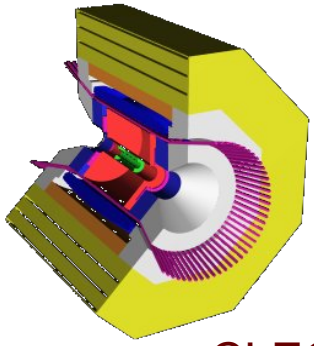
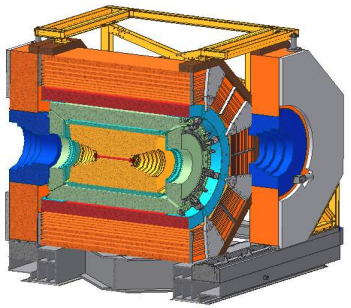
Semileptonic Decays of D and D_s



CLEO

Results from CLEO-c and Prospects for BESIII



BESIII

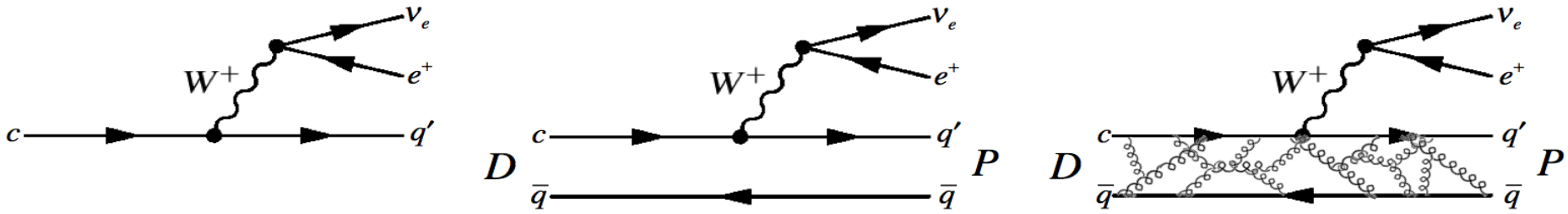
Ron Poling

University of Minnesota

Charm 2010

The 4th International Workshop on Charm Physics

A window on weak and strong physics



- Expt. meets LQCD now: $D \to K(\pi) e\nu$

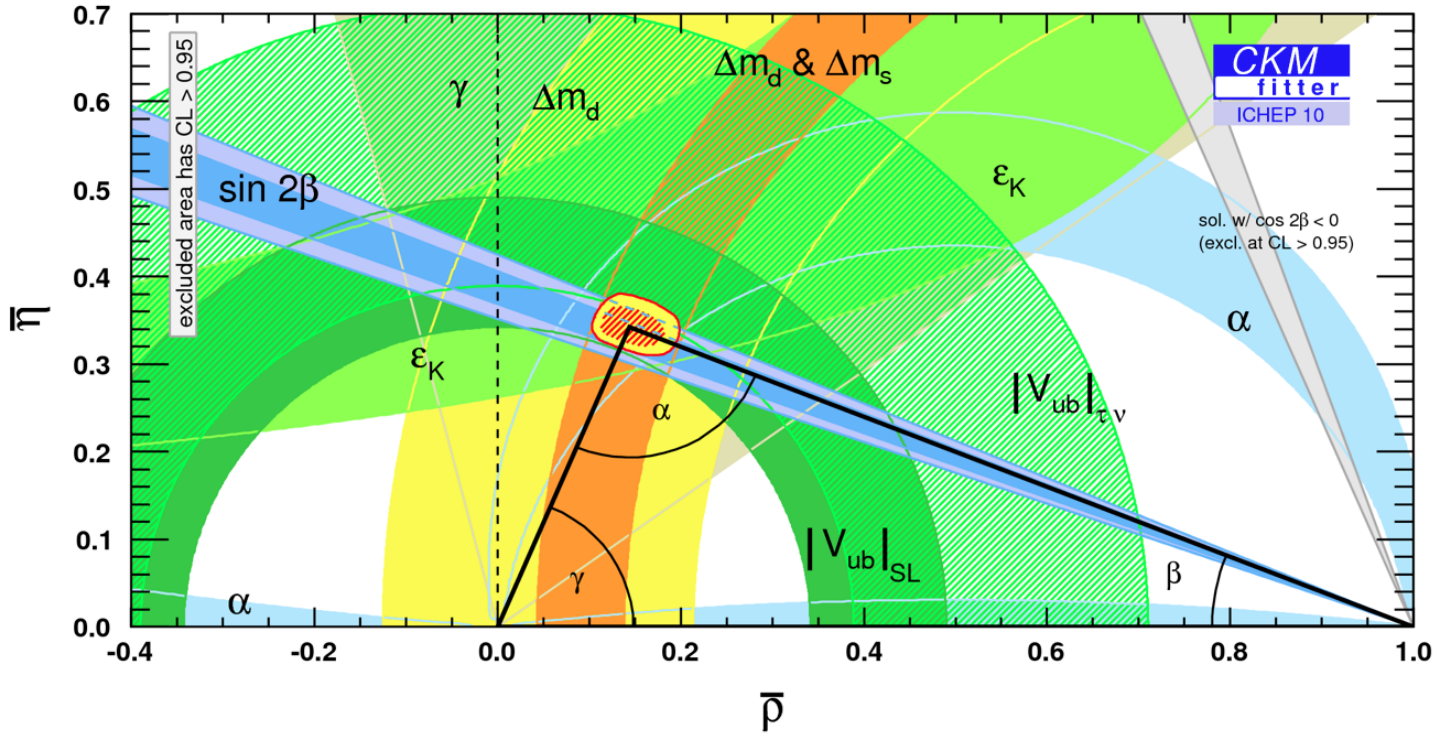
$$\frac{d\Gamma\left(D \to K(\pi) e\nu\right)}{dq^2} = \frac{G_F^2 \left|V_{cs(d)}\right|^2 P_{K(\pi)}^3}{24\pi^3} \left|f_+\left(q^2\right)\right|^2$$

Use theory for form factors
Extract CKM parameters

Use unitarity for CKM parameters, test QCD

- Expt. meets LQCD future: $P \to V$ SL decays (3 hadronic form factors, no unquenched LQCD calculation yet)

Charm's supporting role…



$D \to \pi e \nu$ $B \to \pi e \nu$

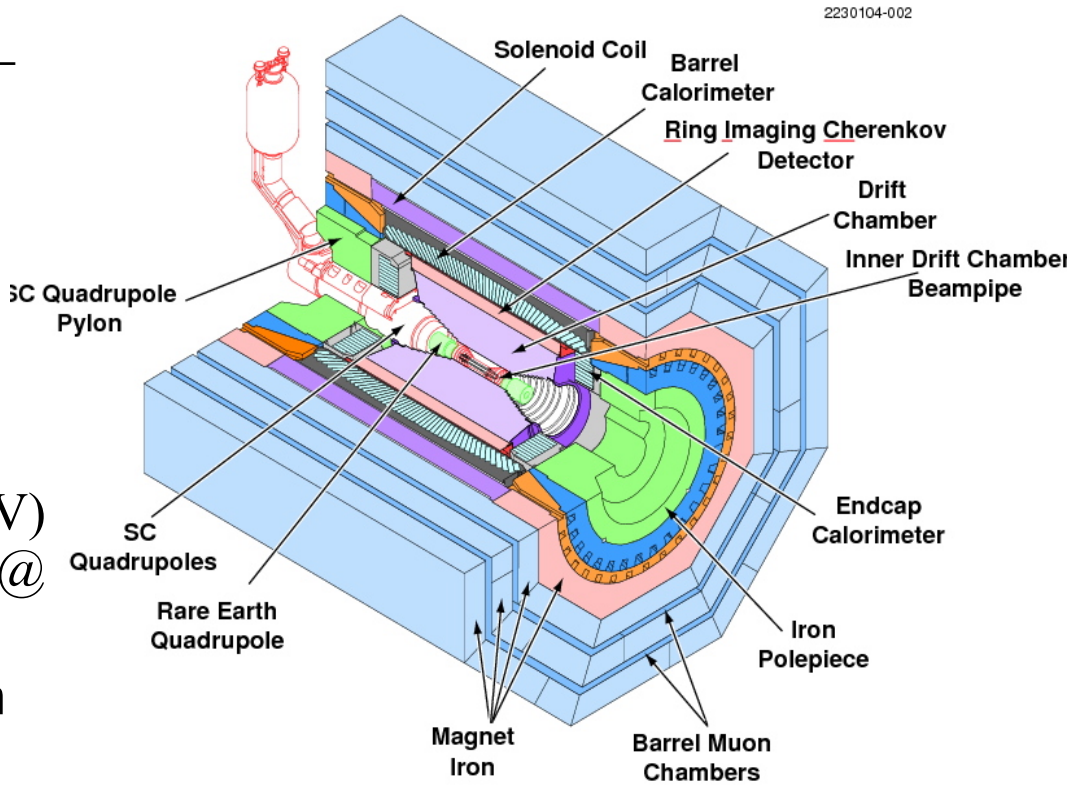
- Use charm to beat down theoretical uncertainties in $|V_{ub}|$ and mixing
- UT angles vs. sides: inconsistency $\Rightarrow$ New Physics

Topics for this talk:

- Tools and data samples: CLEO-c
- Analysis techniques for charm physics in e^+e^- near threshold
- Inclusive D and D_s semileptonic decays
- Exclusive semileptonic decays
  - $D \to K(\pi) e\nu$
  - $D \to \eta e\nu,\ \eta' e\nu,\ \rho e\nu,\ K\pi e(\mu)\nu$
  - Exclusive D_s
- Comments and prospects for BESIII

CLEO-c at CESR-c

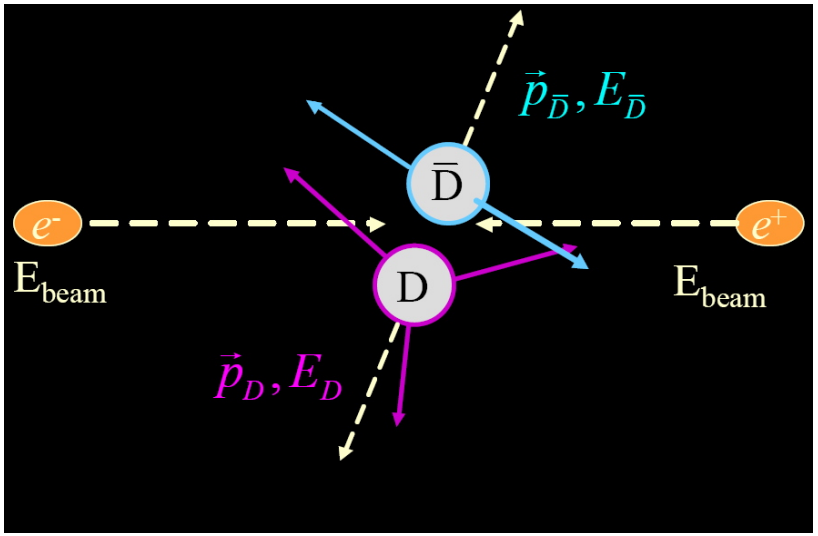
- Symmetric, single-ring, e^+e^- at $E_{CM} \sim 4$ GeV
  - CESR + wigglers
- Detector descended from CLEO II, CLEO III
  - Acceptance ~93% of 4π
  - Great tracking (0.6% @ 1 GeV) and CsI EM calorimeter (2% @ 1 GeV, 5% @ 100 MeV)
  - Excellent K/π separation with dE/dx and RICH



Data Samples

- D^0 and $D^{\pm}$ Physics: 818 pb^{-1} at $E_{CM} = M[\psi(3770)]$
- D_s Physics: 602 pb^{-1} at $E_{CM} = 4170$ MeV

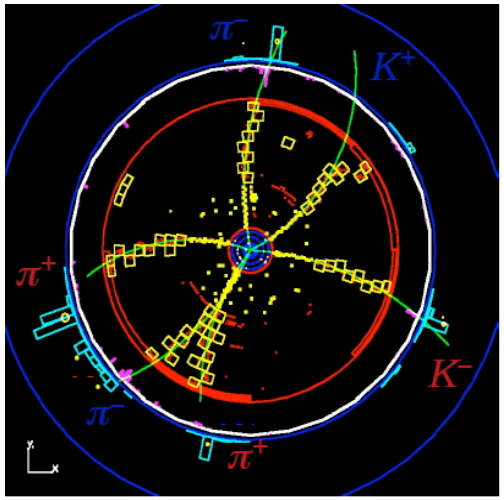
Tools for Charm Decays near Threshold



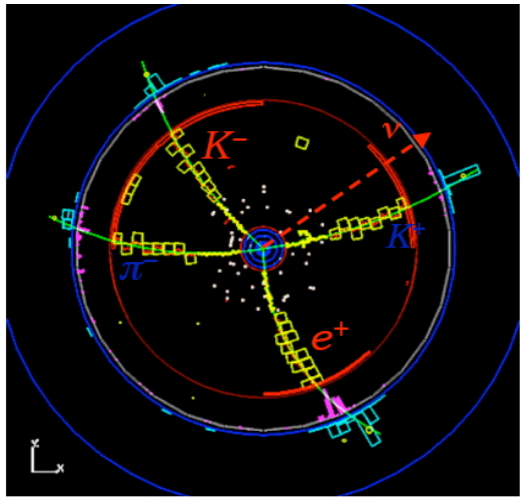
$$\Delta E = E_D - E_{\text{Beam}}$$

$$M_{\text{BC}} = \sqrt{E_{\text{Beam}}^2 - p_D^2}$$

- Extremely clean
- ~20% of ψ(3770) events have a fullly reconstructed D^0 or $D^{\pm}$ hadronic decay
- Extended to $D_s D_s^*$ events at E_{CM}=4170 MeV



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



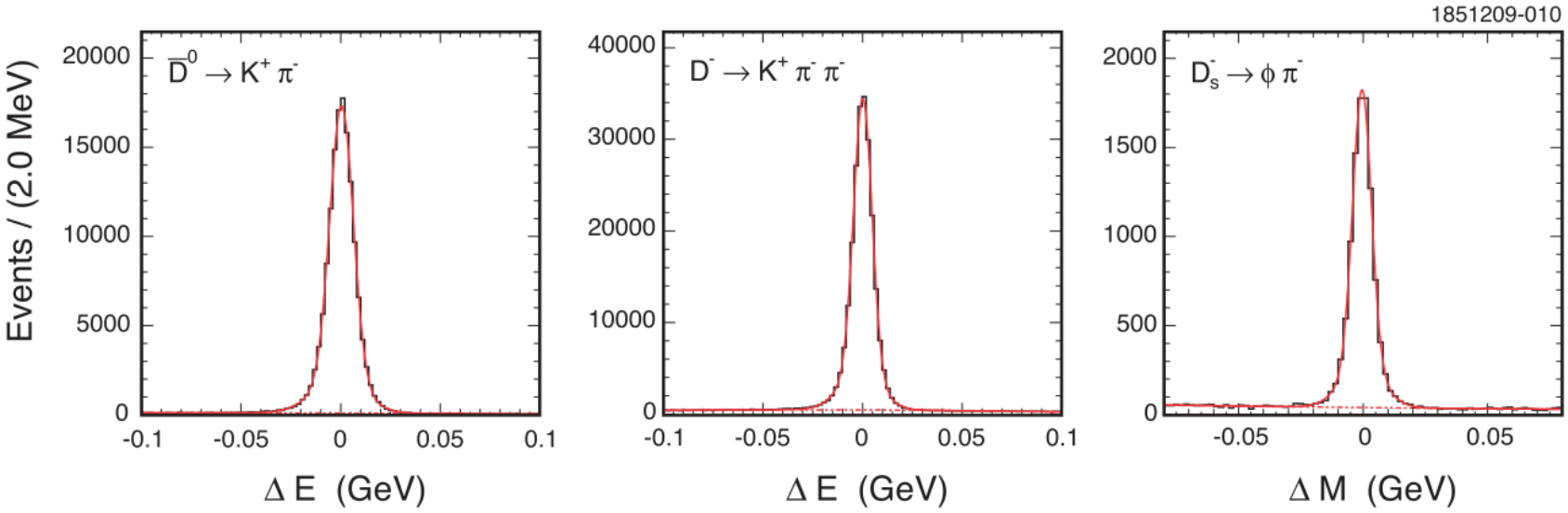
$K^- e^+ \nu$ vs. $K^+ \pi^-$

Inclusive Semileptonic D and D_s Decays

PRD **81**, 052007 (2010)

- Measure SL branching fractions, widths, momentum spectra for verification that overall behavior aligns with expectations
- Insights on relations among modes? Possible implications for B

- Uses all CLEO-c open-charm data (818/pb at $\psi(3770)$ and 602/pb at E_{CM}=4170 MeV) , just the cleanest tag for each of D^+, D^0 and D_s

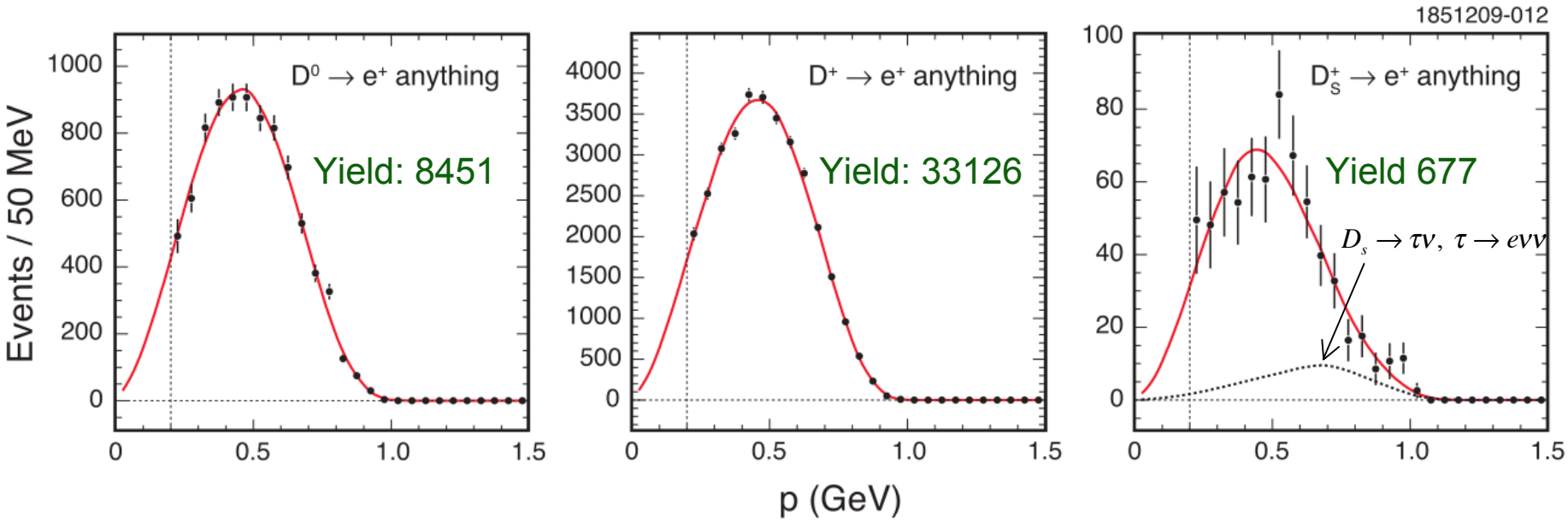


- Pick tag, find accompanying good track ($p \geq 200$ MeV/c) ID'ed as e

Inclusive Electron Spectra

PRD **81**, 052007 (2010)

- Unfolding process extracts true e spectrum from measured π, K and e spectra using response matrices incorporating efficiencies, resolutions, mis-ID probabilities
- Wrong-sign candidates used for real-electron BG correction



- Extrapolate spectrum below cutoff (using measured exclusive BFs and ISGW2 model for excess) to get total SL yield

Results and Interpretation

PRD **81**, 052007 (2010)

Tag mode	$B_{\text{trunc}}(e^+X)$ (%)	Partial BF $p \geq 200$ MeV/c	$B(e^+X)$ (%)	Full BF with extrapolation	$B(Xe^+\nu_e)$ (%)	Final BF with τ correction & systematics
$\bar{D}^0 \to K^+\pi^-$	5.958 ± 0.084		6.460 ± 0.091		$6.46 \pm 0.09 \pm 0.11$	
$D^- \to K^+\pi^-\pi^-$	14.863 ± 0.092		16.147 ± 0.100		$16.13 \pm 0.10 \pm 0.29$	
$D_s^- \to \phi\pi^-$	7.002 ± 0.361		7.525 ± 0.387		$6.52 \pm 0.39 \pm 0.15$	

$$\frac{\Gamma\left(D^+ \to Xe^+\nu\right)}{\Gamma\left(D^0 \to Xe^+\nu\right)} = 0.985 \pm 0.015 \pm 0.024$$

Charged and neutral D decays show expected isospin symmetry

$$\frac{\Gamma\left(D_s^+ \to Xe^+\nu\right)}{\Gamma\left(D^0 \to Xe^+\nu\right)} = 0.825 \pm 0.051 \pm 0.022$$

Charm and charm-strange meson decay widths are different

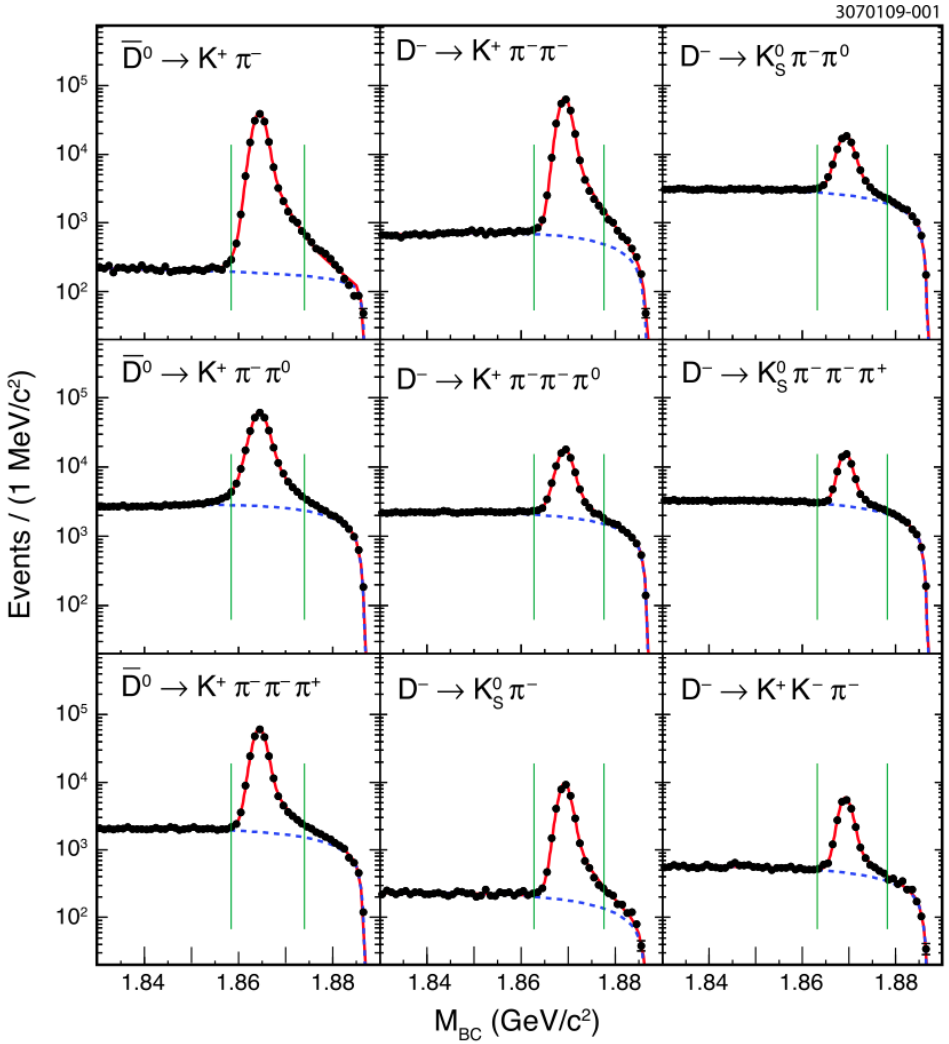
- Voloshin (PLB 515, 74 (2001)): Charm/charm-strange SL width ratio can constrain B^+/B^0 differences in inclusive $|V_{ub}|$ determination
- Recent work (Ligeti *et al.*, Gambino and Kamenik): CLEO-c result limits Weak annihilation contribution to B decays to a few % or less

Improved Measurement of D SL Decays to π and K

PRD **80**, 032005 (2009)

- Full CLEO-c $\psi(3770)$ sample
- Very clean: 3 D^0 and 6 D^+ tag modes
- Total of 1.15M D tags ($\sim$ 20% of $D\bar{D}$ events)
- Search single-tag events for semileptonic decay on the other side: detect hadron tracks and demand that what is missing is consistent with a single neutrino

$$U = E_{\text{miss}} - c\left|\vec{P}_{\text{miss}}\right| \approx 0$$

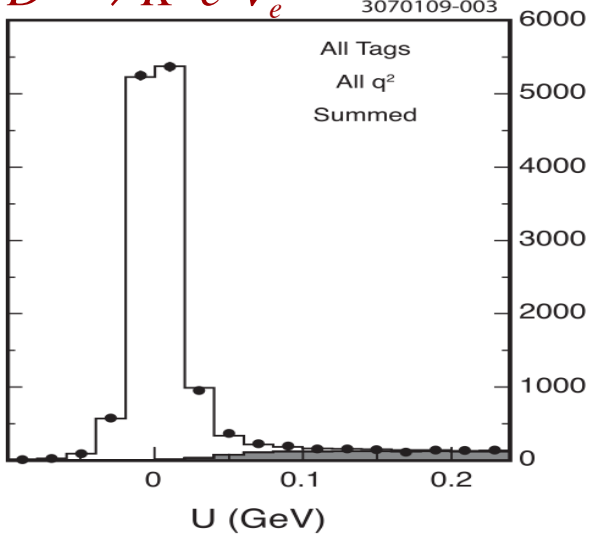


Semileptonic Yield Determination

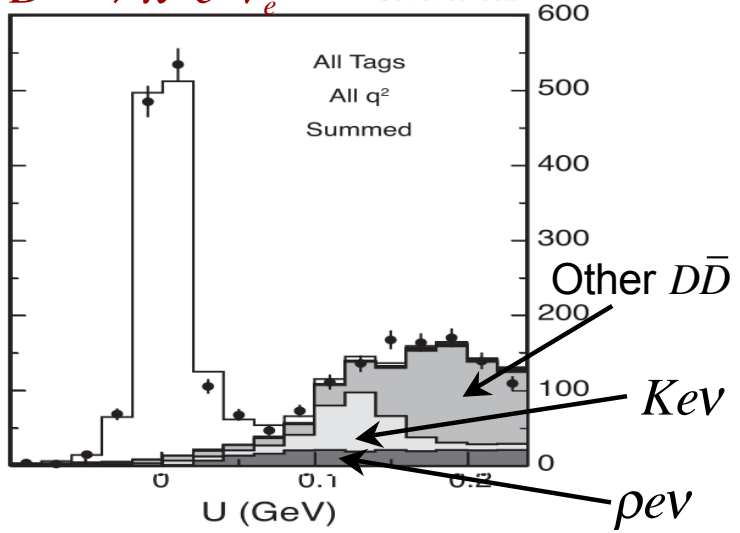
PRD **80**, 032005 (2009)

Fit U signal with smeared MC. Overall fits set normalizations of BG components. Separate fits by tag mode and q^2 bin for final results.

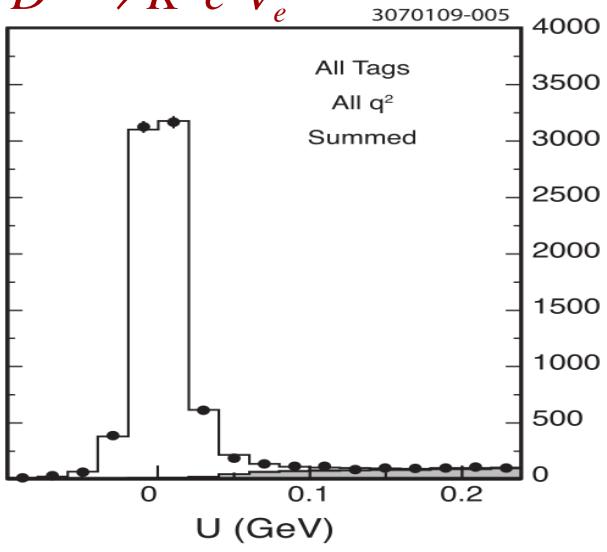
$D^0 \to K^- e^+ \nu_e$



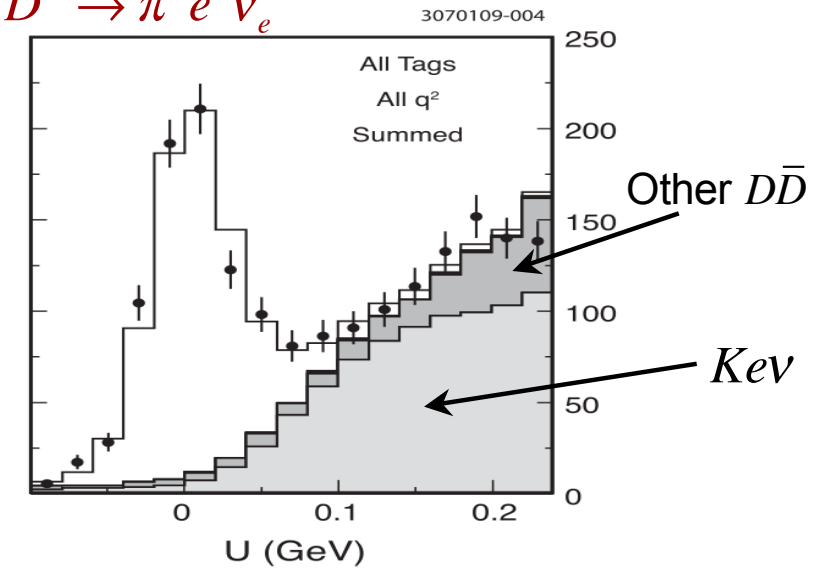
$D^0 \to \pi^- e^+ \nu_e$



$D^+ \to \bar{K}^0 e^+ \nu_e$

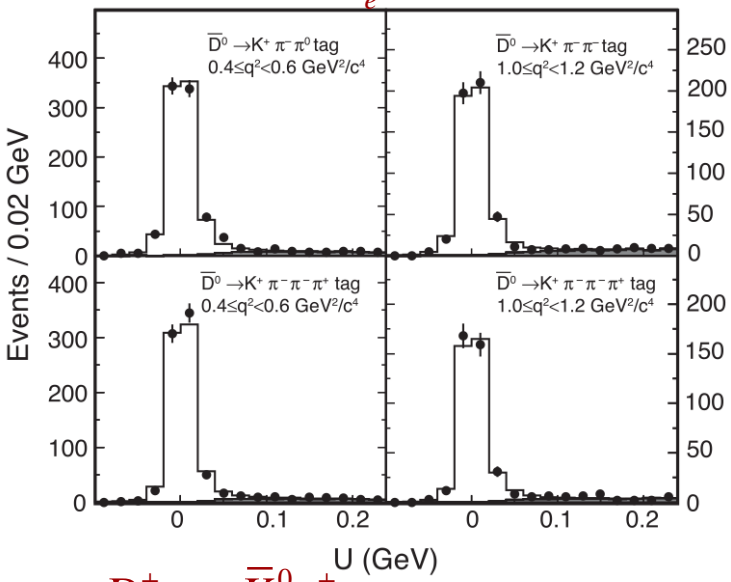


$D^+ \to \pi^0 e^+ \nu_e$

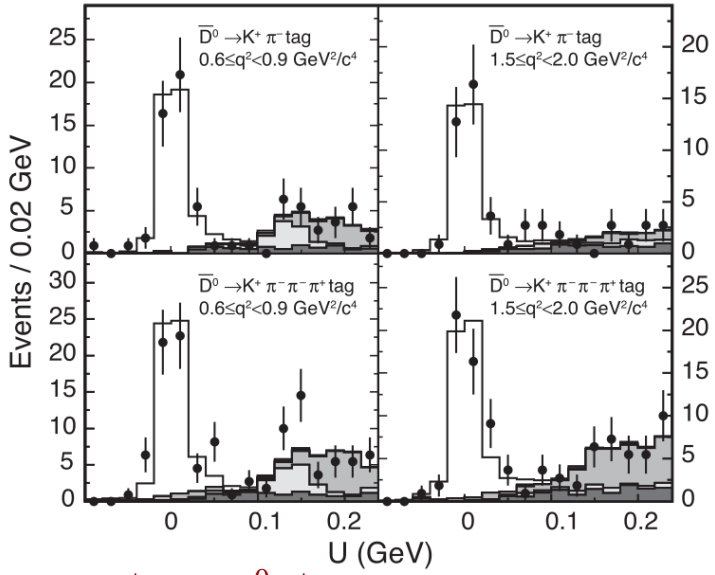


PRD **80**, 032005 (2009)

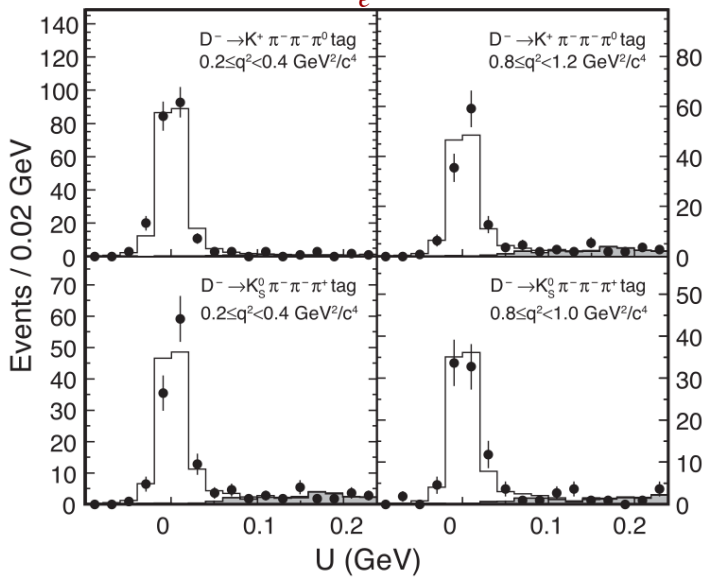
$D^0 \to K^- e^+ \nu_e$



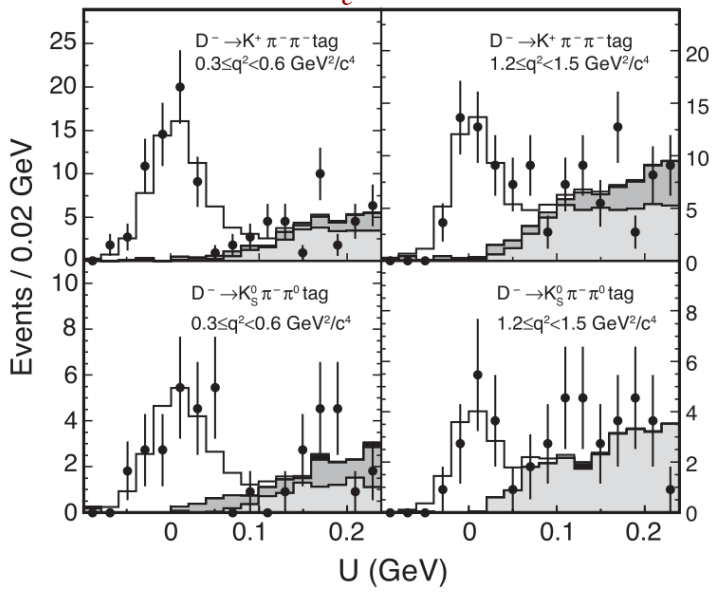
$D^0 \to \pi^- e^+ \nu_e$



$D^+ \to \bar{K}^0 e^+ \nu_e$

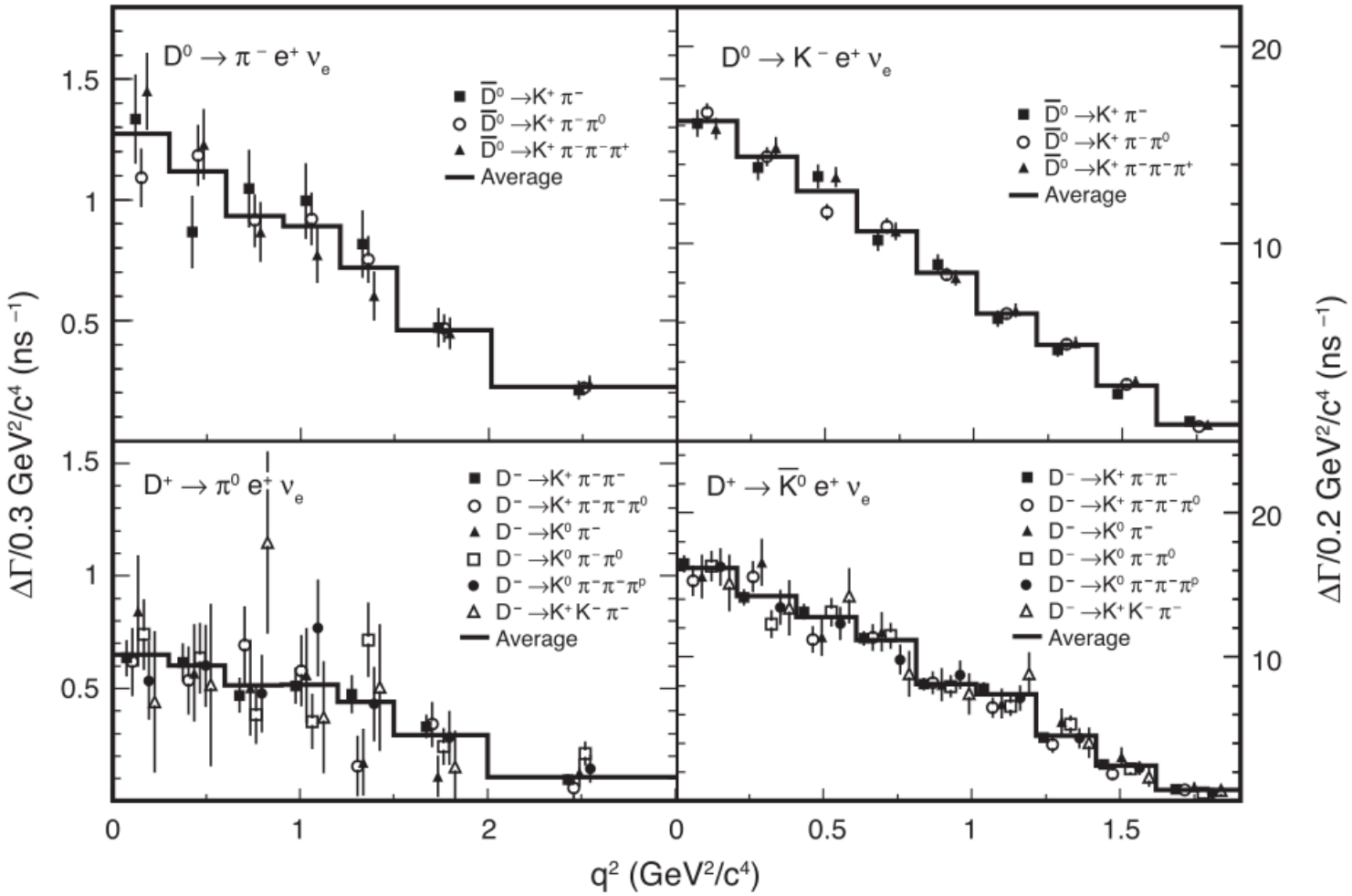


$D^+ \to \pi^0 e^+ \nu_e$



Measured Partial Rates

PRD **80**, 032005 (2009)



Very good consistency among tag modes. Fit projections agree well with MC. Use to extract $f_+(q^2)$.

Form Factor Representations

$D \to \pi(K) e\nu$

Simple Pole Model

(Lowest H^* dominates)

$$f_+(q^2) = \frac{f_+(0)}{\left(1 - \frac{q^2}{m^2_{H^*}}\right)}$$

Modified Pole Model

(additional poles)

Becirevic and Kaidalov
PLB 478, 417 ('00)

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

Series Expansion

Becher and Hill
PLB 633, 61 ('06)

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

$$z(q^2,t_0) = \frac{\sqrt{t_+ - q^2} - \sqrt{t_+ - t_0}}{\sqrt{t_+ - q^2} + \sqrt{t_+ - t_0}} \qquad t_\pm = (m_D \pm m_X)^2$$

Confront parameters extracted from data with theory predictions

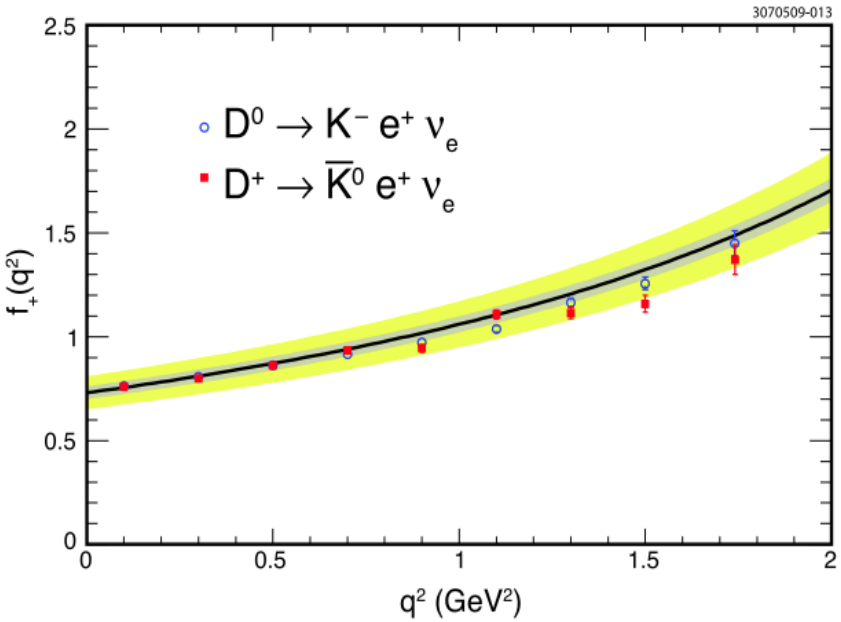
Form Factor Results and Comparisons

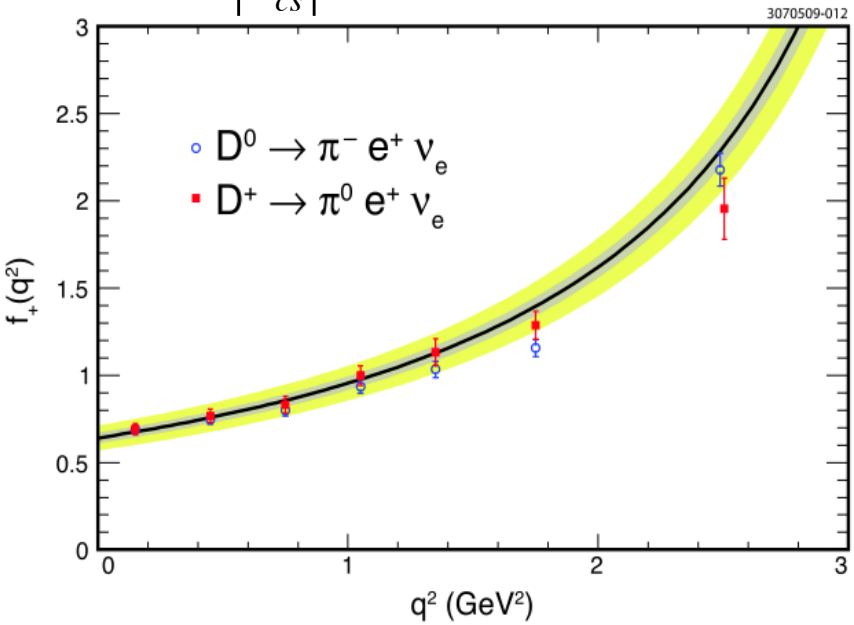
PRD **80**, 032005 (2009)

Use PDG for CKM (I.e., assume unitarity):

$$|V_{cd}| = 0.2256 \pm 0.0010$$

$$|V_{cs}| = 0.97334 \pm 0.00023$$

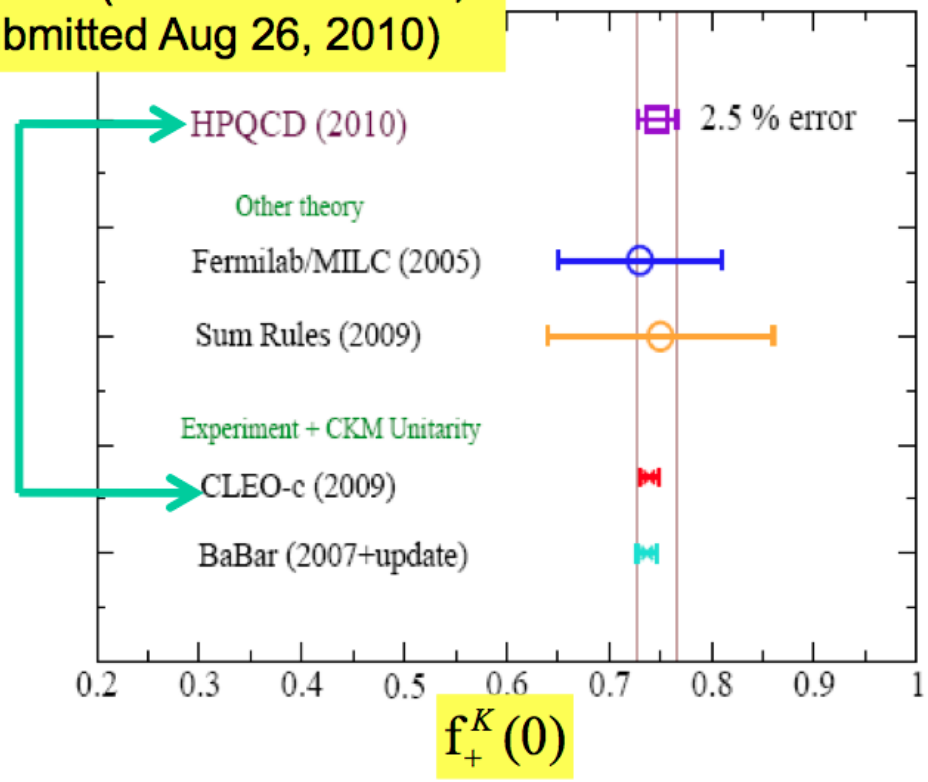


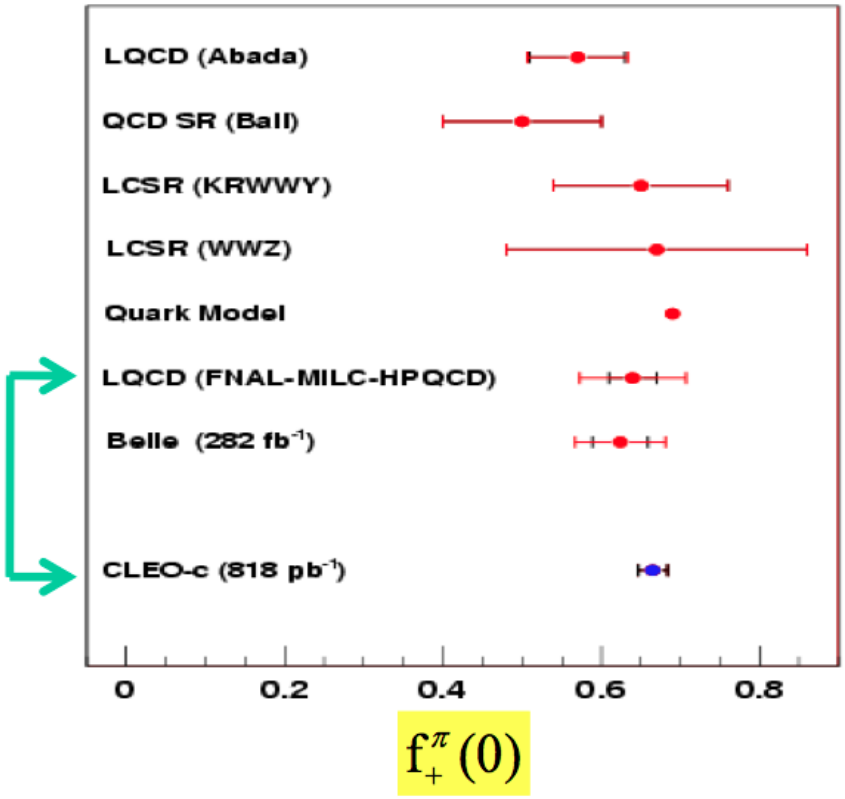


- Isospin-conjugate modes agree within 1.4σ
- Solid line best fit to LQCD with modified pole model
  - Aubin *et al.*, PRL 94, 011601 ('05); Bernard *et al.*, PRD 80, 034026 ('09)
  - Inner bands give LQCD stat. uncert., outer band LQCD stat.+syst.

New D→Kev form factor results (arXiv: 1008.4562, submitted Aug 26, 2010)

From Bo Xin





The LQCD uncertainty on $f_+^K(0)$ was 10% (in 2005), now 2.5%!

The same LQCD technique can be used for D→π to further reduce the theory uncertainty on $f_+^\pi(0)$.

CLEO-c results consistent with LQCD, but more precise. $f_+^K(0)$: 1% vs 3%, $f_+^\pi(0)$: 3% vs. 10%

From Bo Xin

The data determine $|V_{cs(d)}|f_+(0)$.

To extract $|V_{cs(d)}|$, we combine the measured $|V_{cs(d)}|f_+(0)$ values using the Becher-Hill parameterization with (FNAL-MILC-HPQCD) for $f_+(0)$

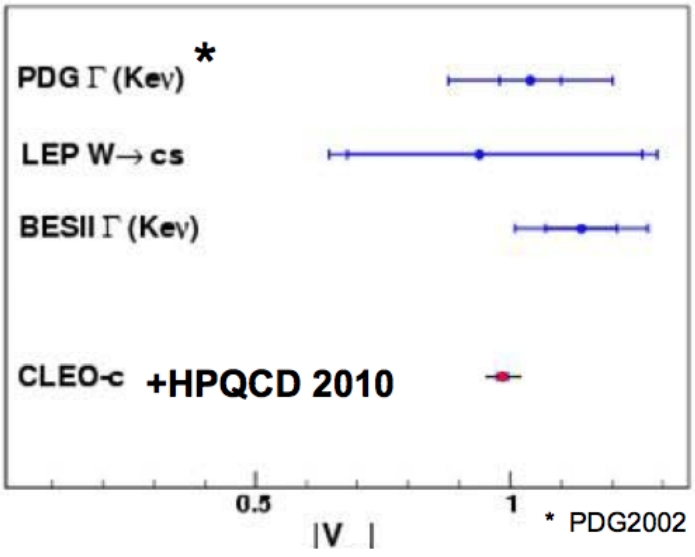
CLEO-c: the most precise *direct* determination of $|V_{cs}|$ $\sigma(|V_{cs}|)/|V_{cs}| \sim 1.1\%(\text{expt}) \oplus 2.5\%(\text{theory})$

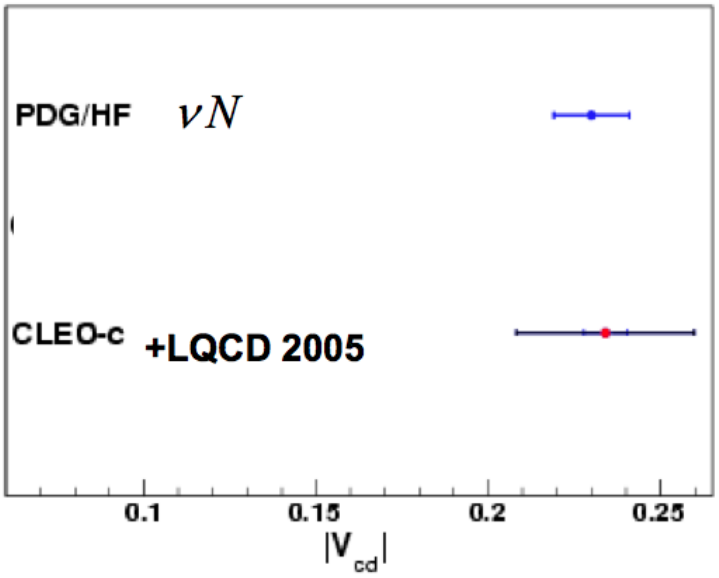
$CLEO-c$	$\lvert V_{cs}\rvert$		
$(818\ \text{pb}^{-1})$	$0.963 \pm 0.009 \pm 0.006 \pm 0.024$		
	stat	syst	theory

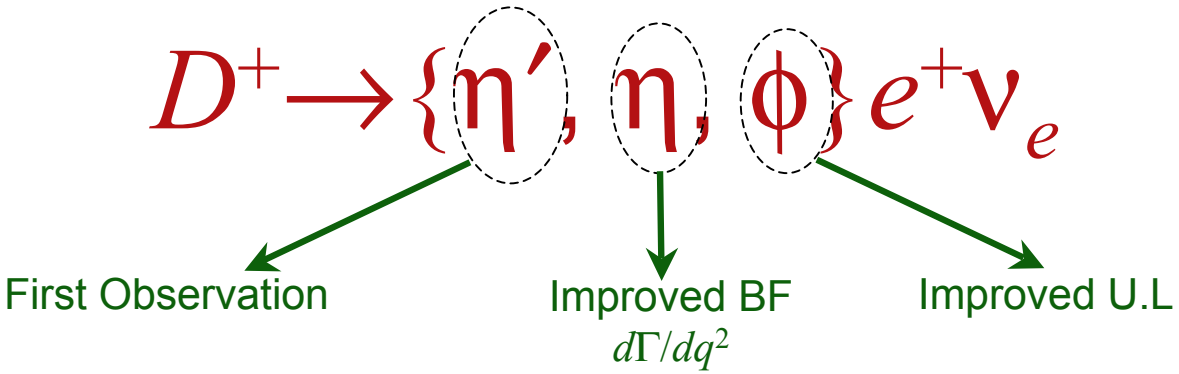
CLEO-c: $\sigma(|V_{cd}|)/|V_{cd}| \sim 3.1\%(\text{expt}) \oplus 10\%(\text{theory})$

νN remains most precise determination

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







CLEO-c Preliminary

$\psi(3770)$ - 818/pb

- Toward a complete picture of SL charm decay
- Possible info on η/η' mixing, QCD anomalies in heavy meson decays to η'
- Search for surprises: $D \to \phi e \nu$ would reveal ω/ϕ mixing
- Two approaches:

Tagged

- Same 6 D^+tag modes
- Select
  - $\eta \to \gamma\gamma$, $\eta \to \pi^+\pi^-\pi^0$
  - $\eta' \to \pi^+\pi^-\eta$
  - $\phi \to K^+K^-$
- Add e^+ and select on U

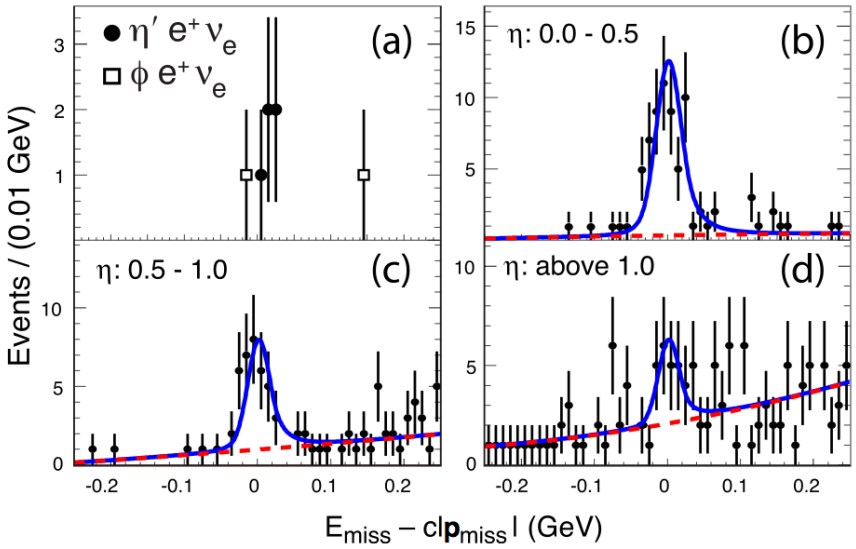
"Generic Reconstruction"

- Select η/η'
- Event cuts to minimize missing particles
- Select e^+
- Require leftovers ~D
- Use $p_\nu \approx p_{\rm miss}$ and select on $M_{\rm BC}$

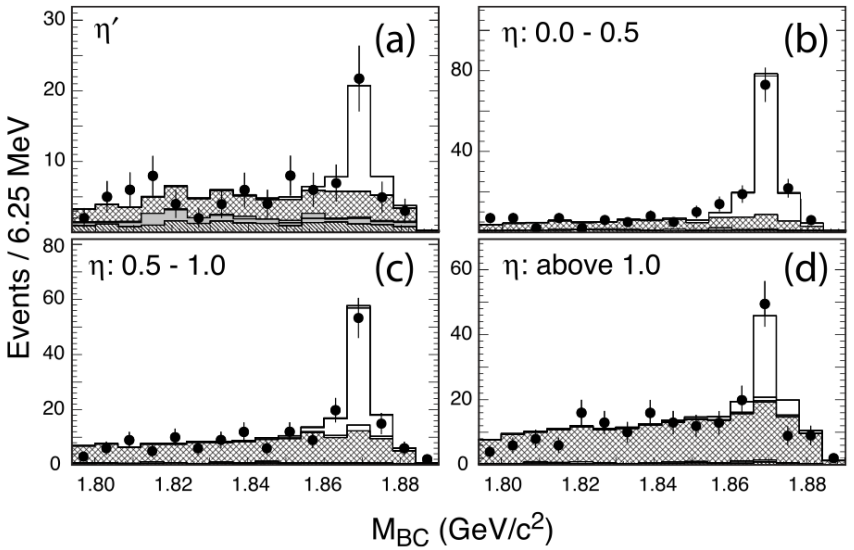
Results

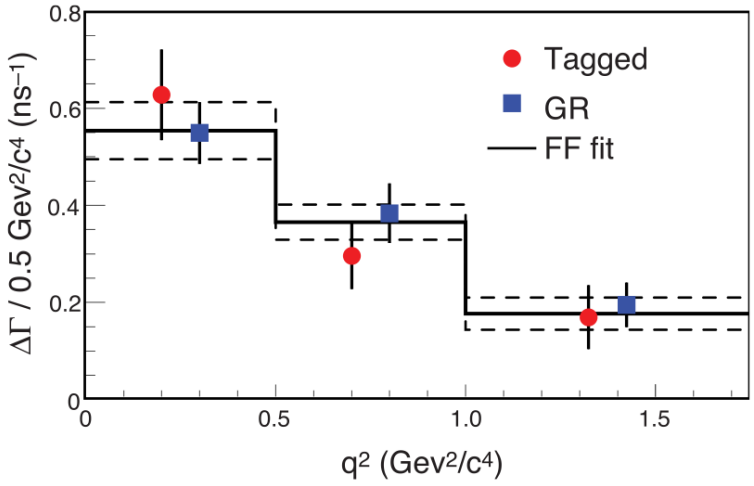
CLEO-c Preliminary

Tagged Analysis
U Distributions



GR Analysis
M_{BC} Distributions





Fit of $D^+ \to \eta e \nu$ to series expansion gives

$$f_+(0)|V_{cd}| = 0.086 \pm 0.006 \pm 0.001$$
$$f_+(0) = 0.381 \pm 0.027 \pm 0.005$$

$$\mathcal{B}(D^+ \to \eta e^+ \nu_e) = (11.4 \pm 0.9 \pm 0.4) \times 10^{-4},$$
$$\mathcal{B}(D^+ \to \eta' e^+ \nu_e) = (2.16 \pm 0.53 \pm 0.07) \times 10^{-4},$$
$$\mathcal{B}(D^+ \to \phi e^+ \nu_e) < 0.9 \times 10^{-4} \quad (90\%\ \text{C.L.})$$

First observation of $D^+ \to \eta' e \nu$ (5.6σ)

$D \to \rho e \nu$

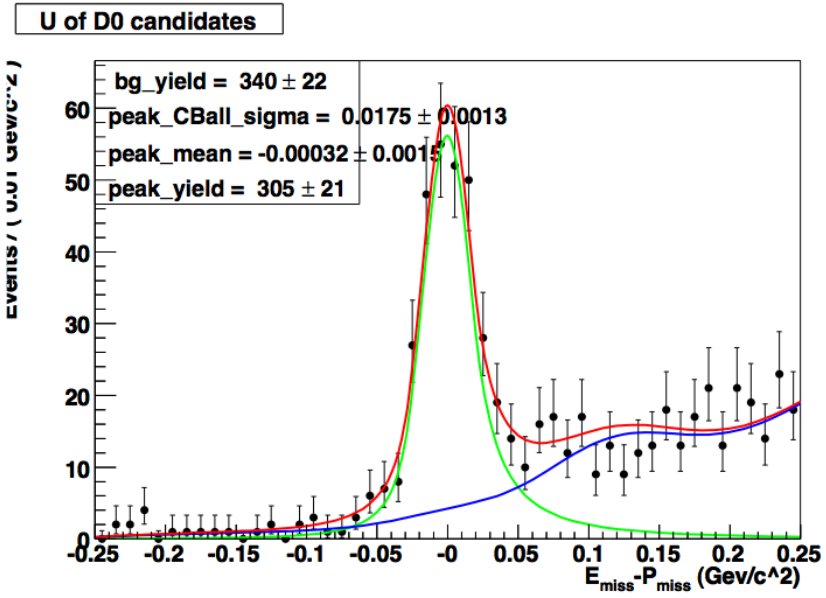
CLEO-c Preliminary

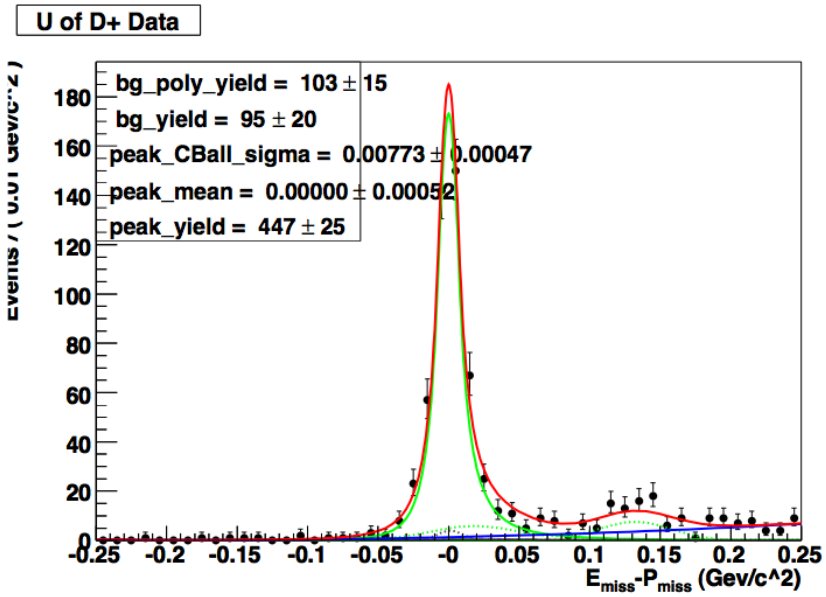
- Importance: $|V_{ub}|$
  - Grinstein/Pirjol PRD 70, 114005 ('04)
- No published measurements on Cabibbo-suppressed $P \to V$ FFs

$$\frac{d\Gamma(B \to \rho e \nu)/dq^2}{d\Gamma(B \to K^* l^+ l^-)/dq^2} \propto \frac{|V_{ub}^2|}{|V_{cb}^2|}$$

Need $D \to K^* e \nu$ and $D \to \rho e \nu$ FFs

- 818/pb $\psi(3770)$, tagged analysis: measure and fit distribution of $U = E_{\rm miss} - cp_{\rm miss}$ (signal: two-sided CB, BG: generic $\psi(3770)$ MC)





$D \to \rho e \nu$ BF Results

CLEO-c Preliminary

	56/pb(%)	281/pb(%)	This work818/pb(%)
$D^0 \to \rho^- e^+ \nu$	0.19 ± 0.04 ± 0.01	0.158 ± 0.016 ± 0.009	0.177 ± 0.011 ± 0.010
$D^+ \to \rho^0 e^+ \nu$	0.21 ± 0.04 ± 0.01	0.236 ± 0.020 ± 0.012	0.217 ± 0.013 ± 0.011
$D^+ \to \omega e^+ \nu$	$0.16\ ^{+0.070}_{-0.06} \pm 0.01$	0.151 ± 0.027 ± 0.007	0.182 ± 0.018 ±0.008

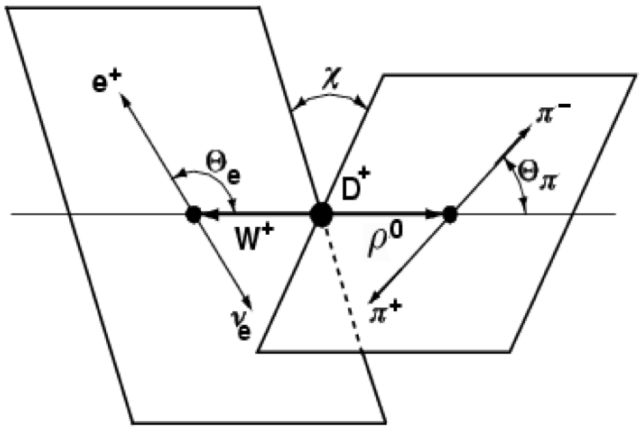
$$\Gamma(D^0 \to \rho^- e^+ \nu_e) = [4.29 \pm 0.27(\text{stat}) \pm 0.24(\text{syst})] \quad \text{ns}^{-1}$$

$$\Gamma(D^+ \to \rho^0 e^+ \nu_e) = [2.05 \pm 0.11(\text{stat}) \pm 0.90(\text{syst})] \quad \text{ns}^{-1}$$

$$\frac{\Gamma(D^0 \to \rho^- e^+ \nu_e)}{2\Gamma(D^+ \to \rho^0 e^+ \nu_e)} = 1.03 \pm 0.08$$

$D \to \rho e \nu$ Form Factors

$$\frac{d\Gamma(D^+ \to \rho^0 e^+ \nu_e, \rho^0 \to \pi^+\pi^-)}{dq^2 d\cos\theta_\pi d\cos\theta_e d\chi dm(\pi\pi)} = \frac{3}{8(4\pi)^4} G_F^2 |V_{cd}|^2 \frac{p_{\rho^0} q^2}{M_D^2} \mathcal{B}(\rho^0 \to \pi\pi) \mathcal{BW}^2(m(\pi\pi)) \times$$
$$\{(1+\cos\theta_e)^2 \sin^2\theta_\pi |H_+(q^2, m(\pi\pi))|^2$$
$$+(1-\cos\theta_e)^2 \sin^2\theta_\pi |H_-(q^2, m(\pi\pi))|^2$$
$$+4\sin^2\theta_e \cos^2\theta_\pi |H_0(q^2, m(\pi\pi))|^2$$
$$+4\sin\theta_e(1+\cos\theta_e)\sin\theta_\pi\cos\theta_\pi\cos\chi H_+(q^2, m(\pi\pi))H_0(q^2, m(\pi\pi))$$
$$-4\sin\theta_e(1-\cos\theta_e)\sin\theta_\pi\cos\theta_\pi\cos\chi H_-(q^2, m(\pi\pi))H_0(q^2, m(\pi\pi))$$
$$-2\sin^2\theta_e \sin^2\theta_\pi \cos 2\chi H_+(q^2, m(\pi\pi))H_-(q^2, m(\pi\pi))\}$$



Helicity Amplitudes

$$H_\pm(q^2) = (M_D + M_{\pi\pi}) A_1(q^2) \mp 2 \frac{M_D p_{\pi\pi}}{M_D + M_{\pi\pi}} V(q^2)$$

$$H_0(q^2) = \frac{1}{2M_{\pi\pi}\sqrt{q^2}} \left[(M_D^2 - M_{\pi\pi}^2 - q^2)(M_D + M_{\pi\pi}) A_1(q^2) - 4 \frac{M_D^2 p_{\pi\pi}^2}{M_D + M_{\pi\pi}} A_2(q^2) \right]$$

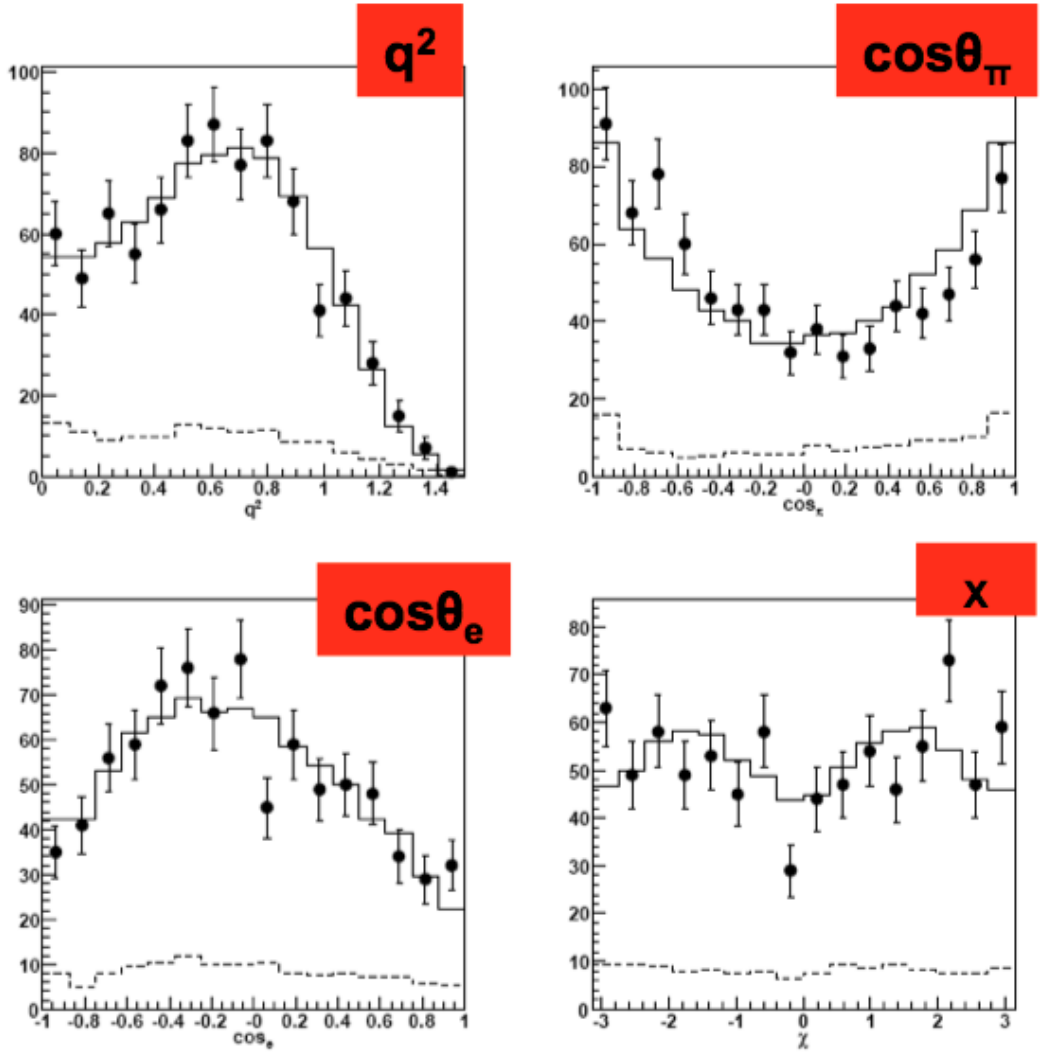
Assume Simple Pole form for the Form Factors $V(q^2), A_1(q^2), A_2(q^2)$

Fit decay rate in 4D to extract FF ratios

$$R_V = V(0)/A_1(0)$$
$$R_2 = A_2(0)/A_1(0)$$

$D \to \rho e \nu$ Form Factor Results

CLEO-c Preliminary



$$R_V = 1.48 \pm 0.15 \pm 0.03$$

$$R_2 = 0.83 \pm 0.11 \pm 0.04$$

First measurement of these ratios in Cabibbo-suppressed mode

$D^+ \to K^-\pi^+e^-\nu$ and $D^+ \to K^-\pi^+\mu^-\nu$

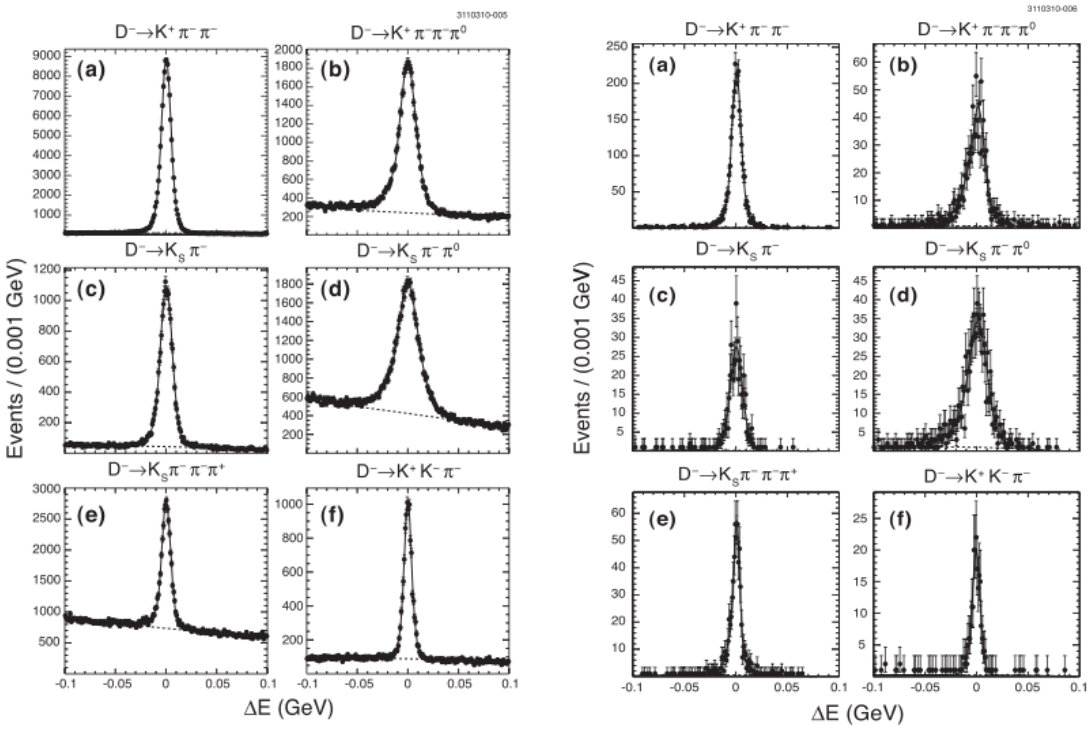
PRD **81**, 112001 (2010)

- 818/pb of $\psi(3770)$ data - tagged analysis with 6 D^- tag modes
- μ/e separation purely kinematic
- Measuring both μ and e provides sensitivity to mass-suppressed helicity amplitudes

Hadronic D^- tag + SL Candidate

$$BF \sim \frac{DT}{ST}$$

Hadronic D^- tag



$$\mathcal{B}\left(D^+ \to \bar{K}^{*0}e^+\nu_e\right) = \left(5.52 \pm 0.07 \pm 0.13\right)\%$$

$$\mathcal{B}\left(D^+ \to \bar{K}^{*0}\mu^+\nu_\mu\right) = \left(5.27 \pm 0.07 \pm 0.14\right)\%$$

$$\mathcal{B}_\mu/\mathcal{B}_e = \left(94.64 \pm 1.95 \pm 1.03\right)\%$$

Phase space ~91%

$D^+ \to K^-\pi^+e^-\nu$ and $D^+ \to K^-\pi^+\mu^-\nu$

PRD **81**, 112001 (2010)

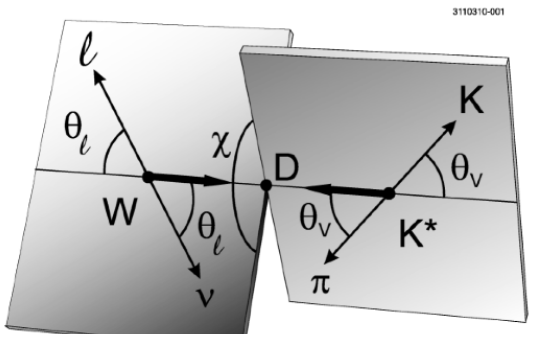
Form Factor Determination

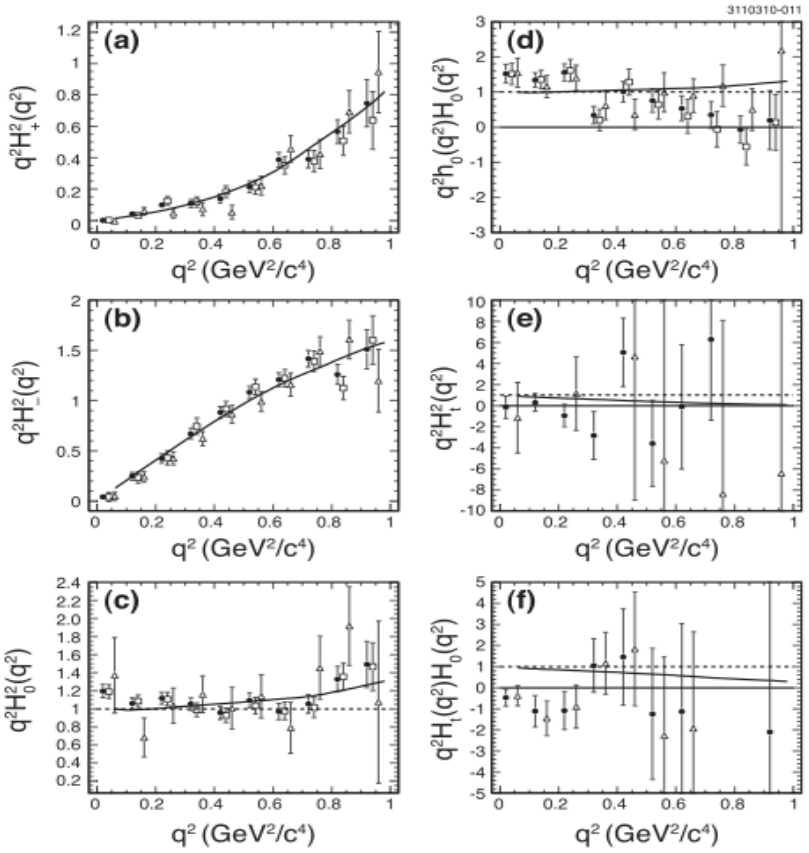
- 5 kinematic variables
  - $M(K\pi)$, $q^2 = M^2(l\nu)$, θ_V, θ_l, χ
- Model-independent extraction of 6 helicity-basis FFs

$$H_+^2(q^2), H_-^2(q^2), H_0^2(q^2),$$

$$H_t^2(q^2), H_t H_0(q^2), h_0 H_0(q^2)$$

- Projective weighting technique
  - FOCUS: PLB 633, 183 (2006)
  - Distinguish contributions of FFs by characteristic decay-angle dists.
- Muons $\to$ mass-suppressed FF
- Good agreement with SPD model (curves) for dominant FFs. Smaller H_t than expected from LQCD?





Exclusive D_s SL Decays

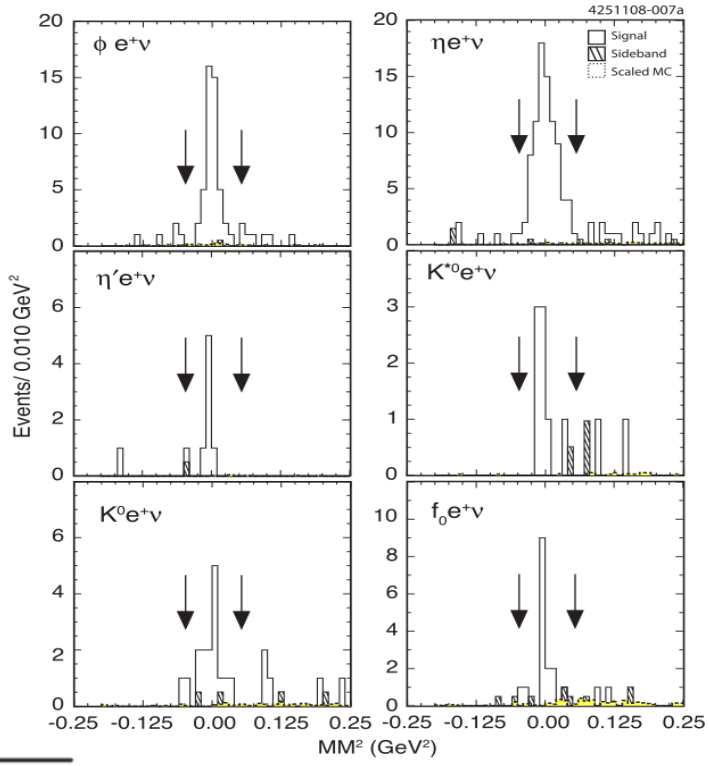
$E_{CM} = 4170$ MeV - ~0.9 nb of $D\bar{D}^*$

PRD 80, 052007 (2009) - 6 modes 310/pb

PRD 80, 052009 (2009) - partial update 600/pb

Extra γ complicates tag selection, but SL samples are still very clean

Include first measurements of exclusive D_s SL decays



Signal Mode	n^i	$n^i_{\rm bkg}$	$\epsilon^i_{\rm SL}$ (%)	$\mathcal{B}$ (%)
$D_s^+ \to \eta e^+ \nu_e$	82.49	0.32	37.65 ± 0.27	$2.48 \pm 0.29 \pm 0.13$
$D_s^+ \to \eta' e^+ \nu_e$	7.50	0.06	21.04 ± 0.22	$0.91 \pm 0.33 \pm 0.05$
$D_s^+ \to K^0 e^+ \nu_e$	13.99	0.29	33.14 ± 0.26	$0.37 \pm 0.10 \pm 0.02$
$D_s^+ \to K^{*0} e^+ \nu_e$	7.50	0.18	27.52 ± 0.23	$0.18 \pm 0.07 \pm 0.01$

$\mathcal{B}\left(D_s^+ \to \phi e\nu\right) = \left(2.36 \pm 0.23 \pm 0.13\right)\%$

$\mathcal{B}\left(D_s^+ \to f_0 e\nu\right)\mathcal{B}\left(f_0 \to \pi^+\pi^-\right) = \left(0.20 \pm 0.03 \pm 0.01\right)\%$

Full analysis of 600/pb data sample coming soon

Parting comments…

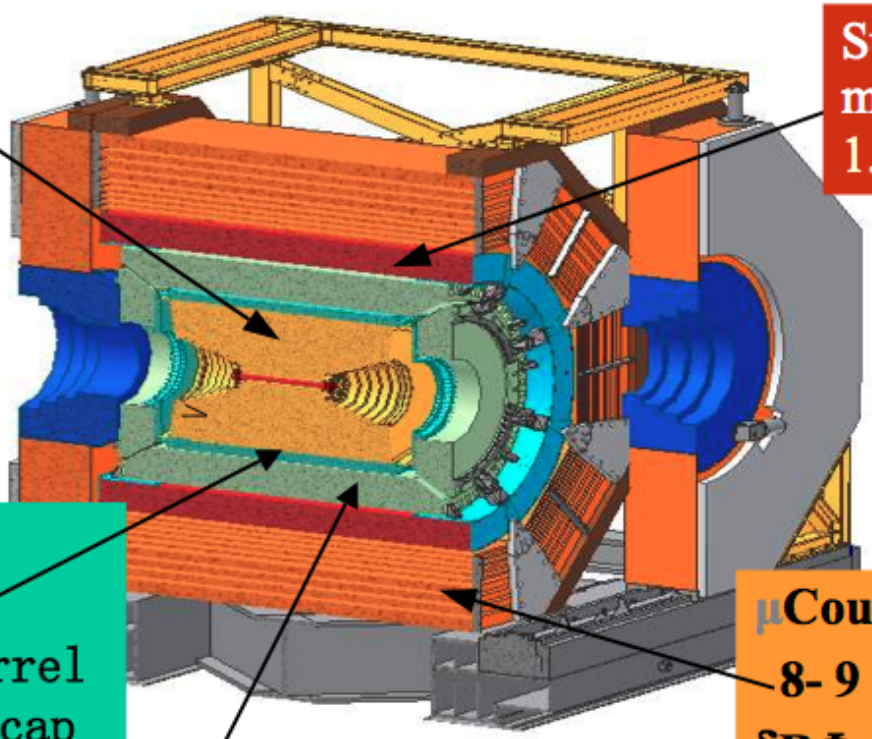
- CLEO-c will soon complete analysis of what has been a unique data sample for charm physics
  - Rigorous tests of QCD theory in SL decays (as well as leptonic, hadronic) have been made. Experiment is ahead of theory for now
- The job is clearly not done
  - Statistics-limited results on Cabibbo-suppressed SL FF measurement. Many details even of Cabibbo-favored modes need greater statistics. Most D_s measurements are statistics limited
- Where do we go next?

BESIII

Main Drift Chamber (MDC)

$\triangle P/P\ (^0/_0) = 0.5\text{-}0.7\ \%$ (1 GeV)

$\sigma_{dE/dx}\ (^0/_0) = 6\text{-}8\%$



Super-conducting magnet 1.0 tesla

Time Of Flight (TOF)

σ_T (ps) =100−120 ps Barrel
110−130 ps endcap

μCounter

8- 9 layers

δRΦ=1.4 cm~1.7 cm

EMC: $\triangle E/\sqrt{E}(^0/_0) = 2.5\text{ -}3\ \%$ (1 GeV)

$\sigma_{z,\phi}$(cm) = 0.5cm-0.7 cm/ $\sqrt{E}$

Parting comments…

- BESIII already has $910/\text{pb}$ of $\psi(3770)$ data, with a plan for $\sim 4/\text{fb}$ total to be in hand within a year or two
- Precision physics is hard! Much work remains to be done, but much work is under way and powerful tools have been inherited from BESII and CLEO-c
- D_s poses special opportunies and challenges
  - Where to collect D_s data?
- Optimistic that BEPCII design luminosity will be achieved, that data samples >10/fb are in reach
- Beyond that, there will doubtless still be compelling charm physics for a future super facility….