Charm Form Factors at CLEO-c

CIPANP 2009

Laura Fields
Cornell University
for the CLEO Collaboration

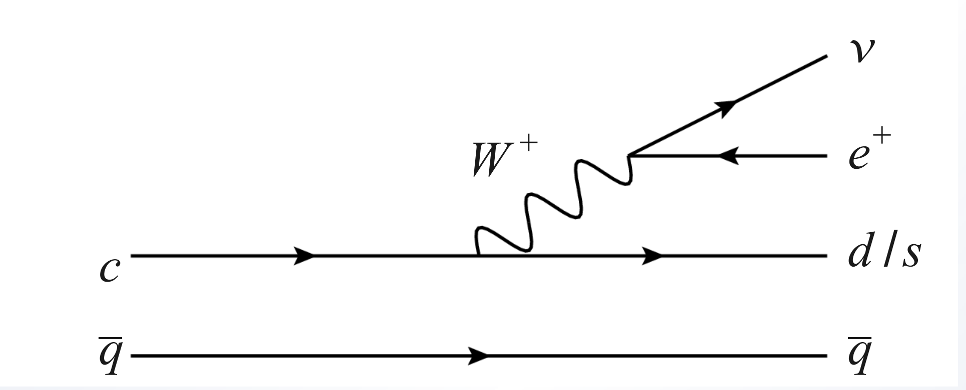
2009-05-29

Talk Outline

- Overview of Semileptonic Decays
- The CLEO-c Program
- Measurements of $D \to \pi e \nu$ and $D \to K e \nu$ Form Factors
  - Overview of Analysis
  - Extraction of Partial Rates
  - Form Factor Fits
  - Comparison with Theory
- Conclusion

Overview of Semileptonic Decays

- **A Semileptonic D Decay:**



- **Pseudoscalar-to-pseudoscalar decay rates are approximated by:**

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

q^2 = invariant mass of W^+

Experimental Measurement of rates gives access to $f_+(q^2)|V_{cq}|$

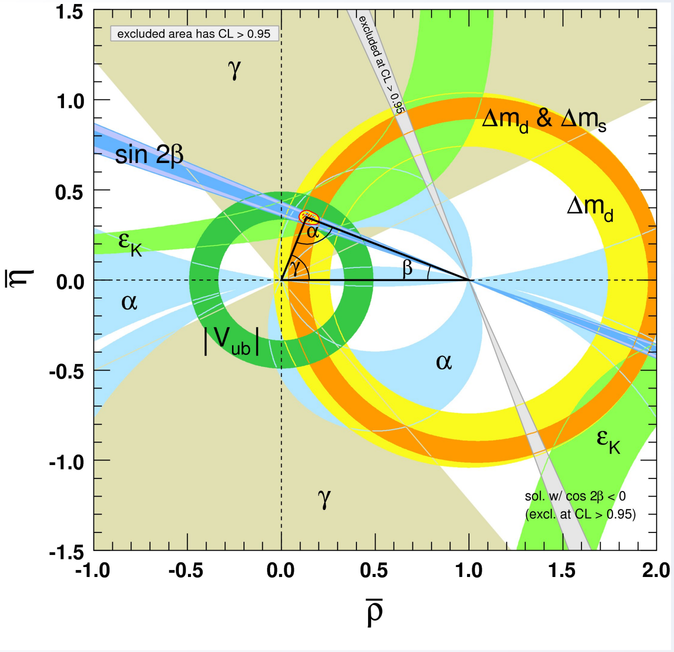
Form Factor (non-perturbative QCD)

CKM Matrix Element

Overview of Semileptonic Decays

- **Semileptonic decays provide two pieces of information:**
  - $f_+(q^2)|V_{cq}|$ + input from theory = CKM matrix elements
  - **$f_+(q^2)|V_{cq}|$ + CKM elements = semileptonic form factors**

- **Importance of charm form factors:**
  - |Vub| measurements are an important constraint on CKM unitarity triangle
  - |Vub| is extracted from $B \to \pi e \nu$ and requires form factor input from theory → Lattice QCD
  - LQCD is providing increasingly precise theoretical predictions
  - Tests of new LQCD techniques in heavy-to-light transitions are needed



Source: PDG 2008

- **Providing tests of Lattice QCD is a primary goal of CLEO-c**

The CLEO-c Program

- **CESR: an e+e- storage ring located at Cornell in Ithaca, NY**

- 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)

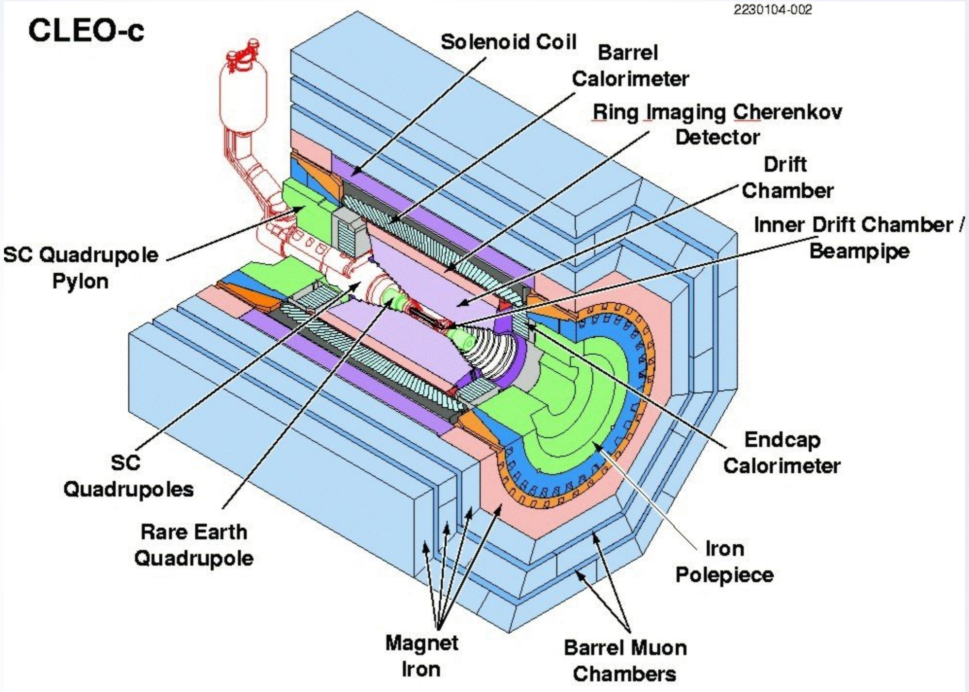
The CLEO-c Program

- **The CLEO-c Detector**

- Dual tracking chambers
  - $\sigma p/p$ = 0.5% at 0.7 GeV
  - Covers $|\cos\theta| < 0.93$

- Particle ID provided by:
  - RICH detector
  - dE/dx

- CsI calorimeter
  - $\sigma E/E$ = 5% at 100 MeV
  - π^0 mass resolution ~ 6 MeV
  - Aids electron ID

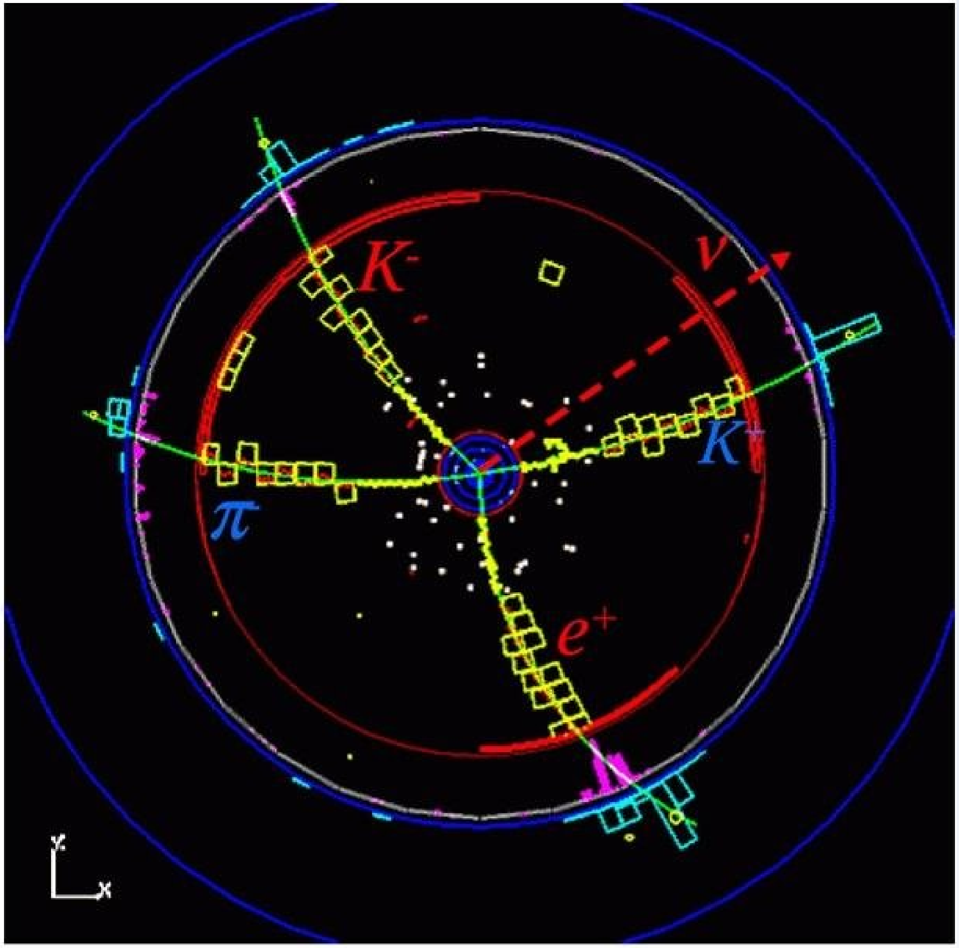


The CLEO-c Program

- **Tagged Analysis Technique**
- D decays at ψ(3770) occur exclusively as part of $D\bar{D}$ pairs → enables "tagging"
- 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
- CLEO uses an alternative untagged technique, but this talk focuses on tagged results

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

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



Overview of Analysis

- **Tagging enables a simple extraction of 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 $D^0\to\pi^\pm e\nu$ and $D^\pm \to \pi^0 e\nu$ in 7 q^2 bins**
- **Measure $\Delta\Gamma_i$ for $D^0\to K^\pm e\nu$ and $D^\pm\to K^0 e\nu$ in 9 q^2 bins**
- In 3 D^0 tag modes ($K\pi$, $K\pi\pi^0$, $K\pi\pi\pi$)
- In 6 $D^\pm$ tag modes ($K\pi\pi$, $K\pi\pi\pi^0$, $K^0\pi$, $K^0\pi\pi^0$, $K^0\pi\pi\pi$, $KK\pi$)

Overview of Analysis

- **Observed yields are corrected by efficiencies to obtain true yields:**

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

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: 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:

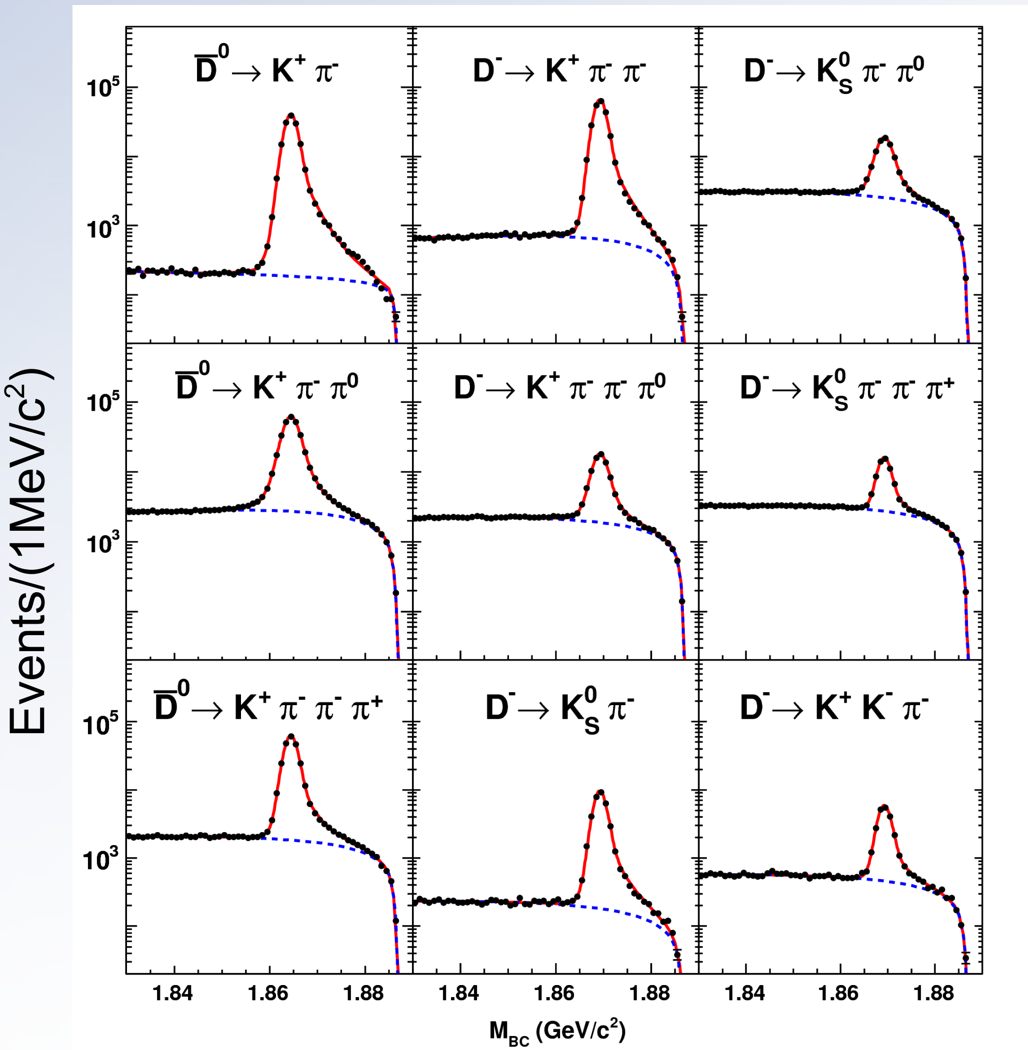
$$\Delta E = E_{tag} - E_{beam}$$

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

- **Tag Yield Fits**



- Tag Fits to Data:
  - Unbinned likelihood fits:
  - Signal shape specially designed to take into account psi(3770) lineshape, ISR and momentum resolution effects
  - Modified ARGUS background

- Tagging Efficiencies
  - Obtained by treating Monte Carlo samples as data

Partial Rate Extraction: Semileptonic Reconstruction

- **Semileptonic Candidates**
  - Formed from combinations of electrons and mesons
  - Yields extracted from distributions of:

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

  - And binned in

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

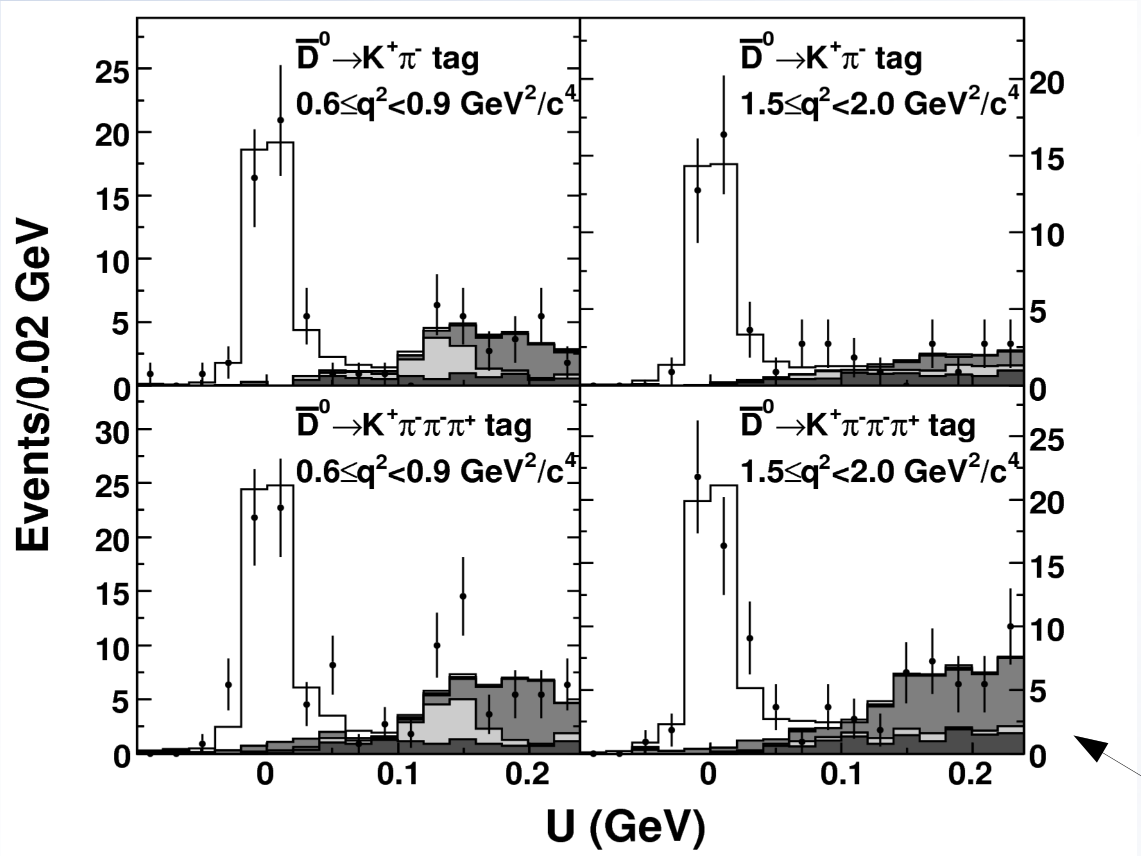
  - Neutrino 4-vector is inferred from missing energy/momentum, constrained by U=0

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

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

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

- **Example Signal Yield Fits: $D^0 \to \pi^\pm e\nu$:**



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

- Separate fit for each tag mode and each q^2 bin
  $\to$ 144 total fits!
- Signal and background shapes are taken from MC
- Most backgrounds are from other semileptonic modes
- $D \to \pi^\pm e\nu$ and $D \to \pi^0 e\nu$ have large backgrounds from $D \to K^\pm e\nu$ and $D \to K^0 e\nu$

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

Partial Rate Extraction: Signal Efficiencies

- **Signal Efficiency Matrices:**
- Efficiency matrices give efficiency and smearing

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

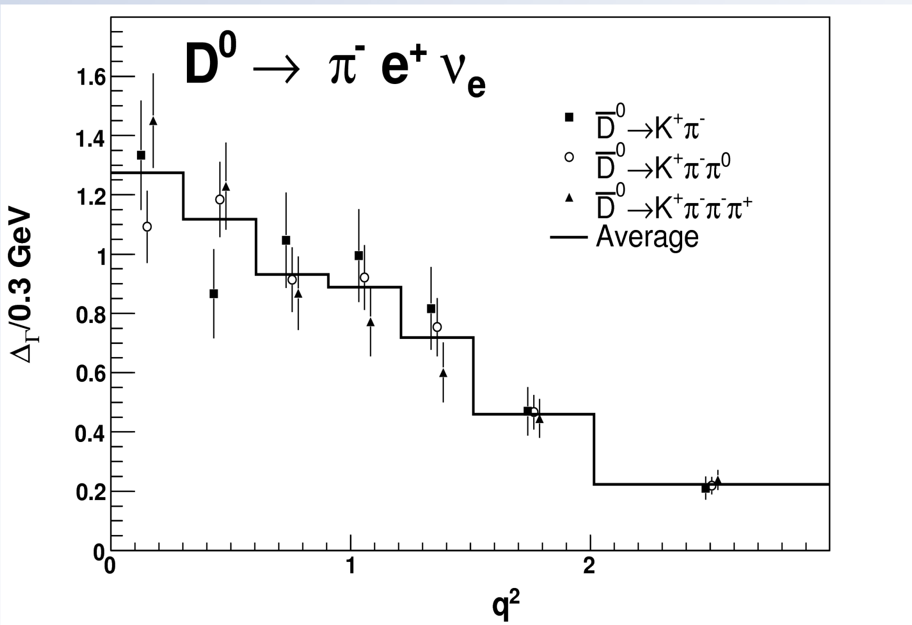
- Obtained from Signal MC
  - Account for efficiency & smearing due to semileptonic and tag reconstruction
  - Off-diagonal elements introduce a small correlation across q^2 in the partial rate measurements

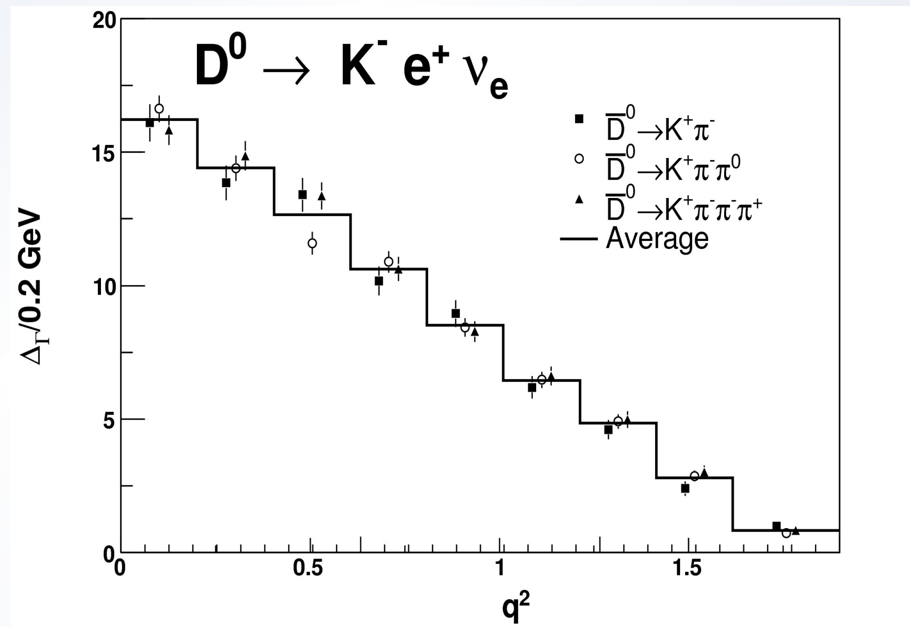
$$\begin{array}{c|c} & \longleftarrow \text{Generated Bin} \longrightarrow \\ \hline \text{Reconstructed Bin} & \begin{bmatrix} 0.420 & 0.012 & 0.000 & 0.000 & 0.000 & 0.000 & 0.000 \\ 0.007 & 0.430 & 0.015 & 0.000 & 0.000 & 0.000 & 0.000 \\ 0.001 & 0.008 & 0.448 & 0.014 & 0.000 & 0.000 & 0.000 \\ 0.000 & 0.001 & 0.012 & 0.457 & 0.014 & 0.000 & 0.000 \\ 0.000 & 0.001 & 0.001 & 0.012 & 0.464 & 0.009 & 0.000 \\ 0.000 & 0.000 & 0.001 & 0.001 & 0.011 & 0.469 & 0.007 \\ 0.000 & 0.000 & 0.000 & 0.000 & 0.000 & 0.007 & 0.469 \end{bmatrix} \end{array}$$

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

Partial Rate Extraction: D^0 Mode Results

- **Partial Rate Results:**





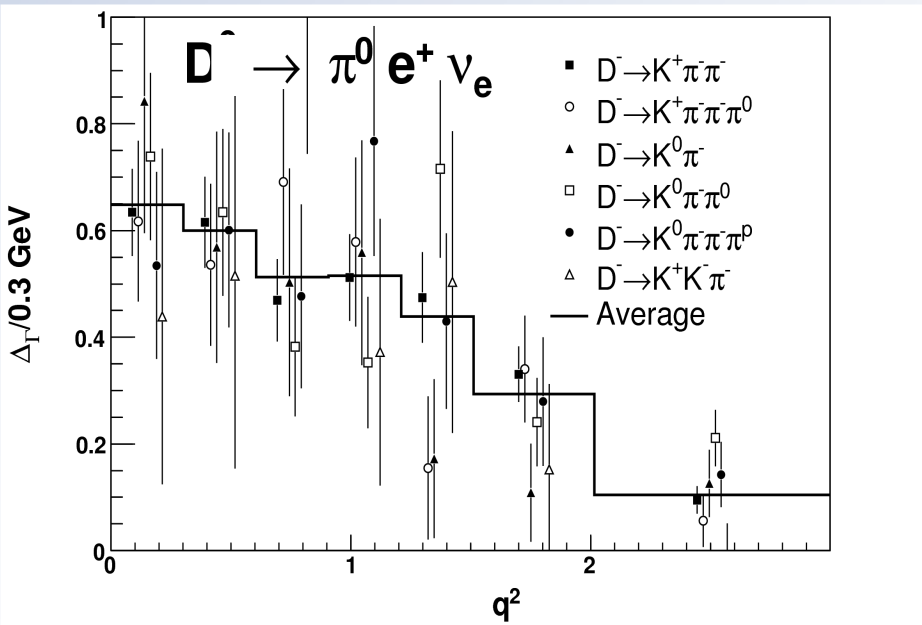
- Partial Rates extracted via:

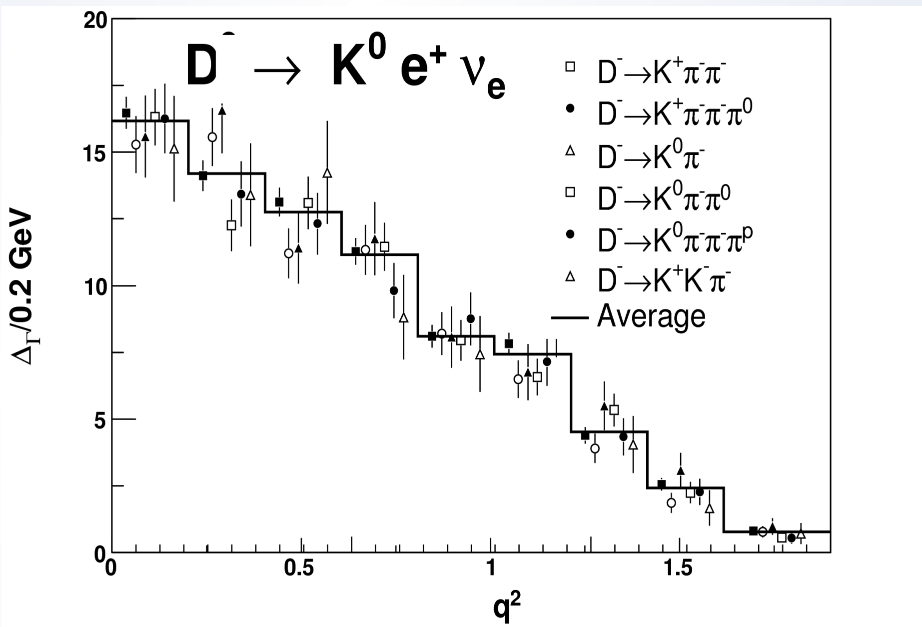
$$\Delta\Gamma_i = \int_{q^2_{low,i}}^{q^2_{high,i}} \frac{d\Gamma(D \to Pe\nu)}{dq^2} dq^2 = \frac{\sum_i \epsilon_{ij}^{-1} N_j}{\tau_D N_{tag}/\epsilon_{tag}}$$

and averaged over tag modes

Partial Rate Extraction: D^+ Mode Results

- **Partial Rate Results:**





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

Partial Rate Extraction: Systematics

- **Systematic Uncertainties on the partial rates:**
- 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

Partial Rate Extraction: Systematics

- **Summary of Systematics for D→K$^{\pm}$eν:**

	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	1.0%	1.0%	0.9%	0.9%	1.0%	0.7%	0.3%	-0.3%	0.5%
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%
Total	1.4%	1.4%	1.4%	1.4%	1.5%	1.4%	1.3%	1.5%	1.5%
Stat. Uncertainty	2.0%	2.2%	2.3%	2.5%	2.7%	3.1%	3.6%	4.9%	8.4%

- **Systematic uncertainties are smaller than statistical uncertainties in all modes**

Form Factor Fits

- **Overview of Form Factor Fits:**
  - Given the partial rates and their covariance matrices, we fit them using:

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

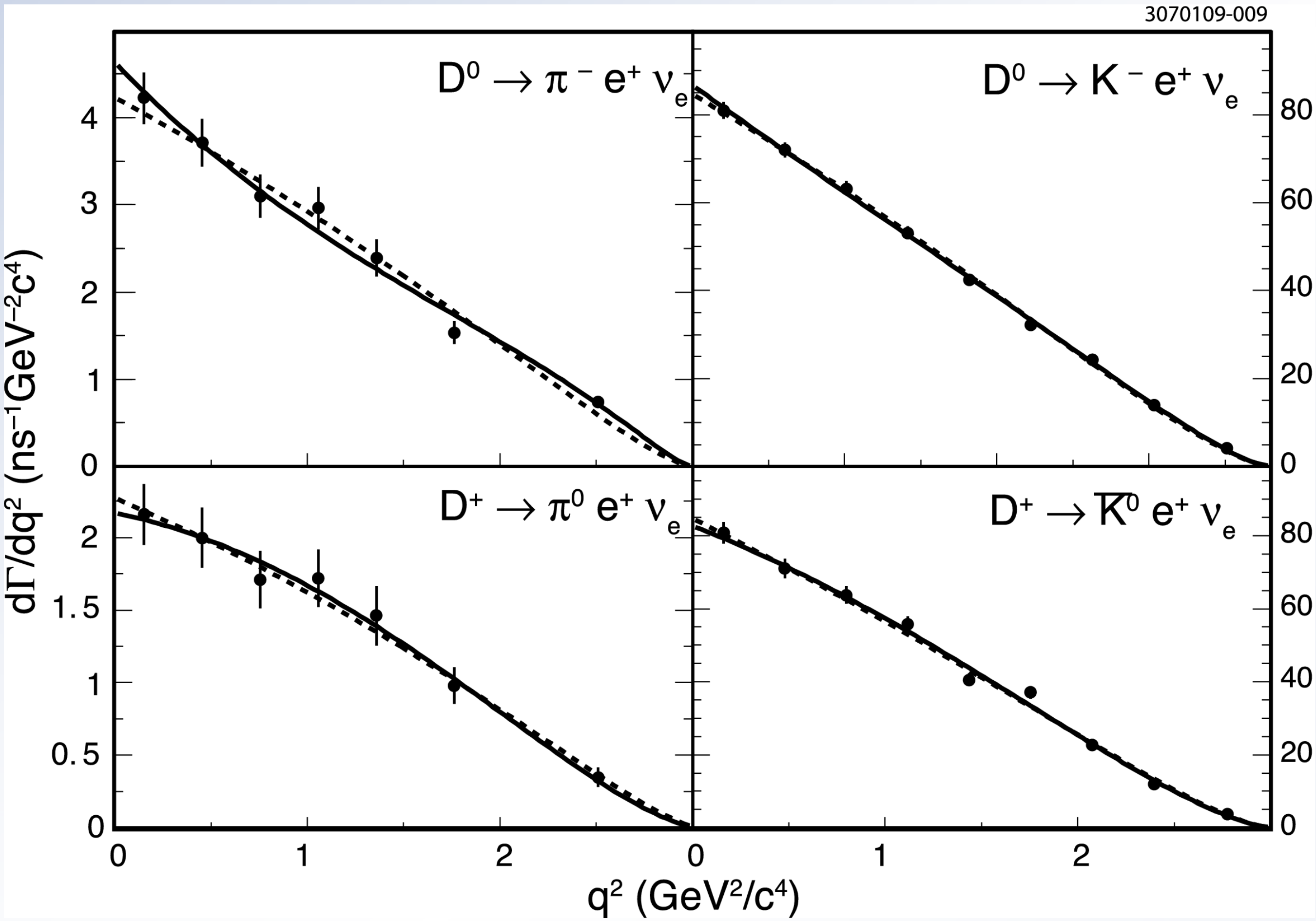
  - In each semileptonic mode, we use five parameterizations of $f_+(q^2)$
  - For nominal fits, we use the Becher-Hill series expansion with three parameters:

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

  - For comparison with LQCD, we use the BK “modified pole” model:

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

Form Factor Fits



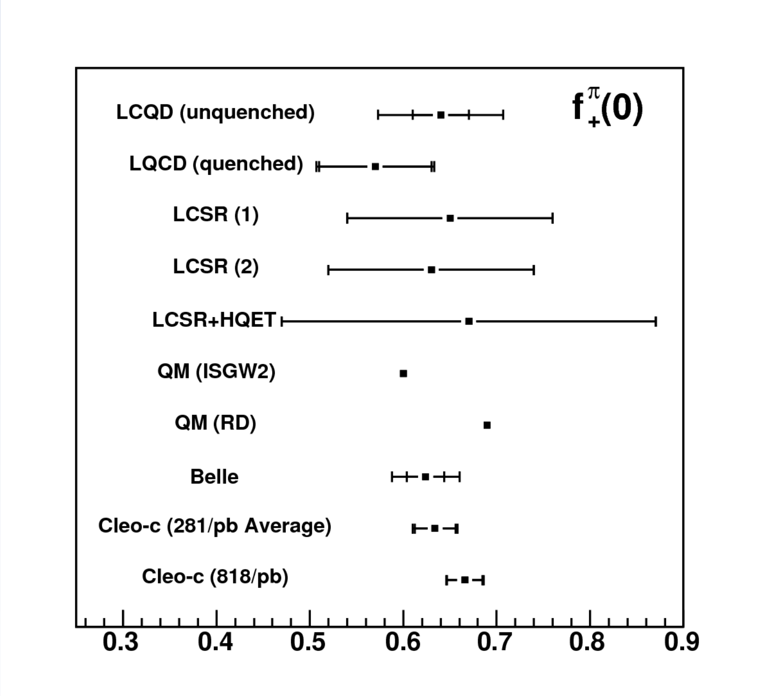
Form factor fits in data to data using the 3-param (solid) and 2-par (dashed) series expansion

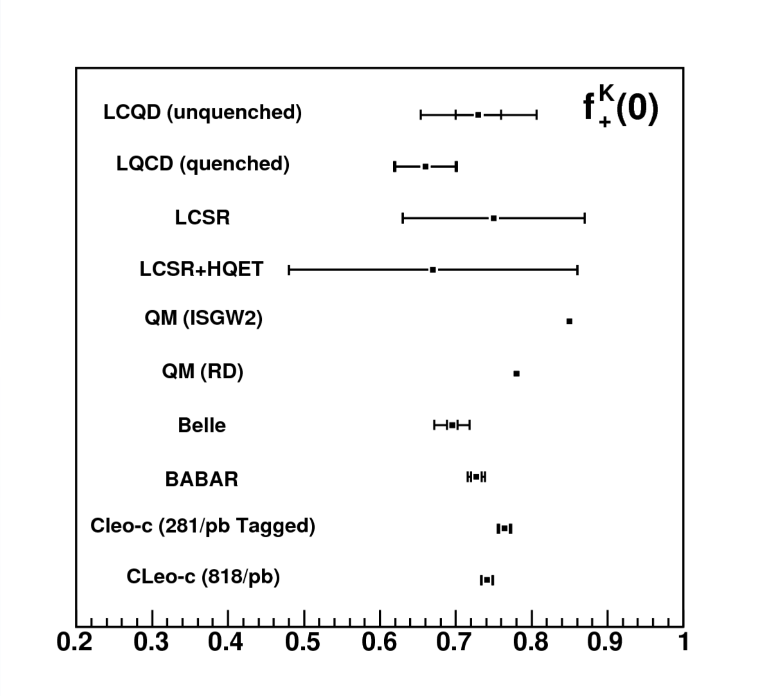
Quality of 3-param fits

	χ^2/dof
$D^0 \to \pi e \nu$	4.5/4
$D^0 \to K e \nu$	2.9/6
$D^- \to \pi^0 e \nu$	0.9/4
$D^- \to K^0 e \nu$	13.3/6

Comparison with Theory

- **Form factor normalization results:**

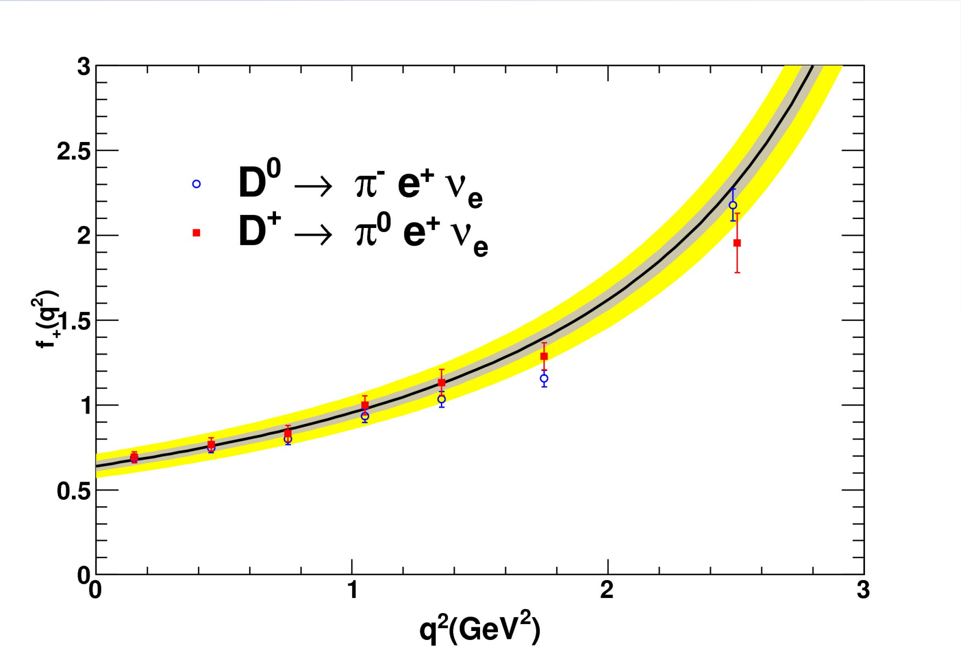




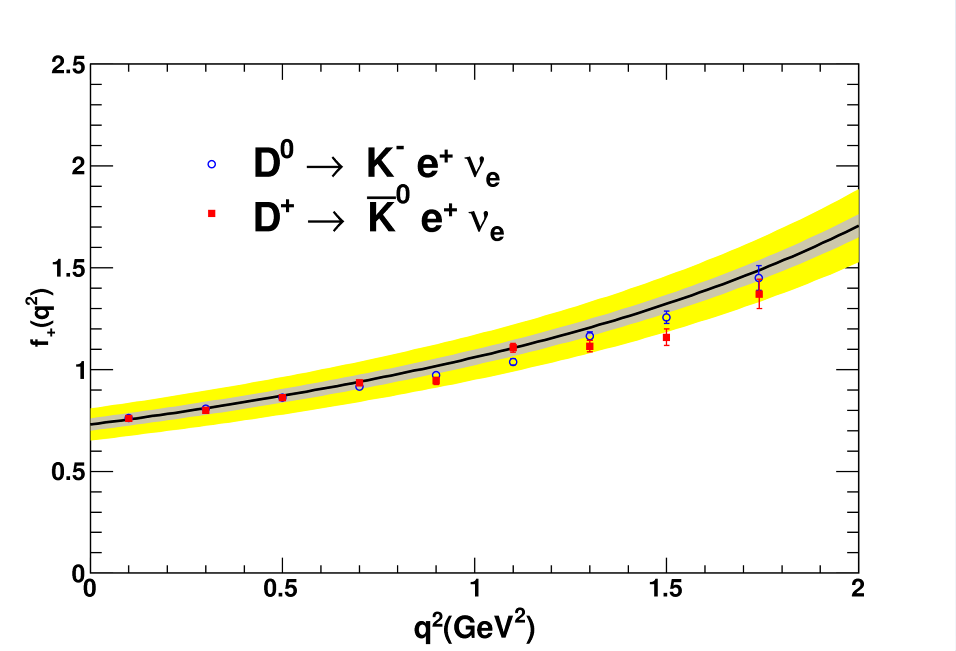
- Results from this work are taken from isospin-combined fits using 3-parameter series expansion fits
- Agree with other experiments to within 2 sigma
- No discrepancy with LQCD at current level of precision

Comparison with Theory

- **Further Comparison with LQCD:**



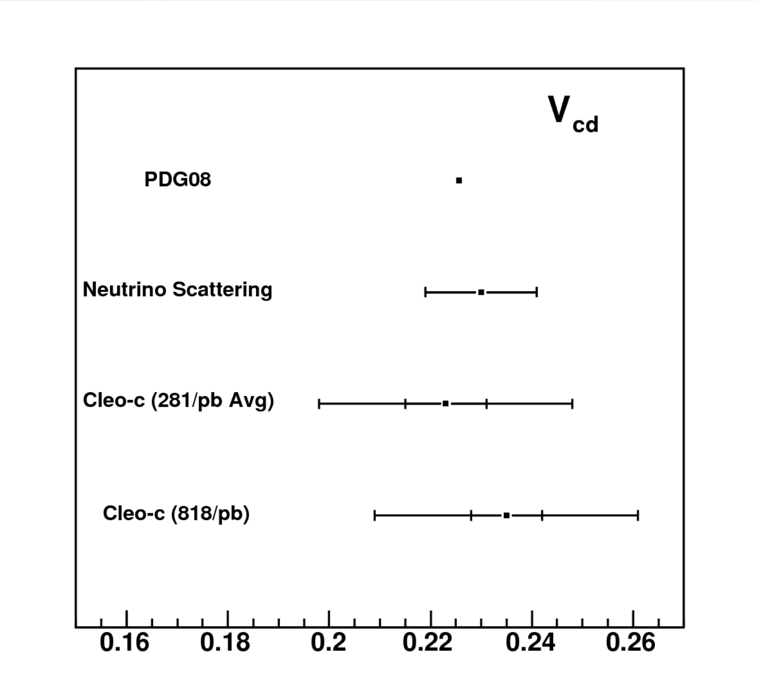
- Points show CLEO's binned form factors with statistical & systematic uncertainties
- Solid line shows fit to unquenched LQCD (using modified pole model) with statistical (grey) and systematic (yellow) uncertainties

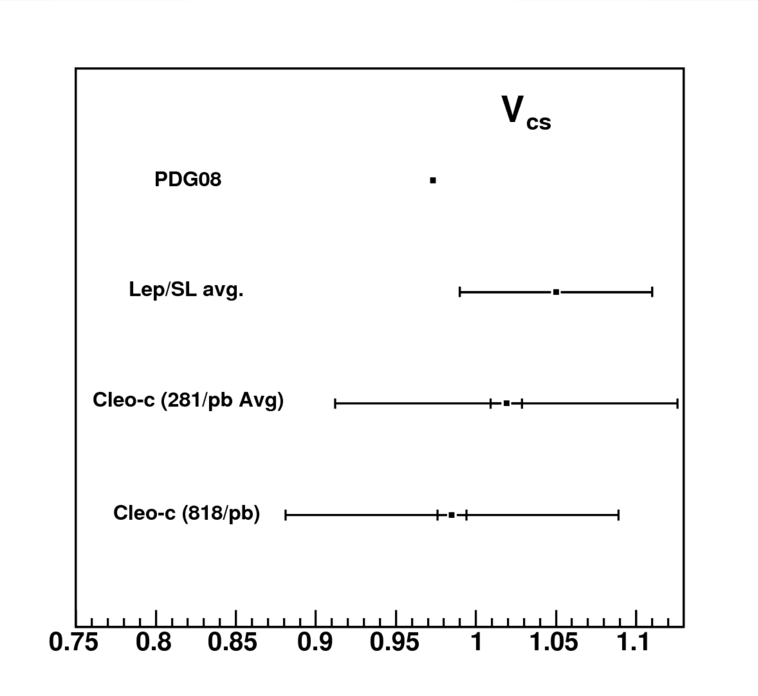


LQCD Fit/Bands courtesy Andreas Kronfeld, based on Fermilab Lattice/MILC/HPQCD Unquenched results (PRL 94, 011601 (2005))

CKM Parameters

- **CKM Results:**





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

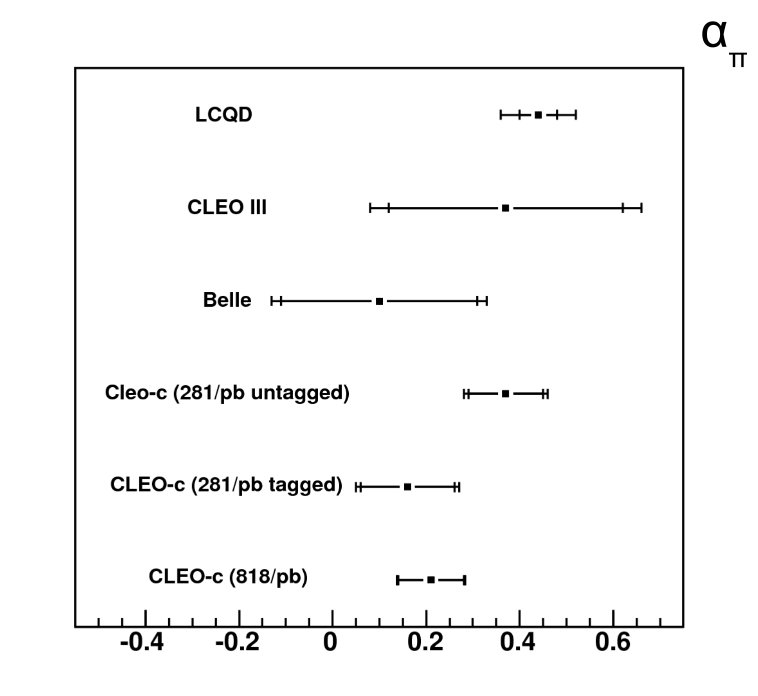
Conclusion

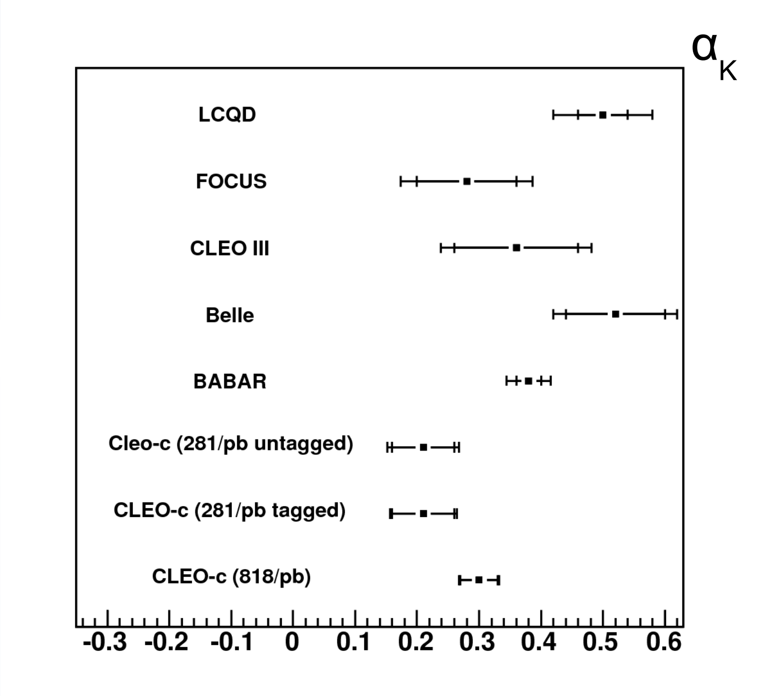
- CLEO-c has measured partial rates in several q^2 bins for the semileptonic decays $D \to \pi^{\pm} e\nu$, $D \to K^{\pm} e\nu$, $D \to \pi^0 e\nu$ and $D \to K^0 e\nu$
- The partial rates have been used to extract form factors parameters and $|V_{cd}|$ and $|V_{cs}|$
- Many of the form factor results are the world's most precise and provide a excellent goal for Lattice QCD

Backup Slides

Comparison with Theory

- **Form factor shape parameter results:**





- All results use the modified pole model
- Results from this work are taken from isospin-combined fits
- Agree with other experiments to within 2 sigma

Branching Fractions

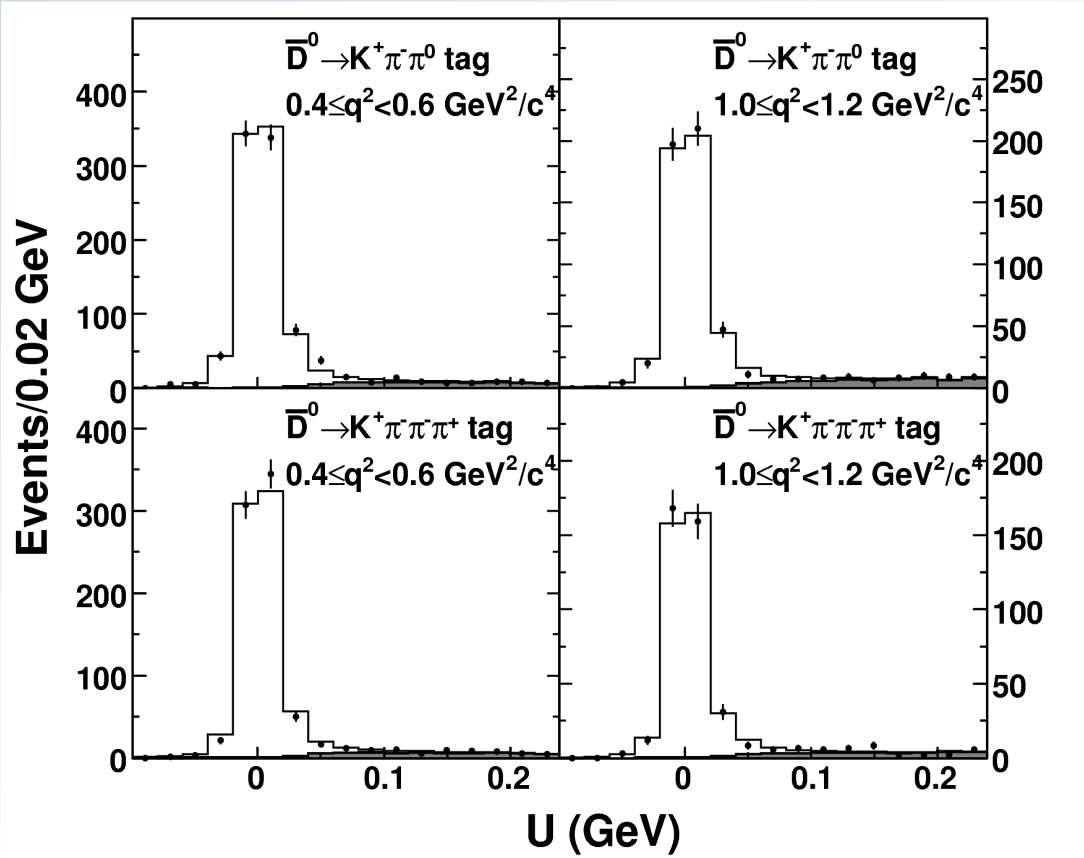
- **Branching fraction results (in %):**

	This Work	CLEO-c 281/pb	BES II	Belle	BABAR
$D^0 \to \pi e\nu$	0.289(8)(3)	0.304(11)(5)		0.279(27)(16)	
$D^0 \to K e\nu$	3.51(3)(5)	3.60(3)(6)	3.82(40)(27)	3.45(10)(19)	3.52(3)(5)(7)
$D^- \to \pi^0 e\nu$	0.41(2)(1)	0.38(2)(1)			
$D^- \to K^0 e\nu$	8.83(10)(19)	8.69(12)(19)	8.71(38)(37)		

- Results from this work are taken from fits using 3 parameter series expansion
- Our results agree well with other experimental results and are signicantly more precise

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

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



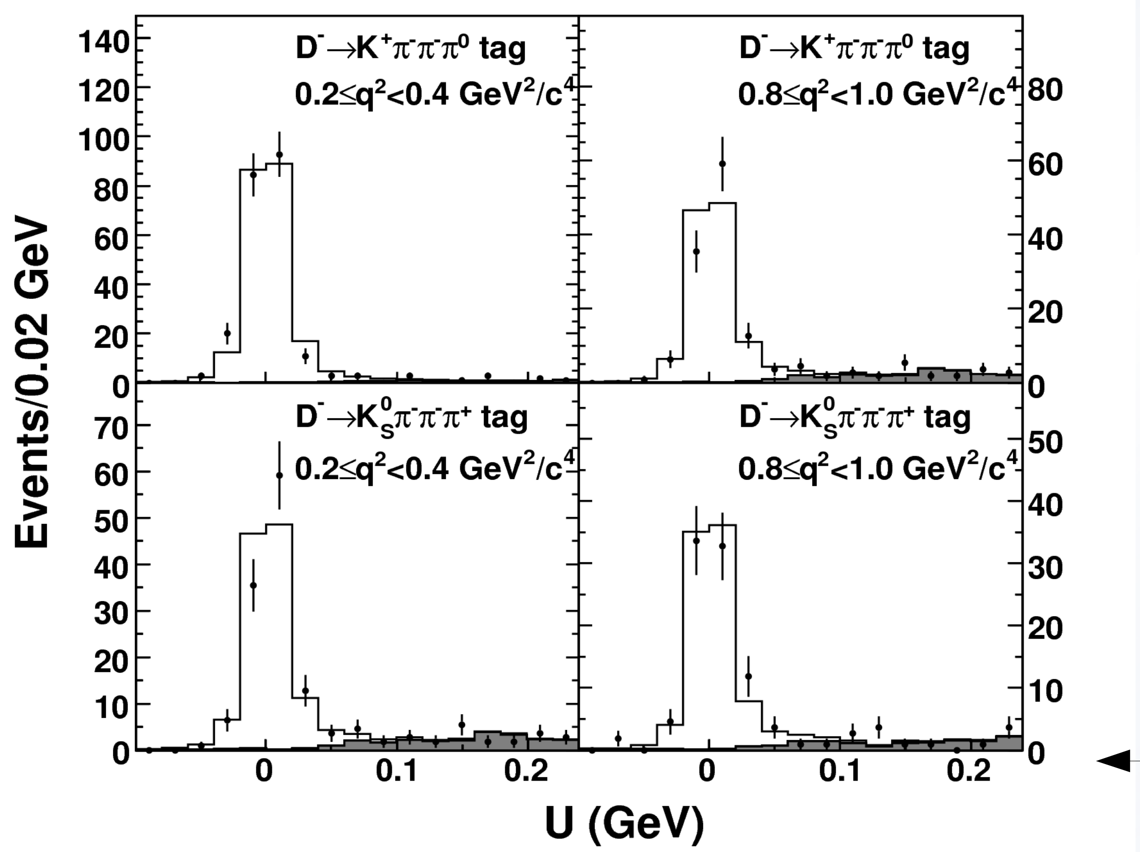
- Signal Yields in $D^0 \to K^{\pm}e\nu$:
  - Normalization of small non-DD background fixed
  - All other backgrounds combined into a single shape
  - Normalization of signal and background shapes float

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

- Signal shapes are wider in data → MC smeared using a double Gaussian
- Smear Parameters are those that minimize LL summed over all tags/q2

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

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



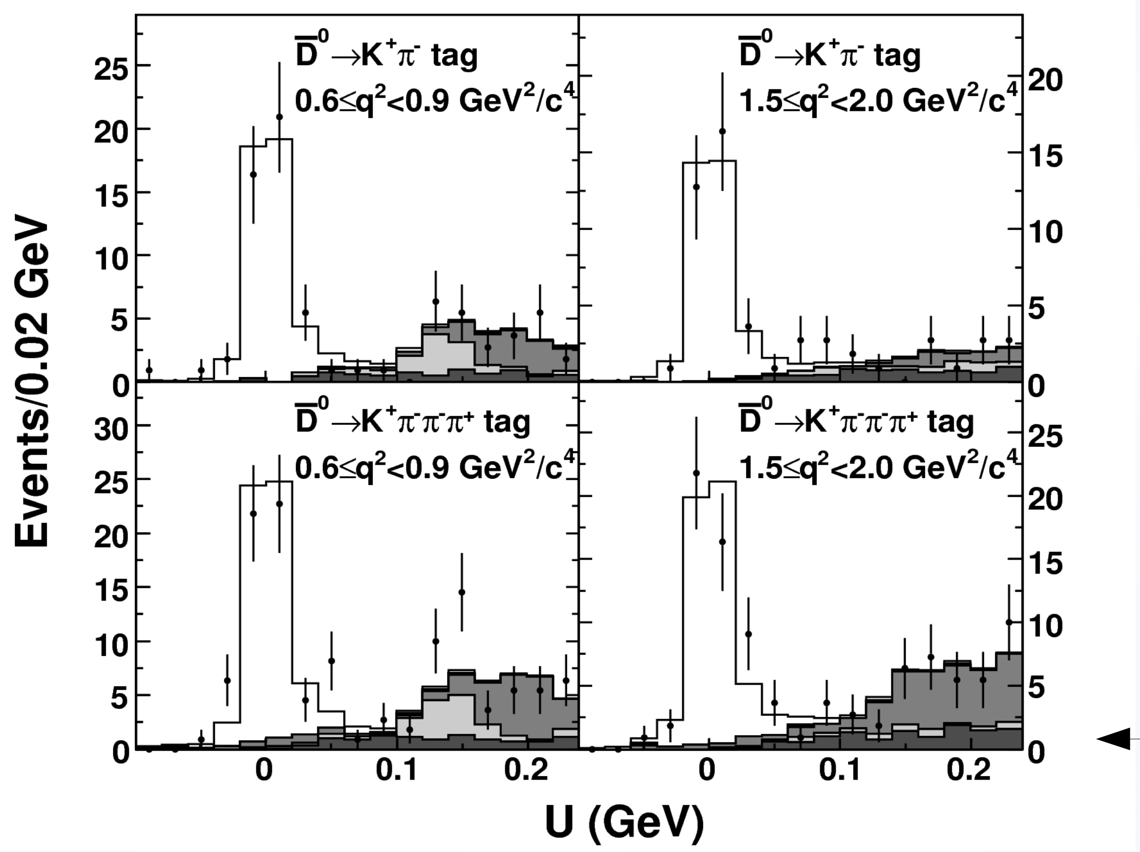
- Signal Yields in $D^{\pm}\to K^0 e\nu$:
  - Normalization of small non-DD background fixed
  - All other backgrounds combined into a single shape
  - Normalization of signal and background shapes float

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

- Signal shapes are wider in data → MC smeared using a double Gaussian
- Smear Parameters are those that minimize LL summed over all tags/q2

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

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



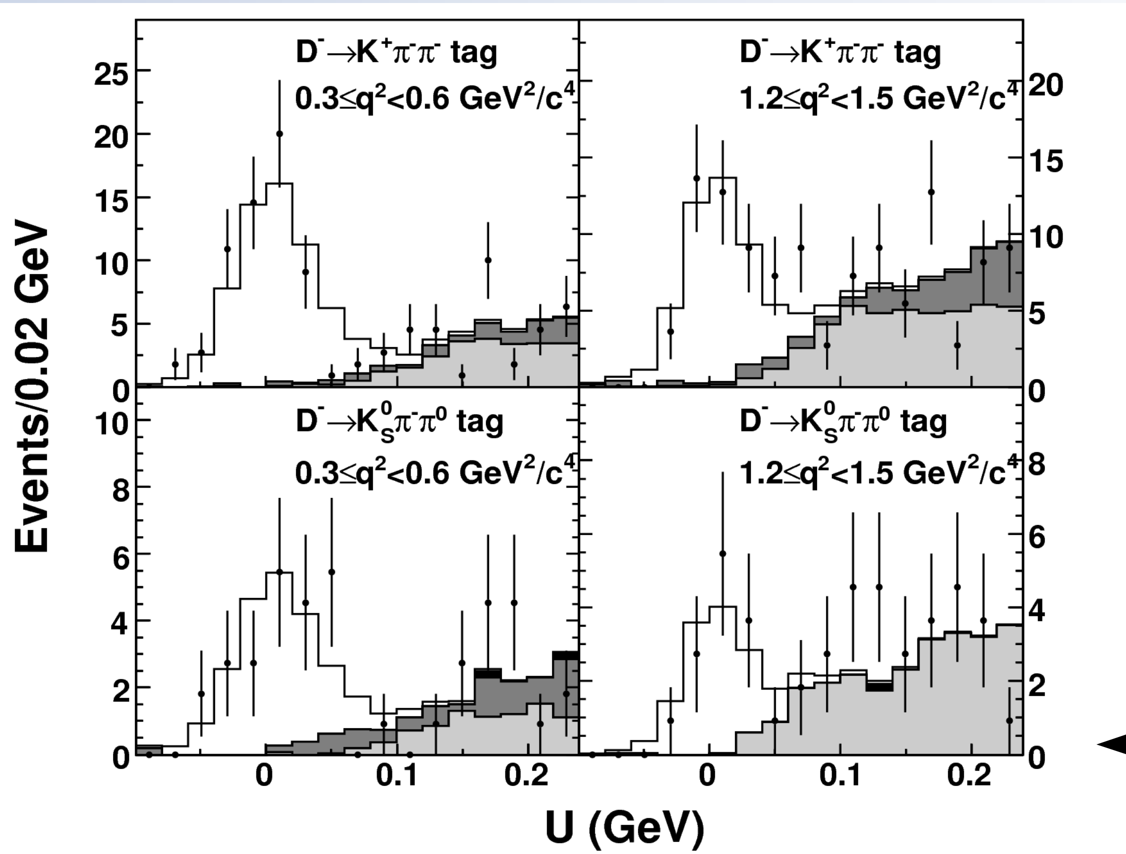
- Signal Yields in $D^0 \to \pi^{\pm} e\nu$:
  - Normalizations of D → Keν, D → ρeν, and small non-DD background are fixed
  - All other backgrounds are combined into a single shape
  - Normalization of signal and background shapes float

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

- Signal shapes are wider in data → MC smeared using a double Gaussian
- Smear Parameters are those that minimize LL summed over all tags/q2
- Fixed $K^{\pm}$enu backgrounds also minimize by LL summed over all tags/q2

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

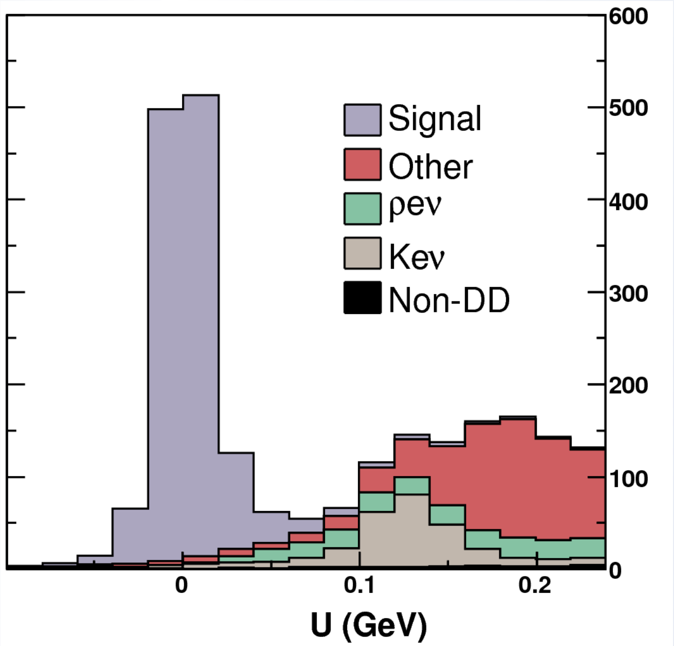
4 of the 42 $D^0 \to \pi^\pm e\nu$ fits

- Signal shapes are wider in data → MC smeared using a double Gaussian
- Smear Parameters are those that minimize LL summed over all tags/q2
- Fixed K^0enu backgrounds also minimize by LL summed over all tags/q2

Partial Rate Extraction: Systematics Example

- **An example: Background Shapes**
  - We vary each of the main background constituents in U fits within uncertainties on branching fractions and remeasure $\Delta\Gamma_j$

- E.g. in $D \rightarrow \pi^{\pm} e\nu$
  - Three backgrounds with fixed normalization:
    - Non-DD: varied by ± 20%
    - K±eν: varied by 8%
    - ρeν: varied by ±12%



$D \rightarrow \pi^{\pm} e\nu$ Candidates in MC

- Change in Partial Rates:

D± → πeν Variations		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%