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

University of Virginia High Energy Seminar

Laura Fields
Cornell University
For the CLEO Collaboration

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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:
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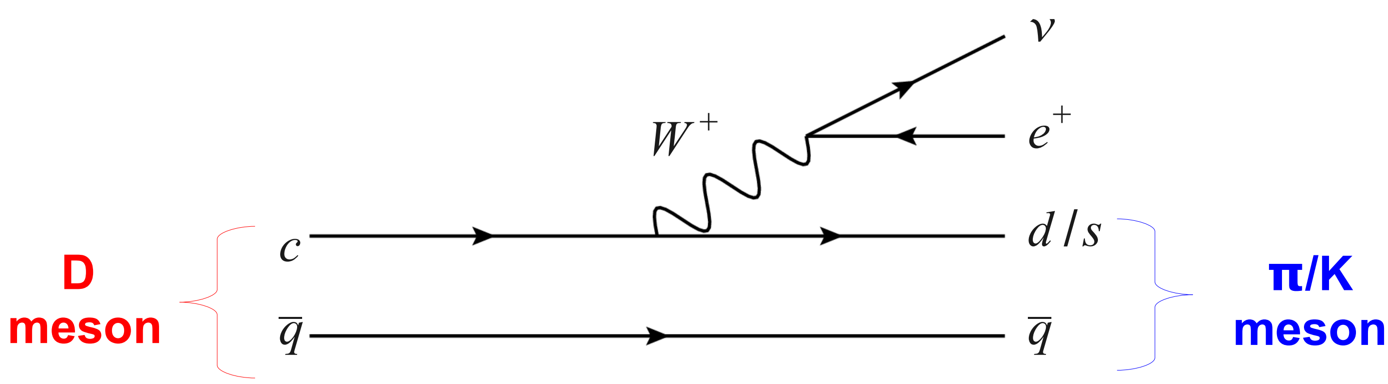
Semileptonic Decays

- A Semileptonic D Decay:



- Governed by both weak and strong forces

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

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

Leptonic Current
(known)

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

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

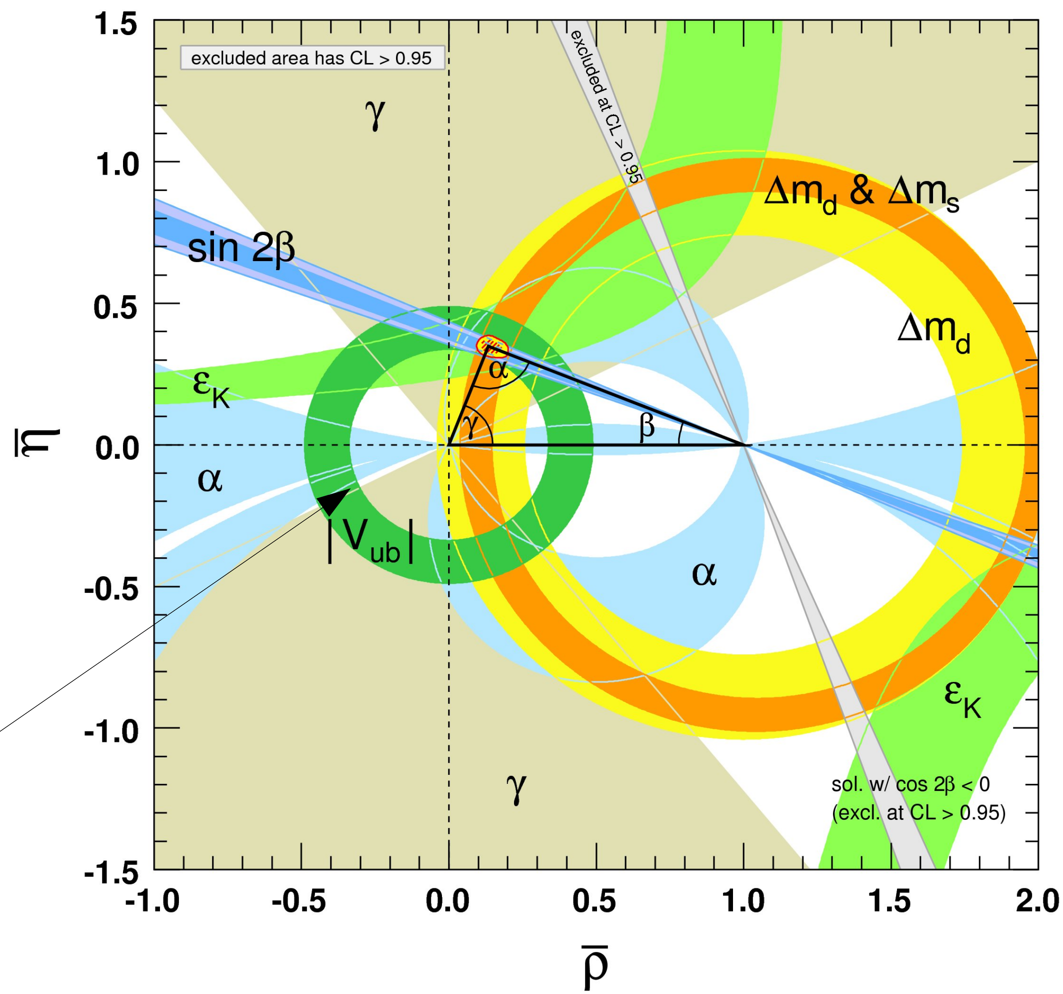
- Several QCD techniques exist to estimate form factors
  - Quark models
    - Ad hoc
    - Uncertainties difficult to quantify
  - Light Cone Sum Rules (LCSR)
    - Uncertainties of 20-30%
  - Lattice QCD
    - Until recently, uncertainties competitive with LCSR
    - New computational techniques +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

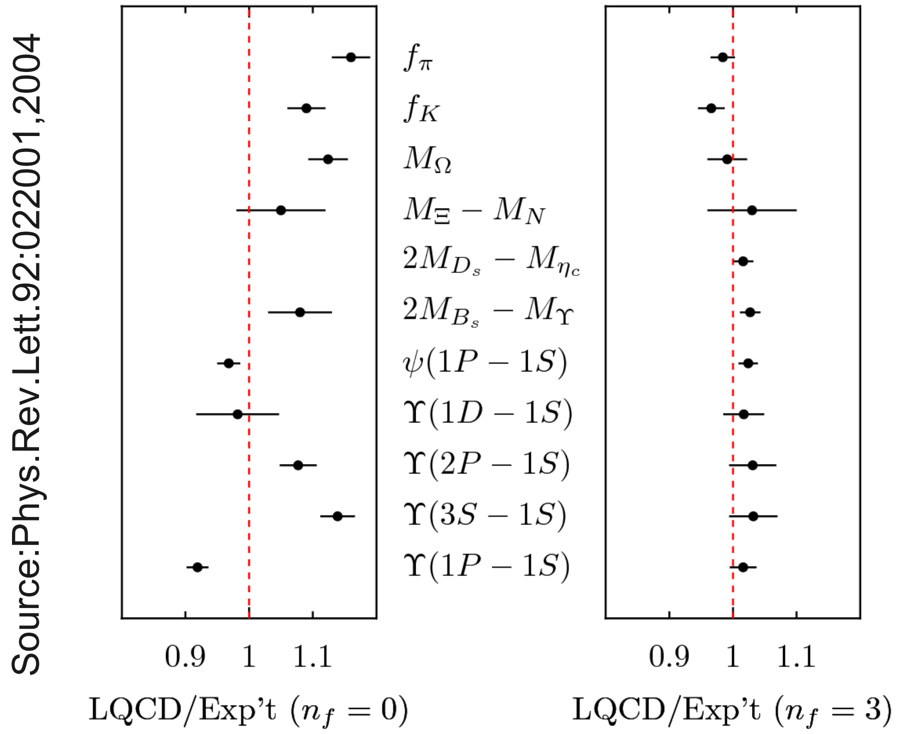
V_{ub} is extracted from B semileptonic decays → shrinking V_{ub} errors requires LQCD predictions



Source: PDG 2008

Semileptonic Decays

- How confident can we be in LQCD?



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:

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

At Cleo-C, we can measure rates for $D^0\rightarrow\pi^- e\nu$, $D^0\rightarrow K^- e\nu$, $D^+\rightarrow\pi^0 e\nu$ and $D^+\rightarrow K^0 e\nu$

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

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

- 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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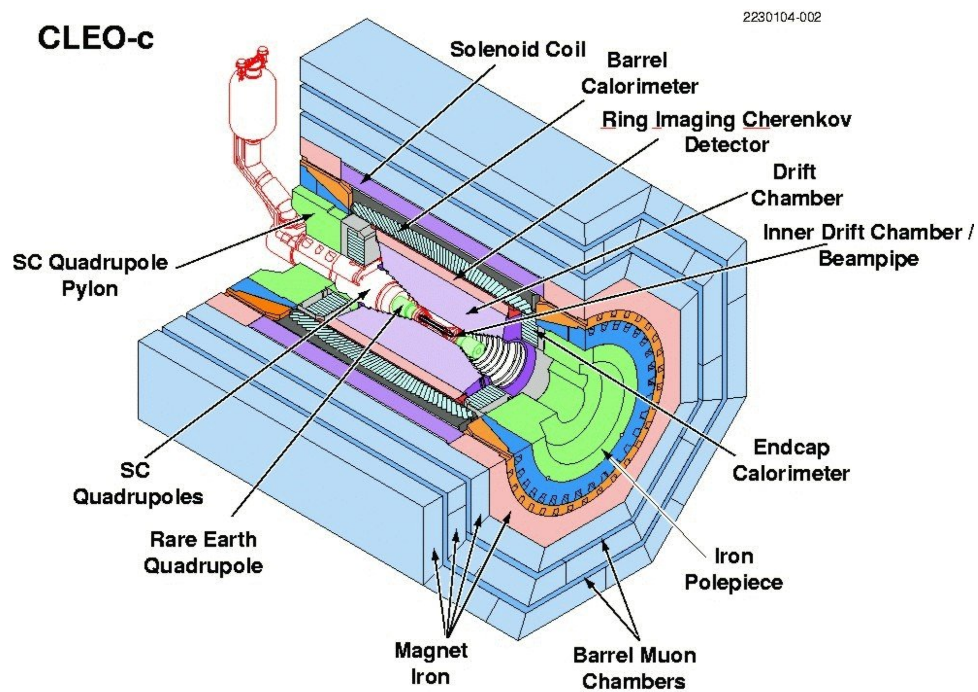
The CLEO-c Program

- CESR: an e+e- collider located at Cornell
- Began collisions in 1979 with COM energies of ~10 GeV
- CLEO studied a wide variety of Υ 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 σp/p = 0.5% at 0.7 GeV
    - Covers |cos θ| < 0.93
- Ring Imaging Cherenkov detector (RICH) provides particle ID
- CsI calorimeter with σE/E = 5% at 100 MeV

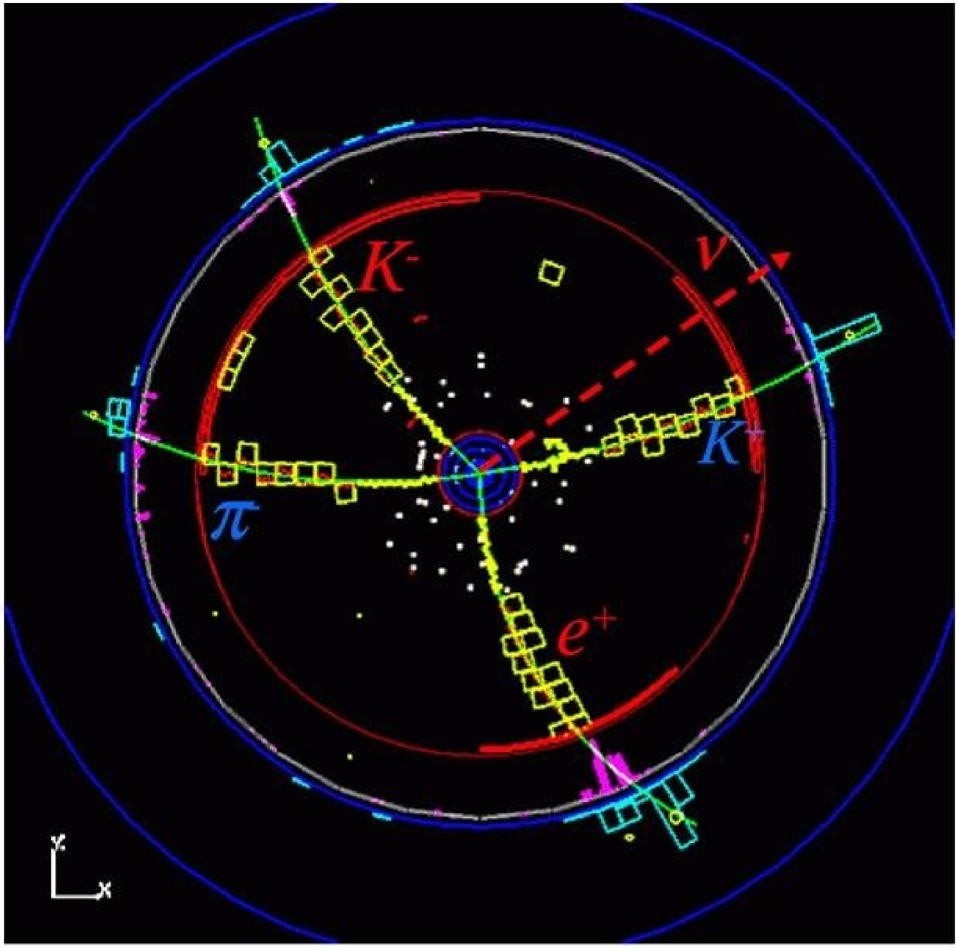


The CLEO-c Program

- 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?

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

Number of tag + semileptonic decays in ith qsq bin

D Lifetime

Number of Tag Decays

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

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

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

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 5° 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:

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

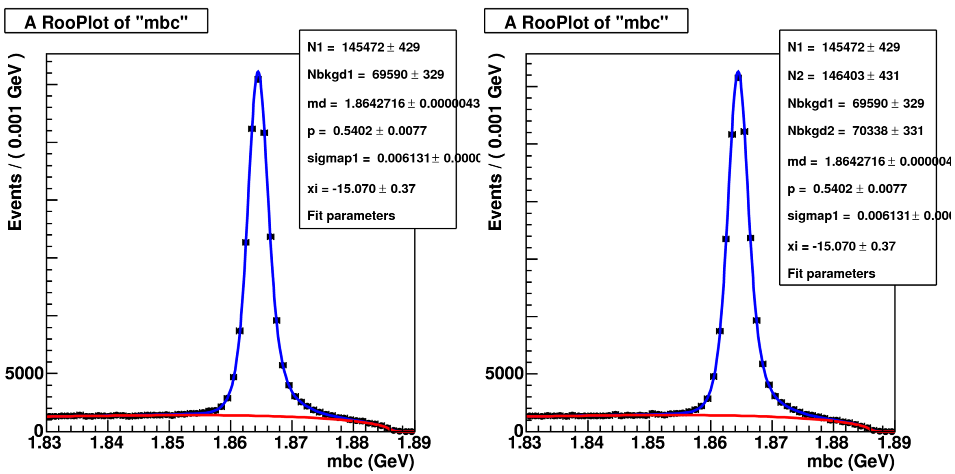
- Backgrounds are suppressed with cuts on two variables:

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

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

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

Partial Rate Extraction: Tag Yields



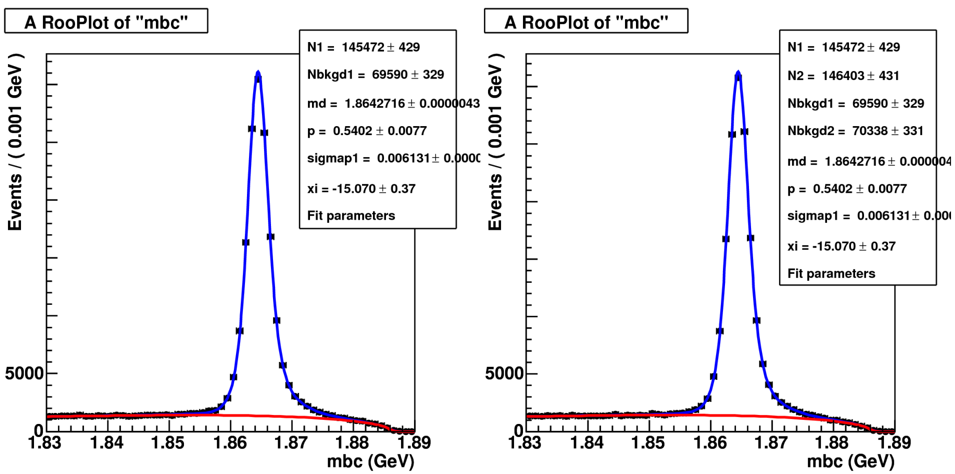
$D^0 \to K\pi\pi^0$ M_{BC} Fits in Data (both flavors)

- 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



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

Tagging Efficiencies:

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

Obtained by fitting Monte Carlo a la data →

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
    - $D^0 \to \pi^- e\nu$ and $D^+ \to \pi^0 e\nu$ have large backgrounds from $D^0 \to K^- e\nu$ and $D^+ \to K^0 e\nu$, respectively
    - $D^0 \to K^- e\nu$ and $D^+ \to K^0 e\nu$ have small backgrounds, mainly from $D \to K^* e\nu$

- To maximize signal/background separation, we extract yields from distributions of:

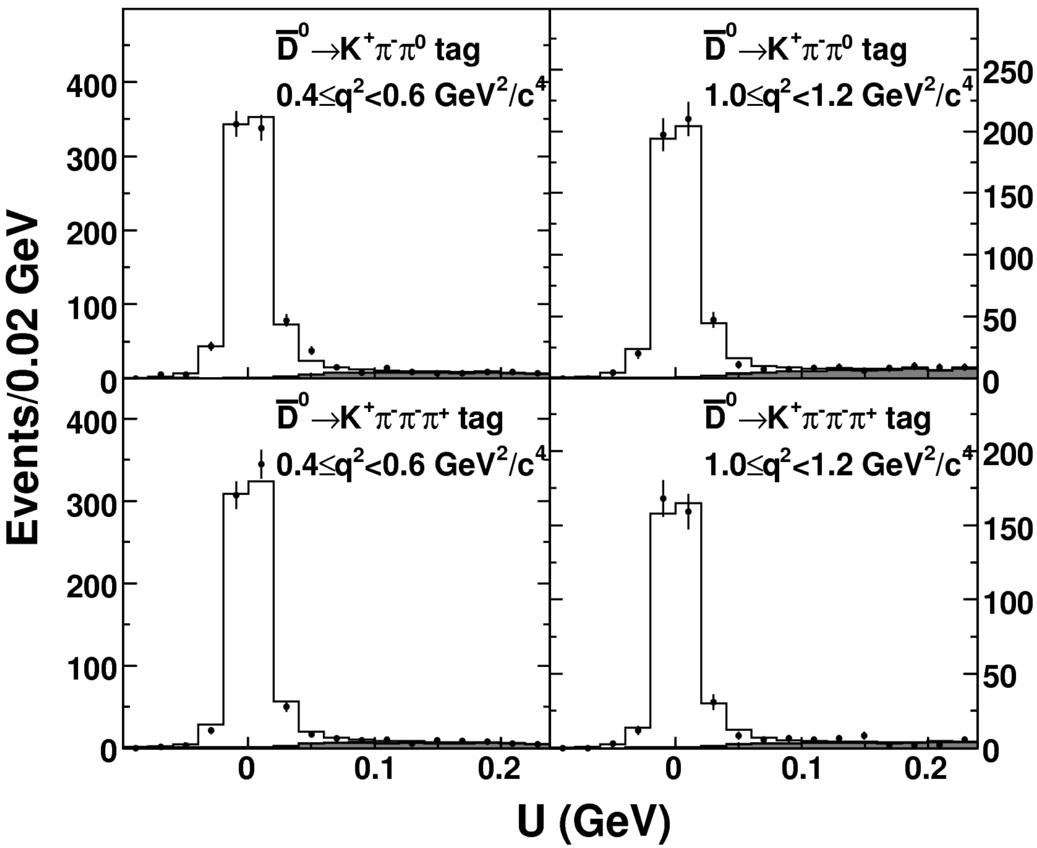
$$U = E_{miss} - c|P_{miss}|$$

  - 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: $D^0 \rightarrow K^{\pm} e \nu$ Signal Yields

data (points), Signal (clear), Bkgd (Grey)



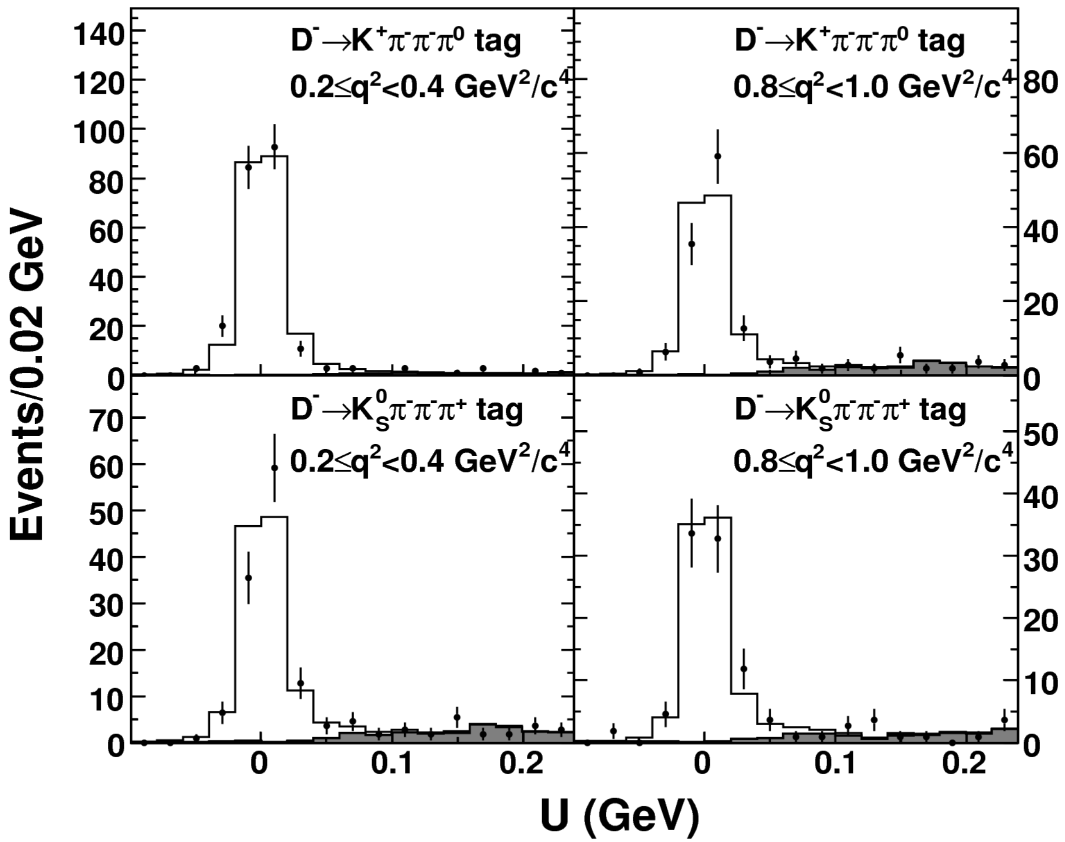
- Signal Yields in $D^0 \rightarrow K^{\pm} e \nu$:
  - Normalization of small non-DD background fixed
  - All other backgrounds combined into a single shape
  - Normalization of signal and background shapes float

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

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

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

data (points), Signal (clear), Bkgd (Grey)



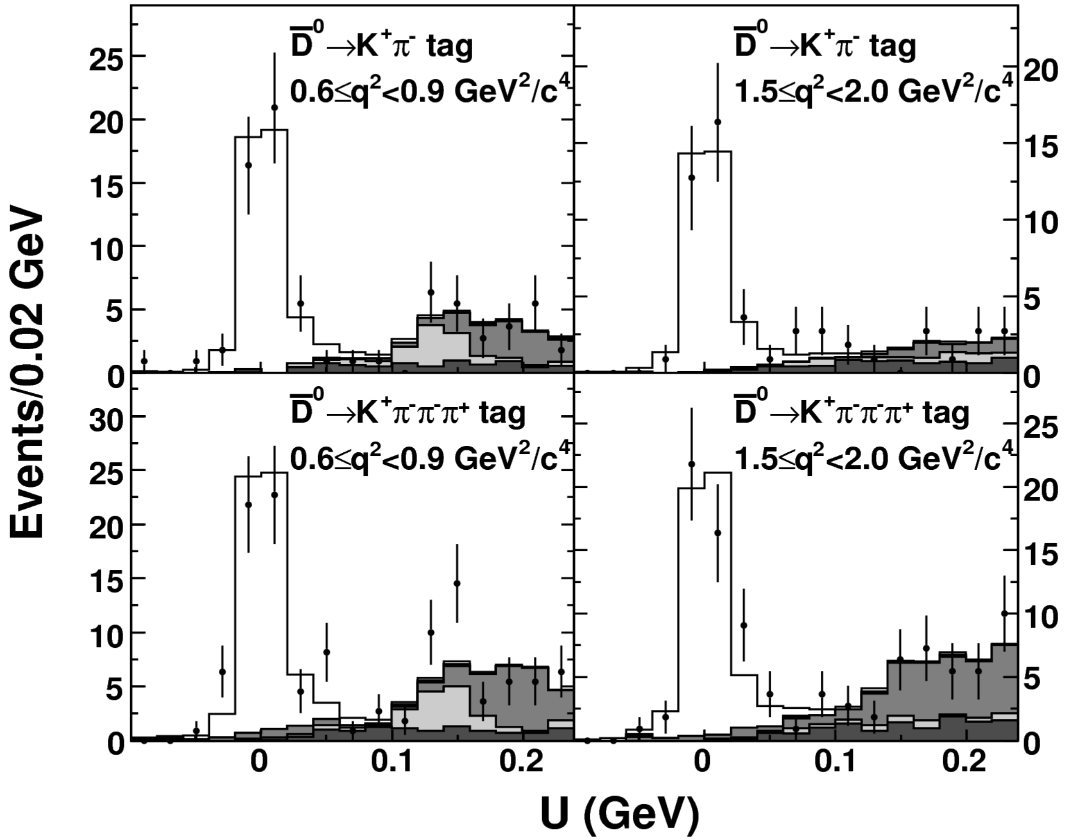
- Signal Yields in $D^{\pm} \rightarrow K^0 e\nu$:
  - Normalization of small non-DD background fixed
  - All other backgrounds combined into a single shape
  - Normalization of signal and background shapes float

← 4 of the 54 $D^{\pm} \rightarrow K^0 e\nu$ 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), ρeν (med) Other(dark gray)



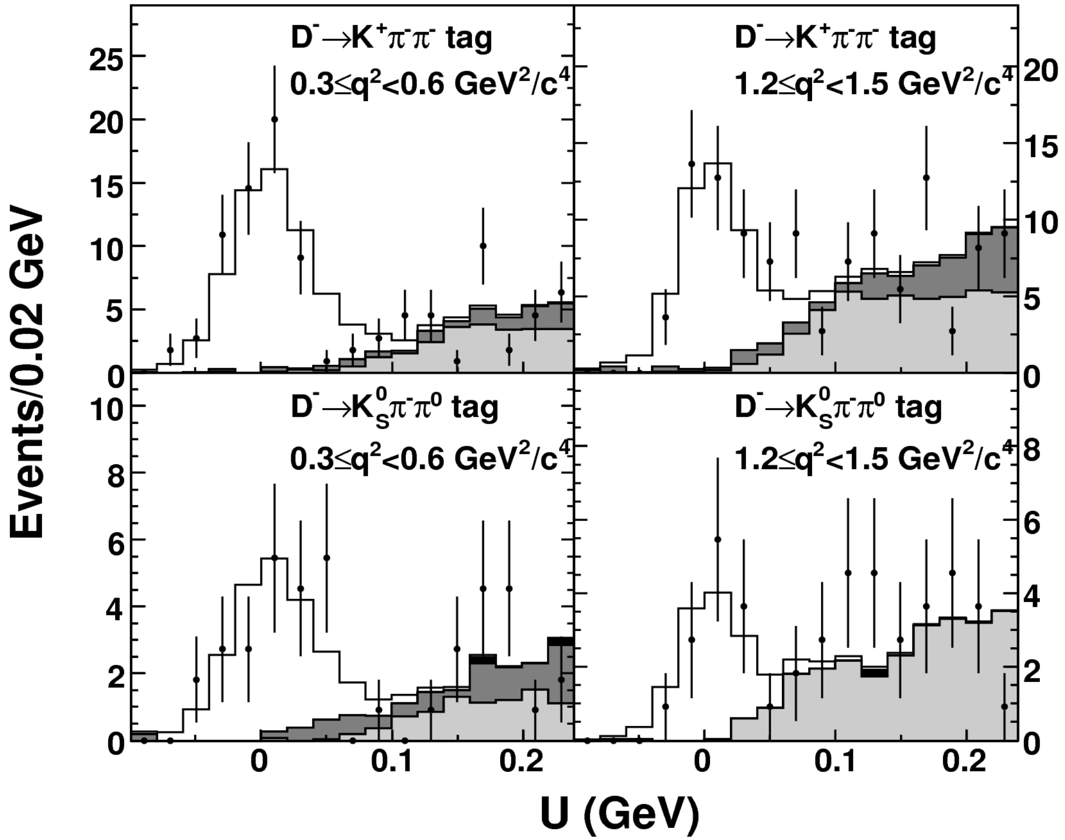
- Signal Yields in $D^0 \to \pi^{\pm} e \nu$:
  - Normalizations of $D \to K e \nu$, $D \to \rho e \nu$, and small non-DD background are fixed
  - All other backgrounds are combined into a single shape
  - Normalization of signal and background shapes float

← 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: $D^+ \rightarrow \pi^0 e\nu$ Signal Yields

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



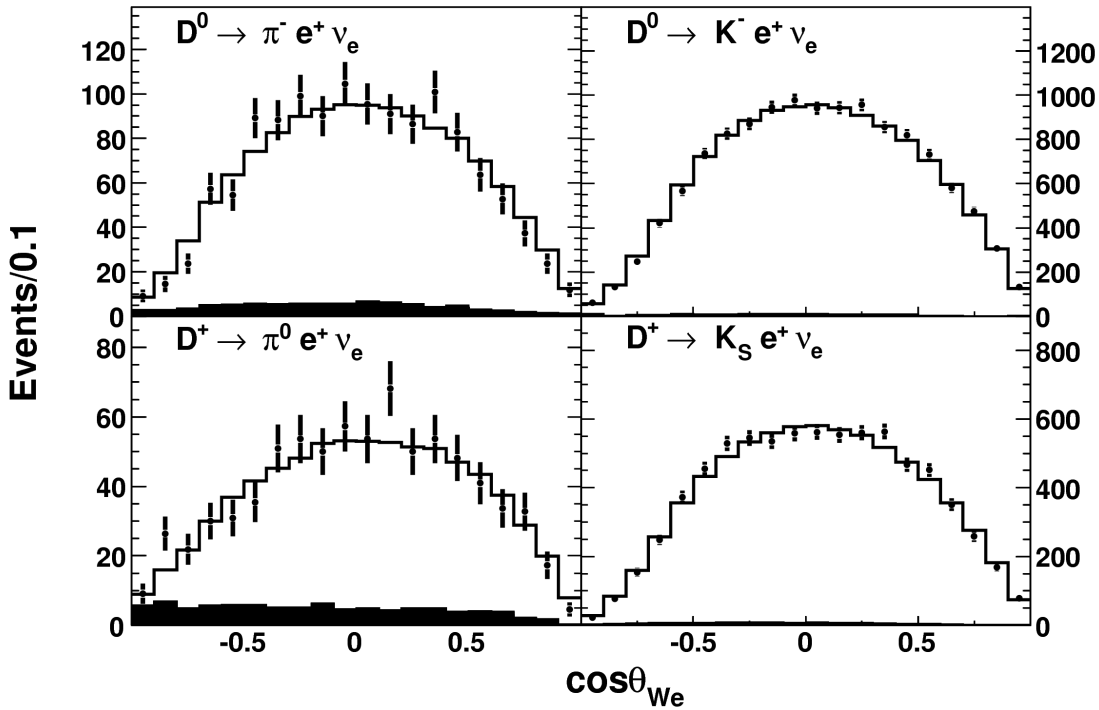
- Signal Yields in $D^+ \rightarrow \pi^0 e\nu$:
  - Normalizations of D → K0eν, and small non-DD background are fixed
  - All other backgrounds are combined into a single shape
  - Normalization of signal and background shapes float

← 4 of the 42 $D^0 \rightarrow \pi^{\pm} e\nu$ 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

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

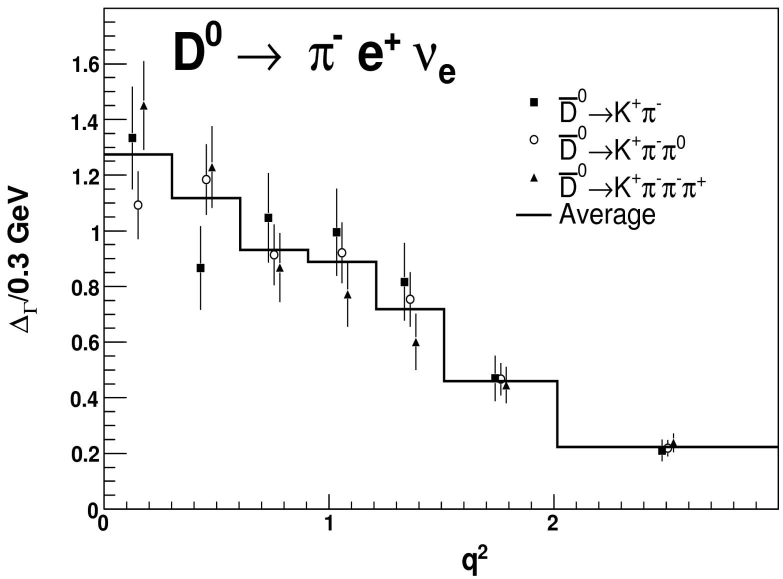
- Obtained from Signal MC
  - Account for efficiency & smearing due to semileptonic and tag reconstruction
  - Off-diagonal elements introduce a small correlation across q2 in the partial rate measurements

Generated Bin (columns) → ; Reconstructed Bin (rows)

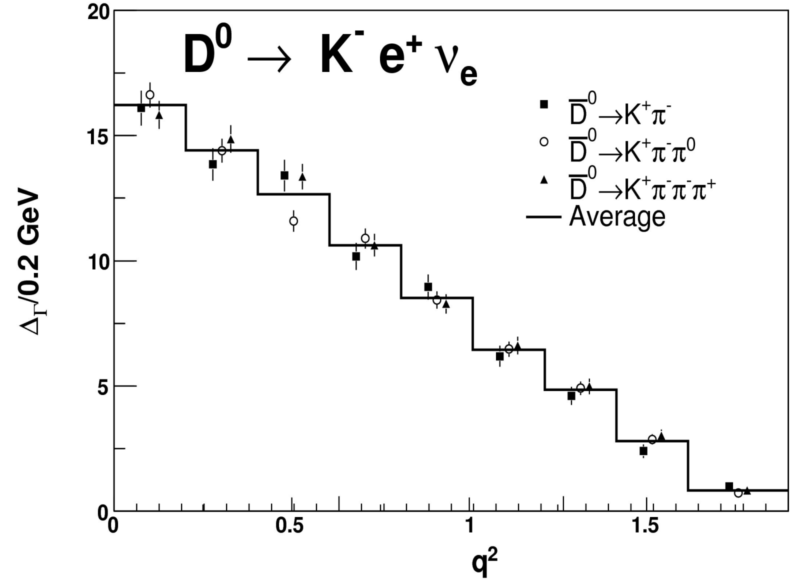
0.420	0.012	0.000	0.000	0.000	0.000	0.000
0.007	0.430	0.015	0.000	0.000	0.000	0.000
0.001	0.008	0.448	0.014	0.000	0.000	0.000
0.000	0.001	0.012	0.457	0.014	0.000	0.000
0.000	0.001	0.001	0.012	0.464	0.009	0.000
0.000	0.000	0.001	0.001	0.011	0.469	0.007
0.000	0.000	0.000	0.000	0.000	0.007	0.469

$\pi^+ e\nu / K\pi$ Signal Efficiency Matrix

Partial Rates Extraction: D^0 Mode Results



Partial Widths for D⟶piev



Partial Widths for D⟶kev

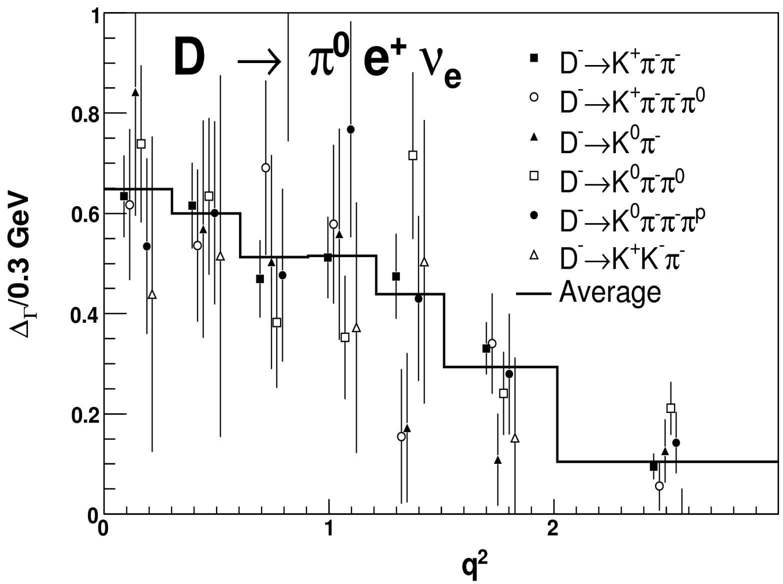
- Partial Rates extracted via:

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

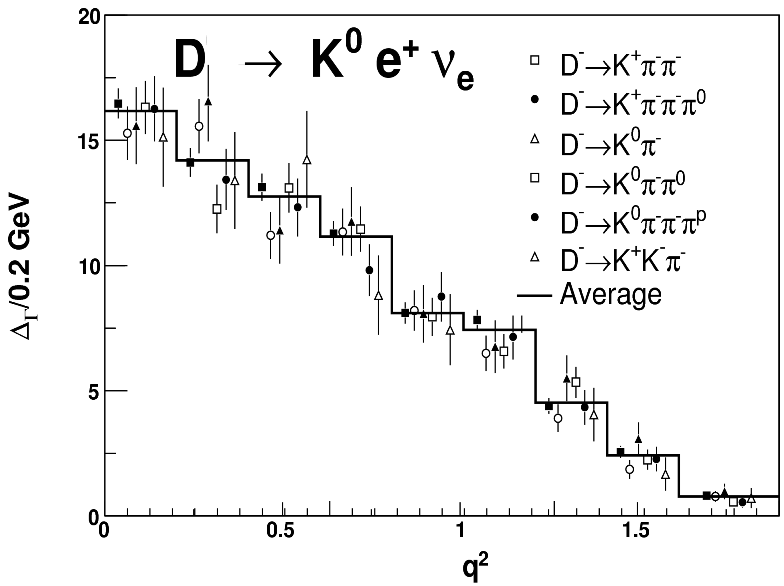
and averaged over tag modes

	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}
$D \rightarrow \pi^0$ e ν	36	35
$D \rightarrow K^0$ e ν	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:

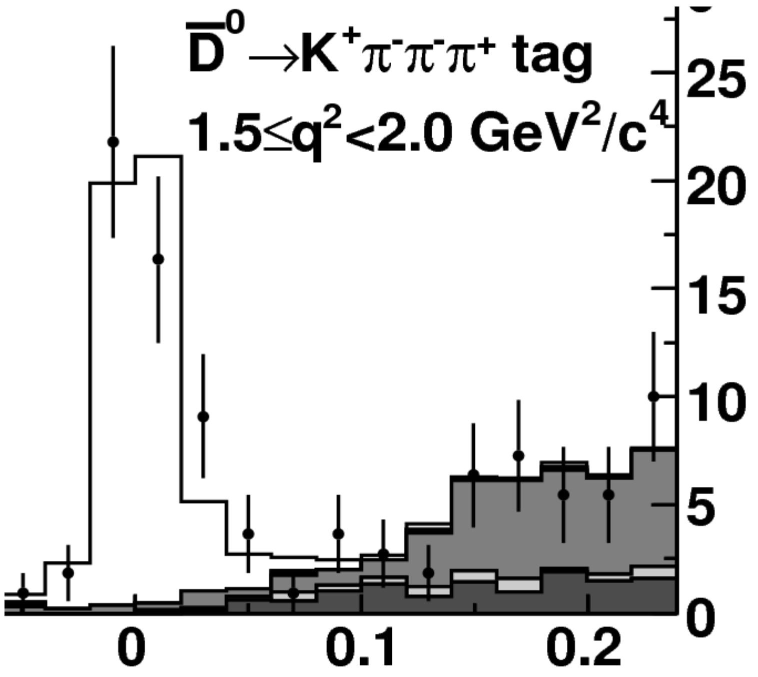
$$M_{ij} = \delta(\Delta\Gamma_i)\delta(\Delta\Gamma_j)$$

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

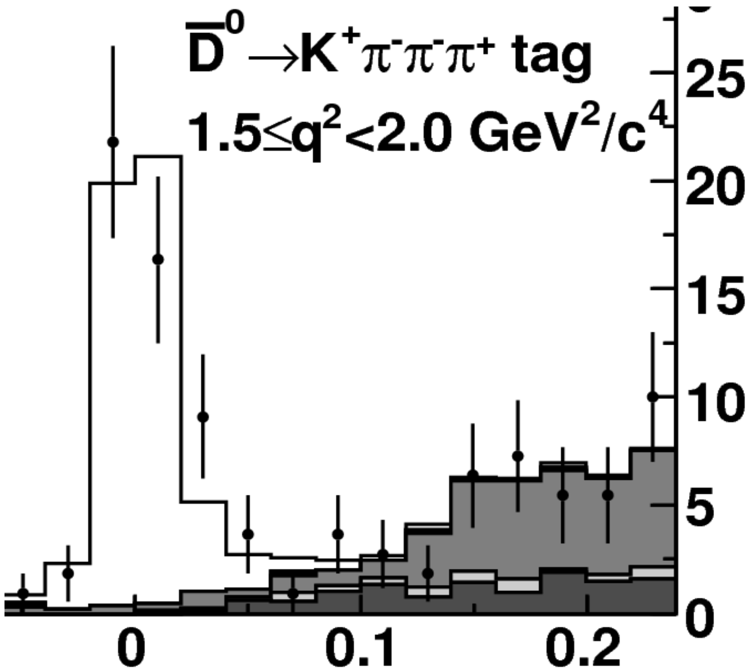
- One systematic uncertainty in detail: background shapes in $D^0 \to \pi^{\pm} e \nu$
  - Taking background shapes from Monte Carlo reduces statistical uncertainties on our signal yields (versus parameterizing backgrounds)
  - But this technique intruduces several systematic uncertainties that must 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 $D^0 \to \pi^{\pm} e \nu$ signal yield fit data (points), signal shape (white), fixed ρeν (med gray), Keν (light) and other (dark gray) backgrounds

Systematics: Background Shapes

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

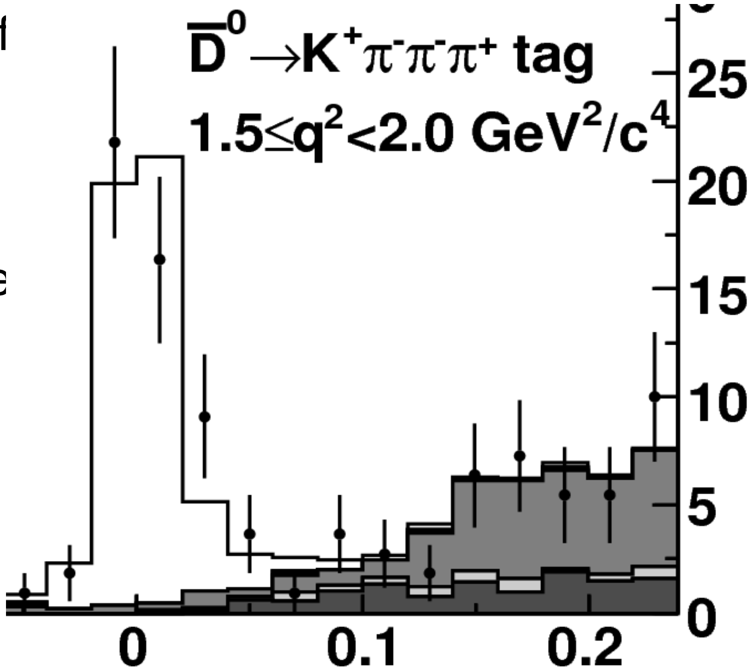


  - Changes in partial rates:

	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.

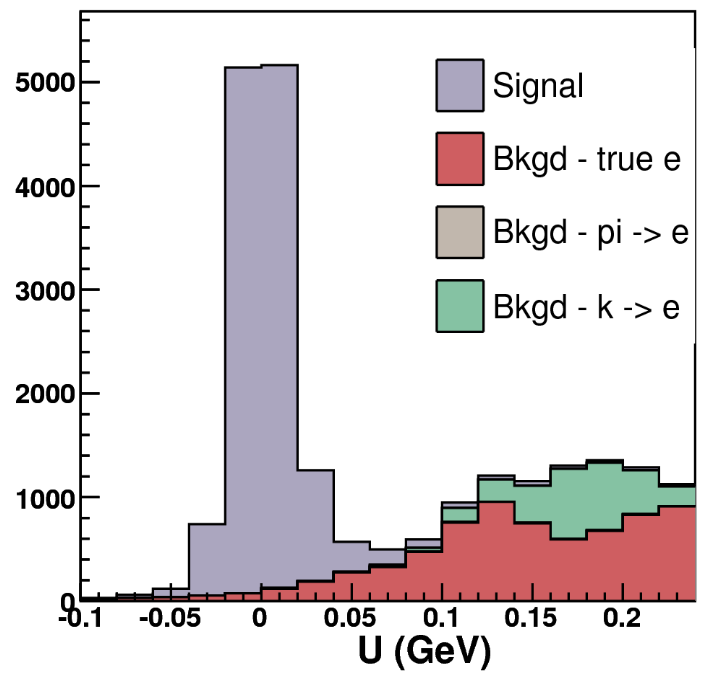


  - Changes in partial rates:

	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 → e fake rates
  - We estimate by increasing electron-fake component of background shapes
    - Estimated as part of CLEO-c EID systematics studies using D → Kππ



Selected D± → πeν 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: 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: 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: Summary

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

	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

- Overview of Semileptonic Decays
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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

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

- 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

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

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

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

- Makes simplifying assumptions to reduce free parameters

Fits to Partial Rates: Series Model

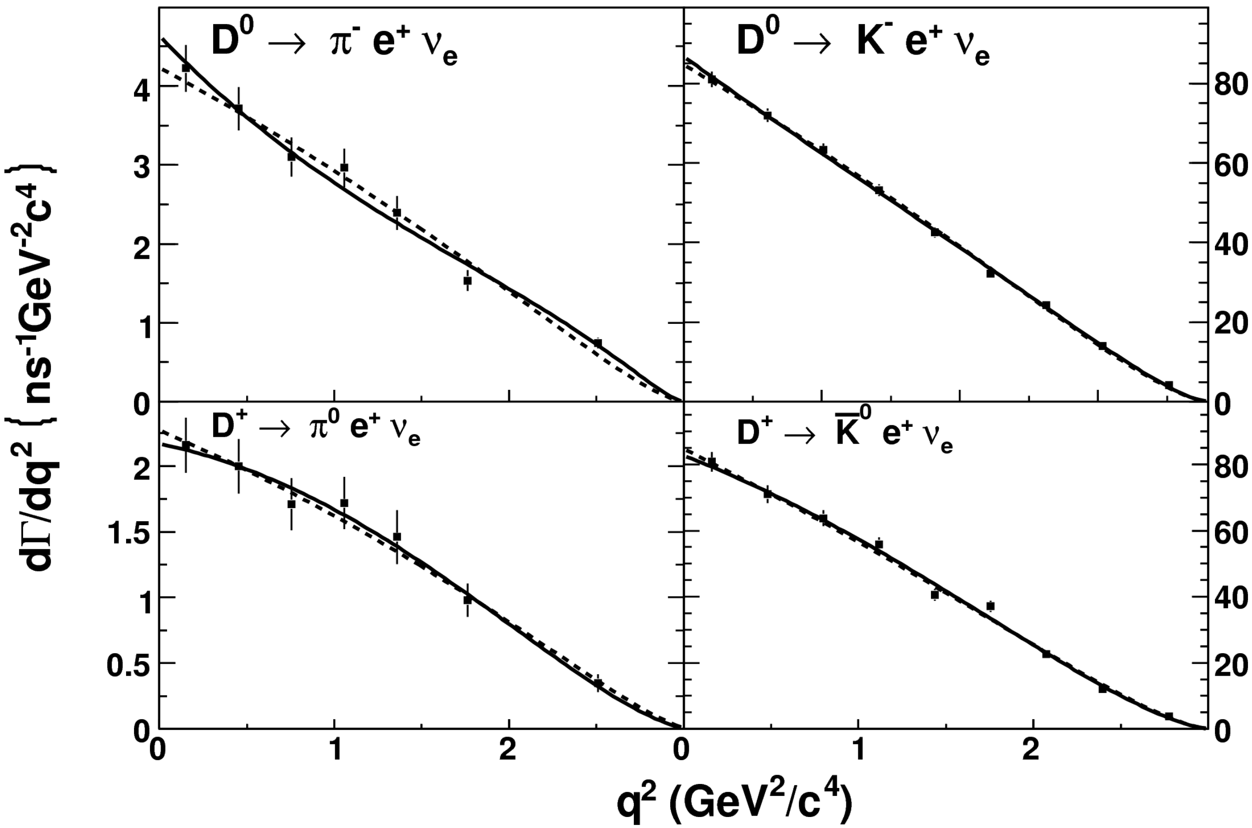
$$f_+(q^2) = \frac{f_+(0)/(1-\alpha)}{1 - \frac{q^2}{M^2_{D^*_{(s)}}}} + \sum_{k=1}^{N} \frac{\rho_k}{1 - \frac{1}{\gamma_k}\frac{q^2}{M_D^2}}$$

- 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 Keνu, ~0.17 for πeν)
- 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

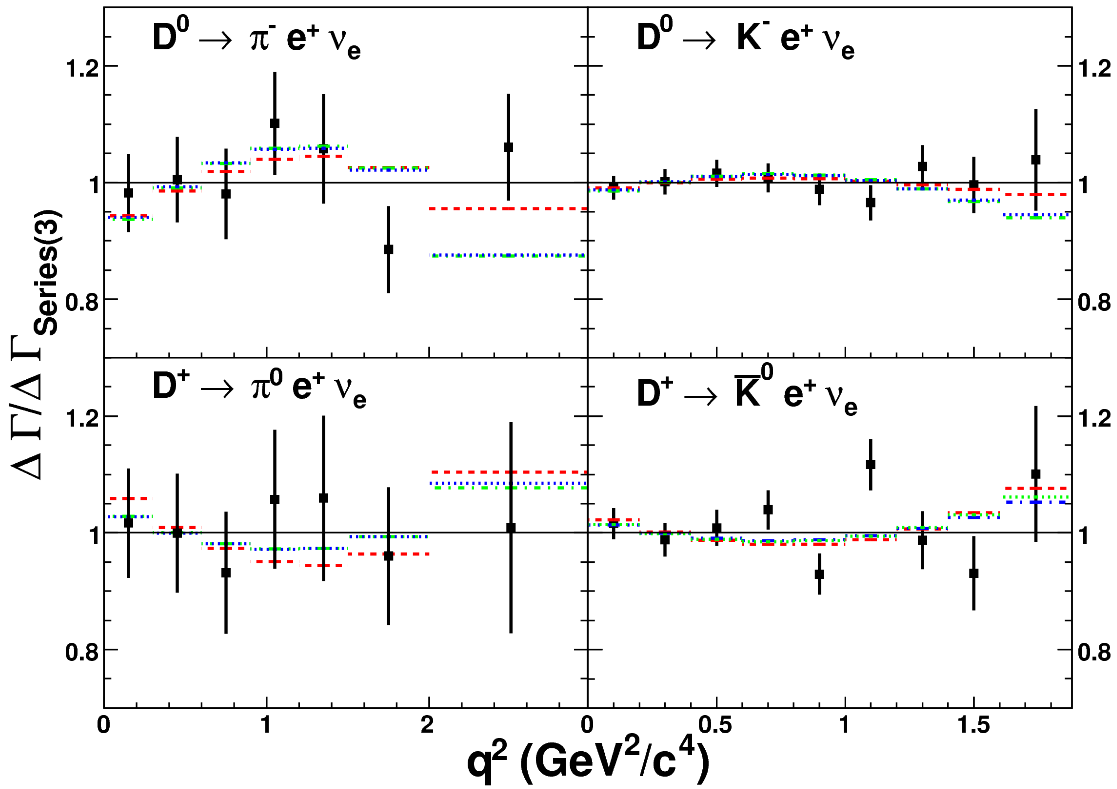
Quality of 3-param fits

	χ^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

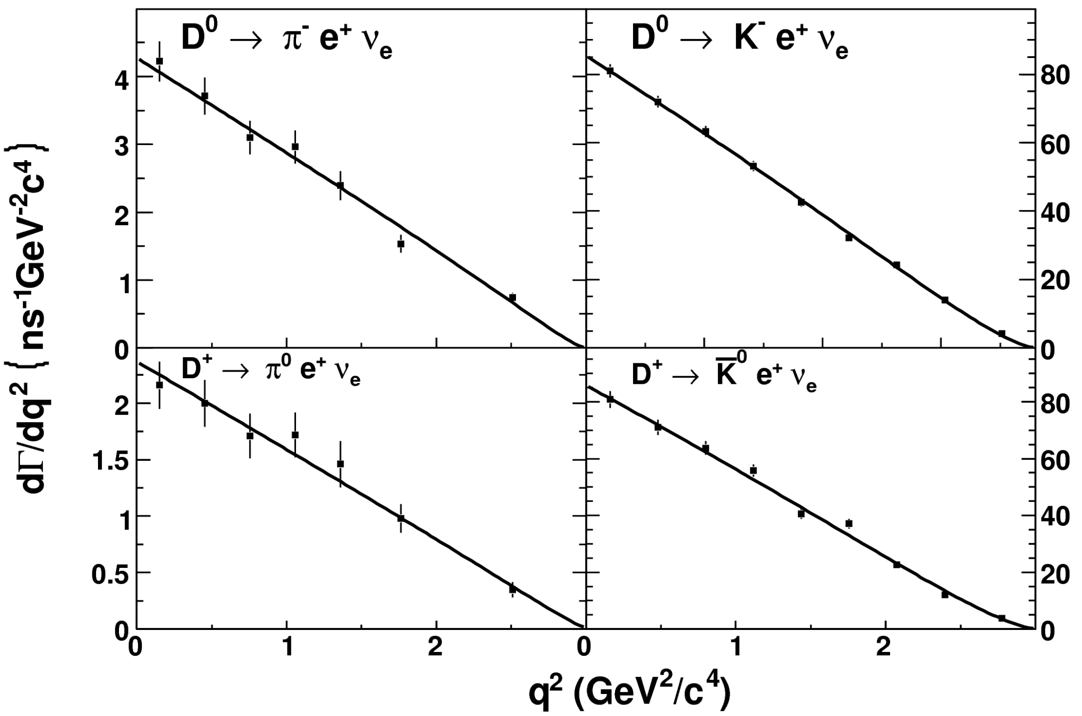
Fits to Partial Rates

- 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

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

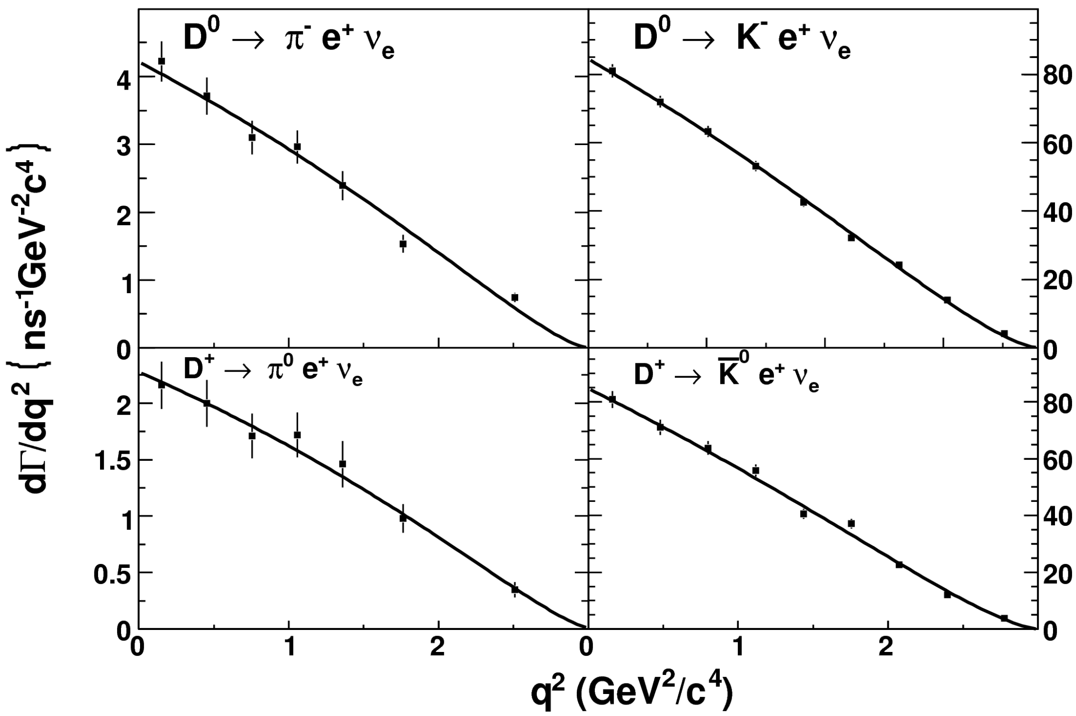


- Preferred pole masses are far from expected values of M_{D^*} = 2.01 GeV and M_{Ds^*} = 2.11 GeV
- Although quality of fits is reasonable, single pole dominance assumption is clearly wrong

Fits to Partial Rates

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

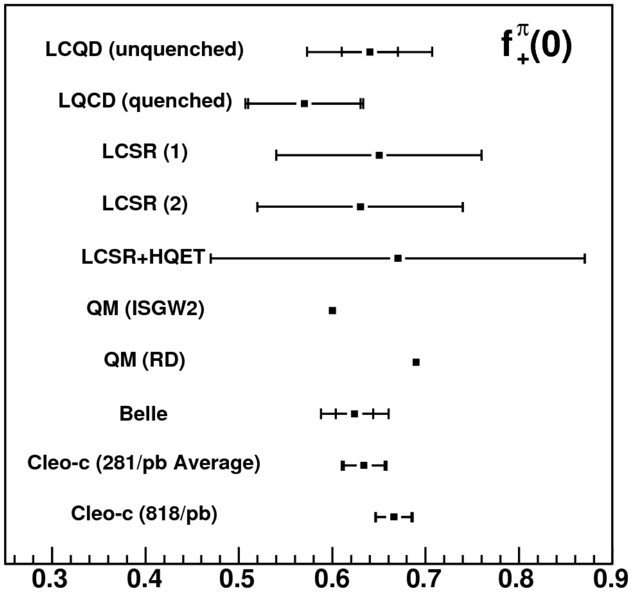
Form factor fits using the modified pole model, with results:
$1+1/\beta-\delta$ ($\pi e\nu$) = 0.93 ± 0.09
$1+1/\beta-\delta$ ($K e\nu$) = 0.89 ± 0.04

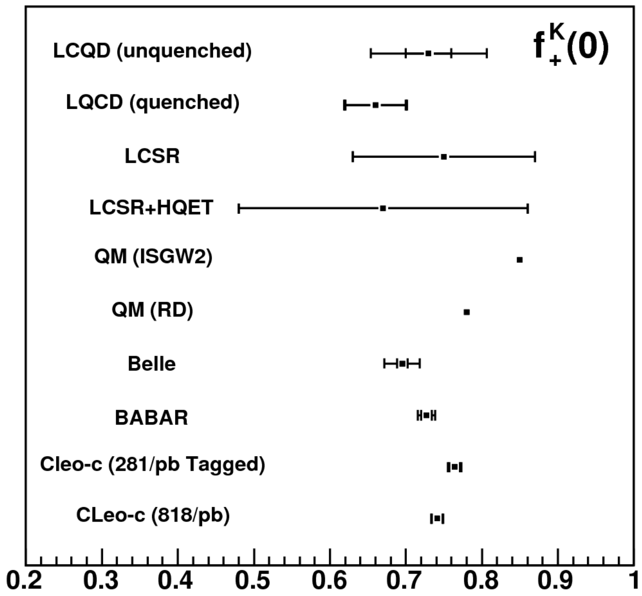


- Preferred pole masses are far from assumed values of $1+1/\beta-\delta = 2$
- Although quality of fits is resonable, assumption made by modified pole model is not valid

Fits to Partial Rates: Form Factor Parameters

- Form factor normalization results, with others:

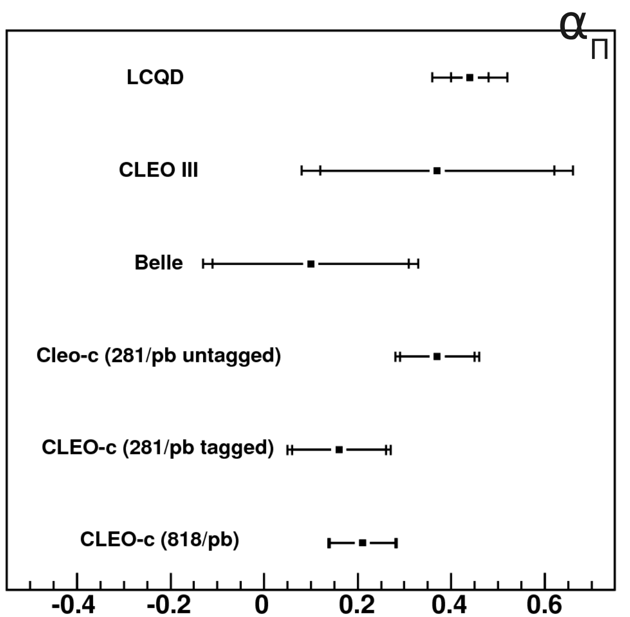


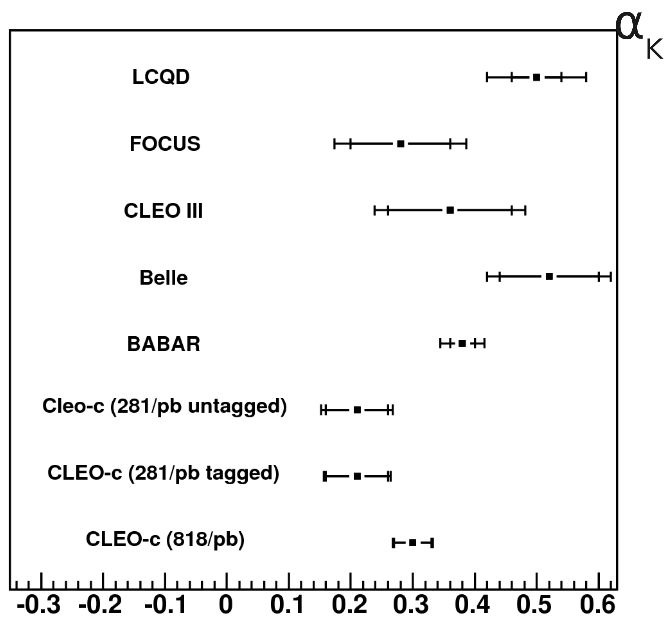


- Results from this work are taken from isospin-combined fits using 3-parameter series expansion fits
- Agree with other experiments to within 2 sigma
- No discrepancy with lattice at current level of precision

Fits to Partial Rates: Form Factor Parameters

- Modified pole parameter α results, with others:

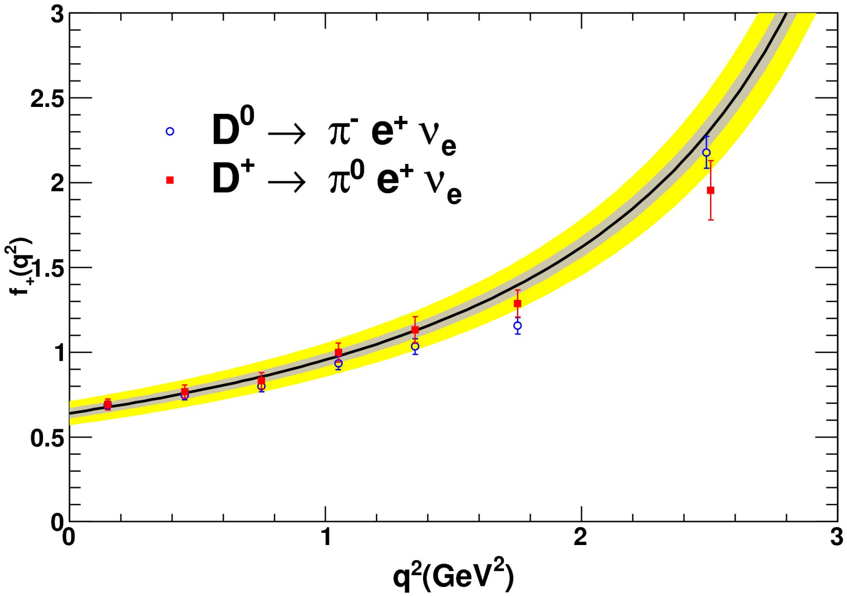




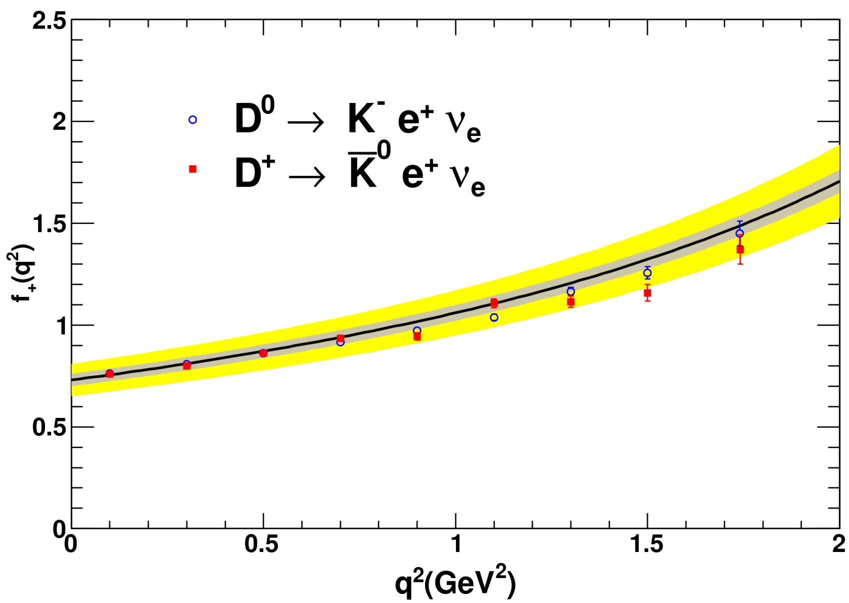
- Shape measurement agree with other experimental results within 2 sigma
- Disagreement with LQCD is slightly more than 2 sigma in both cases

Comparison with Theory

- **Further Comparison with LQCD:**



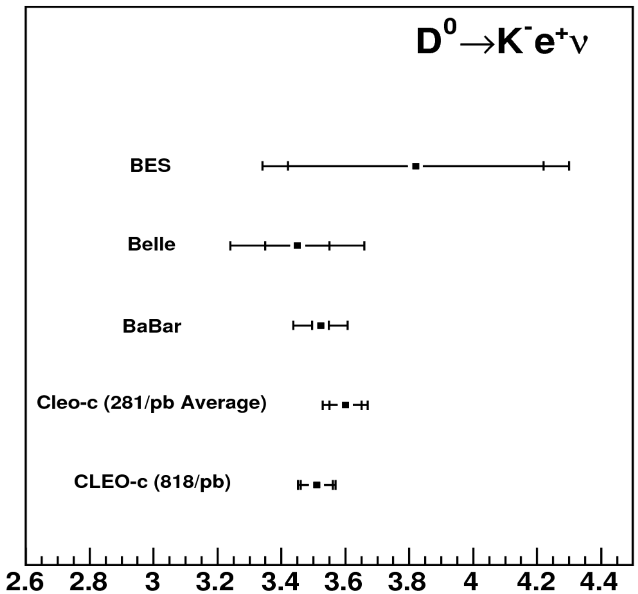
- Points show CLEO's binned form factors with statistical & systematic uncertainties
- Solid line shows fit to unquenched LQCD (using modified pole model) with statistical (grey) and systematic (yellow) uncertainties

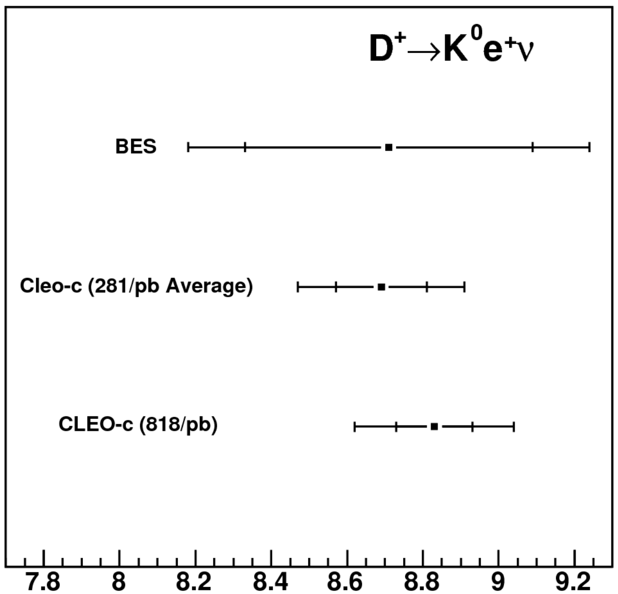


LQCD Fit/Bands courtesy Andreas Kronfeld, based on Fermilab Lattice/MILC/HPQCD Unquenched results (PRL 94, 011601 (2005))

Fits to Partial Rates: Branching Fraction Results

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

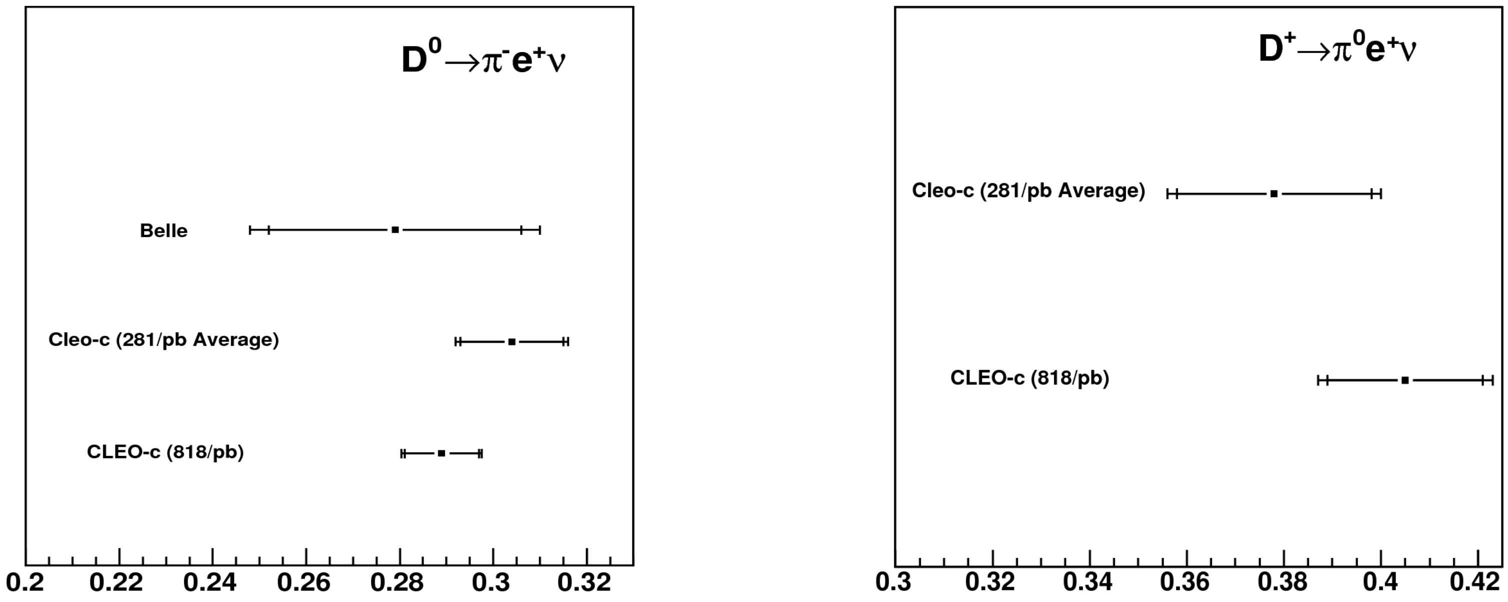




- CLEO-c (818/pb) results are taken from 3-parameter series expansion fits

Fits to Partial Rates: Branching Fraction Results

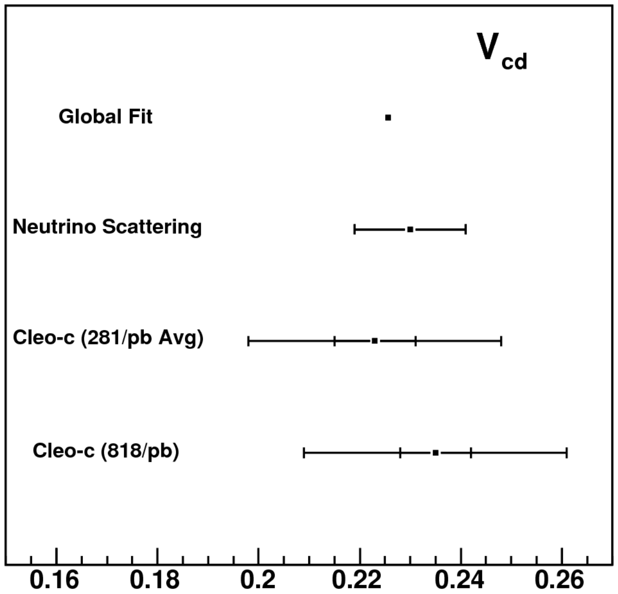
- $D \to \pi$ Branching fraction results, with others:

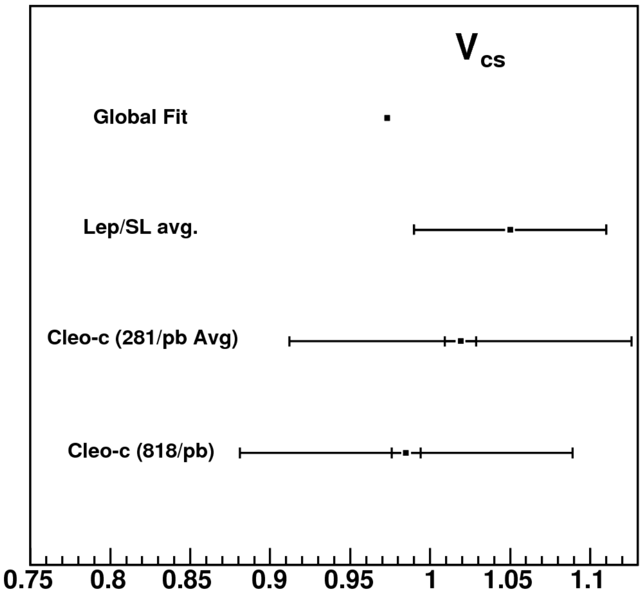


- CLEO-c (818/pb) results are taken from 3-parameter series expansion fits

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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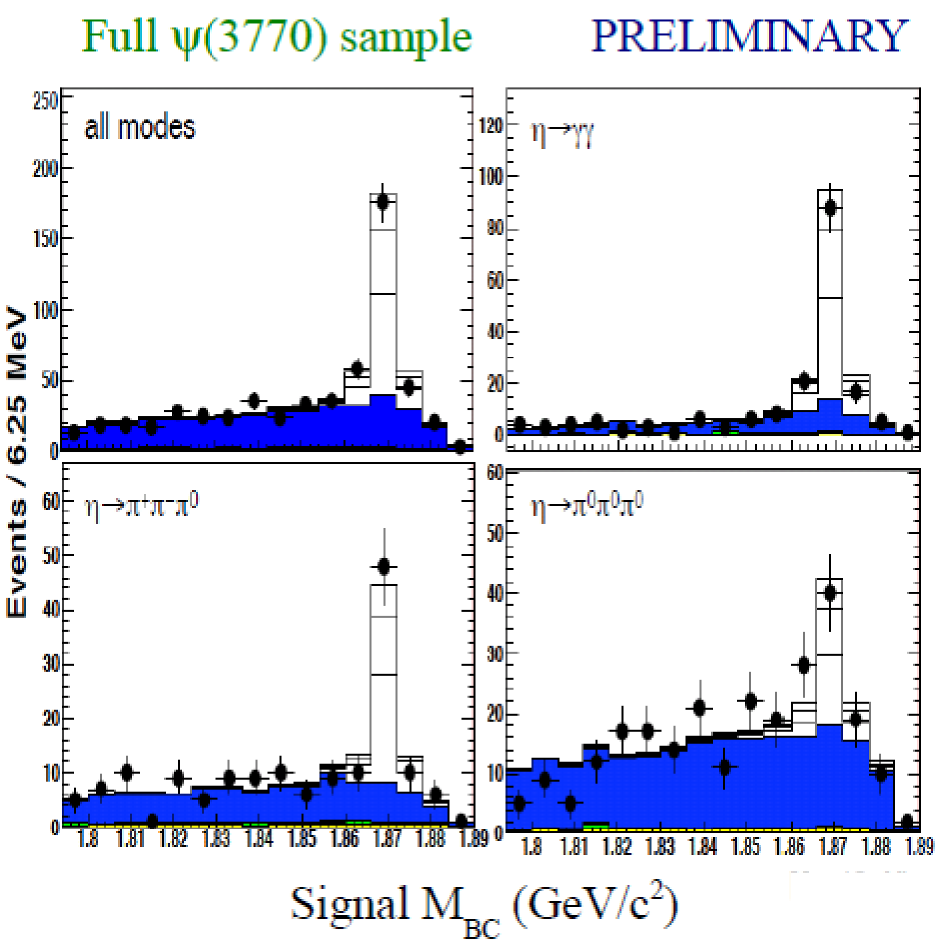
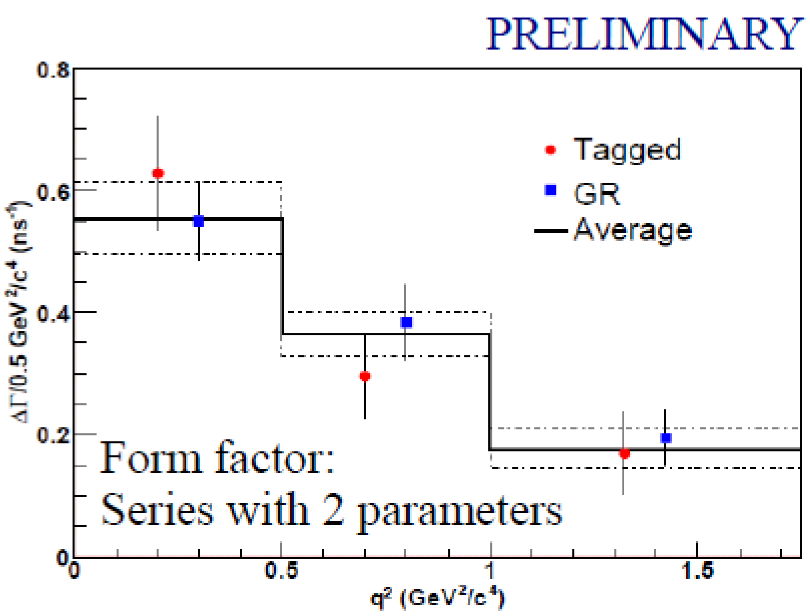
Other CLEO-c Semileptonic Results

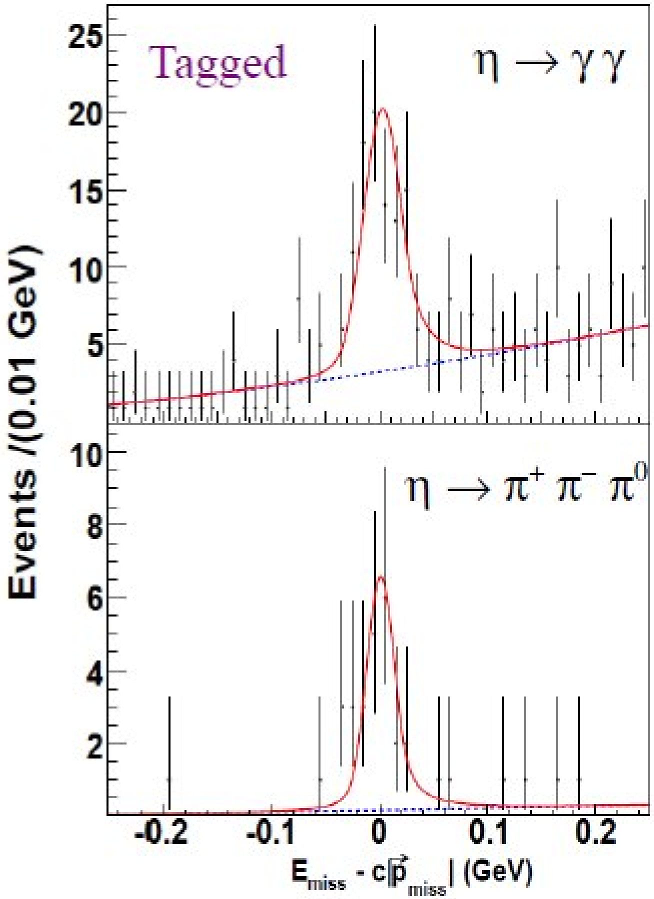
- $D \to \eta e \nu$ via an alternative analysis technique:
- Reconstruct signal: η + e
- Then look for combinations of π's, K's, π^0's, K_S's and η's opposite signal
- Infer neutrino 4-vector from all reconstructed particles
- Bonus of this analysis: measured 38 D → hadron modes, include 13 previously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





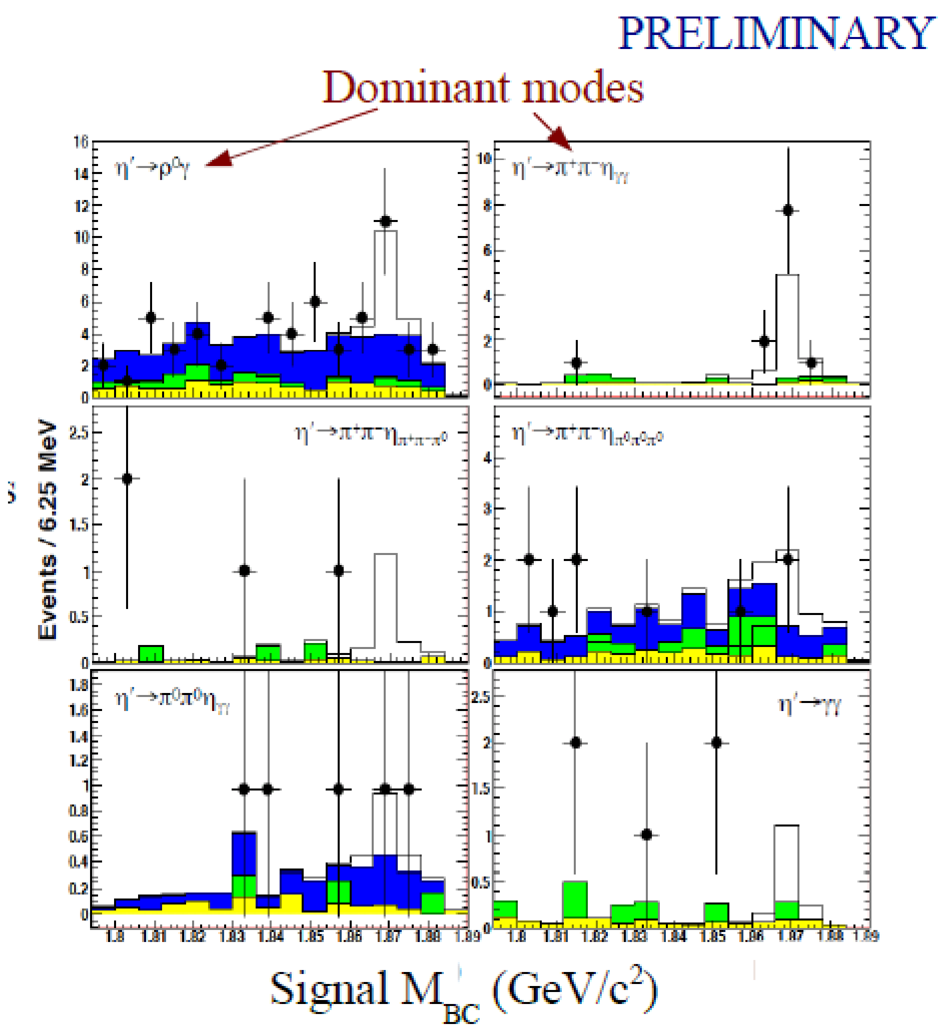
$\mathcal{B}(D^+ \to \eta e \nu) = (11.4 \pm 0.9 \pm 0.4) \times 10^{-4}$
(average of both methods)

Other CLEO-c Semileptonic Results

- D → η'eν generic reconstruction:
- First observation of this mode

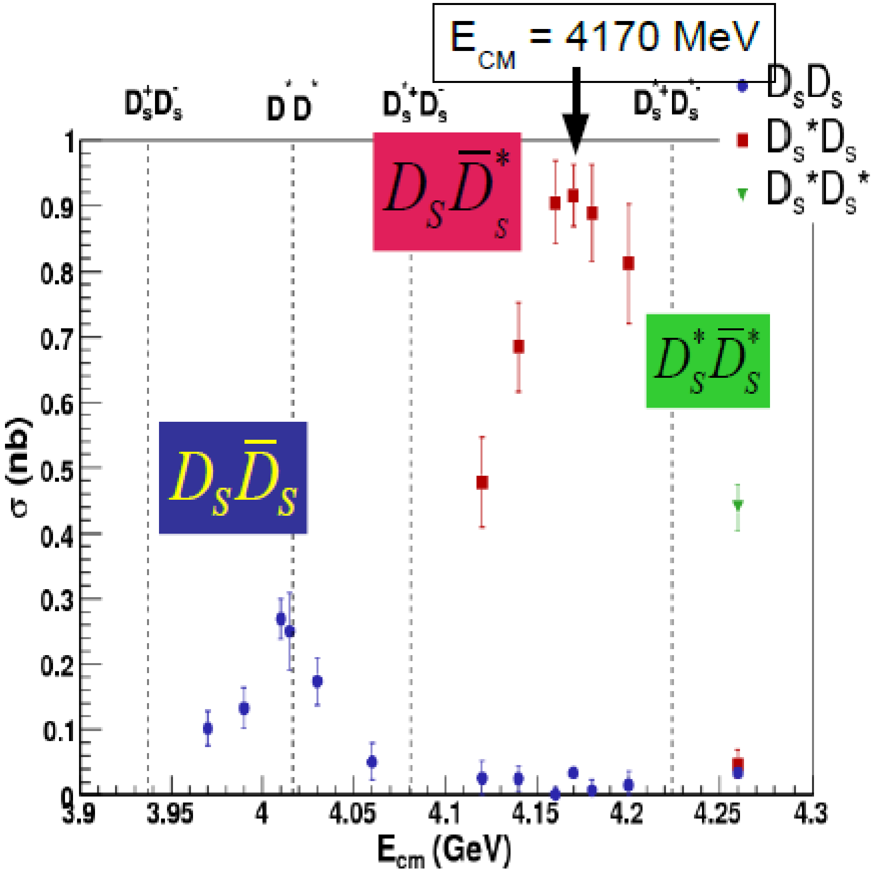
$$B(D^+ \to \eta' e^+ \nu) = (2.16 \pm 0.53 \pm 0.05 \pm 0.05)\times 10^{-4}$$

stat syst Kππ



Other CLEO-c Semileptonic Results

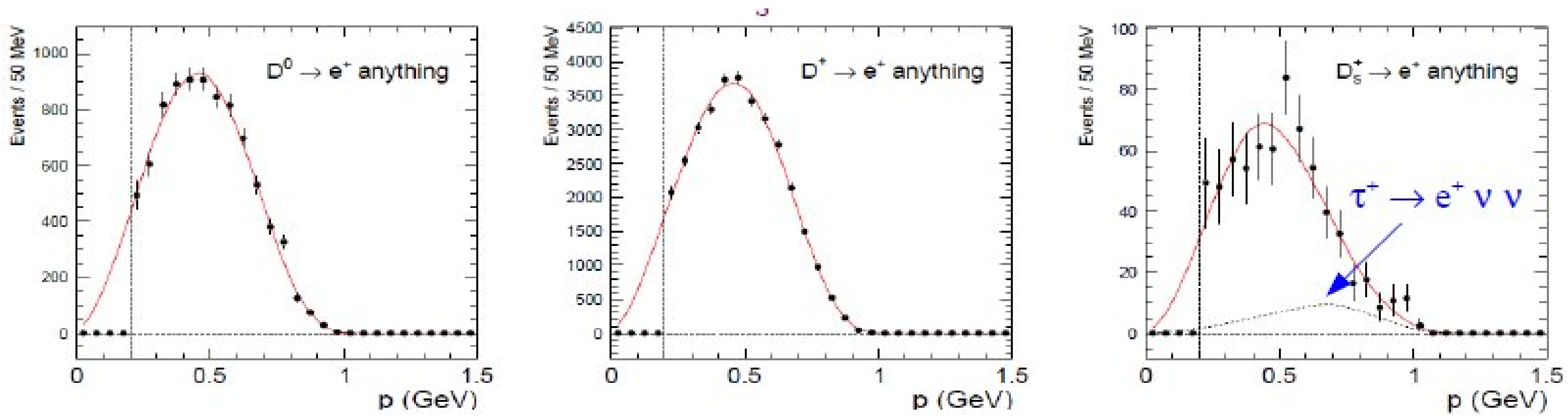
- Ds Semileptonic Decays
- In Fall 2005, CESR scanned the energy range 3.97 < Ecm < 4.26 GeV
- Goal: Find optimal region for producing Ds
- Optimal Energy 4.17 GV
- D's are also produced at this energy, but events are much cleaner at 3.77 GeV



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

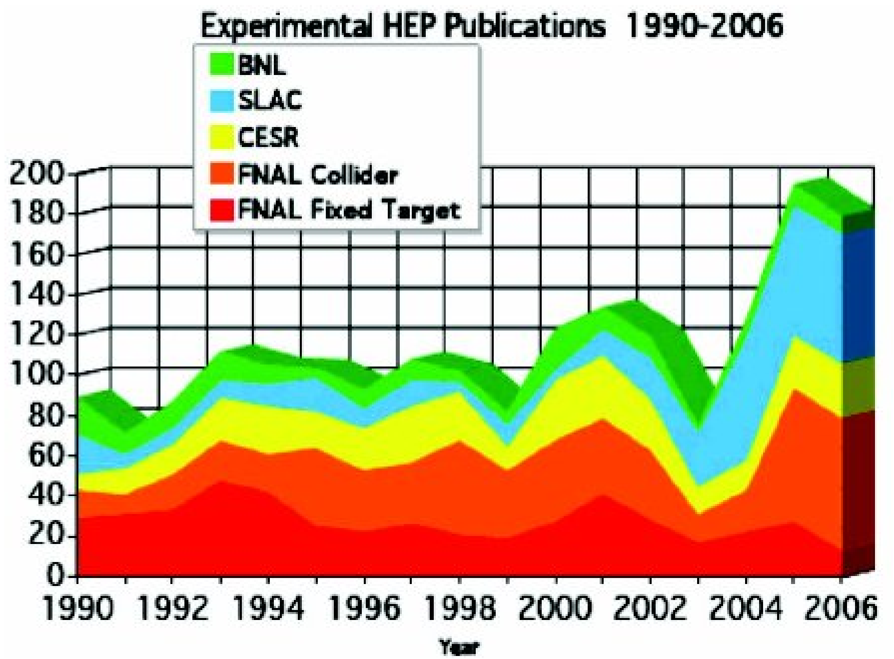
$$\frac{\Gamma(D_S^+ \to Xe^+\nu)}{\Gamma(D^0 \to Xe^+\nu)} = 0.828 \pm 0.051 \pm 0.025$$

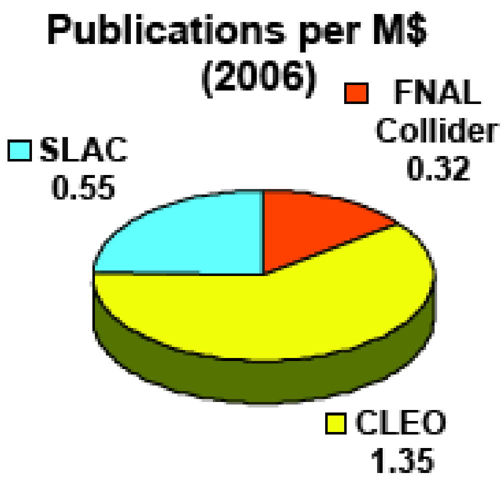
Differences between Ds/D may be similar to those of Bs/B and therefore relevant to Vub

- 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