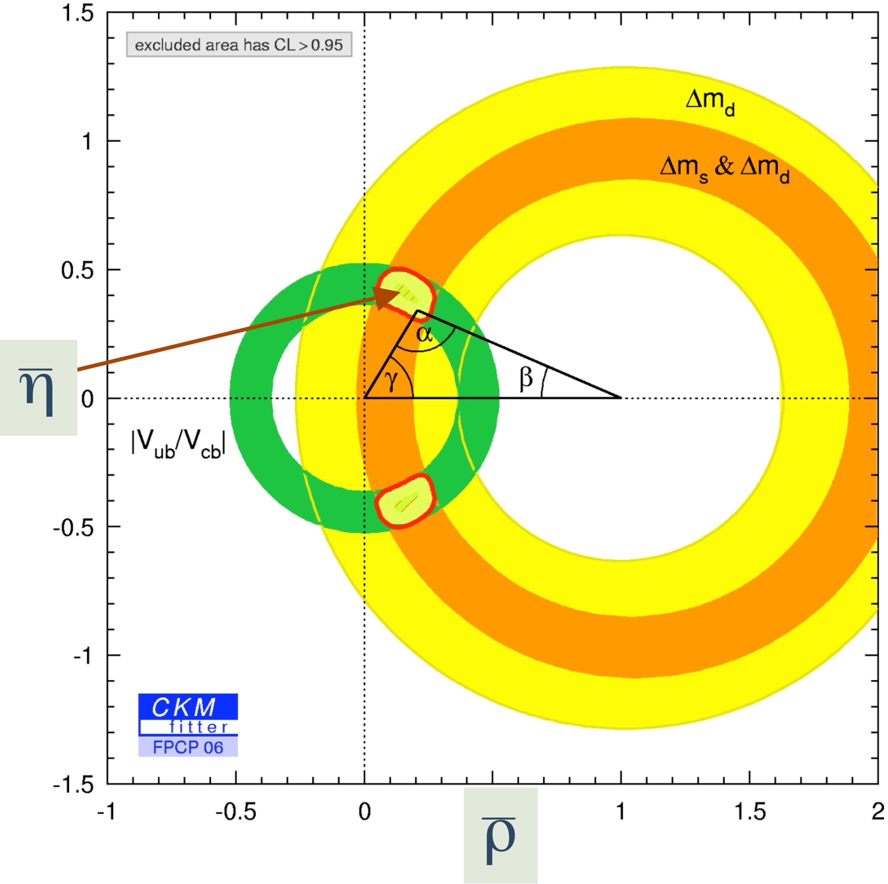
In general for all pseudoscalars:

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

Calculate, or measure if V_{Qq} is known

Goals in Leptonic Decays

- Test theoretical calculations in strongly coupled theories in non-perturbative regime
- f_B & f_{Bs}/f_B needed to improve constraints from Δm_d & $\Delta m_S/\Delta m_d$. Hard to measure directly (i.e. $B \rightarrow \tau^+ \nu$ measures $V_{ub} f_B$), but we can determine f_D & f_{Ds} using $D \rightarrow \ell^+ \nu$ and use them to test theoretical models (i.e. Lattice QCD)



Constraints from V_{ub}, Δm_d, Δm_s & $B \rightarrow \tau + \nu$

New Measurements of f_{Ds}

- Two separate techniques
  - (1) Measure $D_S^+ \to \mu^+\nu$ along with $D_S \to \tau^+\nu$, $\tau \to \pi^+\nu$.
    - Requires finding a D_S^- tag, a γ from either $D_s^{*-} \to \gamma\, D_s^-$ or $D_s^{*+} \to \gamma\, \mu^+\nu$. Then finding the muon or pion using kinematical constraints
  - (2) Find $D_S^+ \to \tau^+\nu$, $\tau \to e^+\nu\nu$ opposite a D_s^- tag

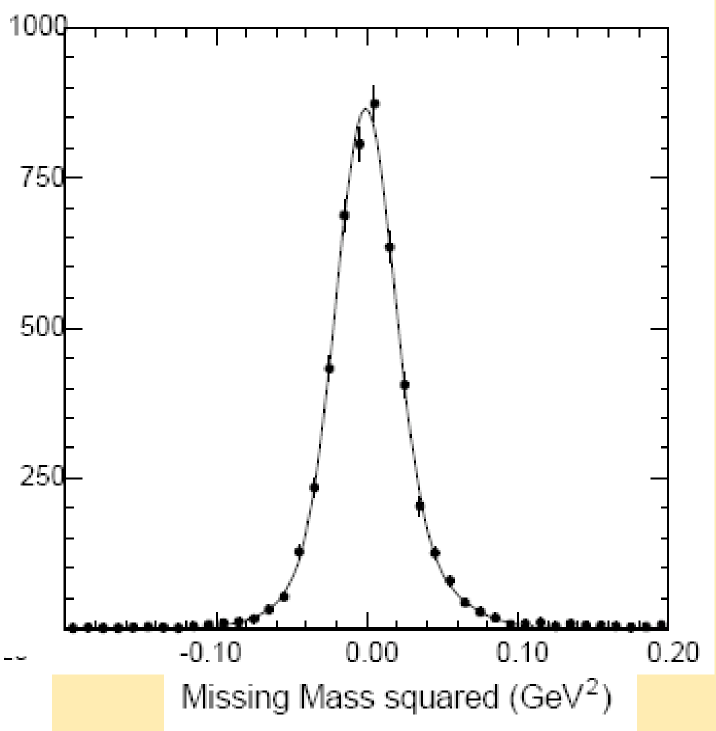
(1) Measurement of $D_S^+ \to \mu^+\nu$

- Use $D_S^* D_S$ events with detected γ from $D_S^* \to \gamma\, D_S$ decay
- Reconstruct all particles from $e^+e^- \to D_S^* D_S$, γ, D_S (tag) + μ^+ except for the ν
- Kinematic fit (i) improves resolution & (ii) remove ambiguities
  - Constraints include: total p & E, tag D_S mass, $\Delta m = M(\gamma D_S) - M(D_S)$ [or $\Delta m = M(\gamma\mu\nu) - M(\mu\nu)$] = 143.6 MeV, E of D_S (or D_S^*) fixed
  - Lowest χ^2 solution in each event is kept. No χ^2 cut is applied

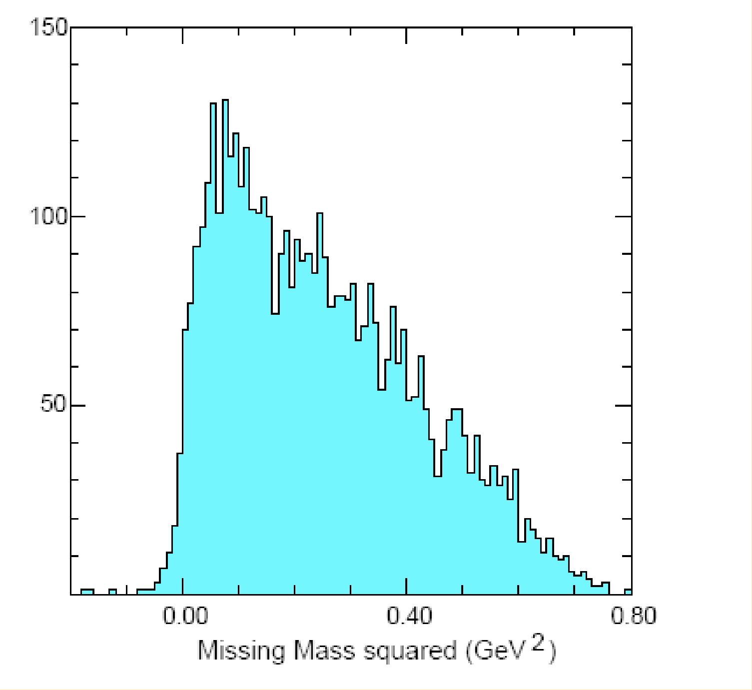
The MM^2

- To find the signal events, we compute

$$MM^2 = \left(E_{cm} - E_{D_s} - E_{\gamma} - E_{\mu}\right)^2 - \left(-\vec{p}_{D_s} - \vec{p}_{\gamma} - \vec{p}_{\mu}\right)^2$$



Signal μν



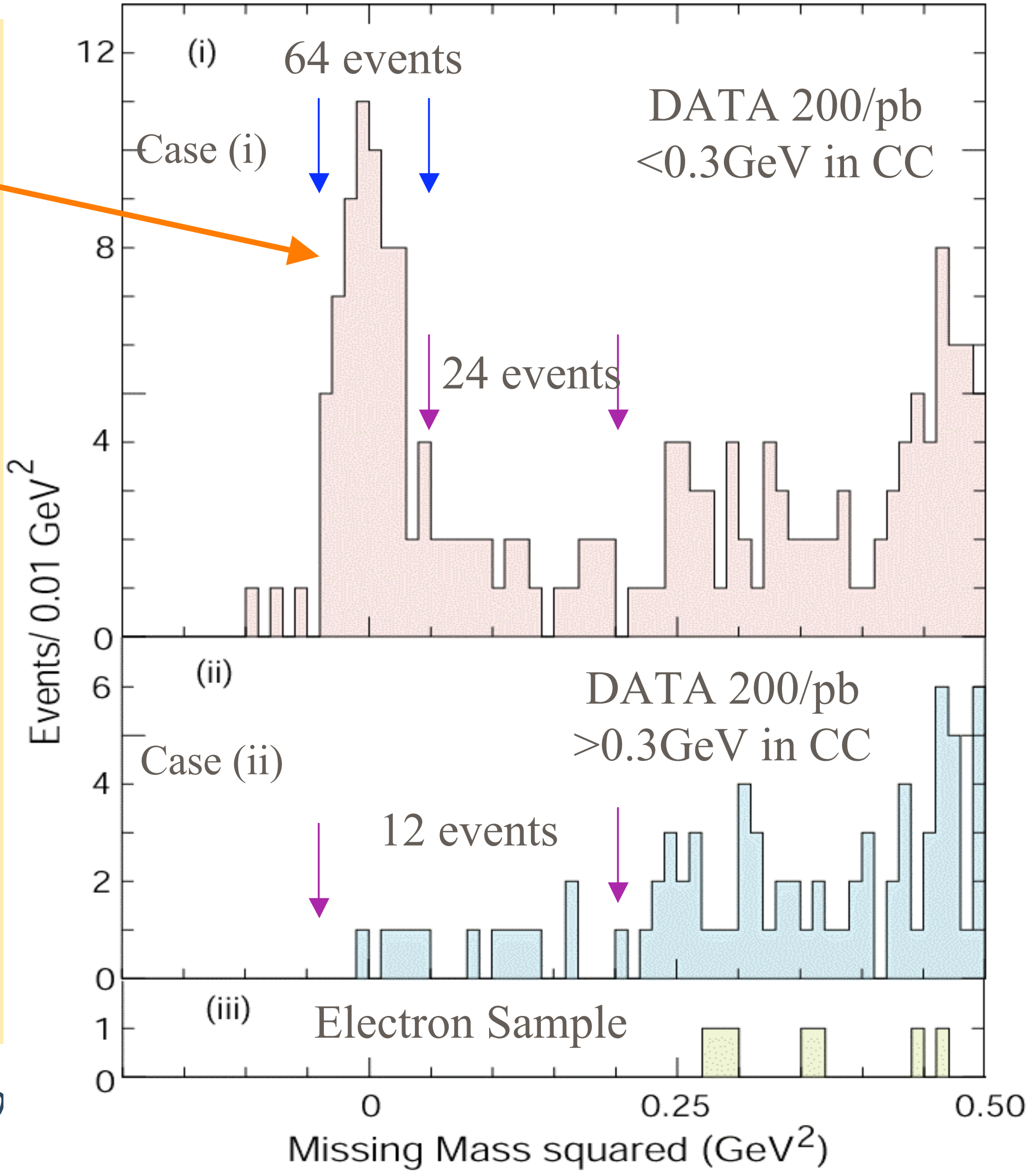
Signal τν, τ→πν

Define Three Classes

- Class (i), single track deposits < 300 MeV in calorimeter (consistent with μ) & no other γ > 300 MeV. (accepts 99% of muons and 60% of kaons & pions)
- Class (ii), single track deposits > 300 MeV in calorimeter & no other γ > 300 MeV (accepts 1% of muons and 40% of kaons & pions)
- Class (iii) single track consistent with electron & no other γ > 300 MeV

MM^2 Results from 200 pb^{-1}

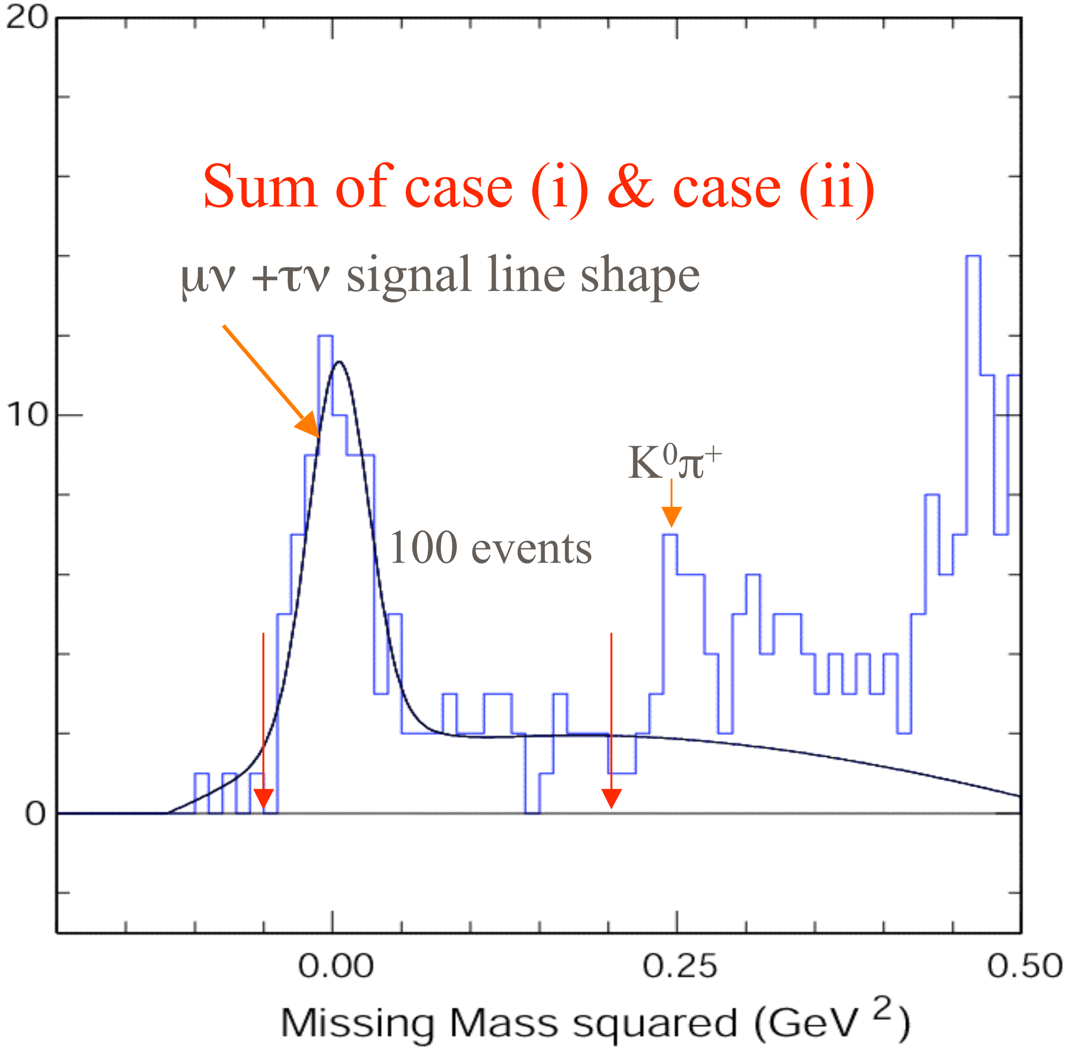
- Clear $D_S^+ \to \mu^+\nu$ signal for case (i)
- Will show that events <0.2 GeV^2 are mostly $D_S \to \tau^+\nu$, $\tau \to \pi^+\nu$ in cases (i) & (ii)
- No $D_S \to e^+\nu$ seen, case (iii)



Sum of $D_S^+ \to \mu^+\nu + \tau^+\nu,\ \tau \to \pi^+\nu$

Two sources of background

- A) Backgrounds under invariant mass peaks - Use sidebands to estimate
  - In $\mu^+\nu$ signal region 2 background (64 signal)
  - Sideband bkgd 5.5±1.9
- B) Backgrounds from real D_S decays, e.g.
  - $\pi^+\pi^o\pi^o$, or $D_S \to \tau^+\nu, \tau \to \pi^+\pi^o\nu$ ... with $MM^2 < 0.2$ GeV^2
  - none in $\mu\nu$ signal region.
  - Total of 1.3 additional events.
  - $B(D_S \to \pi^+\pi^o) < 1.1\times10^{-3}$ <0.1 evts
- Total background < 0.2 GeV^2 is 6.8 events, out of the 100



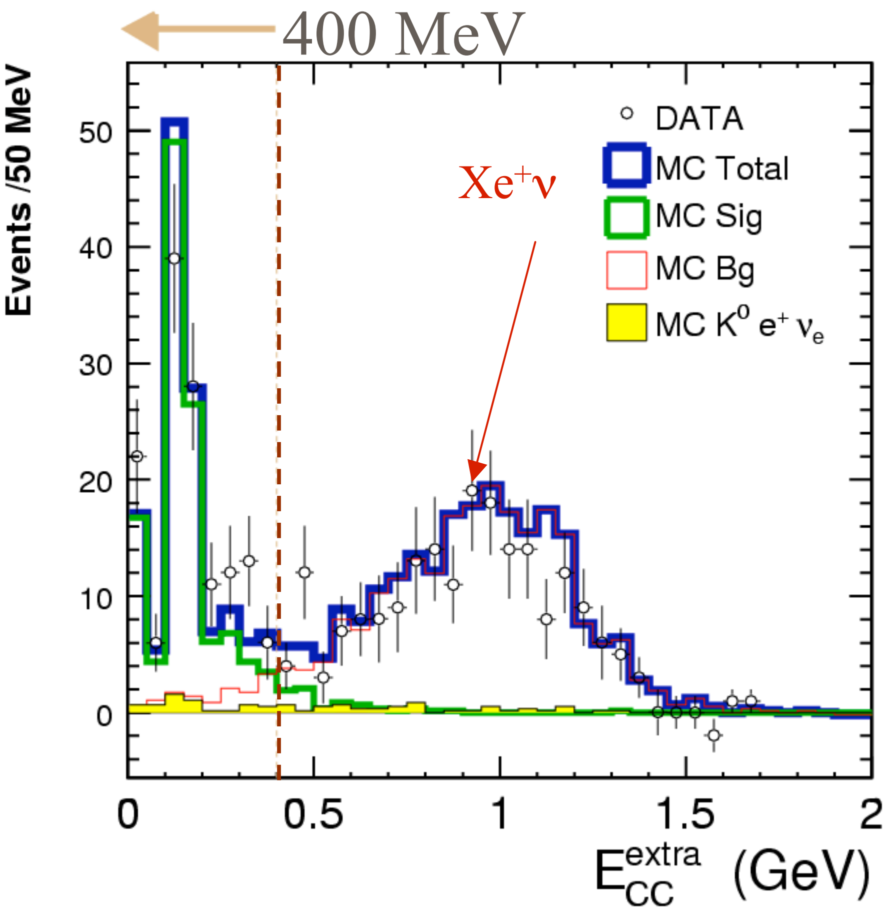
Branching Ratio & Decay Constant

- $D_S^+ \rightarrow \mu^+ \nu$
  - 64 signal events, 2 background, use SM to calculate $\tau\nu$ yield near 0 MM^2 based on known $\tau\nu/\mu\nu$ ratio
  - $B(D_S^+ \rightarrow \mu^+ \nu) = (0.657 \pm 0.090 \pm 0.028)\%$
- $D_S^+ \rightarrow \tau^+ \nu$, $\tau^+ \rightarrow \pi^+ \nu$
  - Sum case (i) $0.2 > MM^2 > 0.05$ GeV^2 & case (ii) $MM^2 < 0.2$ GeV^2. Total of 36 signal and 4.8 bkgrnd
  - $B(D_S^+ \rightarrow \tau^+ \nu) = (7.1 \pm 1.4 \pm 0.03)\%$
- By summing both cases above, find

  $B^{eff}(D_S^+ \rightarrow \mu^+ \nu) = (0.664 \pm 0.076 \pm 0.028)\%$
- $f_{Ds} = 282 \pm 16 \pm 7$ MeV
- $B(D_S^+ \rightarrow e^+ \nu) < 3.1 \times 10^{-4}$

Measuring $D_S^+\to\tau^+\nu$, $\tau^+\to e^+\nu\nu$

- $B(D_S^+\to\tau^+\nu)\bullet B(\tau^+\to e^+\nu\nu)\sim 1.3\%$ is "large" compared with expected $B(D_S^+\to Xe^+\nu)\sim 8\%$
- Technique is to find events with an e^+ opposite D_S^- tags & no other tracks, with Σ calorimeter energy < 400 MeV
- No need to find γ from D_S^*
- $B(D_S^+\to\tau^+\nu) = (6.29\pm0.78\pm0.52)\%$
- $f_{D_S}=278 \pm 17 \pm 12$ MeV



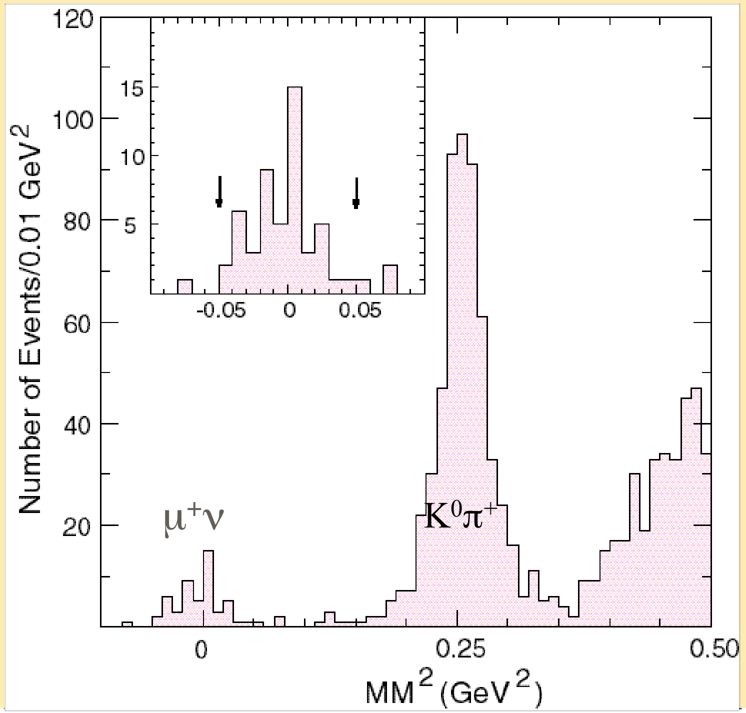
f_{Ds} & f_{Ds}/f_D

- Weighted Average: f_{Ds}=280.1±11.6±6.0 MeV, the systematic error is mostly uncorrelated between the measurements *(More data is on the way & systematic errors are being addressed)*
- Previously CLEO-c measured

[†] M. Artuso et al., Phys .Rev. Lett. 95 (2005) 251801

$$f_{D^+} = (222.6 \pm 16.7^{+2.3}_{-3.4})\ \mathrm{MeV}^{\dagger}$$

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



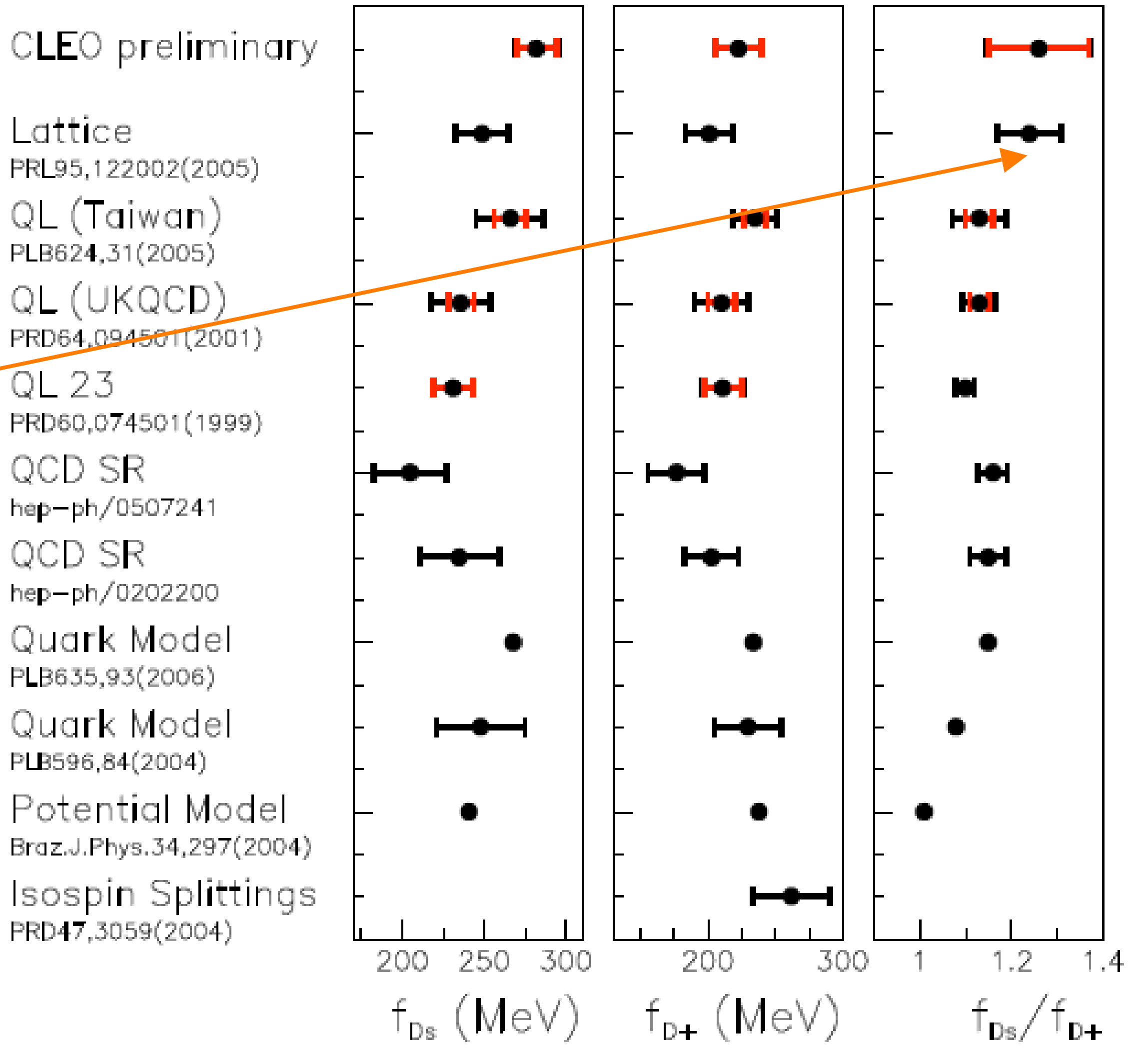
- Thus f_{Ds}/f_{D^+}=1.26±0.11±0.03
- $\Gamma(D_S^+ \to \tau^+\nu)/\Gamma(D_S^+ \to \mu^+\nu)$=

9.9±1.7±0.7, SM=9.72,

consistent with lepton universality

Comparisons with Theory

- Consistent with most models, more precision needed
- Using Lattice ratio find $|V_{cd}/V_{cs}| = 0.22 \pm 0.03$
- CLEO-c is most precise result to date for both f_{D_s} & f_{D^+}

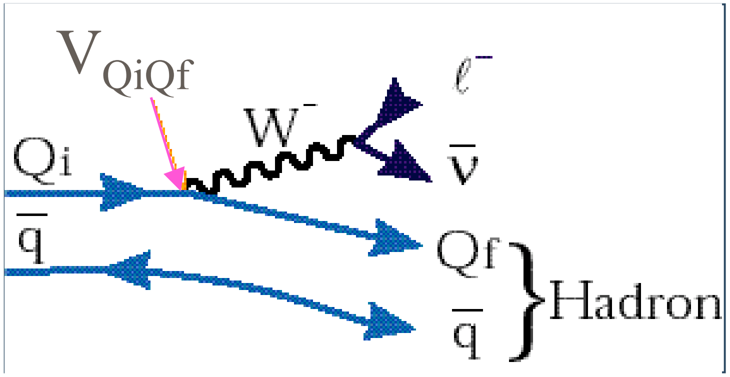


Goals in Semileptonic Decays

- Either take V_{cq} from other information & test theory, or use theory & measure V_{cq}
  - V_{cs} use $D \rightarrow K(K^*)l\nu$ to measure form-factor shapes to distinguish among models & test lattice QCD predictions
  - V_{cd} use $D \rightarrow \pi(\rho)l\nu$
- V_{cd} & V_{cs} with precise unquenched lattice calc + V_{cb} would provide an important unitarity check
- Use $D \rightarrow \pi l\nu$ (& $\rho l\nu$) to get form-factor for $B \rightarrow \pi l\nu$ (& $\rho l\nu$) and use HQET to get V_{ub}

Exclusive Semileptonic Decays

- Best way to determine magnitudes of CKM elements, in principle is to use semileptonic decays. Decay rate $\alpha|V_{QiQf}|^2$



- How V_{us} (λ) and V_{cb} (A) have been determined
- Kinematics:

$$q^2 = \left(p_D^\mu - p_{hadron}^\mu\right)^2 = m_D^2 + m_P^2 - 2E_P m_D$$

- Matrix element in terms of form-factors (for D→ Pseudoscalar l+ν

$$\left\langle P(P_P)\middle|J_\mu\middle|D(P_D)\right\rangle = f_+(q^2)(P_D + P_P)_\mu + f_-(q^2)(P_D - P_P)_\mu$$

- For $\lambda = e$, $f_-(q^2) \to 0$:

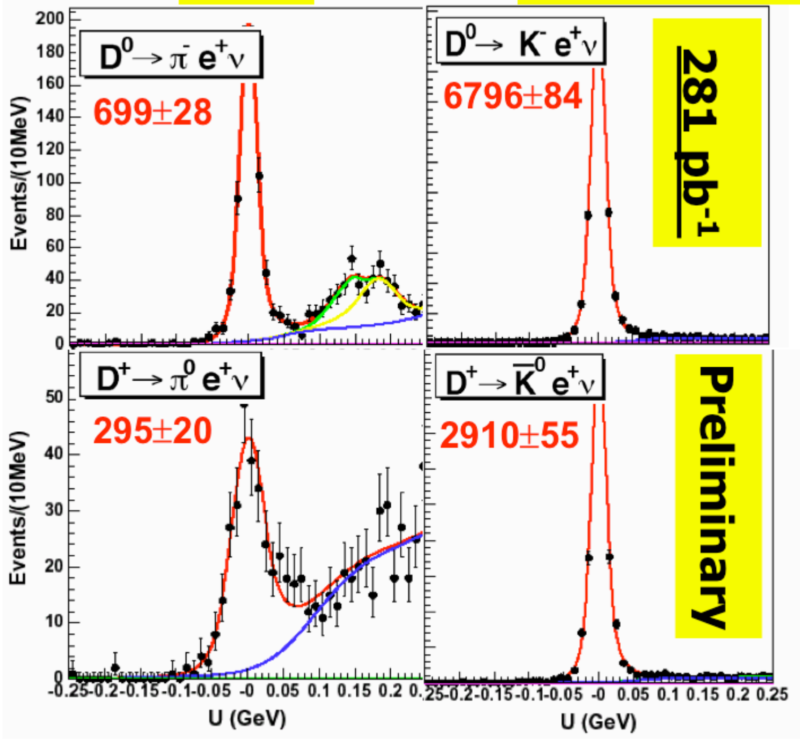
$$\frac{d\Gamma\left(D \to Pe\nu\right)}{dq^2} = \frac{\left|V_{cq}\right|^2 P_P^3}{24\pi^3}\left|f_+(q^2)\right|^2$$

$D^0/D^+ \to K/\pi e\nu$ Tag & Untag

Tag

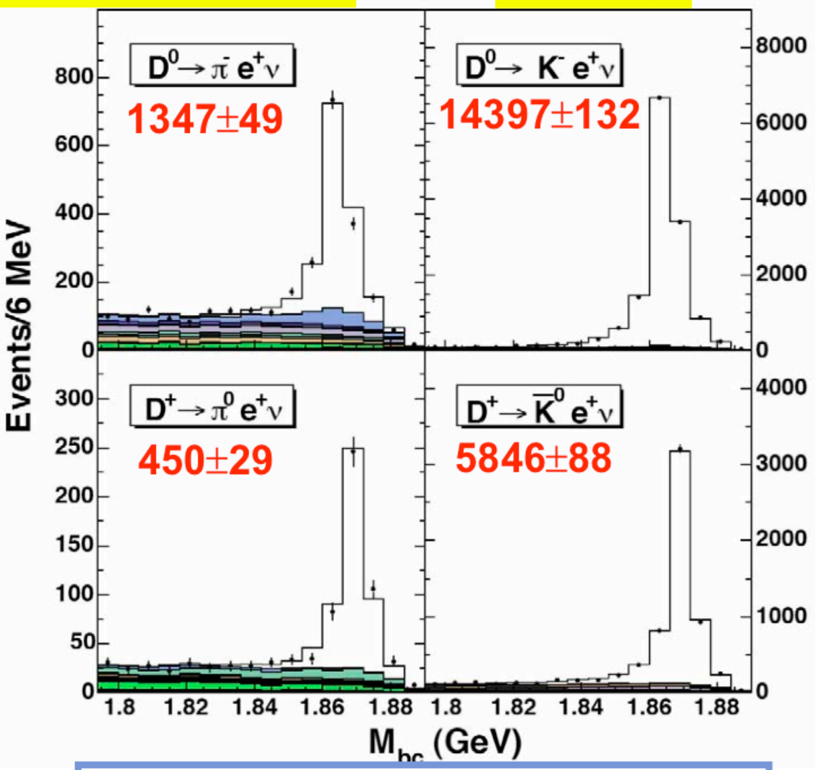
40% common samples!

Untag



$$U = E_{miss} - |P_{miss}| \text{ (GeV)}$$

E_{miss} and P_{miss} are missing energy and momentum of the event



$$\Delta E = E_{K(\pi)} + E_e + |\mathbf{p}_{miss}| - E_{beam}$$

$$M_{bc} = \sqrt{E_{beam}^2 - (\mathbf{p}_{K(\pi)} + \mathbf{p}_e + \varsigma\mathbf{p}_{miss})^2}$$

$D^0/D^+ \rightarrow K/\pi e \nu$ BF (Tag & Untag)

40% common samples, do NOT average them!

D Decay	Br. Frac. (%)		PDG (%)
	Tag	Untag	
$D^0 \rightarrow K^- e^+ \nu$	3.58±0.05±0.05	3.56±0.03±0.11	3.62±0.16
$D^0 \rightarrow \pi^- e^+ \nu$	0.309±0.012±0.006	0.301±0.011±0.010	0.311±0.030
$D^+ \rightarrow \bar{K}^0 e^+ \nu$	8.86±0.17±0.20	8.75±0.13±0.30	7.2±0.8
$D^+ \rightarrow \pi^0 e^+ \nu$	0.397±0.027±0.028	0.383±0.025±0.016	0.38±0.19

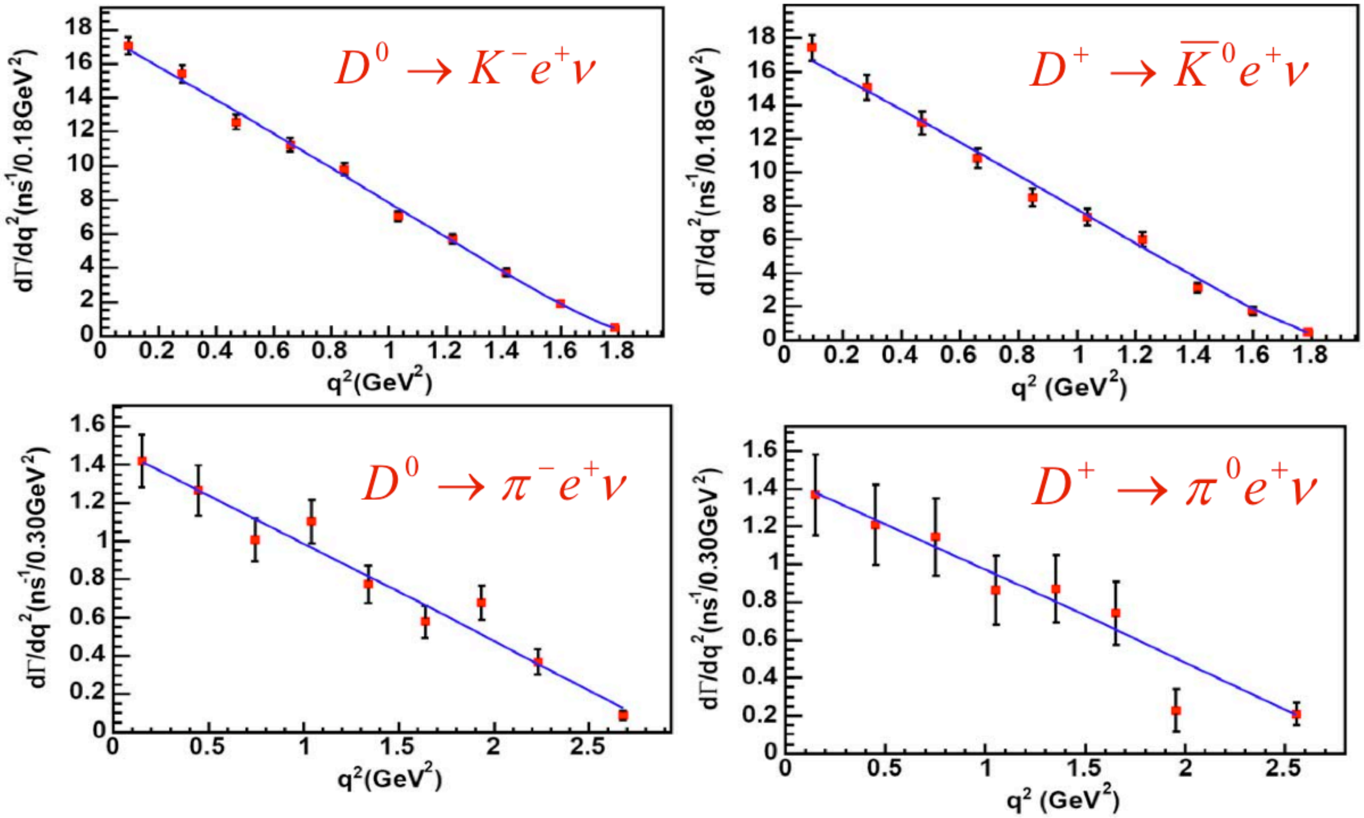
281 pb^{-1}

Ratio	Measured (%)	PDG (%)	Ratio	Measured
$\frac{D^0 \rightarrow \pi^- e^+ \nu}{D^0 \rightarrow K^- e^+ \nu}$	8.5±0.3±0.1	8.6±0.7	$\frac{\Gamma(D^0 \rightarrow \pi^- e^+ \nu)}{\Gamma(D^+ \rightarrow \pi^0 e^+ \nu)}$	1.95±0.15±0.14 1.99±0.15±0.10
$\frac{D^+ \rightarrow \pi^0 e^+ \nu}{D^+ \rightarrow \bar{K}^0 e^+ \nu}$	4.4±0.3±0.1	4.6±1.4±1.7	$\frac{\Gamma(D^0 \rightarrow K^- e^+ \nu)}{\Gamma(D^+ \rightarrow \bar{K}^0 e^+ \nu)}$	1.02±0.02±0.02 1.03±0.02±0.04

Preliminary

Form Factor Fit (Tag)

Preliminary



$281\ \mathrm{pb}^{-1}$ at $\Psi(3770)$

Simple Pole Model

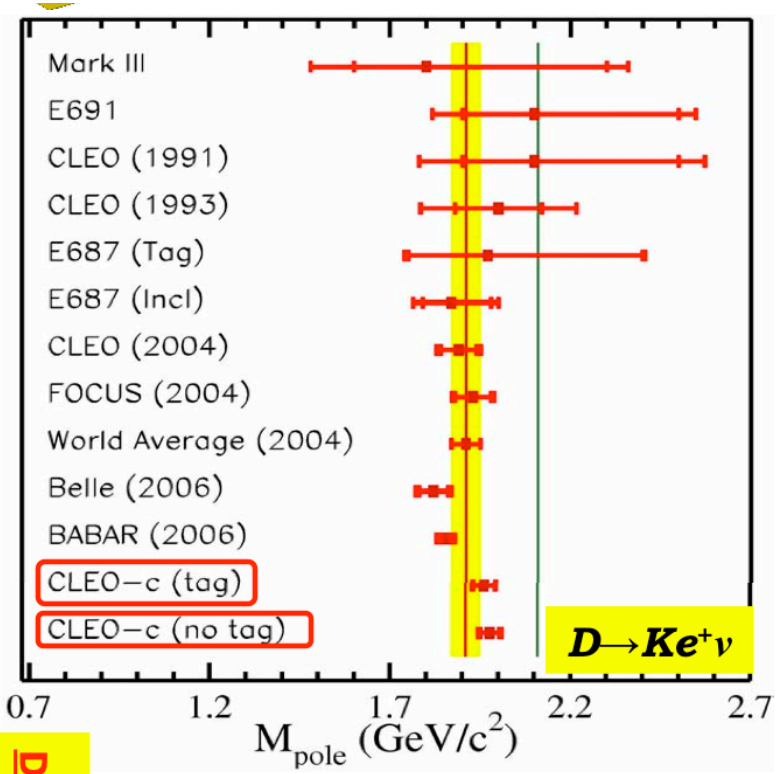
$$f^+(q^2) = \frac{f^+(0)}{\left(1 - q^2/m_{pole}^2\right)}$$

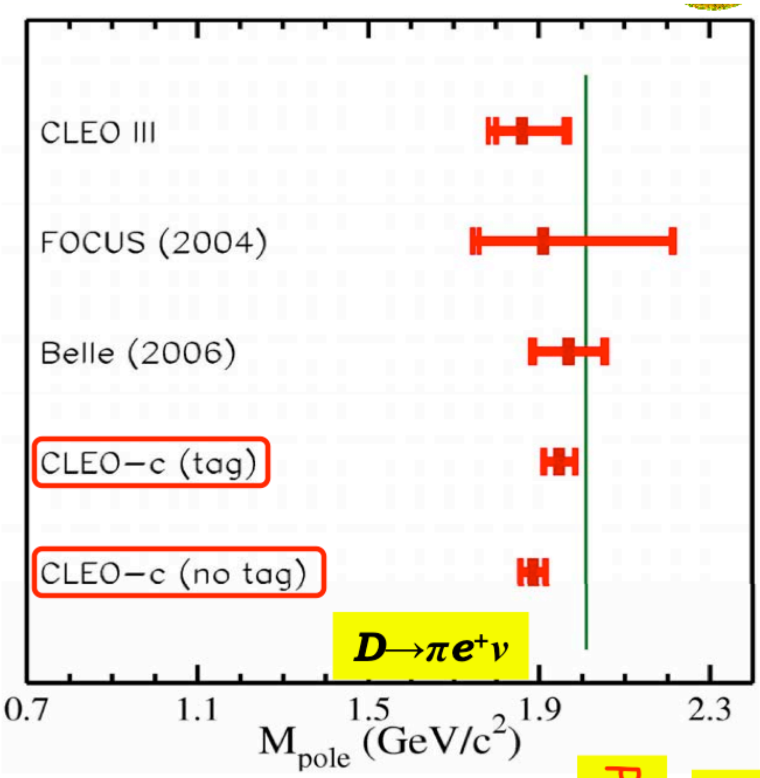
Modified Pole Model

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

Hill series expansion (Phys. Lett. B 633, 61 (2006))

Form Factors (Tag/Untag)





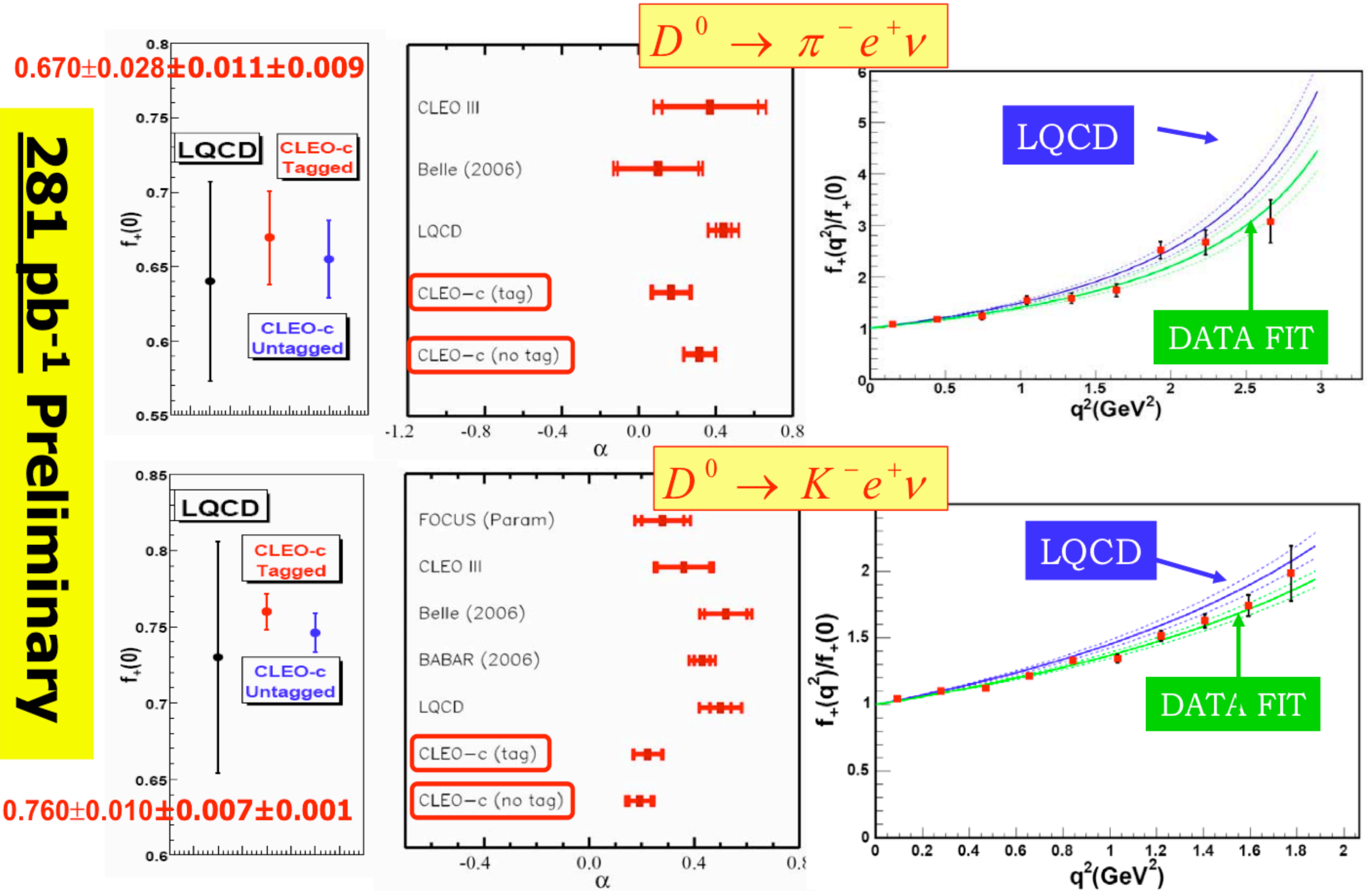
Don't average!

Decay Mode	Mpole (Tag)	Mpole (Untag)
D → Keν (av. D^0 & D^+)	1.96±0.03±0.01	1.98±0.03±0.02
D → πeν (av. D^0 & D^+)	1.95±0.04±0.02	1.88±0.03±0.02

Preliminary

281 pb^{-1}

Form Factors & Test of LQCD



$D^0 \to \pi^- e^+ \nu$

$D^0 \to K^- e^+ \nu$

281 pb^{-1} Preliminary

V_{cs} and V_{cd} Results

Combine $|V_{cx}|f_+(0)$ values from fits with unquenched LQCD results for $f_+(0)$ (Phys. Rev. Lett. 94, 011601 (2005)) to extract $|V_{cs}|$ and $|V_{cd}|$.

Decay Mode	**$|V_{cx}|$ ± (stat) ± (syst) ± (theory)**	**PDG Value**
D → πeν (tag)	**0.234 ± 0.010 ± 0.004 ± 0.024**	
D → πeν (untag)	**0.229 ± 0.007 ± 0.005 ± 0.024**	**0.224 ± 0.012**
D → Keν (tag)	**1.014 ± 0.013 ± 0.009 ± 0.106**	
D → Keν (untag)	**0.996 ± 0.008 ± 0.015 ± 0.104**	**0.976 ± 0.014**

Preliminary

Tag/Untag: 40% of comment sample. **DO NOT AVERAGE!!!**

Expt. uncertainties Vcs <2% Vcd~4% LQCD uncertainty 10%

Since Vcs (W→ cs LEP) and Vcd (νN) are well measured, good agreement between PDG and CLEO-c results is primarily a check of the LQCD value for $f_+(0)$. Nevertheless, the most precise & robust Vcs & Vcd determinations using semileptonic decays to date.

Looking forward to 2010

Where will Charm physics be in 2010?

- Hadronic Branching Ratios
  - D^0 and D+ branching ratios systematics limited at (1-2)% CLEO-c
  - D_s^+ branching ratios statistics limited at 6% CLEO-c
    - CLEO-c will improve to ~4%
    - BESIII will improve to (1-2)%
- Decay constants: statistics limited
  - D^+ 7.5% for 281 pb^{-1} at 3770. CLEO-c
    - CLEO-c will improve to (4-5)%
    - BESIII will improve to (1-2)%
    - Ultimate systematic limit may be ~1%
  - D_S 4.1% for 200 pb^{-1} at 4170. CLEO-c
    - CLEO-c will improve to (2-3)%
    - BESIII can improve
    - Ultimate systematic limit may be ~2%
- Semileptonic Decays
  - Branching ratio of Cabibbo favored $D^0 \to K e \nu$ known to 2% CLEO-c
  - Branching ratio of Cabibbo suppressed $D^0 \to \pi e \nu$ known to 4% CLEO-c
    - CLEO-c will improve to (2-3)%
    - BESIII can improve
  - Ultimate systematics limit for Semileptonic BR may be 1-2%
  - Vcs ~ 2%, Vcd~4% CLEO-c
    - CLEO-c will improve Vcd~2%
  - Form-factors will need 10 fb^{-1} BESIII

- CP tagged Dalitz plot analyses e.g. $D^o \to$CP vs. $D^o \to K_S \pi^+ \pi^-$ Important for γ
  - Statistics starved until at least~10 fb^{-1}
  - CLEO-c can limit sys err on $\gamma < 3^o$
- Rare Decays
  - CLEO-c sensitivity 10^{-5}-10^{-6}
  - BESIII sensititity 10^{-6}-10^{-7}
  - Standard Model rates ~10^{-8}
  - Need Super Flavor Factory @ ~4 GeV
- Charm Mixing
  - Exploiting the quantum coherent initial state CLEO-c will measure cosδ ~ ±0.1
  - BESIII sensitivity to $y=\Delta\Gamma/2\Gamma$~few x 10^{-3}
  - Need (Upgraded) LHC-b or Super B to cover full range of SM expectations
- CP Violation
  - BESIII sensitive to asymmetery in $D^+ \to K_{S,L}\pi +$ ~few x 10^{-3} . Approximately SM expectation.
  - Need (Upgraded) LHC-b or Super B to reach SM expectation in SCS decays.

CLEO-c will complete most measurements needed for precision CKM. New Physics searches require more statistics than anticipated at BESIII

The End

Form-Factor Parameterizations

- In general

$$f_+(q^2) = \frac{f_+(0)}{1-\alpha}\frac{1}{1-q^2/m_{pole}^2} + \frac{1}{\pi}\int_{(M_D+m)^2}^{\infty} dq'^2\,\frac{\mathrm{Im}(f(q'^2))}{q'^2-q^2}$$

- Modified Pole

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

- Series Expansion

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

$$t_\pm \equiv \left(M_D \pm m_{\pi(K)}\right)^2, \quad z(q^2,t_0) = \frac{\sqrt{t_+-q^2}-\sqrt{t_+-t_0}}{\sqrt{t_+-q^2}+\sqrt{t_+-t_0}}$$

Hill & Becher, Phys. Lett. B 633, 61 (2006)