Studies of $D \to \pi e \nu$ and $D \to K e \nu$ at CLEO-c

Fermilab Seminar

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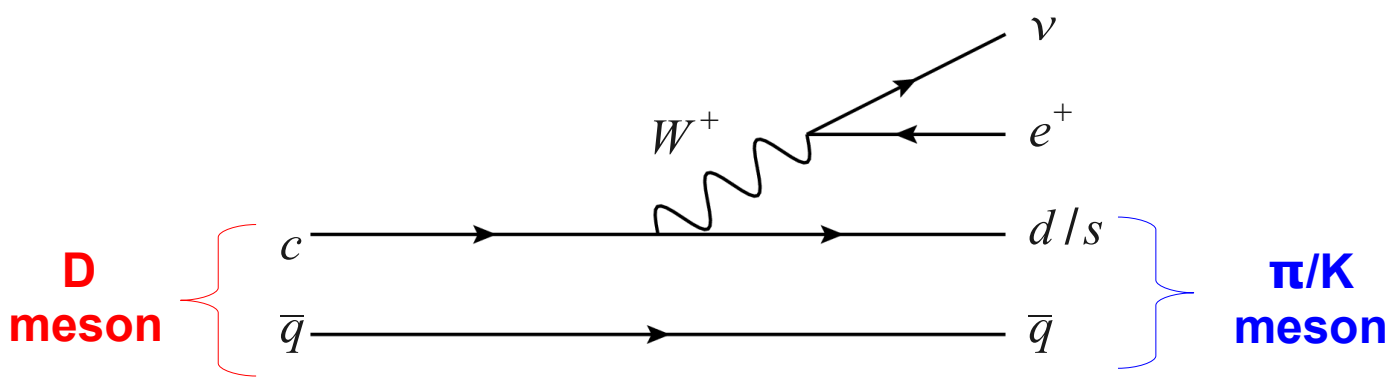
Talk Outline

- Overview of Semileptonic Decays
- The CLEO-c Program
- Analysis
  - Partial Rate Extraction
  - Systematic Uncertainties
  - Form Factor and Branching Fraction Fits
- Other CLEO-c Semileptonic Results
- Conclusion

The work described here was published in the August edition of PRD:
Phys. Rev. D 80, 032005 (2009) / arXiv:0906.2983

Semileptonic Decays

- A Semileptonic D Decay:



- Governed by both weak and strong forces

$$\mathcal{M}(D \to Pe\nu) = -i\frac{G_F}{\sqrt{(2)}} V_{cq} L^\mu H_\mu$$

$$L^\mu = \bar{u}_l \gamma^\mu (1-\gamma_5) v_\nu$$

Leptonic Current
(known)

$$H_\mu = \langle P | \bar{q} \gamma_\mu (1-\gamma_5) c | D \rangle$$

Hadronic Current
(non-perturbative QCD)

Semileptonic Decays

- We can't explicitly calculate the hadronic current
- What do we know?
  - For pseudo-scalar to pseudo-scalar decays, it can be expanded in terms of two lorentz-independent form factors:

$$H_\mu = f_+(q^2)(p_D + p_P)^\mu + f_-(q^2)(p_D - p_P)^\mu$$

  - In the limit of small lepton mass, this simplifies even further:

$$H_\mu = f_+(q^2)(p_D + p_P)^\mu$$

An unknown form factor, dependent on q^2 – the invariant mass of the lepton-neutrino system

Semileptonic Decays

- Using the simplified current, the differential decay rate becomes:

Daughter meson momentum

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

Can be measured experimentally

- Knowledge of the form factor allows extraction of CKM elements
- Are there predictions of the form factors?

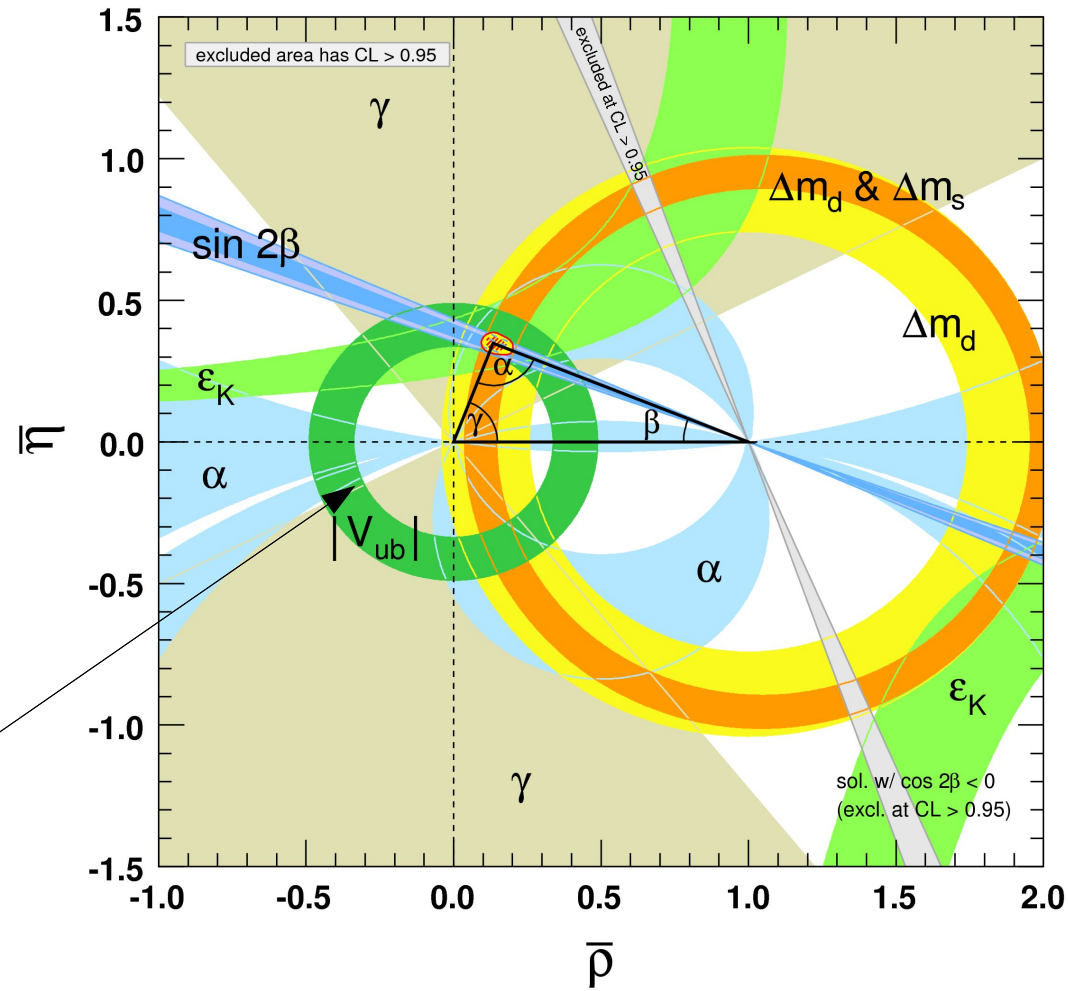
Semileptonic Decays

- Several QCD techniques exist to estimate form factors
  - Quark models
    - Ad hoc
    - Uncertainties difficult to quantify
  - Light Cone Sum Rules (LCSR)
    - Uncertainties of 20-30%
  - Lattice QCD
    - Until recently, uncertainties competitive with LCSR
    - New computational techniques + computing power
      → uncertainties of a few percent possible

Semileptonic Decays

- What are the implications of the new LQCD form factor predictions?

- More precise CKM measurements
  - Fundamental parameters of the standard model are important in their own right
  - Multiple measurements of sides and angles of unitarity triangles → important test for new physics



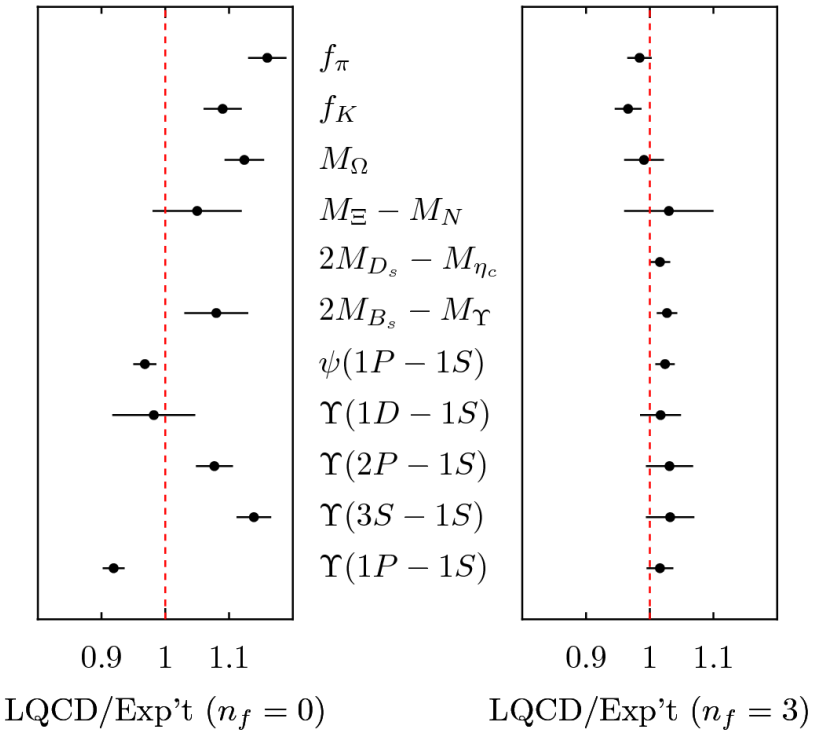
Source: PDG 2008

V_{ub} is extracted from B semileptonic decays → shrinking V_{ub} errors requires LQCD predictions

Semileptonic Decays

- How confident can we be in LQCD?

Source:Phys.Rev.Lett.92:022001,2004



Ratio of LQCD predictions of various parameters to experimental measurements, before and after new "unquenching" techniques

- Recent progress seems very promising
- BUT none of the tests above involve heavy-to-light transitions

Semileptonic Decays

- D semileptonic decays are a testing ground for LQCD:

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

At Cleo-C, we can measure rates for $D^0 \to pi^- enu$, $D^0 \to K^- enu$, $D^+ \to pi^0 enu$ and $D^+ \to K^0 enu$

$$|V_{cd}| f_+^{D\to\pi}(q^2)$$

$$|V_{cs}| f_+^{D\to K}(q^2)$$

- We can use LQCD to extract V_{cd} and V_{cs}
- We can use prior measurements of V_{cd} & V_{cs} to test LQCD predictions

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- **The CLEO-c Program**
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  - Partial Rate Extraction
  - Systematic Uncertainties
  - Form Factor and Branching Fraction Fits
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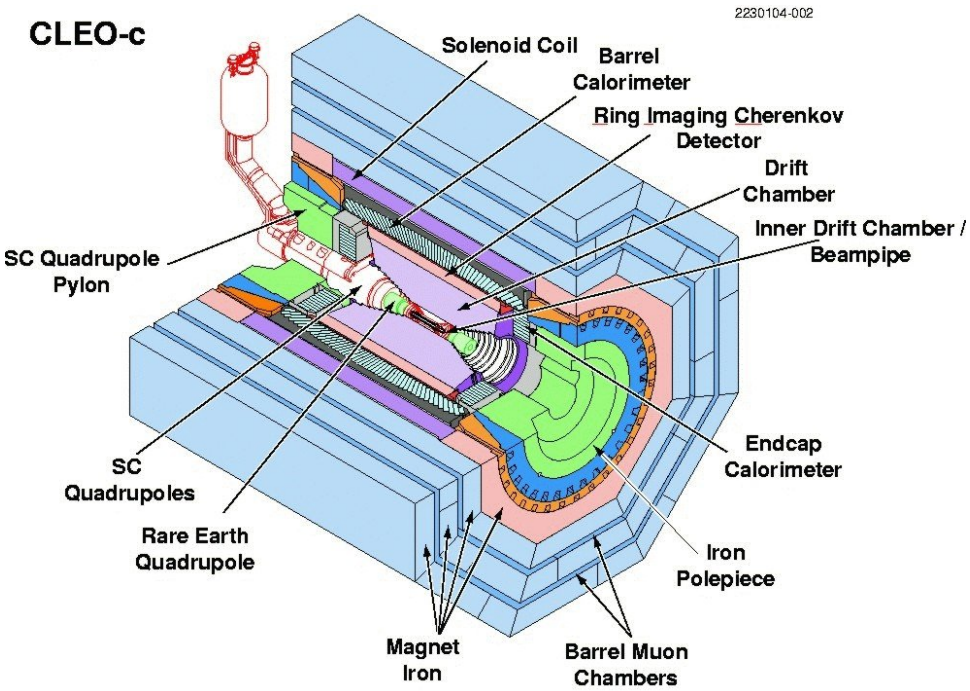
The CLEO-c Program

- CESR: an e+e- collider located at Cornell
- Began collisions in 1979 with COM energies of ~10 GeV
- CLEO studied a wide variety of Y and B decays between 1979 and 2003
- In 2003, accelerator was altered to run near charm production threshold
- CLEO-c data sample includes 818/pb of data taken at the ψ(3770) resonance (10.4 million D meson decays)

The CLEO-c Program

- The CLEO detector: one of two particle detectors originally on CESR
- Went through many changes over its lifetime
- Most recently: Silicon vertex detector replaced with a precision tracking chamber (the ZD)
- Dual tracking chambers provide $\sigma p/p = 0.5\%$ at 0.7 GeV
  - Covers $|\cos\theta| < 0.93$
- Ring Imaging Cherenkov detector (RICH) provides particle ID
- CsI calorimeter with $\sigma E/E = 5\%$ at 100 MeV

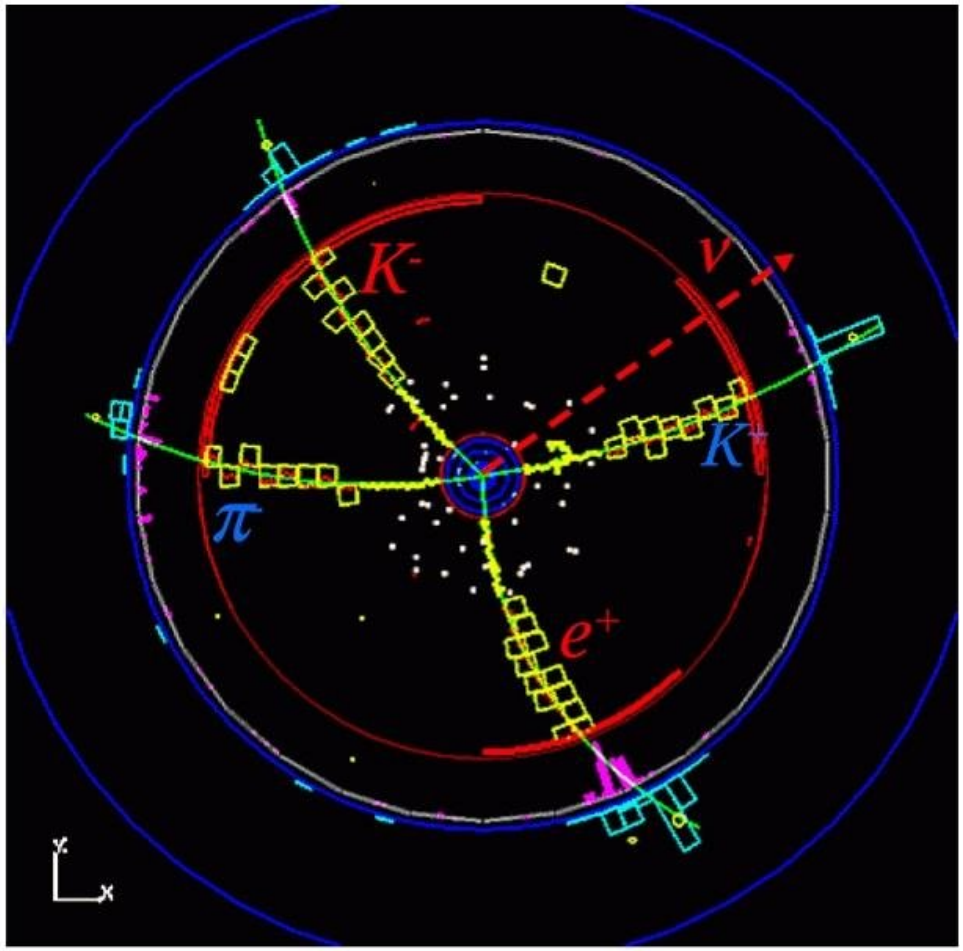


The CLEO-c Program

- CLEO-c analyses benefit from an extremely clean event environment
- D decays at ψ(3770) occur exclusively as part of DD pairs
- This enables an analysis technique known as "tagging"
- We fully reconstruct one D decay in a clean hadronic mode – the "tag"
- Search for the semileptonic decay opposite the tag
- Neutrino 4-vector can be inferred from missing energy and momentum

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

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



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Partial Rate Extraction: Overview

- How exactly do we measure the decay rates?

$$\Delta\Gamma_i = \int_{q^2_{low,i}}^{q^2_{high,i}} \frac{d\Gamma(D\to Pe\nu)}{dq^2} dq^2 = \frac{N_{signal,i}}{\tau_D N_{tag}}$$

Number of tag + semileptonic decays in ith qsq bin

D Lifetime

Number of Tag Decays

- Measure $\Delta\Gamma_i$ for 7 ($D\to\pi e\nu$) or 9 ($D\to Ke\nu$) q^2 bins
- 3 D^0 tag modes: $D^0\to K^+\pi^-$, $D^0\to K^+\pi^-\pi^0$, $D^0\to K^+\pi^-\pi^+\pi^-$
- 6 D^- tag modes: $D^-\to K^+\pi^-\pi^-$, $D^-\to K^+\pi^-\pi^-\pi^0$, $D^-\to K^0\pi^-$,
  $D^-\to K^0\pi^-\pi^0$, $D^-\to K^0\pi^-\pi^+\pi^-$, $D^-\to K^+K^-\pi^-$

Partial Rate Extraction: Overview

- How exactly do we measure the decay rates?

$$\Delta\Gamma_i = \int_{q^2_{low,i}}^{q^2_{high,i}} \frac{d\Gamma(D\to Pe\nu)}{dq^2} dq^2 = \frac{N_{signal,i}}{\tau_D N_{tag}}$$

Signal Efficiency + Smearing Matrix

Signal Yield

$$= \frac{\sum_j \epsilon_{ij}^{-1} N^{obs}_{signal,j}}{\tau_D N^{obs}_{tag}/\epsilon_{tag}}$$

Tag Yield

Tag Efficiency

Partial Rate Extraction: Particle Reconstruction

- Electron Identification

Electrons:

Charged tracks identified as electrons with dE/dx, RICH and calorimetery information

Efficiency = 92% @ 300 MeV
Hadron Fake Rates ~ 0.1 %

Bremstrallung Photons:

Energy depositions in calorimeter with 5º of electron
(and not matched to tracks)

The 4-vector of any bremstrallung photons are added to the track 4-vector to become the "**electron candidate**"

Partial Rate Extraction: Particle Reconstruction

- Hadron Identification

$K^{\pm}/\pi^{\pm}$ Identification

Tracks in drift chamber, identified using dE/dx and RICH information

Efficiency ~ 85%
Fake Rates ~ a few percent

K^0 Identification

$K^0 \rightarrow \pi^+\pi^-$

Constrained fit to track pairs within ~5σ of nominal K^0 mass
Mass Resolution = 2-2.5 MeV
Efficiency ~ 80 %

π^0 Identification

$\pi^0 \rightarrow \gamma\gamma$

Fit to pairs of showers within 3σ of nominal π^0 mass
Mass Resolution = 6 MeV
Efficiency ~ 50%

Partial Rate Extraction: Tag Yields

- Tag Candidates formed from combinations of pions & kaons:

$D^0 \to K^+\pi^-$	$D^- \to K^+\pi^-\pi^-$	$D^- \to K^0\pi^-\pi^0$
$D^0 \to K^+\pi^-\pi^0$	$D^- \to K^+\pi^-\pi^-\pi^0$	$D^- \to K^0\pi^-\pi^-\pi^+$
$D^0 \to K^+\pi^-\pi^+\pi^-$	$D^- \to K^0\pi^-$	$D^- \to K^+K^-\pi^-$

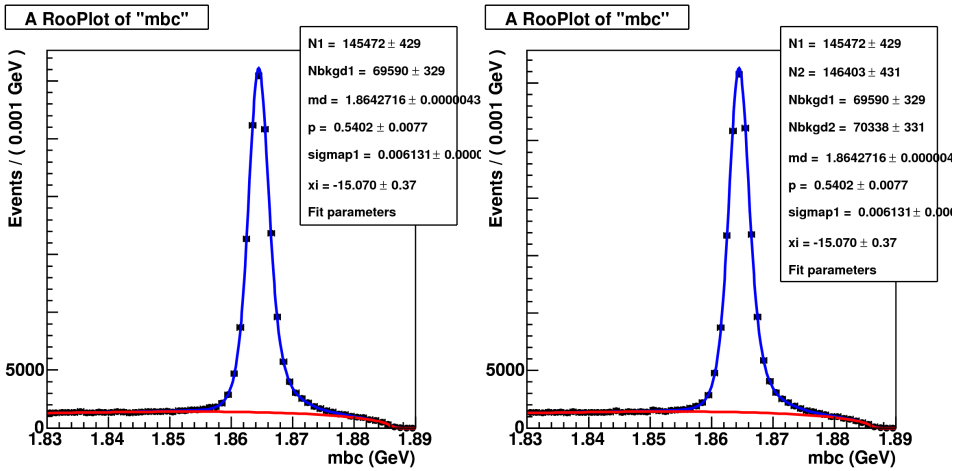
- Backgrounds are suppressed with cuts on two variables:

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

Tag-side yields and efficiencies are extracted from Beam Constrained Mass distributions

$$\longrightarrow M_{BC} = \sqrt{E_{beam}^2 - P_{tag}^2}$$

Partial Rate Extraction: Tag Yields



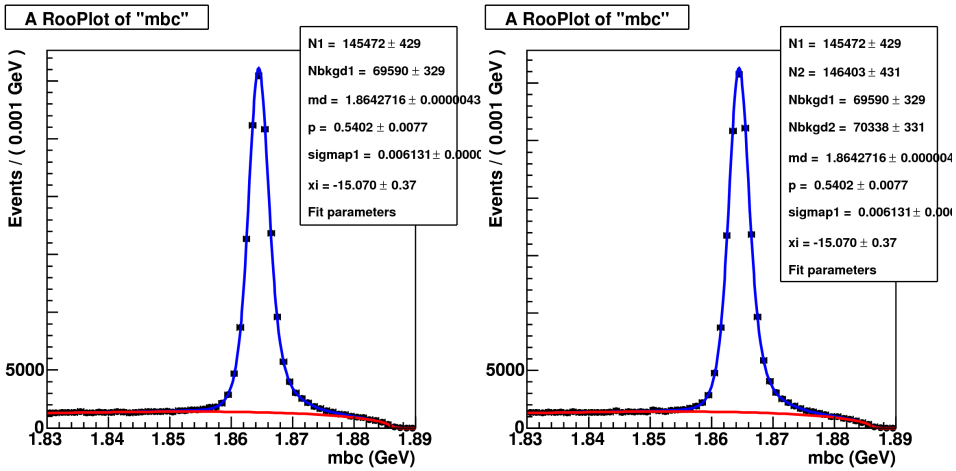
$D^0 \to K\pi\pi^0$ M_{BC} Fits in Data (both flavors)

- Tag Fits to Data:
  - Unbinned likelihood fits
  - Signal Shape takes into account natural ψ(3770) lineshape, ISR and momentum resolution
  - Background shape: ARGUS function

Tag Yields in Data

$D^0 \to K^+\pi^-$	149616±392
$D^0 \to K^+\pi^-\pi^0$	284617±589
$D^0 \to K^+\pi^-\pi^+\pi^-$	227536±517
$D^- \to K^+\pi^-\pi^-$	233670±497
$D^- \to K^+\pi^-\pi^-\pi^0$	69798±330
$D^- \to K^0\pi^-$	33870±194
$D^- \to K^0\pi^-\pi^0$	74842±357
$D^- \to K^0\pi^-\pi^-\pi^+$	49117±323
$D^- \to K^+K^-\pi^-$	19926±171

Partial Rate Extraction: Tag Efficiencies



$D^0 \to K\pi\pi^0$ M_{BC} Fits in MC (both flavors)

Obtained by fitting Monte Carlo a la data →

Tagging Efficiencies:

$D^0 \to K^+\pi^-$	65.3%
$D^0 \to K^+\pi^-\pi^0$	35.2%
$D^0 \to K^+\pi^-\pi^+\pi^-$	45.6%
$D^- \to K^+\pi^-\pi^-$	55.4%
$D^- \to K^+\pi^-\pi^-\pi^0$	27.4%
$D^- \to K^0\pi^-$	51.1%
$D^- \to K^0\pi^-\pi^0$	28.7%
$D^- \to K^0\pi^-\pi^-\pi^+$	43.6%
$D^- \to K^+K^-\pi^-$	42.1%

Partial Rate Extraction: Semileptonic Reconstruction

- Semileptonic Candidates are formed from combinations of electrons and mesons (e/π^-, e/K^-, e/π^0, or e/K^0)
- Neutrino 4-vector calculated using:

$$E_\nu = E_{miss}$$

$$P_\nu = E_{miss} \hat{P}_{miss}$$

- Candidates are binned in q2, defined by

$$q^2 = (E_e + E_\nu)^2 - |P_e + P_\nu|^2$$

Partial Rate Extraction: Semileptonic Reconstruction

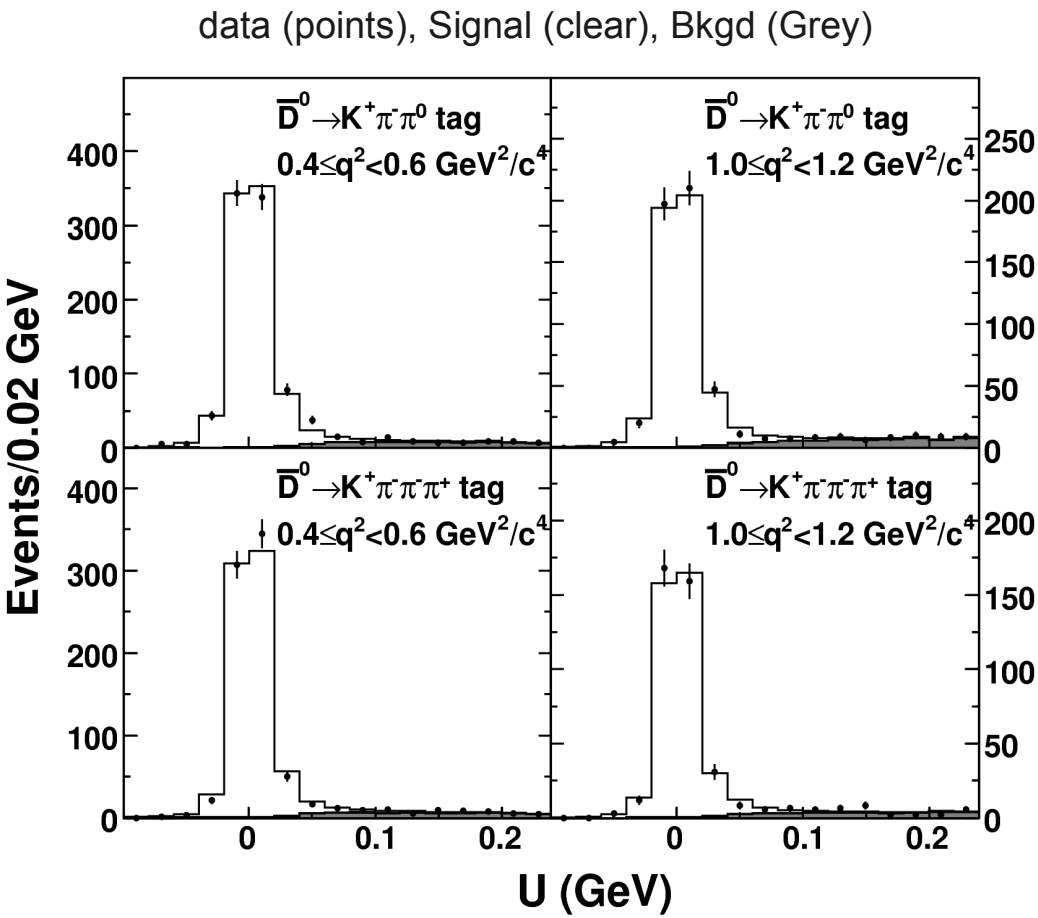
- Semileptonic Backgrounds:
  - Most backgrounds arise from a correctly reconstructed tag + misreconstructed semileptonic decay
    - $D^0 \rightarrow \pi^- e\nu$ and $D^+ \rightarrow \pi^0 e\nu$ have large backgrounds from $D^0 \rightarrow K^- e\nu$ and $D^+ \rightarrow K^0 e\nu$, respectively
    - $D^0 \rightarrow K^- e\nu$ and $D^+ \rightarrow K^0 e\nu$ have small backgrounds, mainly from $D \rightarrow K^* e\nu$
- To maximize signal/background separation, we extract yields from distributions of:

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

  - All fits are binned likelihood fits with shapes taken from Monte Carlo
  - A separate fit for each q2 bin, each tag + semileptonic combination

144 Total Fits!

Partial Rate Extraction: $D^0 \to K^{\pm} e \nu$ Signal Yields

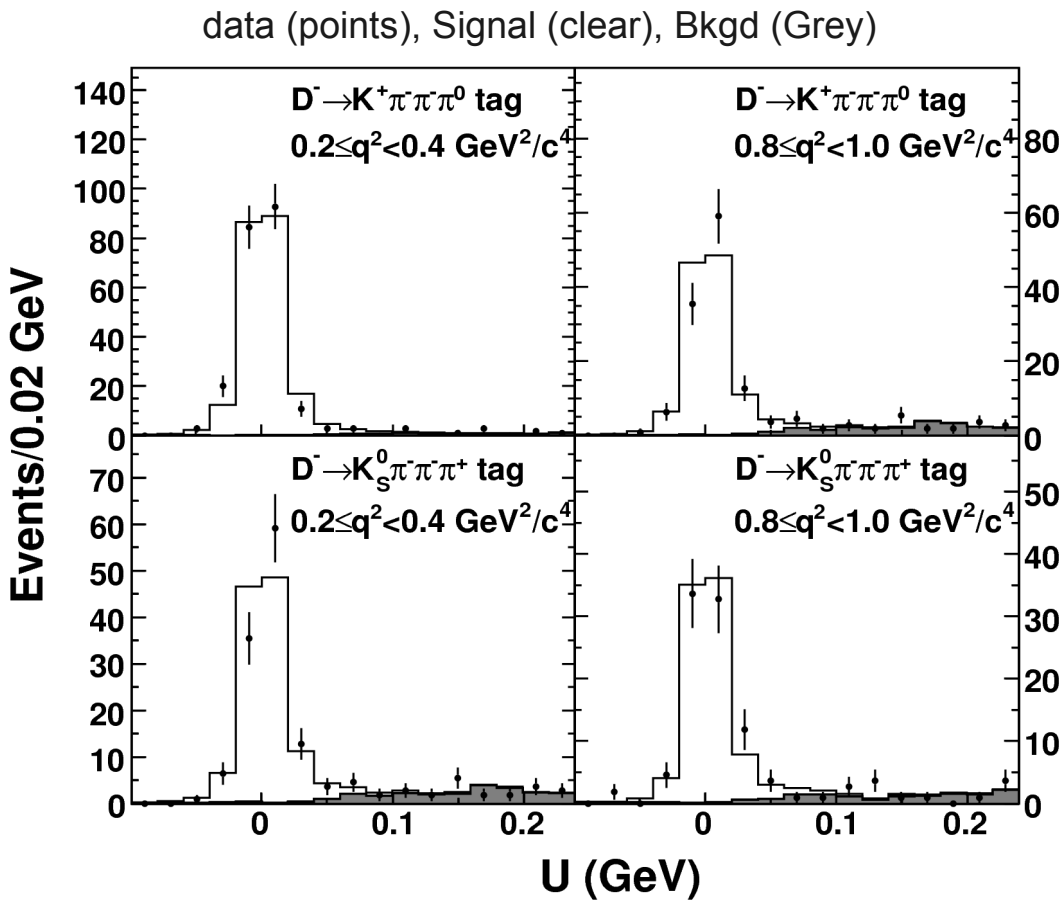


- Signal Yields in $D^0 \to K^{\pm} e \nu$:
  - Normalization of small non-DD background fixed
  - All other backgrounds combined into a single shape
  - Normalization of signal and background shapes float

4 of the 27 $D \to K^{\pm} e \nu$ fits

- Signal shapes are wider in data → MC smeared using a double Gaussian

Partial Rate Extraction: $D^{\pm}\to K^0 e\nu$ Signal Yields



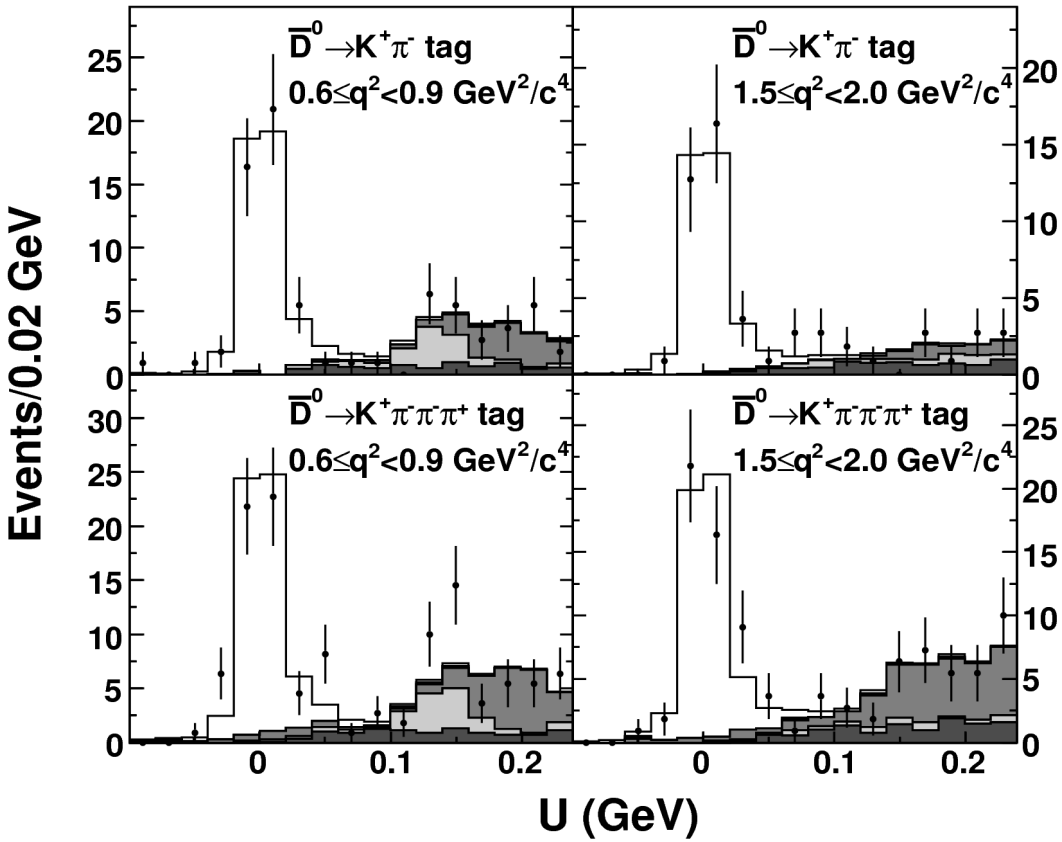
- Signal Yields in $D^{\pm}\to K^0 e\nu$:
  - Normalization of small non-DD background fixed
  - All other backgrounds combined into a single shape
  - Normalization of signal and background shapes float

4 of the 54 $D^{\pm}\to K^0 e\nu$ fits

- Signal shapes are wider in data → MC smeared using a double Gaussian

Partial Rate Extraction: $D^0 \to \pi^{\pm} e \nu$ Signal Yields

data (points), Signal (clear), Kenu(light), ρev (med) Other(dark gray)



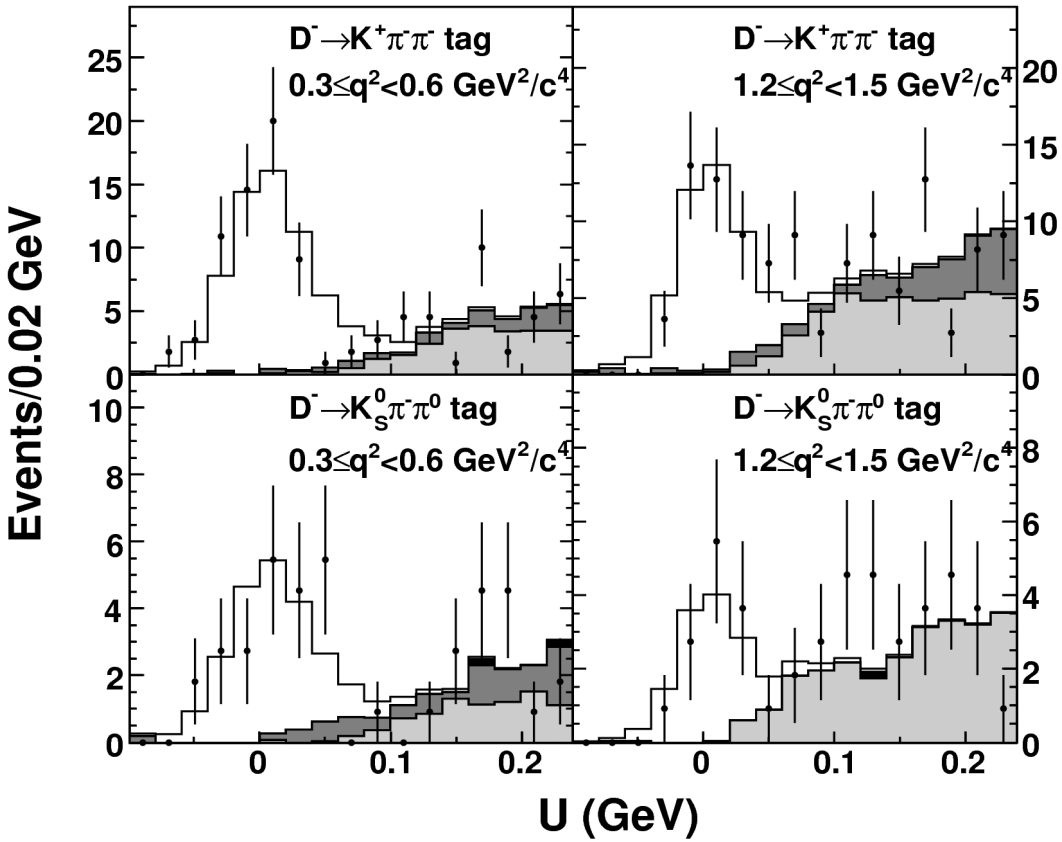
- Signal Yields in $D^0 \to \pi^{\pm} e \nu$:
  - Normalizations of $D \to K e \nu$, $D \to \rho e \nu$, and small non-DD background are fixed
  - All other backgrounds are combined into a single shape
  - Normalization of signal and background shapes float

4 of the 21 $D^0 \to \pi^{\pm} e \nu$ fits

- Signal shapes are wider in data → MC smeared using a double Gaussian

Partial Rate Extraction: $D^+ \to \pi^0 e\nu$ Signal Yields

data (points), Signal (clear), K0enu(light gray), Other (gray)



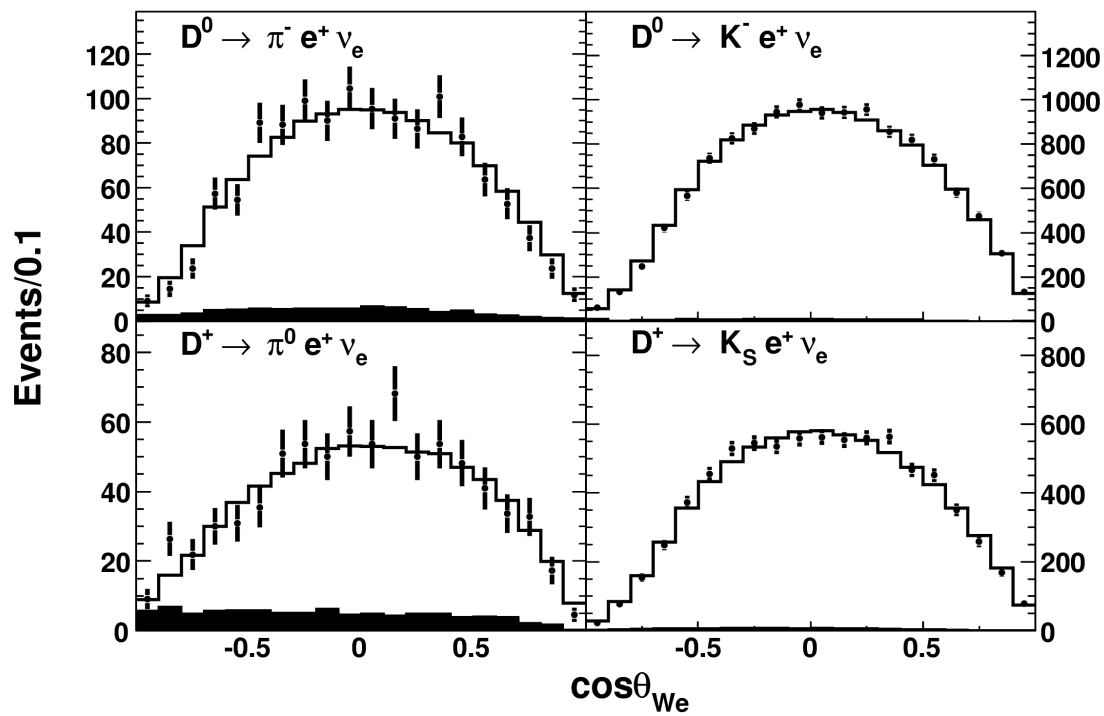
- Signal Yields in $D^+ \to \pi^0 e\nu$:
  - Normalizations of $D \to K0e\nu$, and small non-DD background are fixed
  - All other backgrounds are combined into a single shape
  - Normalization of signal and background shapes float

4 of the 42 $D^0 \to \pi^\pm e\nu$ fits

- Signal shapes are wider in data → MC smeared using a double Gaussian

Partial Rate Extraction: Consistency Check

- We've compared data and Monte Carlo in distributions other than U, scaling MC as in the signal yield fits.
- All distributions have shown good agreement.
- An example:



Cosine of the angle between the virtual W and the electron in data (points) and MC (histograms), in events with -60 < U < 60 MeV

Partial Rate Extraction: Signal Efficiencies

- Efficiency matrices give efficiency and smearing

$$\epsilon_{ij} = \frac{N_{Reconstructed,i+Generated,j}}{N_{Generated,j}}$$

- Obtained from Signal MC
  - Account for efficiency & smearing due to semileptonic and tag reconstruction
  - Off-diagonal elements introduce a small correlation across q2 in the partial rate measurements

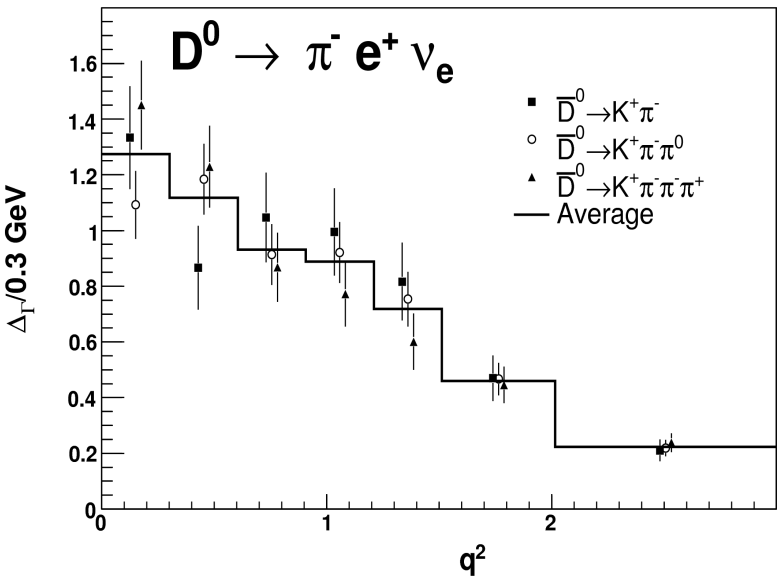
Generated Bin →

Reconstructed Bin

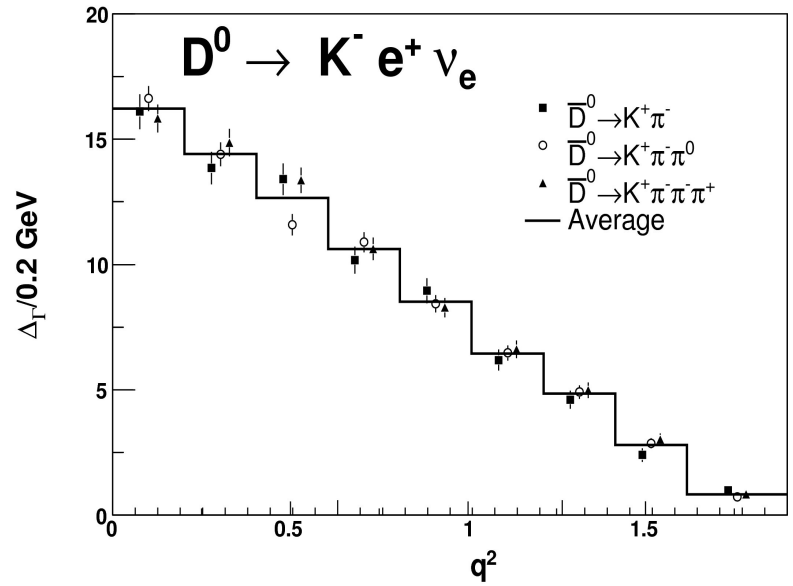
$$\begin{bmatrix} 0.420 & 0.012 & 0.000 & 0.000 & 0.000 & 0.000 & 0.000 \\ 0.007 & 0.430 & 0.015 & 0.000 & 0.000 & 0.000 & 0.000 \\ 0.001 & 0.008 & 0.448 & 0.014 & 0.000 & 0.000 & 0.000 \\ 0.000 & 0.001 & 0.012 & 0.457 & 0.014 & 0.000 & 0.000 \\ 0.000 & 0.001 & 0.001 & 0.012 & 0.464 & 0.009 & 0.000 \\ 0.000 & 0.000 & 0.001 & 0.001 & 0.011 & 0.469 & 0.007 \\ 0.000 & 0.000 & 0.000 & 0.000 & 0.000 & 0.007 & 0.469 \end{bmatrix}$$

$\pi^+ev/K\pi$ Signal Efficiency Matrix

Partial Rates Extraction: D^0 Mode Results



Partial Widths for D⟶piev



Partial Widths for D⟶kev

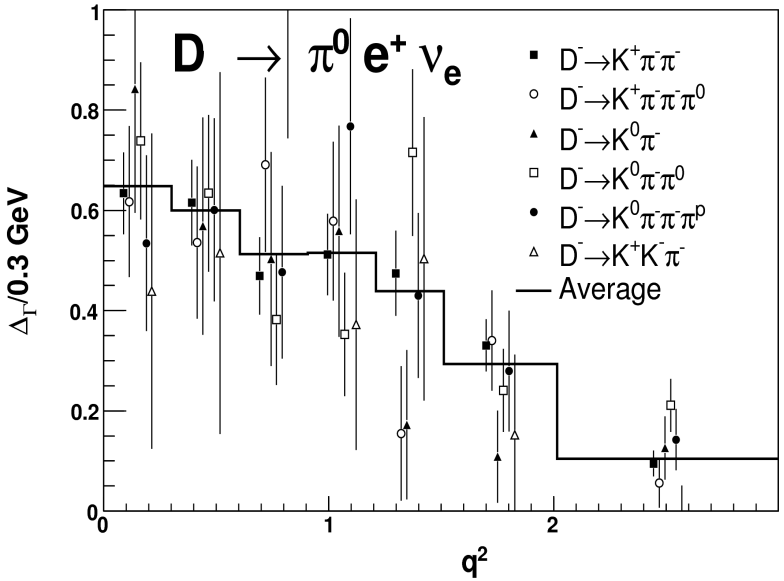
- Partial Rates extracted via:

$$\Delta\Gamma_i = \int_{q^2_{low,i}}^{q^2_{high,i}} \frac{d\Gamma(D \to Pe\nu)}{dq^2} dq^2 = \frac{\sum_i \epsilon_{ij}^{-1} N_j}{\tau_D N_{tag}/\epsilon_{tag}}$$

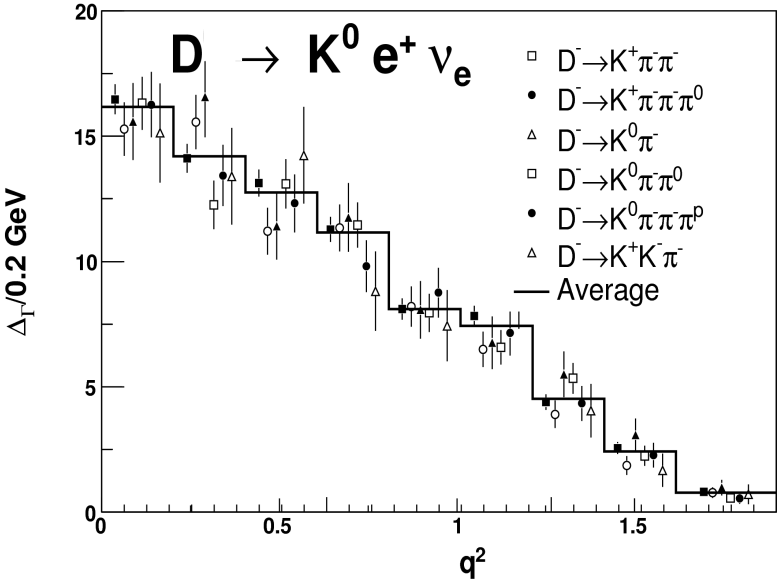
and averaged over tag modes

	χ^2	n_{dof}
$D \to \pi^0 e \nu$	12	14
$D \to K^0 e \nu$	21	18

Partial Rate Extraction: D^+ Mode Results



Partial Widths for D⟶pi0ev



Partial Widths for D⟶k0enu

- Results agree well across tags in all modes
- Isospin conjugate pairs also agree well

	χ^2	n_{dof}
$D \to \pi^0$ e v	36	35
$D \to K^0$ e v	37	45

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Systematics

- Our general approach to systematic uncertainties:
  - For each source of systematic uncertainty and for each semileptonic mode, we construct a covariance matrix that
    - gives the uncertainties on each of the $\Delta\Gamma_i$ and
    - their correlations across q2
- One method of constructing covariance matrices: make one or several variations to the analysis & remeasure the partial rates:

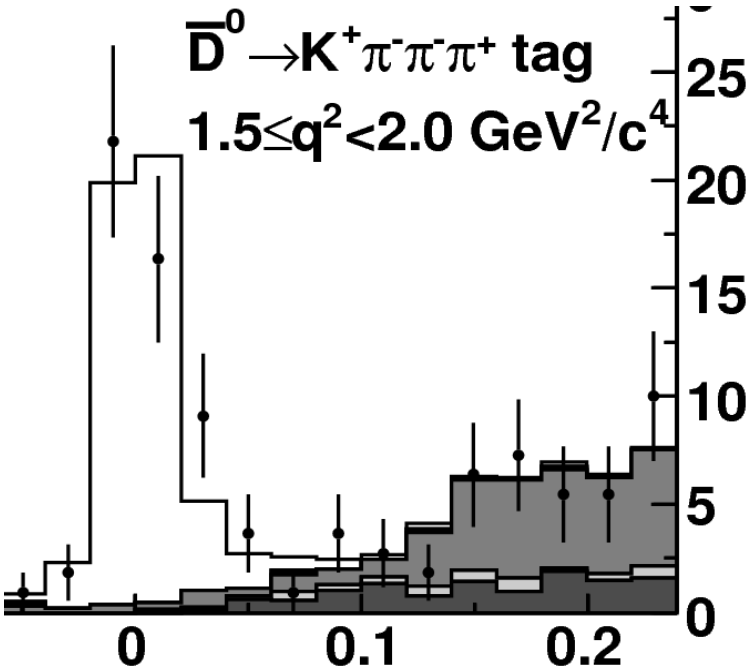
$$M_{ij} = \delta(\Delta\Gamma_i)\delta(\Delta\Gamma_j)$$

where $\delta(\Delta\Gamma_i)$ is the change in $\Delta\Gamma_i$ given the analysis variation

When several variations are made, the resulting matrices are summed

Systematics: Background Shapes

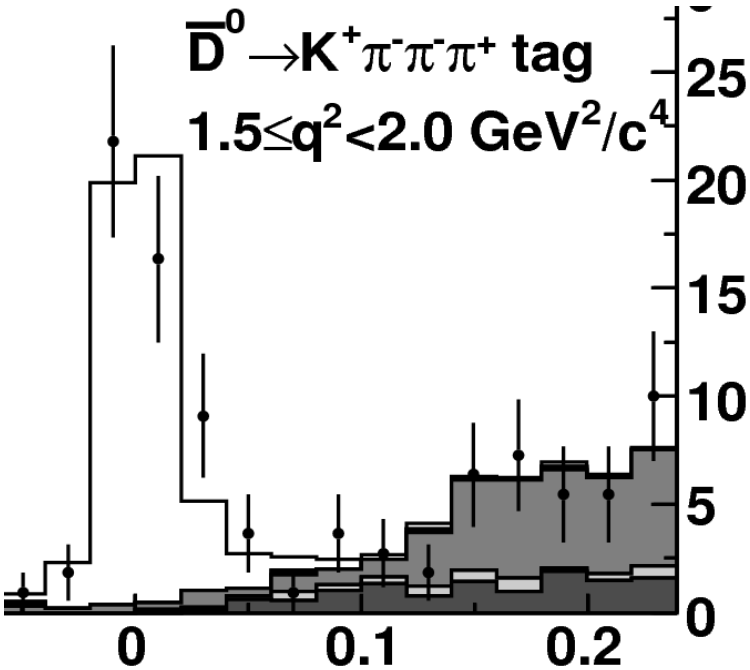
- One systematic uncertainty in detail: background shapes in $D^0 \rightarrow \pi^{\pm}ev$
  - Taking background shapes from Monte Carlo reduces statistical uncertainties on our signal yields (versus parameterizing backgrounds)
  - But this technique intruduces several systematic uncertainties that must be quantified.
  - The largest of these uncertainties are those due to:
    - The normalizations of fixed backgrounds
    - Incorrect Monte Carlo branching fractions
    - Incorrect Monte Carlo fake rates



A sample $D^0 \rightarrow \pi^{\pm}ev$ signal yield fit data (points), signal shape (white), fixed ρev (med gray), Kev (light) and other (dark gray) backgrounds

Systematics: Background Shapes

- One systematic uncertainty in detail: background shapes in $D^0 \rightarrow \pi^{\pm}ev$
  - To estimate the systematic uncertainty due to fixed backgrounds, we vary their normalizations within their uncertainties.
  - In $D^0 \rightarrow \pi^{\pm}ev$, there are three fixed backgrounds:
    - Non-DD: fixed using data/MC luminosities; varied by ± 20% (based on studies of continuum MC)
    - $K^{\pm}ev$: fixed to value that minimizes LL summed over q2/tags; varied by ~8% (varies the summed LL by +1)
    - ρev: fixed to ratio of tags in data/MC; varied by ±12% (based on ρev BF uncertainty)

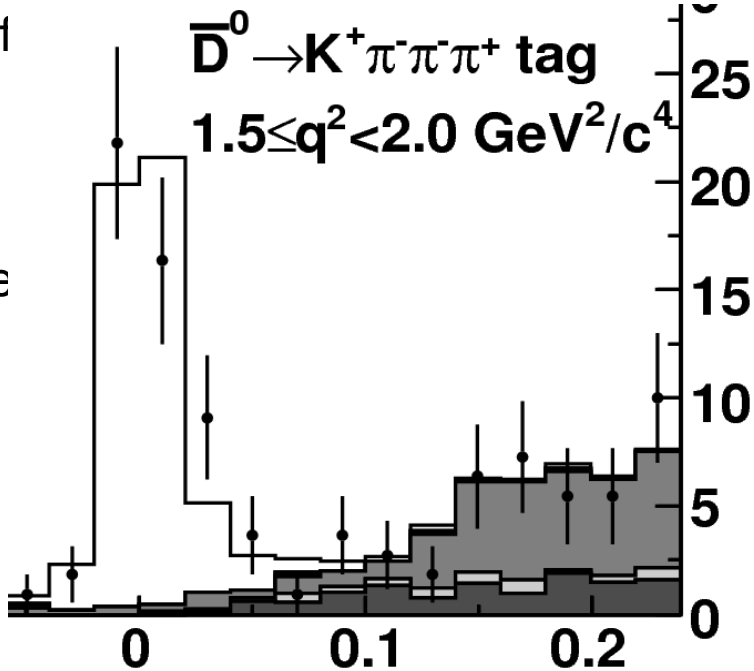


  - Changes in partial rates:

	Δ(ΔΓ1)	Δ(ΔΓ2)	Δ(ΔΓ3)	Δ(ΔΓ4)	Δ(ΔΓ5)	Δ(ΔΓ6)	Δ(ΔΓ7)
rhoenu+	-0.1%	-0.2%	-0.2%	-0.2%	-0.2%	-0.2%	-0.2%
rhoenu-	0.1%	0.2%	0.2%	0.2%	0.2%	0.2%	0.2%
cont+	-0.1%	-0.1%	0.0%	0.0%	-0.1%	-0.1%	0.0%
cont-	0.2%	0.1%	0.0%	0.0%	0.1%	0.1%	0.0%
Kenu+	-0.3%	-0.3%	-0.2%	-0.3%	-0.2%	-0.1%	-0.1%
Kenu-	0.2%	0.2%	0.1%	0.2%	0.2%	0.1%	0.1%

Systematics: Background Shapes

- One systematic uncertainty in detail: background shapes in $D^0 \rightarrow \pi^{\pm} e \nu$
  - One of our background shapes contains a lot of different modes combined.
  - The normalization is allowed to float
  - But, if the relative branching fractions of each of the modes are incorrect, the overall shape will be wrong
  - To estimate this effect, we vary the branching fractions within their uncertainties.



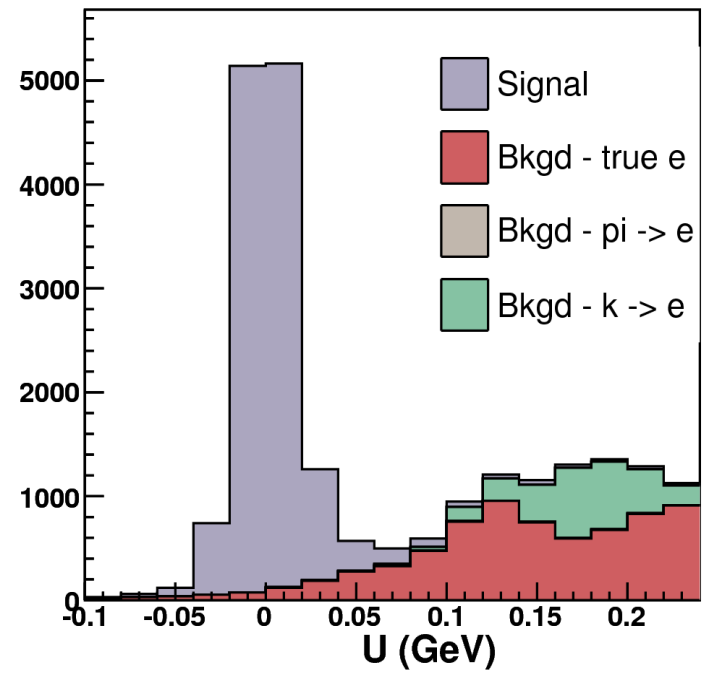
  - Changes in partial rates:

	Δ(ΔΓ1)	Δ(ΔΓ2)	Δ(ΔΓ3)	Δ(ΔΓ4)	Δ(ΔΓ5)	Δ(ΔΓ6)	Δ(ΔΓ7)
combined, Kpipi0+	0.0%	0.1%	0.1%	0.1%	0.0%	0.0%	0.1%
combined, Kpipi0-	0.0%	-0.1%	-0.1%	-0.1%	0.0%	0.0%	0.1%
combined, Kpi+	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
combined, Kpi-	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
combined, fake tags+	-0.2%	-0.2%	-0.5%	-0.4%	-0.4%	-0.4%	-0.6%
combined, fake tags -	0.2%	0.2%	0.5%	0.4%	0.4%	0.4%	0.6%
⋮							

Systematics: Background Shapes

- One systematic uncertainty in detail: background shapes in $D^0 \rightarrow \pi^{\pm} e \nu$

  - Finally, incorrect electron ID fake rates can case inaccurate background shapes
  - Our analysis is most sensitive to $K \rightarrow e$ fake rates
  - We estimate by increasing electron-fake component of background shapes
    - Estimated as part of CLEO-c EID systematics studies using $D \rightarrow K\pi\pi$



Selected $D\pm \rightarrow \pi e \nu$ Variations

	Δ(ΔΓ1)	Δ(ΔΓ2)	Δ(ΔΓ3)	Δ(ΔΓ4)	Δ(ΔΓ5)	Δ(ΔΓ6)	Δ(ΔΓ7)
eid fakes, k->e	0.1%	0.0%	0.1%	0.1%	0.1%	0.1%	0.1%

Systematics: EID, Signal Shape, MC Form Factor and q2 smearing

- Electron ID
  - Efficiencies in data/MC measured in eeγ and eeee events
  - Correct for biases of ~1.5%
  - Vary biases by their uncertainties and remeasure the $\Delta\Gamma_j$
- Signal Shape
  - Vary the parameters of the signal shape smear by their uncertainties and remeasure the $\Delta\Gamma_j$
- Smearing in q2
  - Estimate additional smearing in q^2 based on U resolution differences in data/MC, smear q2 distributions in MC and remeasure $\Delta\Gamma_j$
- MC Form Factor
  - Reweight MC efficiency matrices to different q^2 shapes, where altered shapes are based on form factors measured in data
- FSR
  - Reweight MC efficiency matrices so that energy and angular distributions of photons reconstructed in neighborhood of electron in MC match those found in data

Systematics: Particle ID

- To estimate systematic uncertainties due to track/hadron ID, we use the standard CLEO-c studies that measure data/MC efficiencies using fully hadronic decays:
  - Tracking: $D^0 \to K^- \pi^+$, $D^0 \to K^- \pi^+ \pi^0$, $D^0 \to K^- \pi^+ \pi^- \pi^+$
  - Neutral Kaon ID: $D^0 \to K^0_S \pi^+ \pi^-$
  - Charged Hadron ID: $D^0 \to K^- \pi^+ \pi^0$, $D^0 \to K^0_S \pi^+ \pi^-$, $D^+ \to K^- \pi^+ \pi^+$
  - Neutral pion: $D^0 \to K^- \pi^+ \pi^0$
- Each of these studies measures efficiencies binned in particle momentum
  - Using info from these studies, we construct covariance matrices binned in particle momentum and transform these into covariance matrices binned in q2 using signal MC
- Where applicable, we correct for observed biases
  - π^- overall correction: 0.3%
  - K^- overall correction: 0.8%
  - π^0 overall correction: 6%
  - e^- overall correction: 1.5%

Systematics: Fully Correlated Uncertainties

- Systematic Uncertainties that are fully correlated across q^2:
  - Number of Tags
    - Vary tag yield fitter in many different ways
    - Obtain overall uncertainty of 0.4% in all modes
  - Fake Tags:
    - Due to the best tag selection in presence of tag fakes (mainly pi0 fakes)
    - 0.4% / 0.7% overall uncertainty in D^0 / D^+ modes
  - D Lifetimes
    - 0.4% / 0.7% in D^0 / D^+ modes

Systematics: Summary

- Summary of Systematics for $D \rightarrow K^{\pm} e \nu$:

	σ(ΔΓ1)	σ(ΔΓ2)	σ(ΔΓ3)	σ(ΔΓ4)	σ(ΔΓ5)	σ(ΔΓ6)	σ(ΔΓ7)	σ(ΔΓ8)	σ(ΔΓ9)
Number of Tags	0.4%	0.4%	0.4%	0.4%	0.4%	0.4%	0.4%	0.4%	0.4%
Fake Tags	0.4%	0.4%	0.4%	0.4%	0.4%	0.4%	0.4%	0.4%	0.4%
Tracking	0.7%	0.7%	0.8%	0.8%	0.8%	0.9%	1.0%	1.3%	1.2%
Kaon ID	0.2%	0.1%	0.1%	0.1%	0.1%	0.1%	0.1%	0.1%	0.2%
electron ID	0.4%	0.4%	0.4%	0.4%	0.5%	0.5%	0.4%	0.3%	0.2%
Signal Shape	0.2%	0.1%	0.1%	0.1%	0.1%	0.1%	0.1%	0.1%	0.2%
Backgrounds	0.2%	0.0%	0.2%	0.1%	0.1%	0.1%	0.0%	0.1%	0.4%
FSR	0.1%	0.1%	0.1%	0.0%	-0.1%	-0.2%	-0.2%	-0.3%	-0.3%
MC Form Factor	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	-0.1%
q2 smearing	0.6%	-0.1%	0.1%	-0.1%	-0.1%	-0.5%	0.1%	-0.6%	-2.0%
D Lifetime	0.4%	0.4%	0.4%	0.4%	0.4%	0.4%	0.4%	0.4%	0.4%
Total	1.3%	1.1%	1.1%	1.2%	1.2%	1.4%	1.4%	1.6%	2.6%
Stat. Uncertainty	2.0%	2.2%	2.3%	2.5%	2.7%	3.1%	3.6%	4.9%	8.4%

- σ(ΔΓ1) are set positive; signs are with respect to σ(ΔΓ1)

Talk Outline

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Fits to Partial Rates: Form Factor parameterizations

- Given the partial rates and their covariance matrices, we fit them using:

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

- We need some parameterization of $f_+(q^2)$
  - To guess at possible parameterizations, start with a dispersion relation:

$$f_+(q^2)=\frac{f_+(0)/(1-\alpha)}{1-\frac{q^2}{M^2_{D^*_{(s)}}}}+\sum_{k=1}^{N}\frac{\rho_k}{1-\frac{1}{\gamma_k}\frac{q^2}{M_D^2}}$$

Fits to Partial Rates: Simple Pole Model

$$f_+(q^2) = \frac{f_+(0)/(1-\alpha)}{1-\frac{q^2}{M^2_{D^*_{(s)}}}} + \sum_{k=1}^{N} \frac{\rho_k}{1-\frac{1}{\gamma_k}\frac{q^2}{M^2_D}}$$

- The "Simple Pole Model" assumes that the series can be truncated after the first term:

$$f_+(q^2) = \frac{f_+(0)}{(1-\frac{q^2}{m^2_{pole}})}$$

- If assumption is valid, we expect $m_{pole} = M_{D^*}$

Fits to Partial Rates: Modified Pole Model

$$f_+(q^2) = \frac{f_+(0)/(1-\alpha)}{1-\frac{q^2}{M^2_{D^*_{(s)}}}} + \sum_{k=1}^{N} \frac{\rho_k}{1-\frac{1}{\gamma_k}\frac{q^2}{M^2_D}}$$

- The "Modified Pole Model" adds a second effective pole:

$$f_+(q^2) = \frac{f_+(0)}{(1-\frac{q^2}{m^2_{D^*}})(1-\alpha\frac{q^2}{m^2_{pole}})}$$

- Makes simplifying assumptions to reduce free parameters

Fits to Partial Rates: Series Model

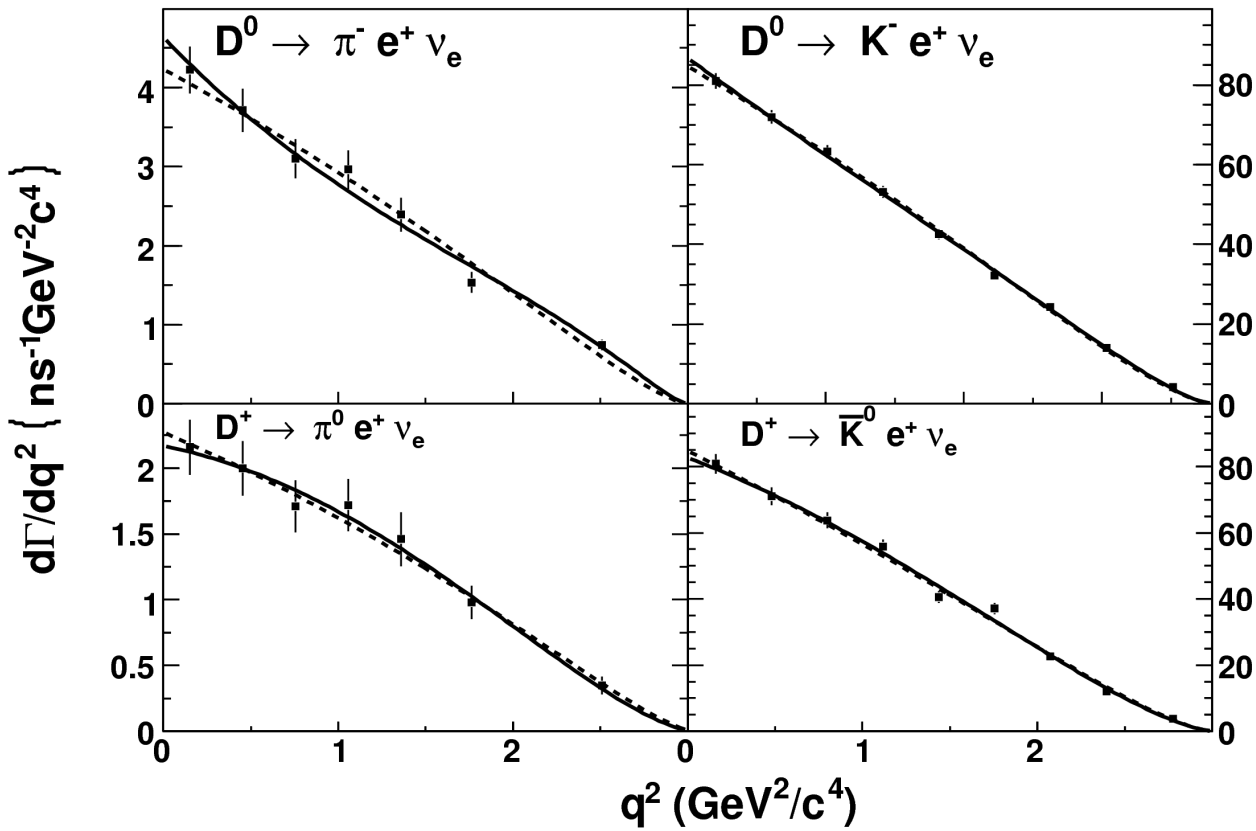
$$f_+(q^2) = \frac{f_+(0)/(1-\alpha)}{1-\frac{q^2}{M^2_{D^*_{(s)}}}} + \sum_{k=1}^{N} \frac{\rho_k}{1-\frac{1}{\gamma_k}\frac{q^2}{M^2_D}}$$

- The "Series" Model makes a transformation of variables

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

- Convergence properties are much improved by transformation
  - With wisely chosen Φ and t_0, z is small (~0.05 for Kenu, ~0.17 for πev)
- We fit using 2 and 3 parameter versions of this model, taking the 3 parameter fits as our nominal results

Fits to Partial Rates



Form factor fits in data to individual semileptonic modes using the 3-param (solid) and 2-param (dashed) series expansion

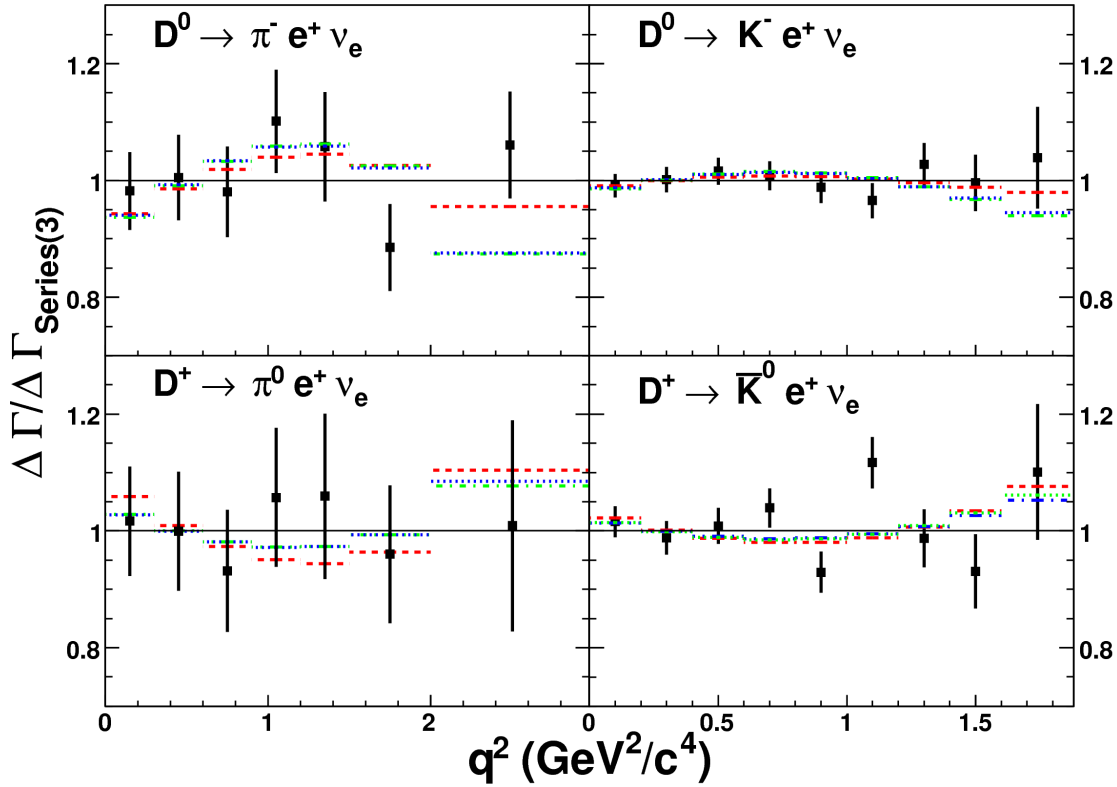
Quality of 3-param fits

	X^2/dof
$D^0 \to \pi e \nu$	4.6/4
$D^0 \to K e \nu$	3.2/6
$D^- \to \pi^0 e \nu$	0.9/4
$D^- \to K^0 e \nu$	11.9/6

Fits to Partial Rates

- What can CLEO-c say about the various parameterizations?

Deviation of fit results using various parameterizations from our standard results using 3-parameter series.
Simple Pole Model
Modified Pole Model
2-parameter series
Data (points)



- Fit results are quite similar → differences between parameterizations are very subtle
- Quality of all fits is good → chisquares don't prefer any model

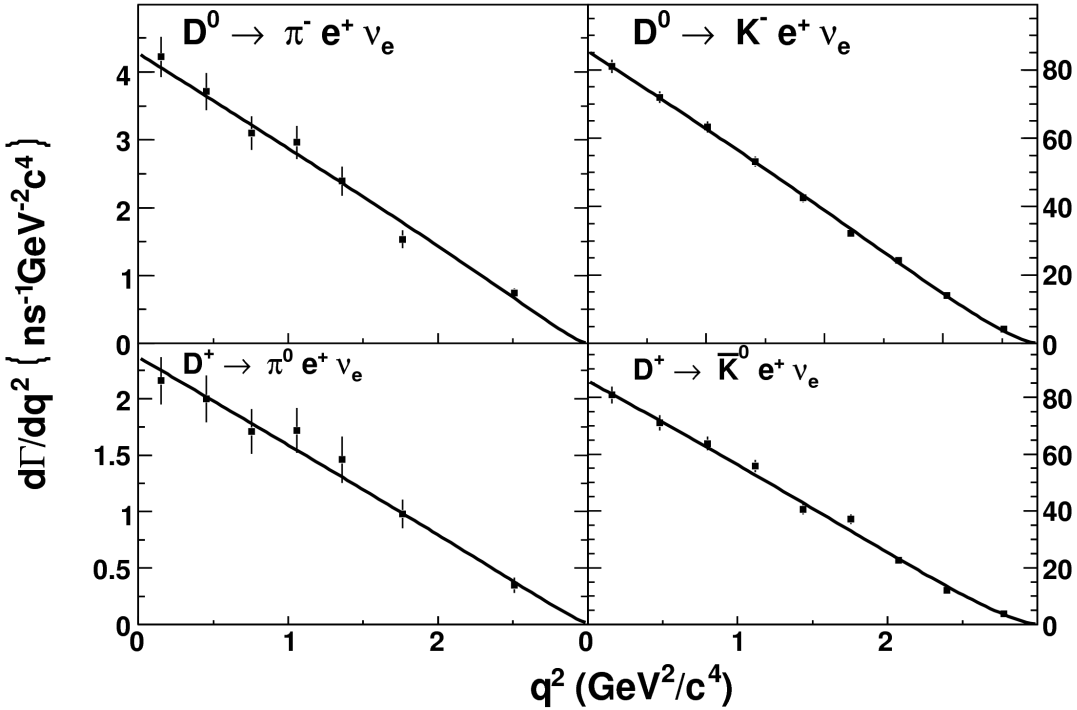
Fits to Partial Rates

- What can CLEO-c say about the various parameterizations?

Form factor fits using the simple pole model, with results:

$M_{pole}(\pi e\nu) = 1.91 \pm 0.02$ GeV

$M_{pole}(Ke\nu) = 1.93 \pm 0.02$ GeV

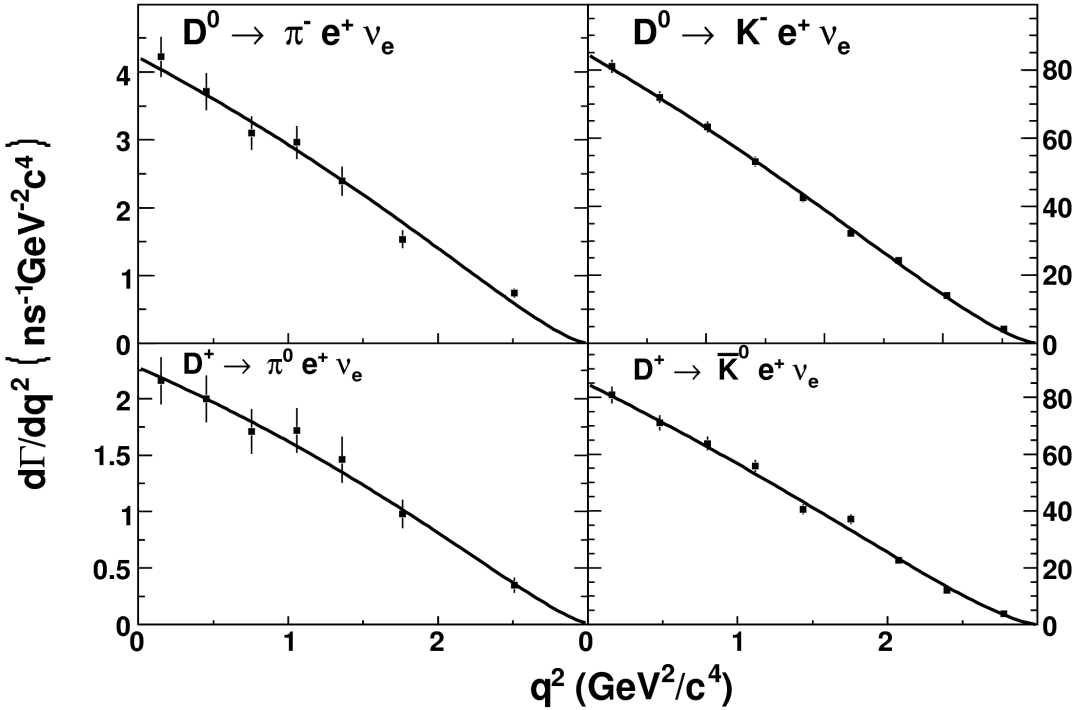


- Preferred pole masses are far from expected values of $M_{D^*} = 2.01$ GeV and $M_{Ds^*} = 2.11$ GeV
- Although quality of fits is reasonable, single pole dominance assumption is clearly wrong

Fits to Partial Rates

- What can CLEO-c say about the various parameterizations?

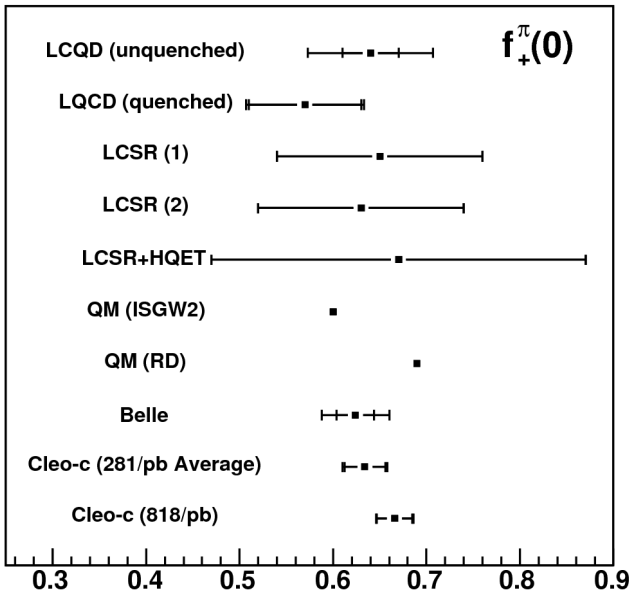
Form factor fits using the modified pole model, with results:
1+1/β-δ (πev) = 0.93±0.09
1+1/β-δ (Kev) = 0.89±0.04

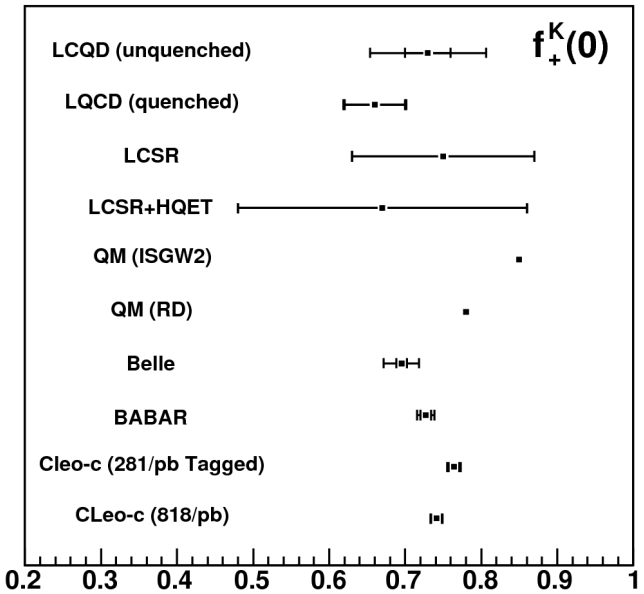


- Preferred pole masses are far from assumed values of 1+1/β-δ = 2
- Although quality of fits is resonable, assumption made by modified pole model is not valid

Fits to Partial Rates: Form Factor Parameters

- Form factor normalization results, with others:

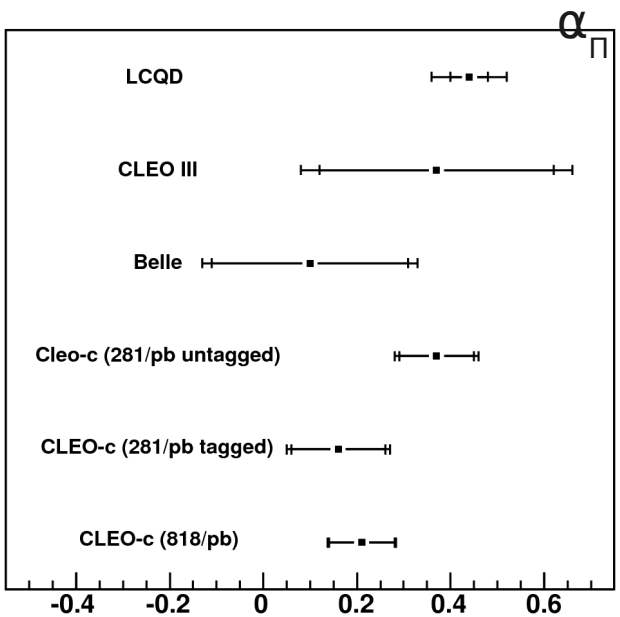


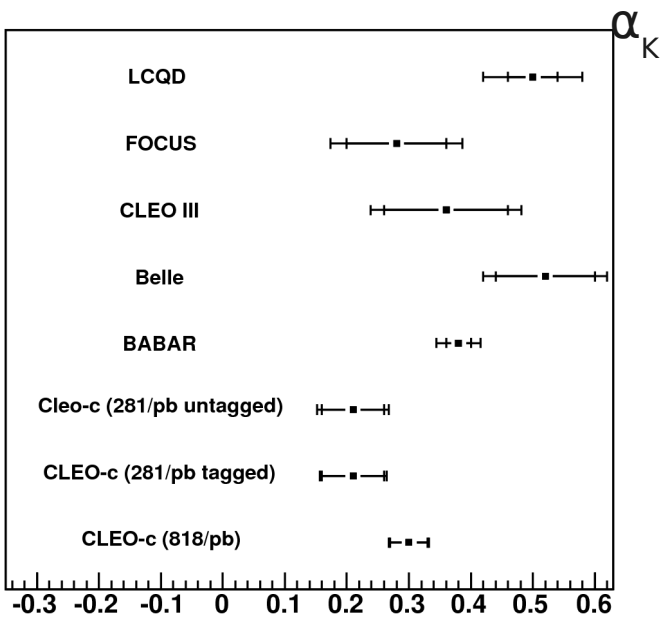


- Results from this work are taken from isospin-combined fits using 3-parameter series expansion fits
- Agree with other experiments to within 2 sigma
- No discrepancy with lattice at current level of precision

Fits to Partial Rates: Form Factor Parameters

- Modified pole parameter α results, with others:

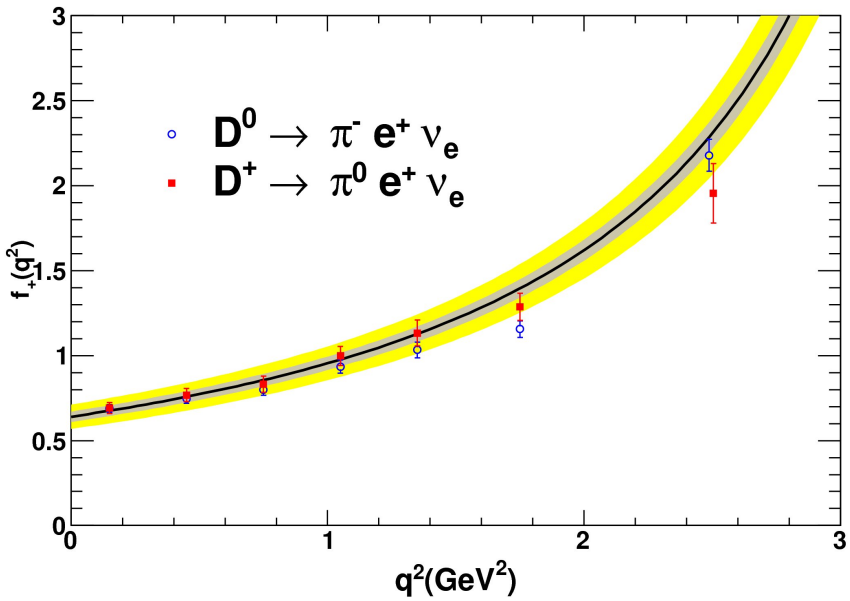




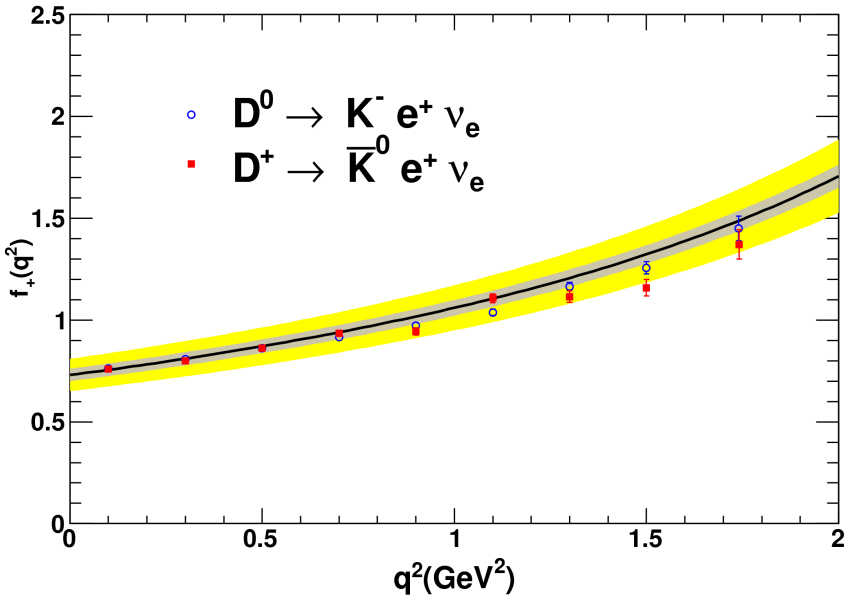
- Shape measurement agree with other experimental results within 2 sigma
- Disagreement with LQCD is slightly more than 2 sigma in both cases

Comparison with Theory

- **Further Comparison with LQCD:**



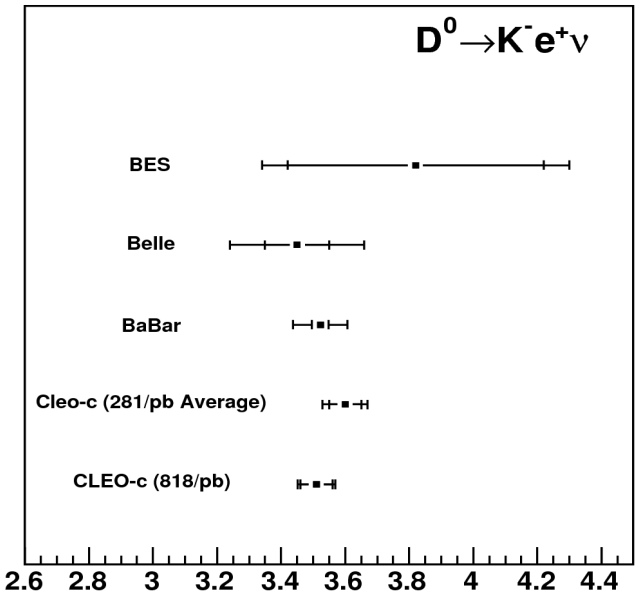
- Points show CLEO's binned form factors with statistical & systematic uncertainties
- Solid line shows fit to unquenched LQCD (using modified pole model) with statistical (grey) and systematic (yellow) uncertainties

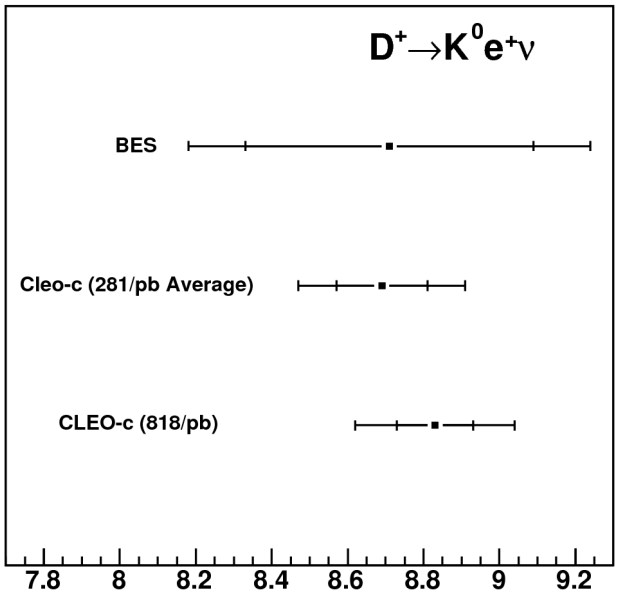


LQCD Fit/Bands courtesy Andreas Kronfeld, based on Fermilab Lattice/MILC/HPQCD Unquenched results (PRL 94, 011601 (2005))

Fits to Partial Rates: Branching Fraction Results

- D → K Branching fraction results, with others:

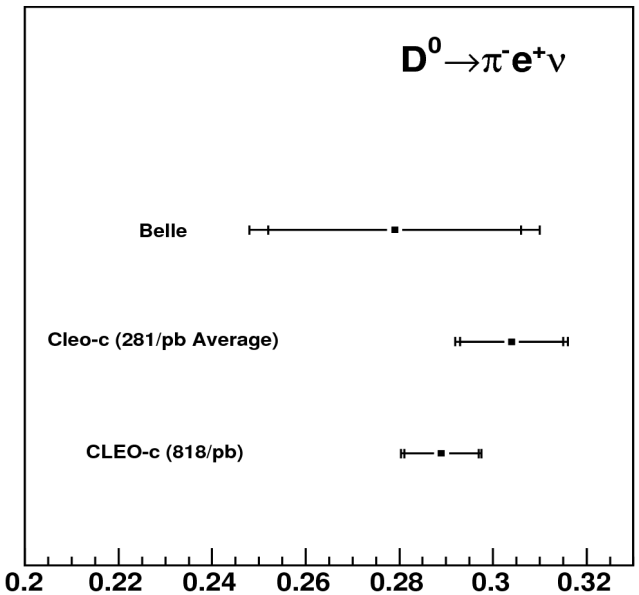


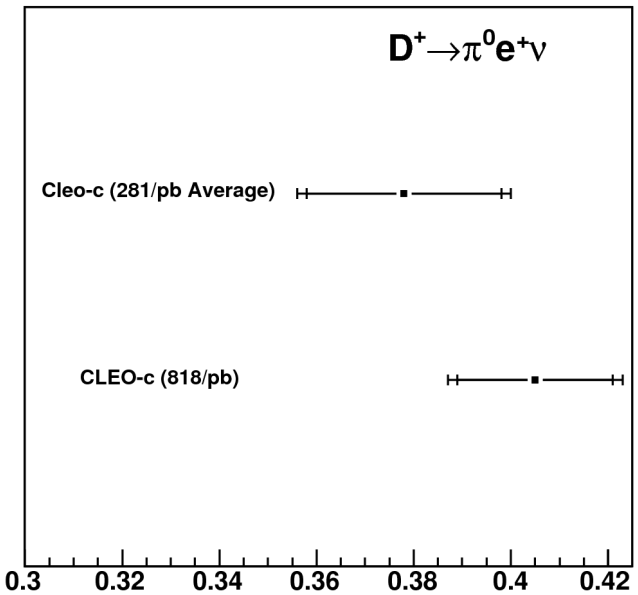


- CLEO-c (818/pb) results are taken from 3-parameter series expansion fits

Fits to Partial Rates: Branching Fraction Results

- $D \rightarrow \pi$ Branching fraction results, with others:

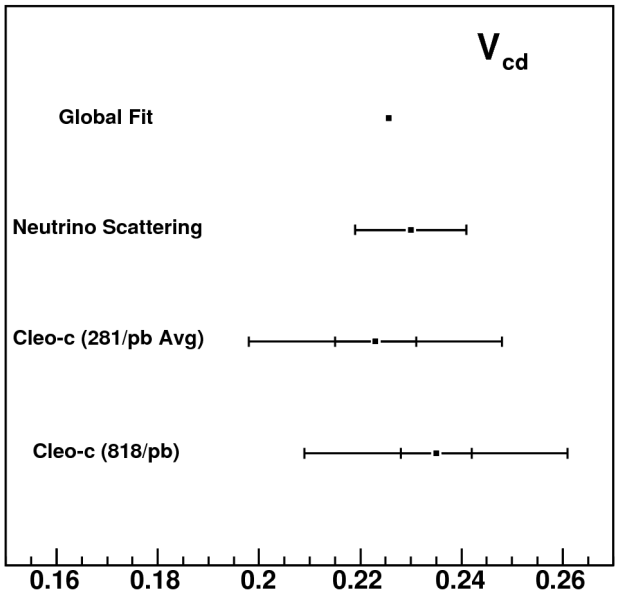


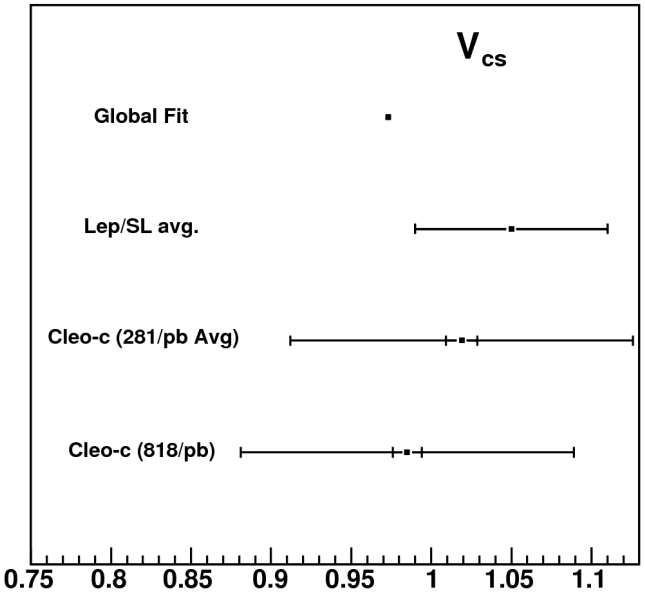


- CLEO-c (818/pb) results are taken from 3-parameter series expansion fits

Fits to Partial Rates: CKM Parameters

- CKM Results (with others):





- Results are dominated by theoretical uncertainty due to LQCD
- Within large uncertainties, consistent with other measurements and with PDG fits assuming CKM unitarity

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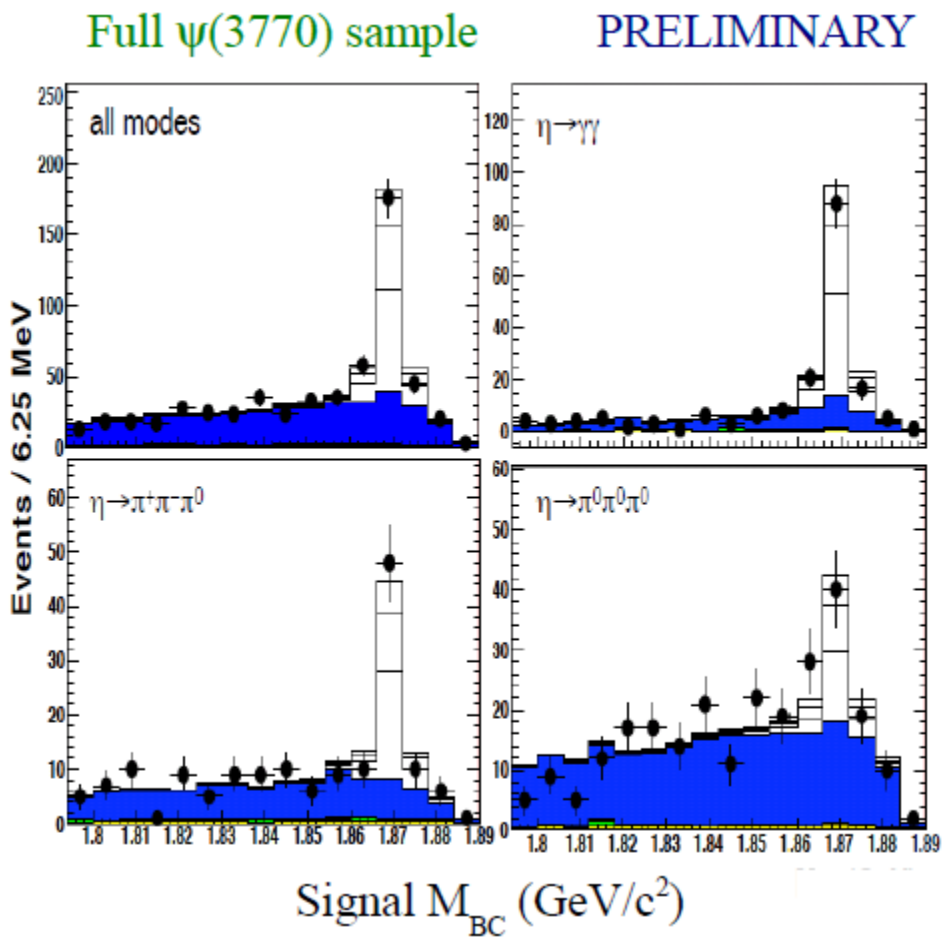
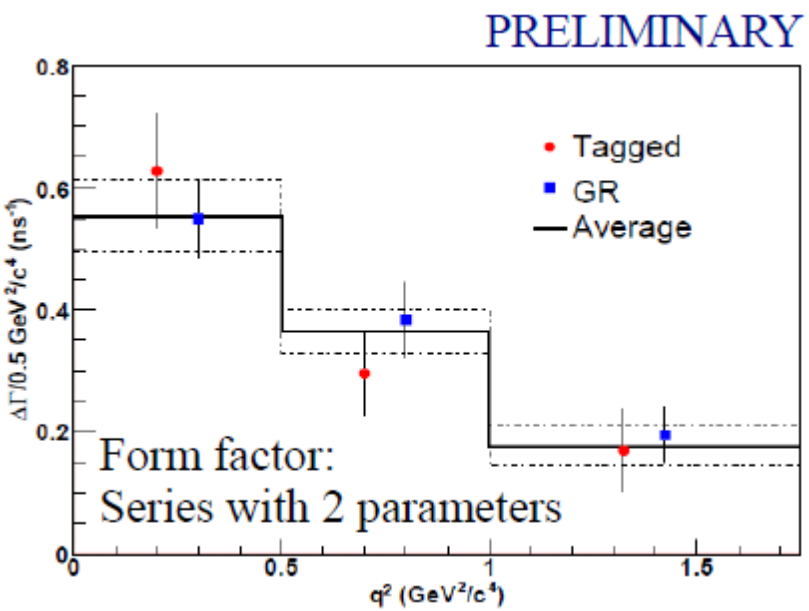
Other CLEO-c Semileptonic Results

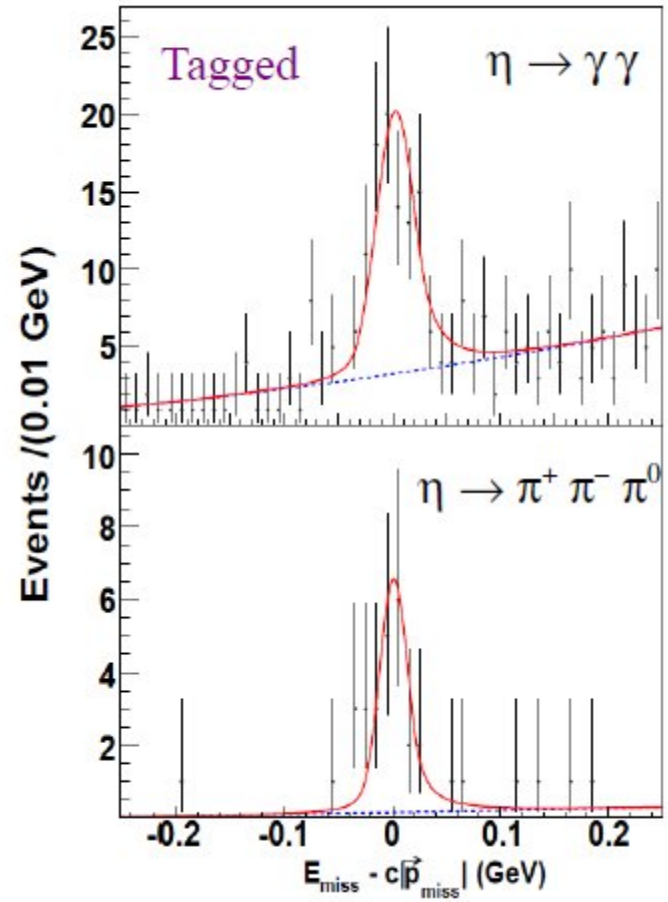
- $D \rightarrow \eta e \nu$ via an alternative analysis technique:
- Reconstruct signal: $\eta + e$
- Then look for combinations of π's, K's, π^0's, K_S's and η's opposite signal
- Infer neutrino 4-vector from all reconstructed particles
- Bonus of this analysis: measured 38 $D \rightarrow$ hadron modes, include 13 previously unmeasured



Other CLEO-c Semileptonic Results

- $D \to \eta e \nu$ via a tagged analysis technique:
- Similar to $D \to \pi/K\ e\ \nu$
- Averaged with generic reconstruction technique (including highly non-trivial correlation calculation!)
- Made first form factor measurement





$B(D^+ \to \eta e \nu) = (11.4 \pm 0.9 \pm 0.4) \times 10^{-4}$
(average of both methods)

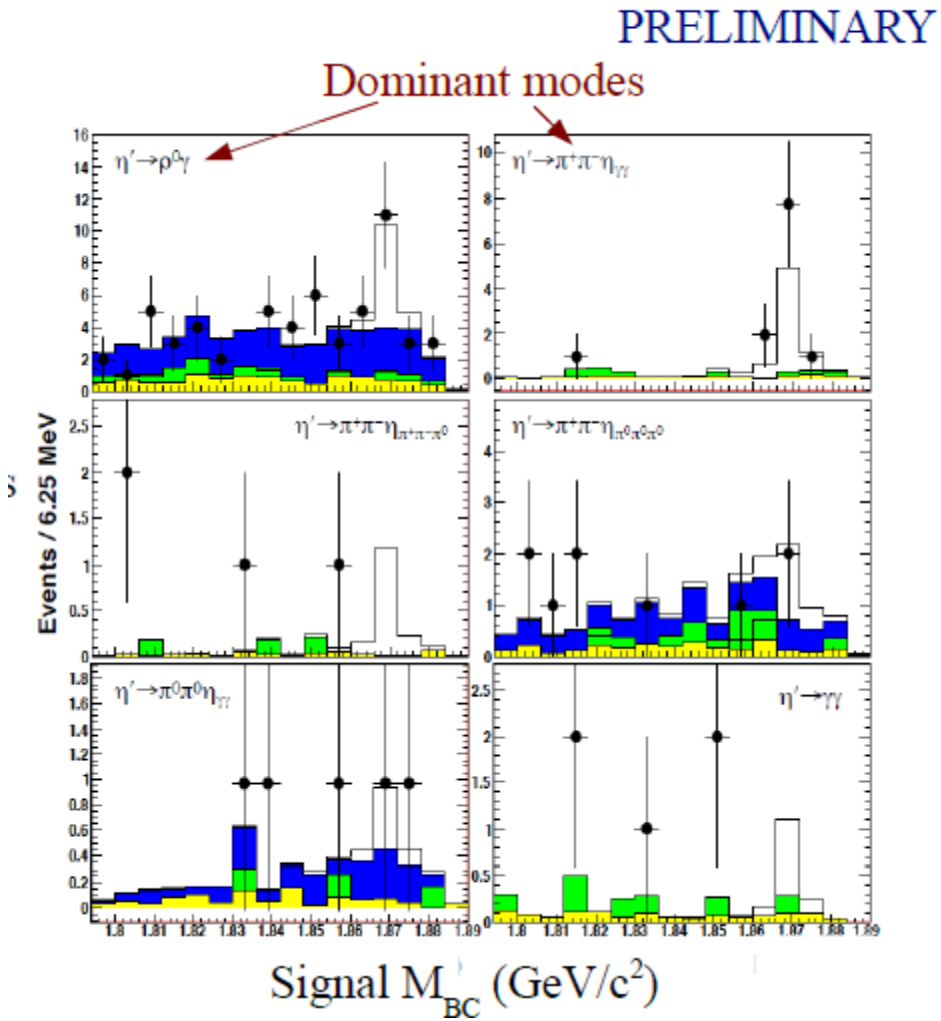
Other CLEO-c Semileptonic Results

- $D \rightarrow \eta' e \nu$ generic reconstruction:

- First observation of this mode

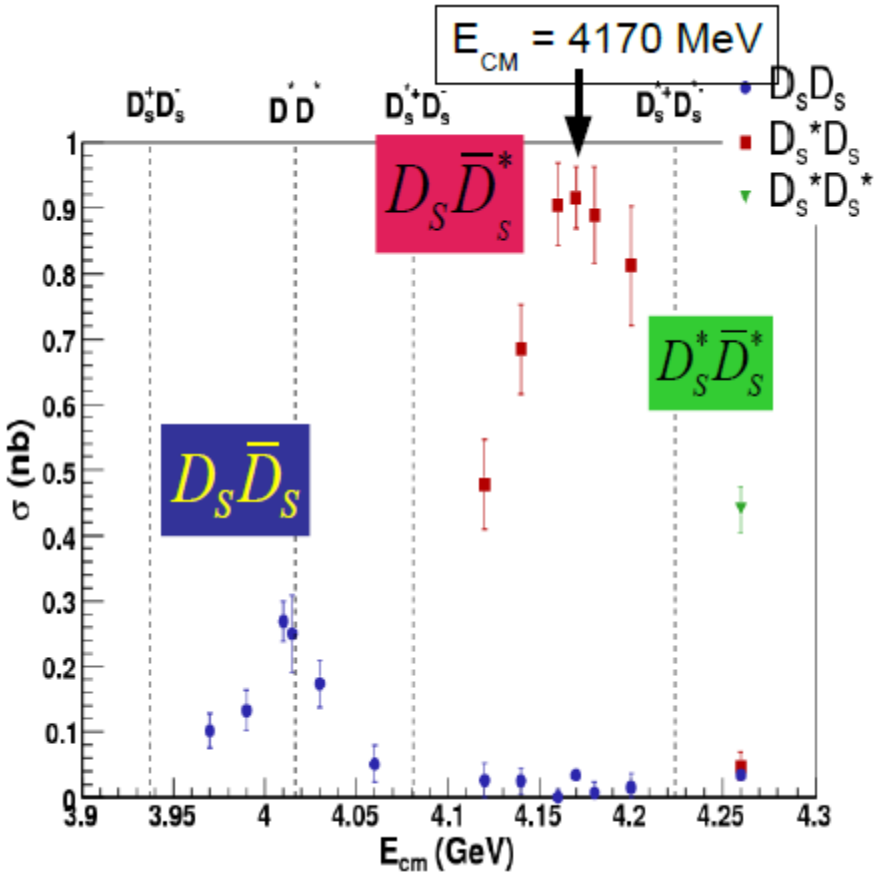
$$B(D^+ \rightarrow \eta' e^+ \nu) = (2.16 \pm 0.53 \pm 0.05 \pm 0.05) \times 10^{-4}$$

stat syst $K\pi\pi$



Other CLEO-c Semileptonic Results

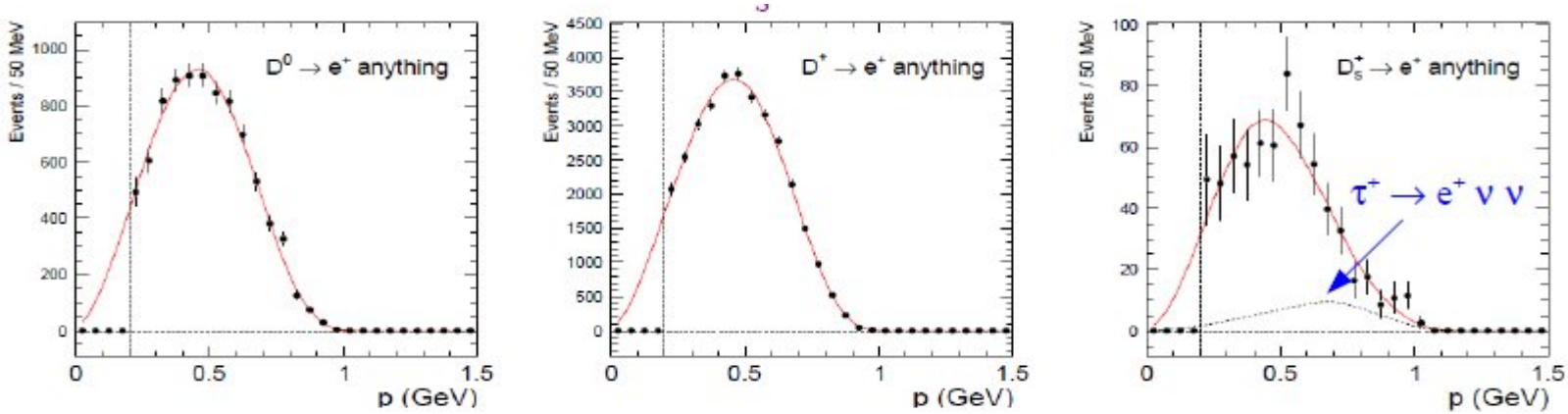
- Ds Semileptonic Decays
- In Fall 2005, CESR scanned the energy range 3.97 < Ecm < 4.26 GeV
- Goal: Find optimal region for producing Ds
- Optimal Energy 4.17 GV
- D's are also produced at this energy, but events are much cleaner at 3.77 GeV



CLEO: PRD 80, 072001 (2009)

Other CLEO-c Semileptonic Results

- D and Ds Inclusive Semileptonic Decays



$$\frac{\Gamma(D^+ \to Xe^+\nu)}{\Gamma(D^0 \to Xe^+\nu)} = 0.989 \pm 0.015 \pm 0.024$$

Consistent with isospin symmetry

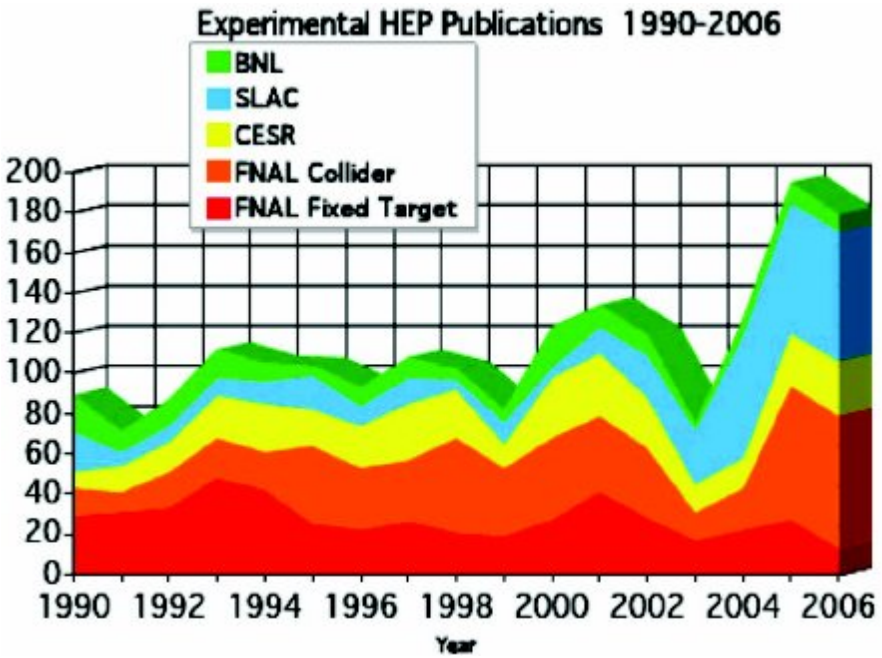
$$\frac{\Gamma(D_S^+ \to Xe^+\nu)}{\Gamma(D^0 \to Xe^+\nu)} = 0.828 \pm 0.051 \pm 0.025$$

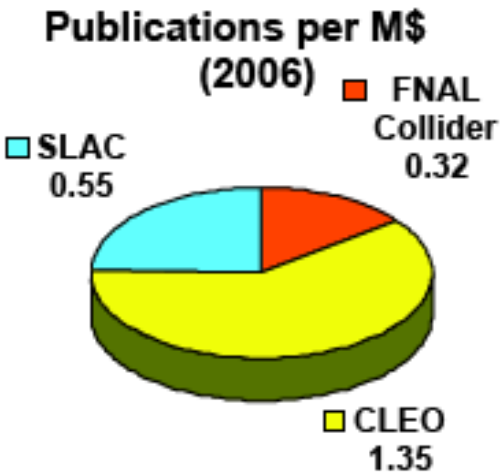
Differences between Ds/D may be similar to those of Bs/B and therefore relevant to Vub

- Analysis of spectrum shape is underway.

Other CLEO-c Semileptonic Results

- Some final trivia (compiled by FNAL, via S. Stone):





Conclusion

- We have measured partial rates in several q^2 bins for the semileptonic decays $D \to \pi^{\pm} e \nu$, $D \to K^{\pm} e \nu$, $D \to \pi^0 e \nu$, $D \to K^0_S e \nu$
- The partial rates have been used to extract:
    - Branching fractions
    - Form factors
    - CKM elements
- The branching fraction and D → pi form factor measurements are the world's most precise, and provide a excellent goal for Lattice QCD