Semileptonic Charm Decays

Karl M. Ecklund
Rice University

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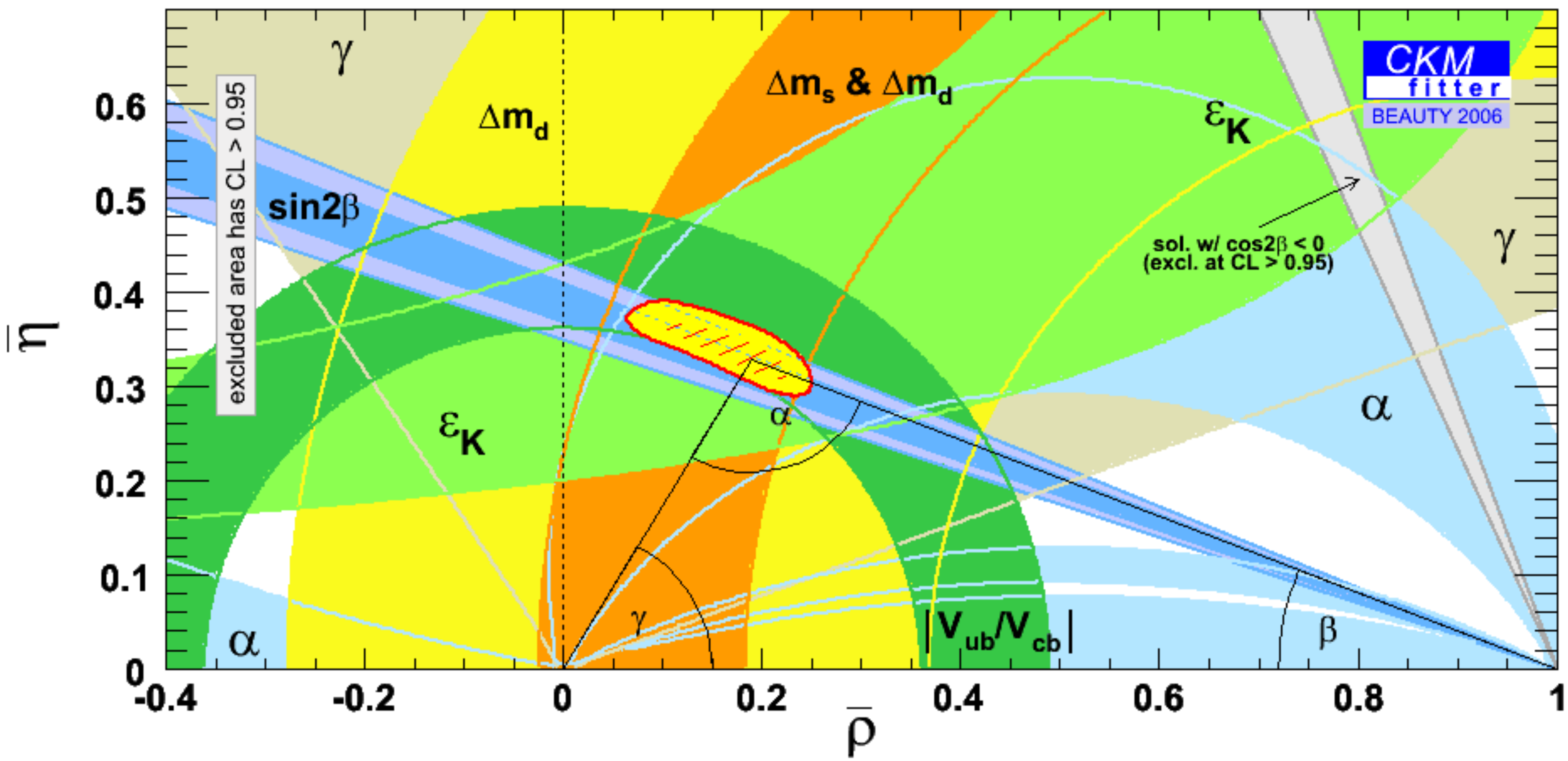
Charm's role in flavor physics



Flavor physics:

- Overconstrain V_{CKM}
- Inconsistency → new physics

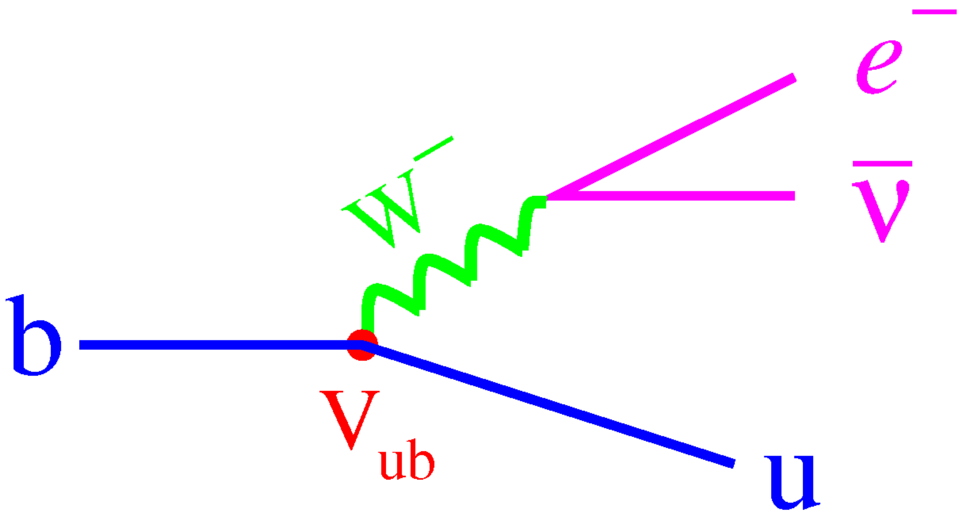
Unitarity Triangle Constraints

- sin 2β is theoretically clean
- $|V_{ub}|$ is not
- B mixing is not

Hadronic uncertainties confound extraction of weak physics

Charm decay measurements can validate QCD corrections needed to extract weak physics parameters from experimental observables: New physics or QCD?

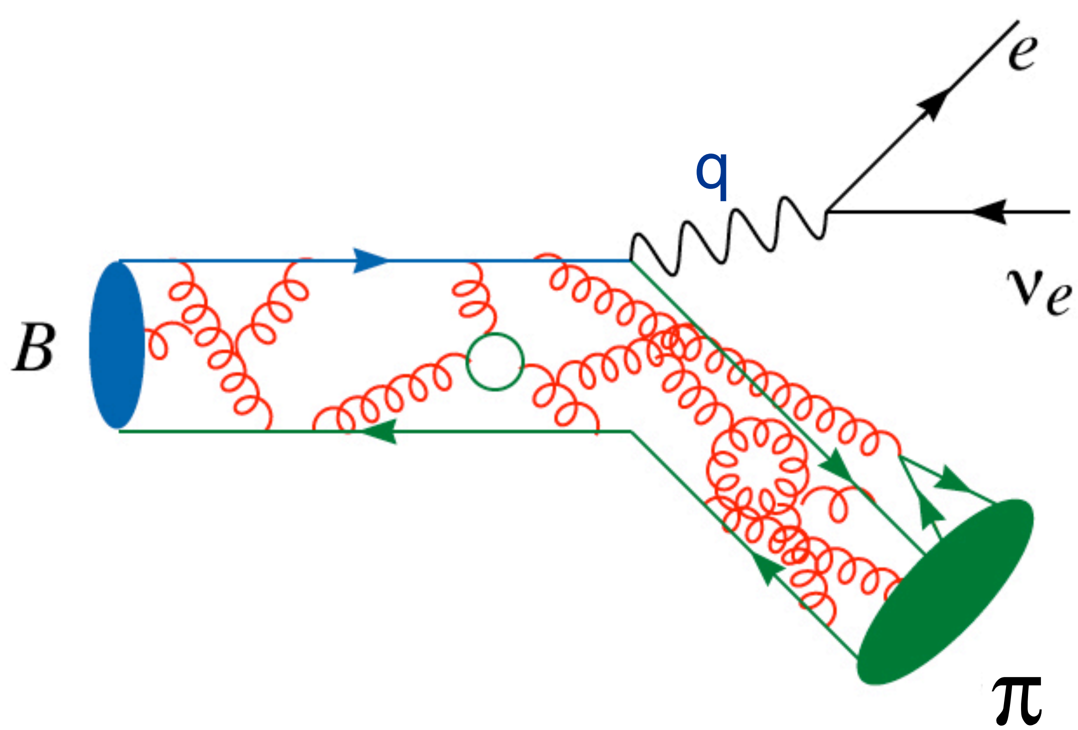
$|V_{ub}|$ from semileptonic B decay



If quarks were like leptons:

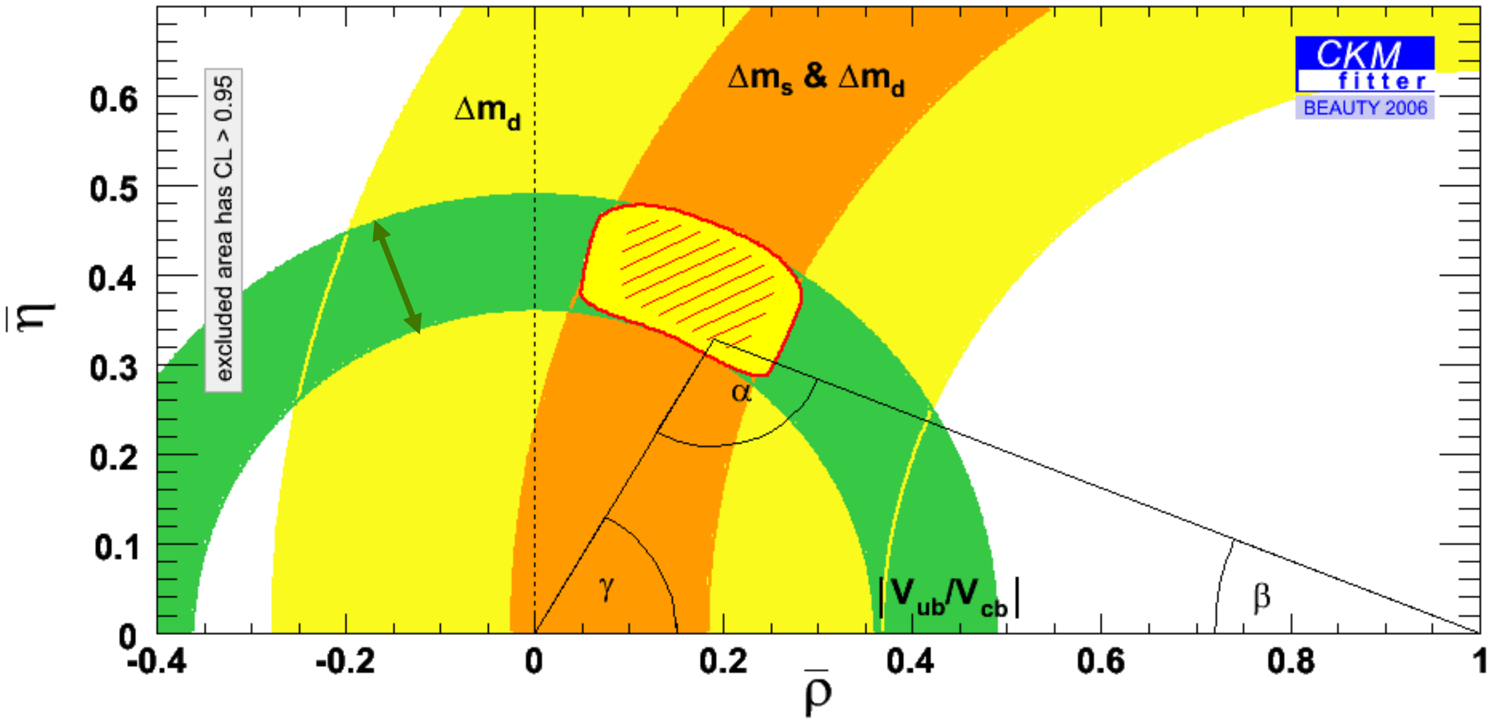
$$\Gamma(b \to ue\nu) = \frac{G_F^2 m_b^5}{192\pi^3} |V_{ub}|^2$$

- Rate goes like $|V_{ub}|^2$
- But quarks always in hadrons
  - QCD form factor $f_+(q^2)$ needed to extract weak interaction physics



$$\frac{d\Gamma}{dq^2} = \frac{G_F^2}{24\pi^3} |V_{ub}|^2 \, p_\pi^3 \, |f_+(q^2)|^2$$

UT Constraint from $|V_{ub}|$



$|V_{ub}|$ from $B \to \pi \ell \nu$:

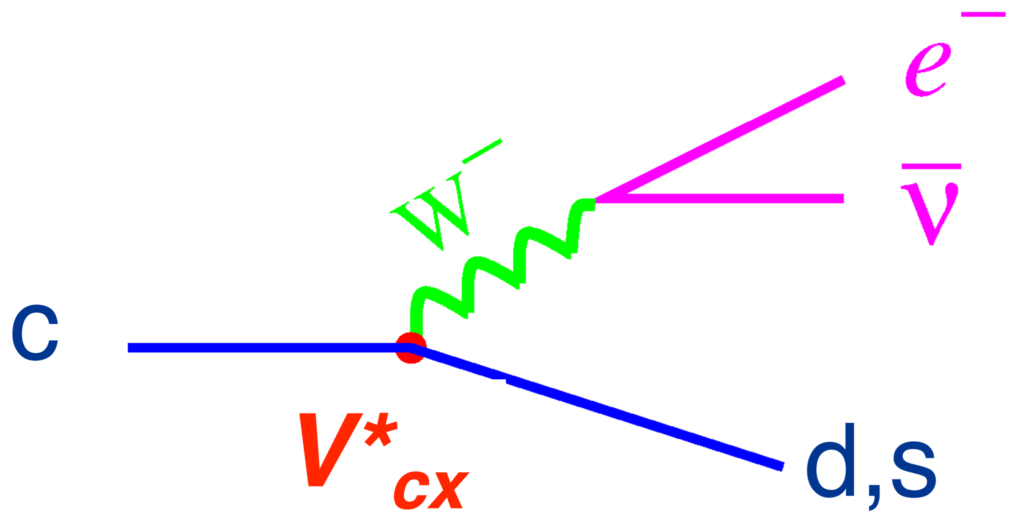
$$\frac{d\Gamma}{dq^2} = \frac{G_F^2}{24\pi^3} |V_{ub}|^2 p_\pi^3 |f_+(q^2)|^2$$

Form factor $f(q^2)$:

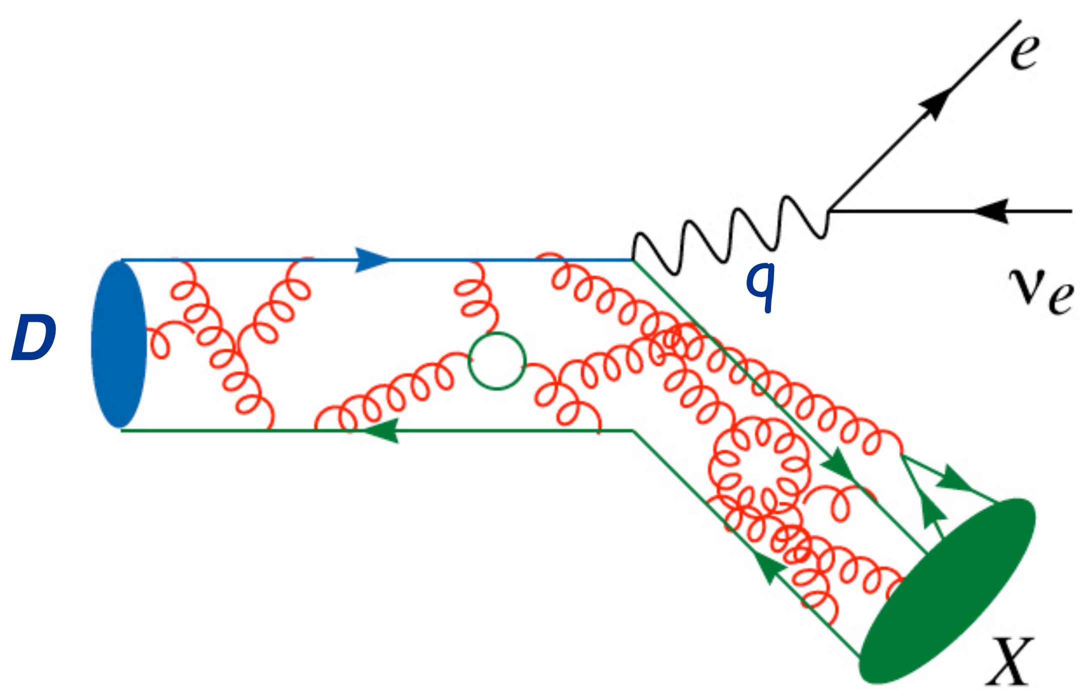
- Hard to calculate
- Limits $|V_{ub}|$ precision
- Lattice QCD can do from first principles

- $D \to \pi \ell \nu$ to $B \to \pi \ell \nu$ are both "heavy to light" decays
- Precise measurement of $D \to \pi \ell \nu$ can calibrate LQCD and allow a precise extraction of $|V_{ub}|$ from $B \to \pi \ell \nu$
- Absolute rate and shape is a stringent test of theory

Semileptonic Decays



- Decay rate depends on kinematics and V_{CKM}
- Form factor encapsulates QCD bound-state effects
- Consider Pseudoscalar final states: K, π



$$\frac{d\Gamma}{dq^2} = \frac{G_F^2}{24\pi^3} |V_{cx}|^2 \, p_X^3 \, |f_+(q^2)|^2$$

$$\begin{aligned} q^2 &= (p_D - p_X)^2 \\ &= M_D^2 + M_X^2 - 2E_X M_D + 2\vec{p}_D \cdot \vec{p}_X \end{aligned}$$

Charm Semileptonic Form Factors

- Pole ansatz:
  - dominated by lowest lying vector meson H* with correct flavor
  - e.g. D* for D→π
  - D_s* for D→K

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

- Modified pole:

Becirevic & Kaidalov PLB 478, 417 (2000)

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

- Analyticity expansions:

Becher & Hill PLB 633, 61 (2006)

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

  - expand in z around t_0
  - better convergence
  - 2 or 3 parameters

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

$$t_\pm = (m_D \pm m_X)^2$$

Belle $D^0 \rightarrow \pi^- \ell^+ \nu$ & $D^0 \rightarrow K^- \ell^+ \nu$

Uses fully reconstructed

$e^+e^- \rightarrow D^{(*)}D^*X$ events

$\sqrt{s}$=10.6 GeV

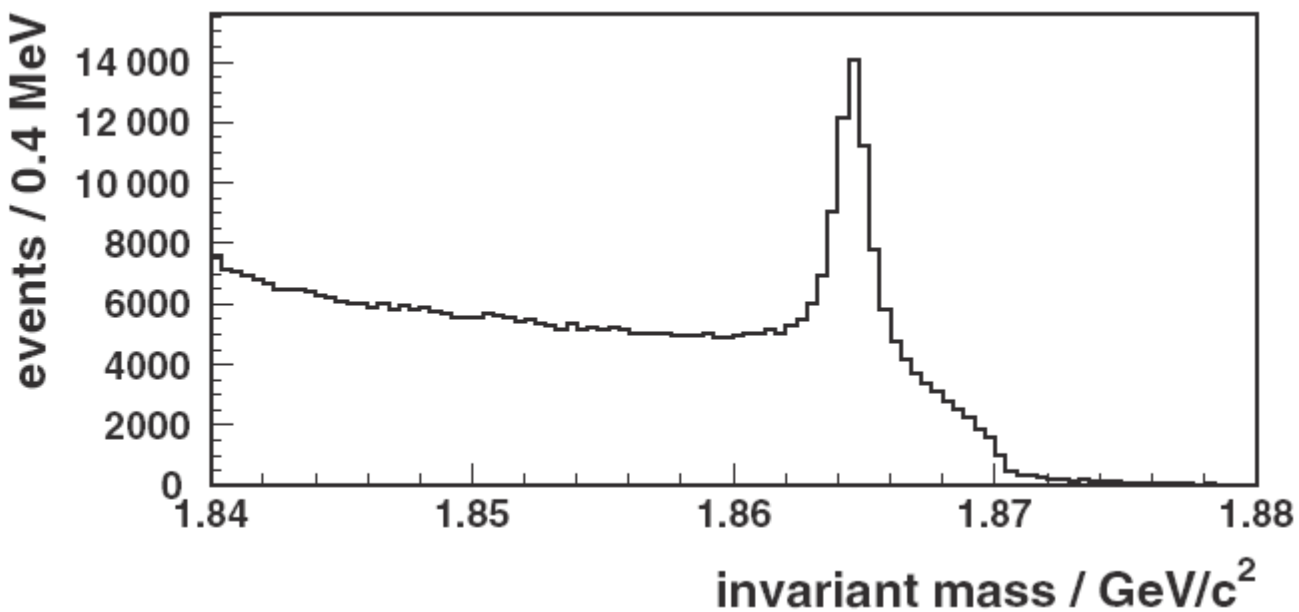
Allows direct count of # D^0

Tag side:

- $D^0 \rightarrow K^-(n\pi)^+$, n=1,2,3
- Also use $D^* \rightarrow D^0\pi$ tags

Signal side:

- $D^{*+} \rightarrow D^0\pi^+$
  - Kinematic fit to event
  - Reconstruct mass of D^0
  - No decay products needed



D^0 = 56,461±309±830

- Look for SL decays:
  - $D^0 \rightarrow \pi/K^- \ell^+ \nu$
  - Neutrino inferred from missing E,p
- ~2500 $K\ell\nu$ candidates

BF = (3.45±0.07±0.20)%

- ~230 $\pi\ell\nu$ candidates

BF = $(25.5\pm1.9\pm1.6)\times10^{-4}$

Belle $D^0 \to \pi^- \ell^+ \nu$ & $D^0 \to K^- \ell^+ \nu$

Excellent q^2 resolution:

$\sigma(q^2) = 0.017\ \text{GeV}^2$

Measure rate directly in q^2 bins

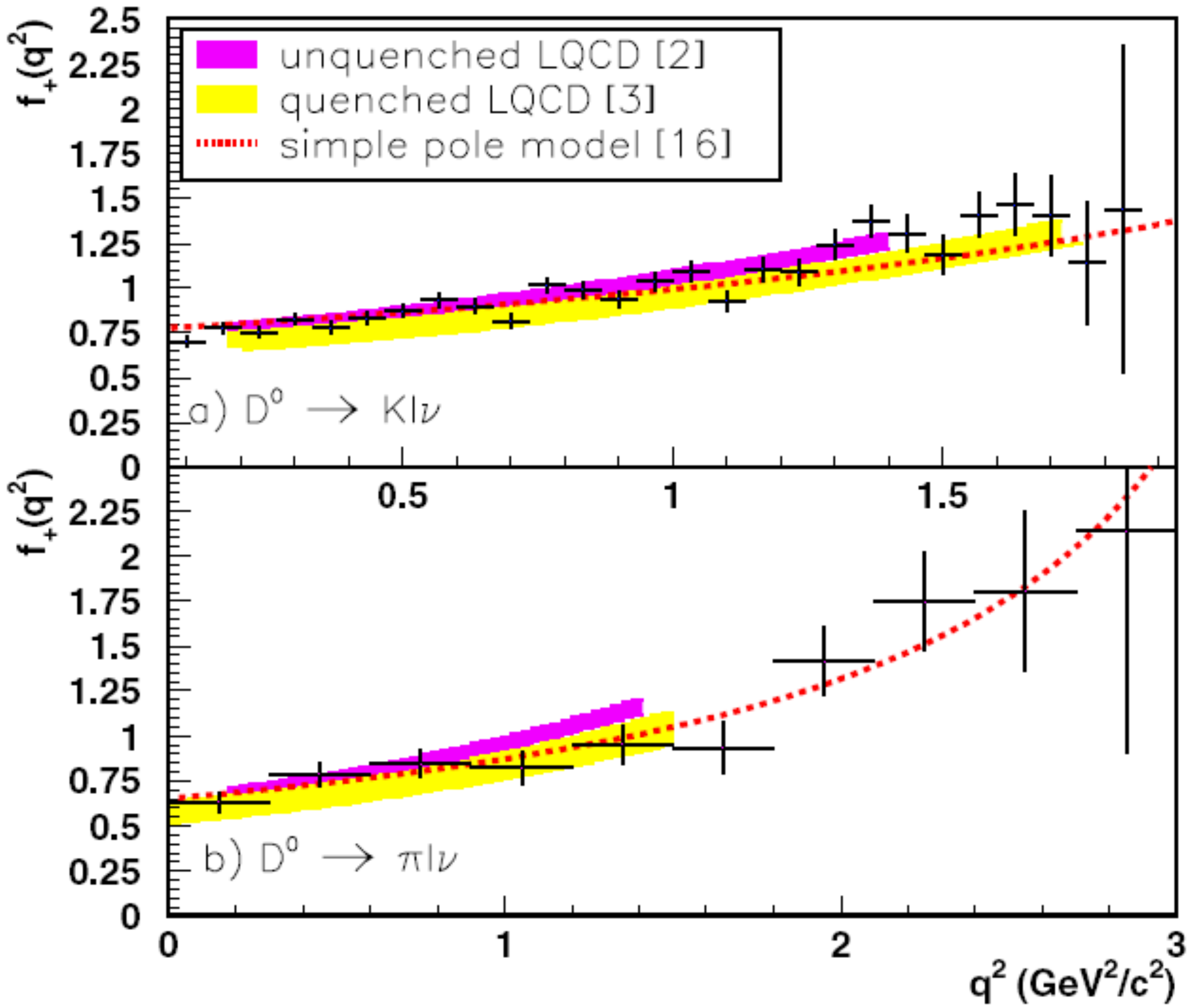
$$\frac{d\Gamma}{dq^2} = \frac{G_F^2}{24\pi^3} |V_{cx}|^2 \, p_X^3 \, |f_+(q^2)|^2$$

Compare to

LQCD Form Factor

Simple Pole parameterization

Modified Pole Model

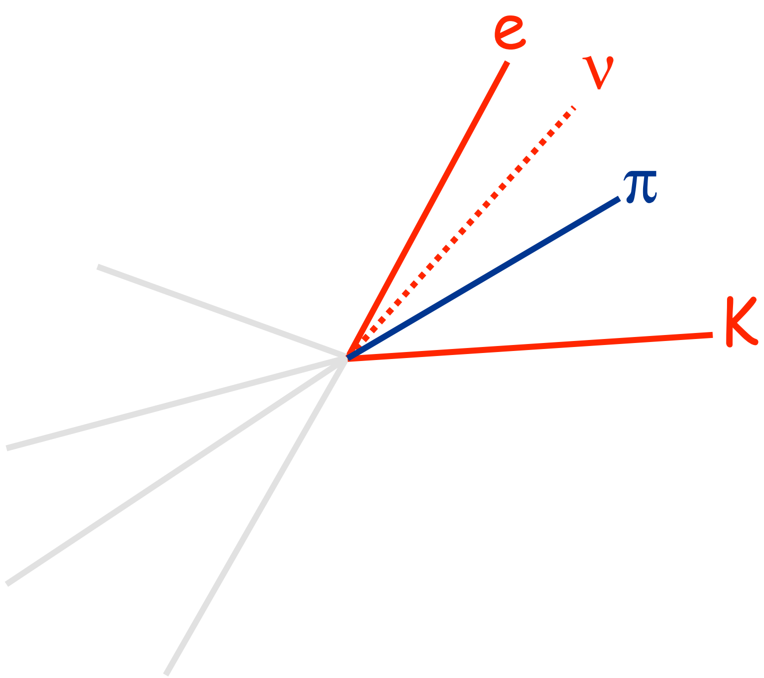


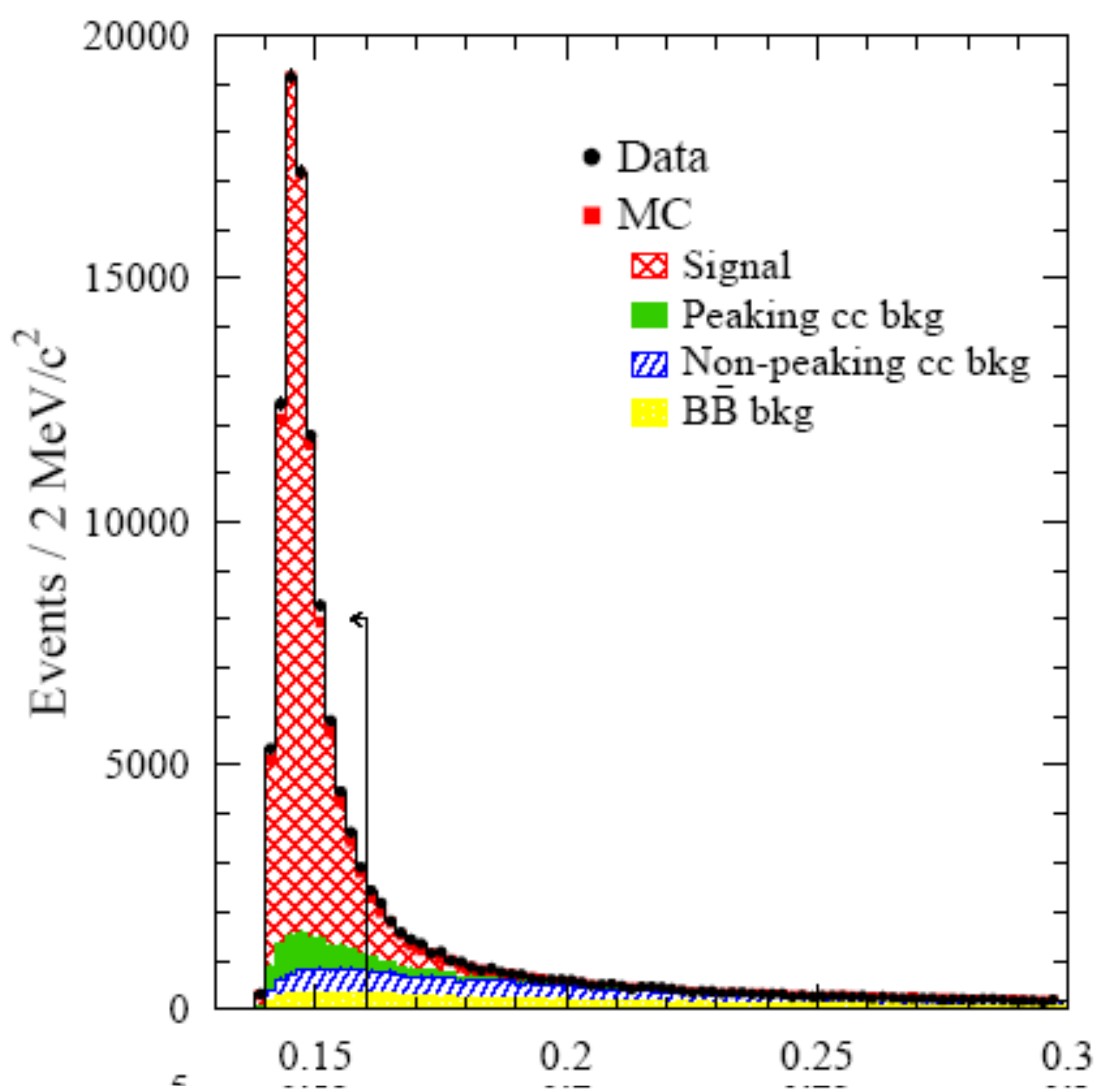
Lattice Form Factors
[2]Aubin et al. PRL 94, 011601 (2005)
[3]Abada et al. Nucl. Phys. B619, 565 (2001)

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

$e^+e^- \to c\bar{c}$ at $\sqrt{s}$=10.6 GeV

- Reconstruct $D^{*+} \to \pi^+ D^0$ and signal $D^0 \to K e \nu$
- Estimate p_D and E_ν with remaining event & kinematic fits
- Use Neural Nets to suppress backgrounds



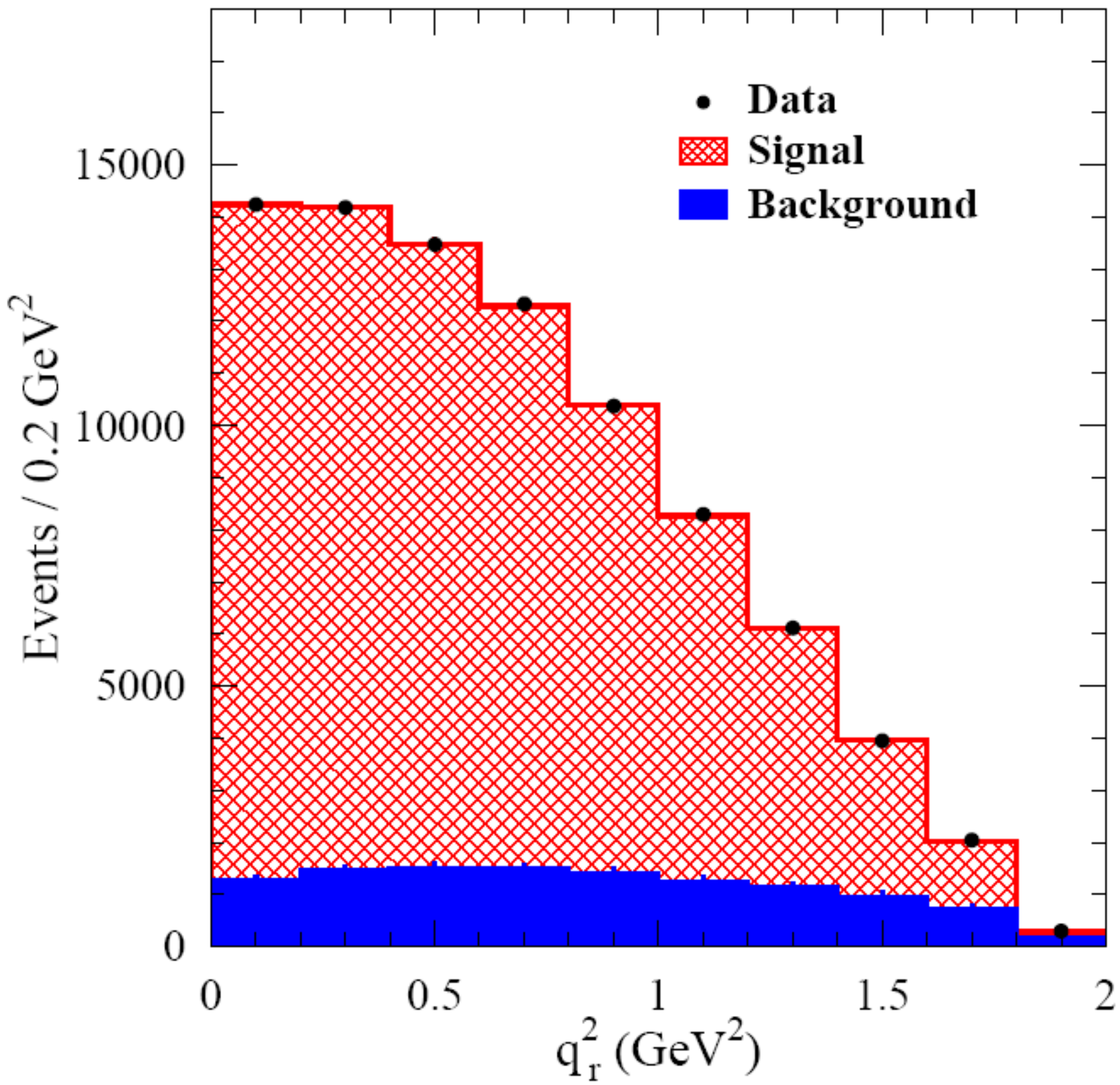


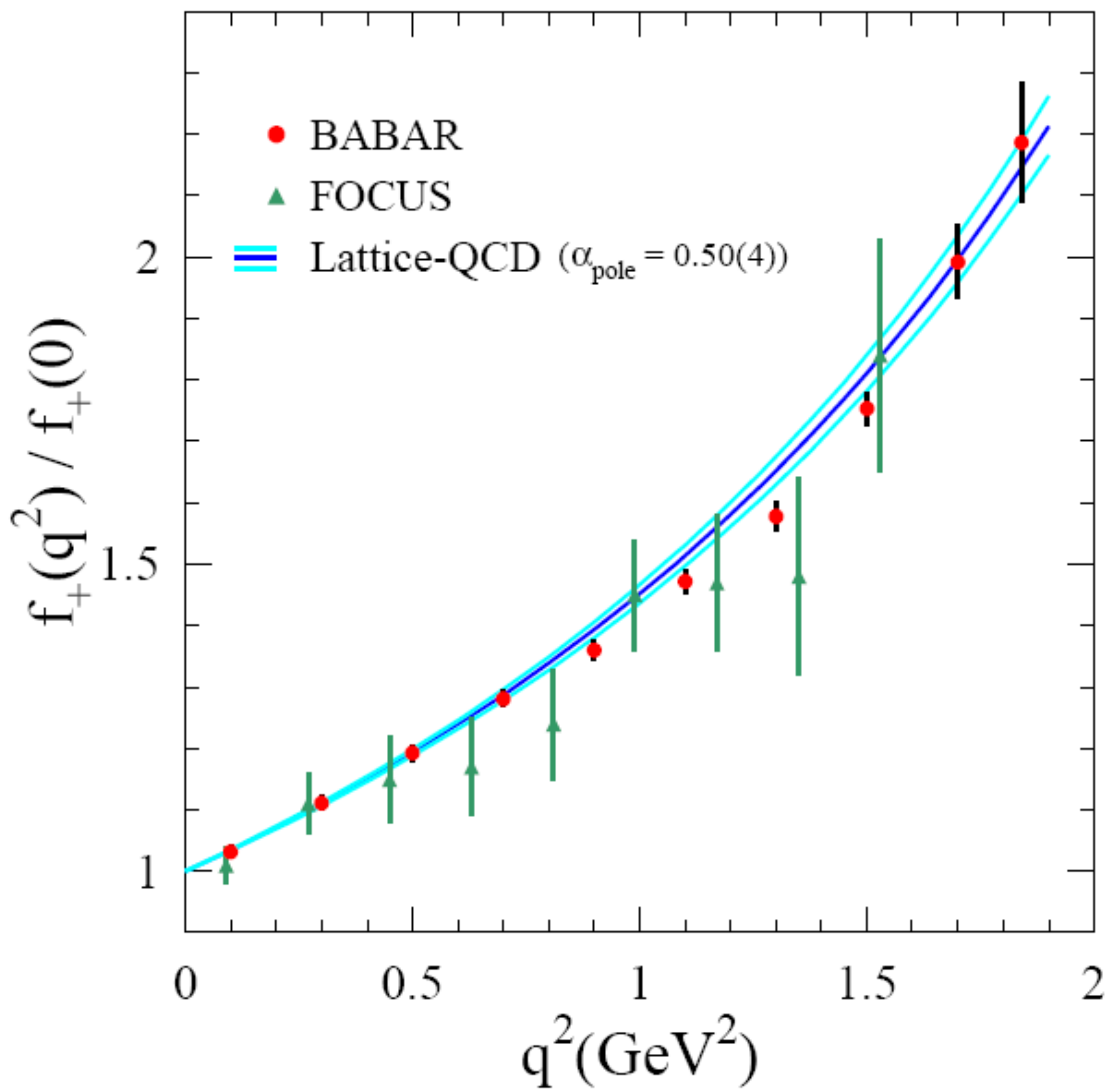
δm=M(D*)-M(D)

- high statistics: ~74,000
- good S/N

PRD 76 052005 (2007)
75 fb^{-1}

BaBar $f_+(q^2)$ $D^0 \to K^- e^+ \nu$





$$q^2 = (p_D - p_X)^2$$

85k signal/11k background

- Corrected spectrum compared to LQCD[1], FOCUS[2]

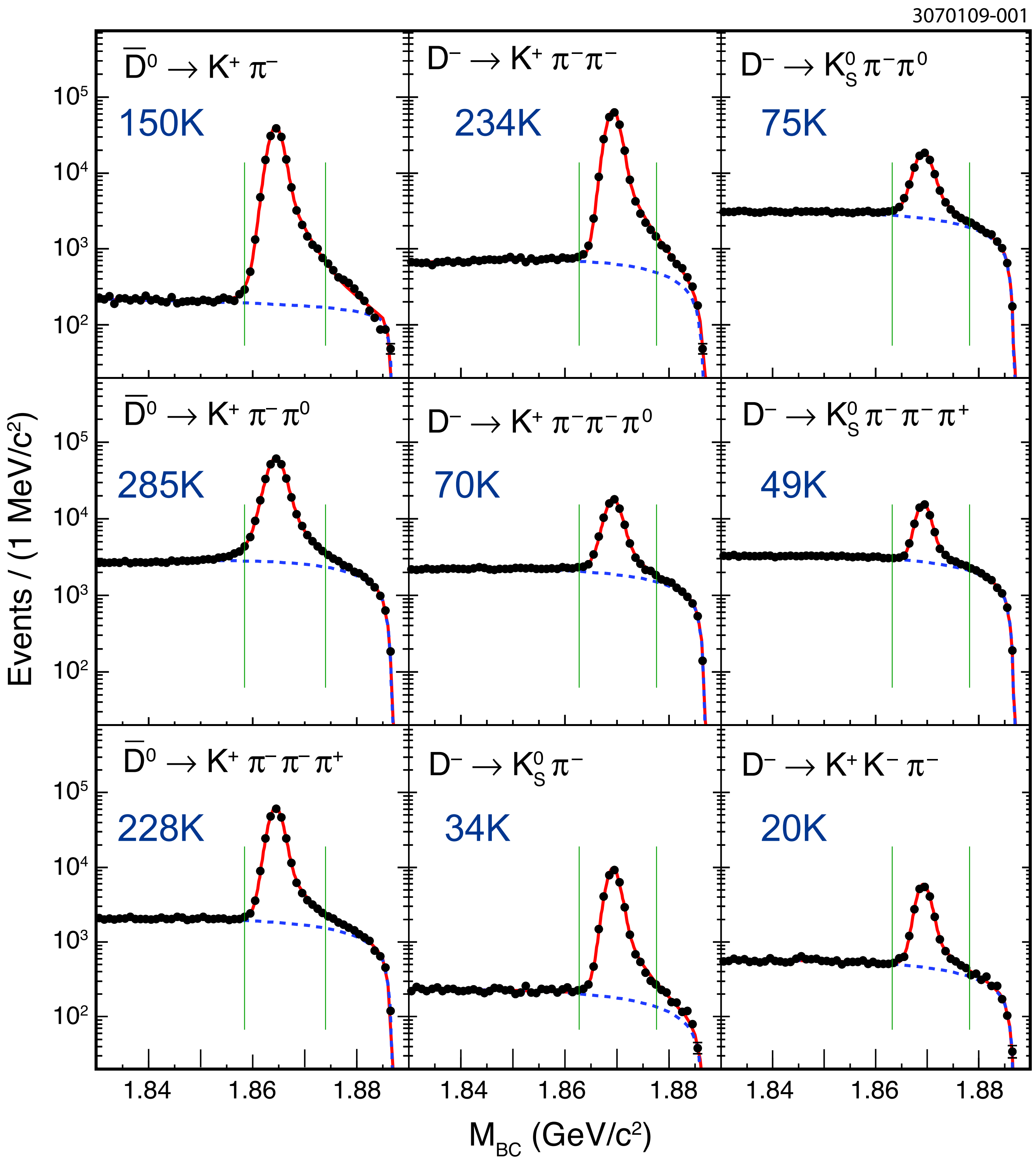
[1] Aubin et al. PRL 94, 011601 (2005)

[2] PLB607, 233 (2005)

PRD 80 032005 (2009)
CLEO-c 818 pb^{-1}

CLEO-c $D \rightarrow K e \nu$ and $\pi e \nu$

- Analysis of full CLEO-c $\psi(3770)$ dataset 818 pb^{-1}
- D tag reconstruction
  - 9 hadronic decay modes
  - exceptionally clean events
  - excellent kinematic resolution
- Semileptonic modes
  - $D^0 \rightarrow K^- e^+ \nu$
  - $D^+ \rightarrow \overline{K}^0 e^+ \nu$
  - $D^0 \rightarrow \pi^- e^+ \nu$
  - $D^+ \rightarrow \pi^0 e^+ \nu$



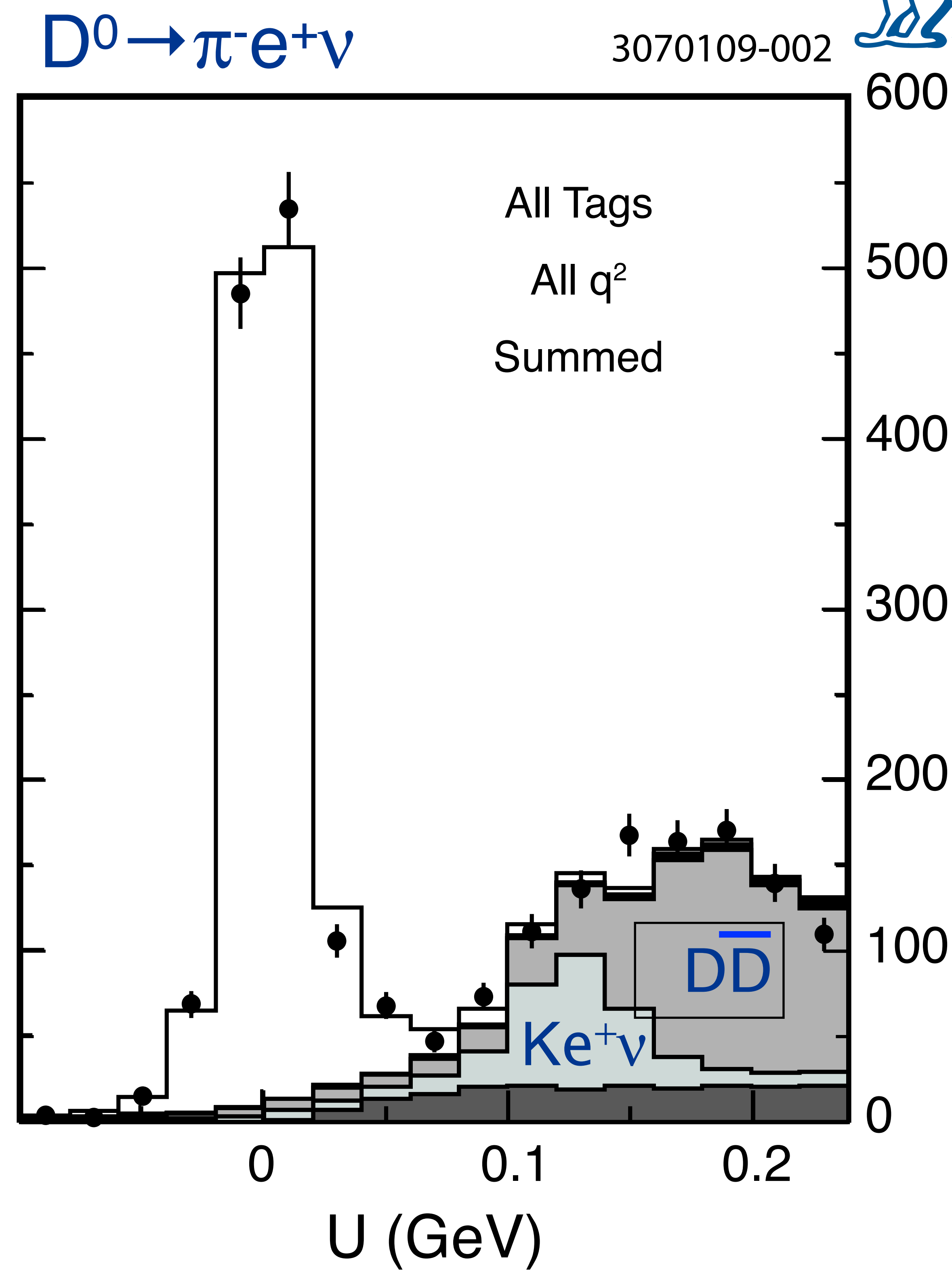
1.15 Million D tags
3 D^0 modes, 6 D^+ modes

Signal Side Reconstruction

- Against the tagged D
  - pion candidate
    - with dE/dx and RICH
  - positron candidate
- Fit U for signal

$$U \equiv E_{\mathrm{miss}} - |\mathbf{p}_{\mathrm{miss}}|$$

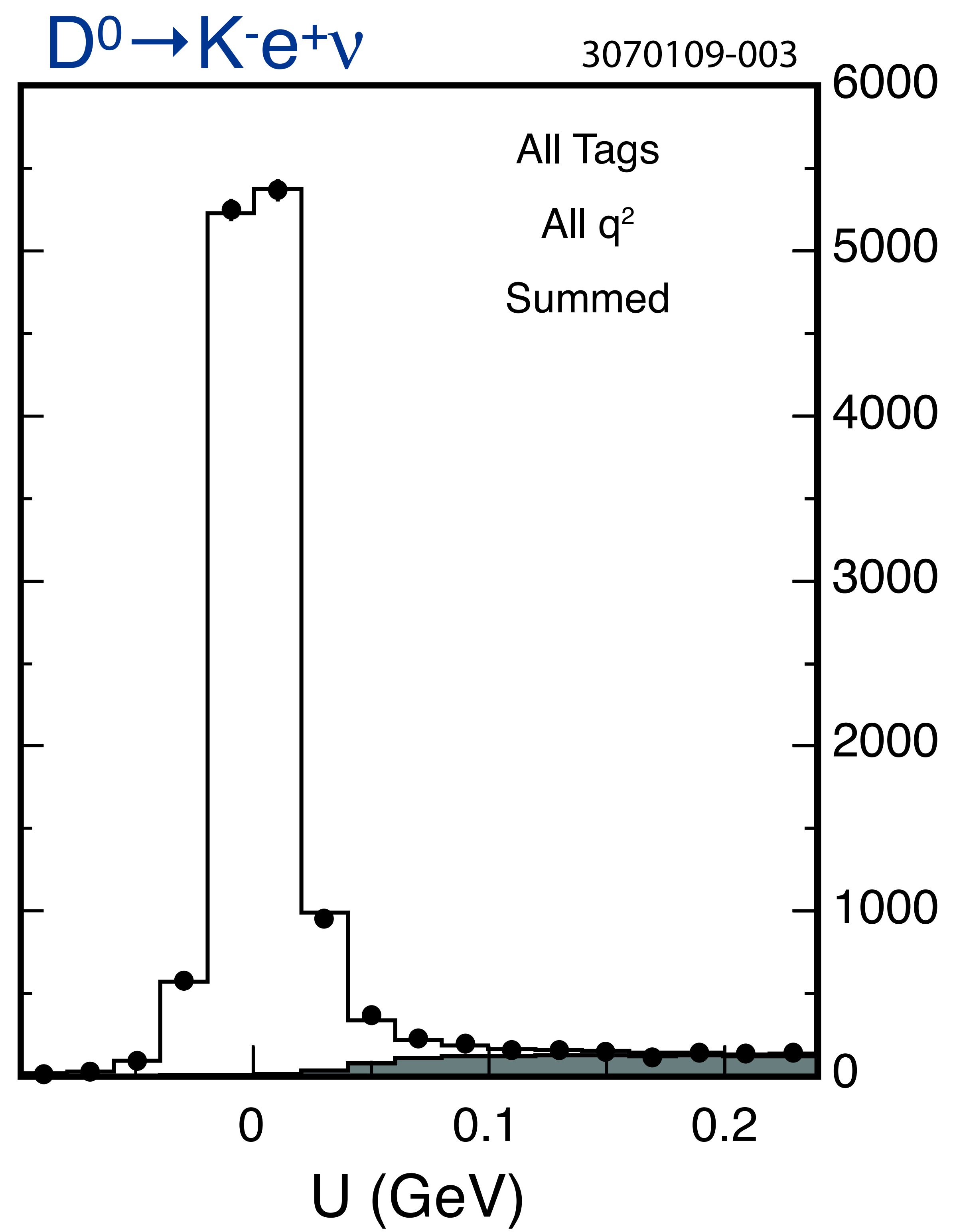
- Peaks at 0 for signal
  - kinematic separation for backgrounds
    - $Ke^+\nu$ cross feed to $\pi e^+\nu$
    - $\rho e^+\nu$ from known BF
- Fit four modes in q^2 bins



PRD 80 032005 (2009)
CLEO-c 818 pb^{-1}

Signal Side Reconstruction

- Against the tagged D
  - kaon candidate
    - with dE/dx and RICH
  - positron candidate
- Compared to pi mode
  - Higher statistics
  - DD background
- Fit four modes in q^2 bins
  - more q^2 bins in $Ke^+\nu$
- Also include K^0 and π^0



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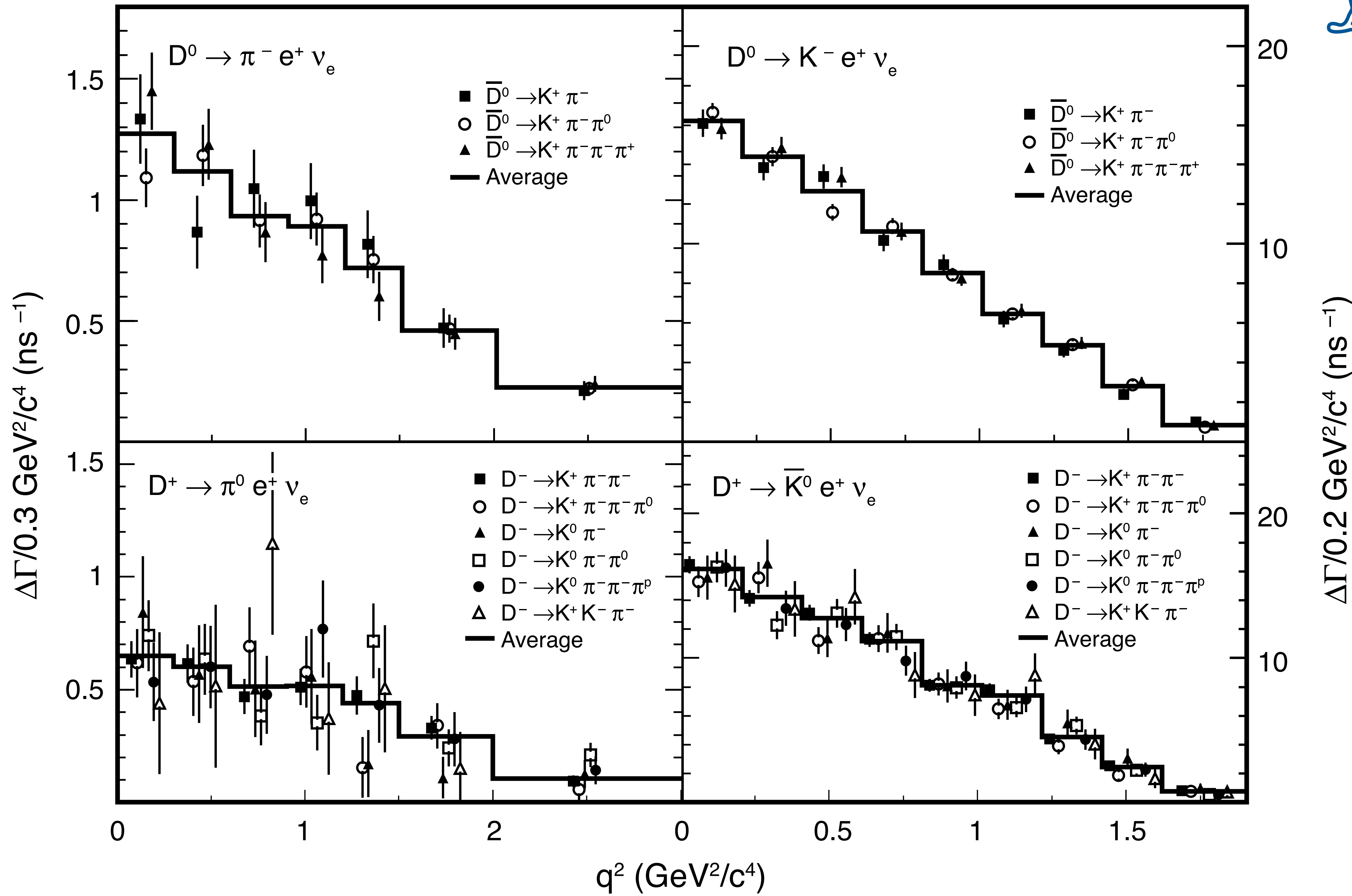
Partial Rates



- Extract rates from yields in q^2 bins, eff. matrix, # tags
- Good agreement across tag modes

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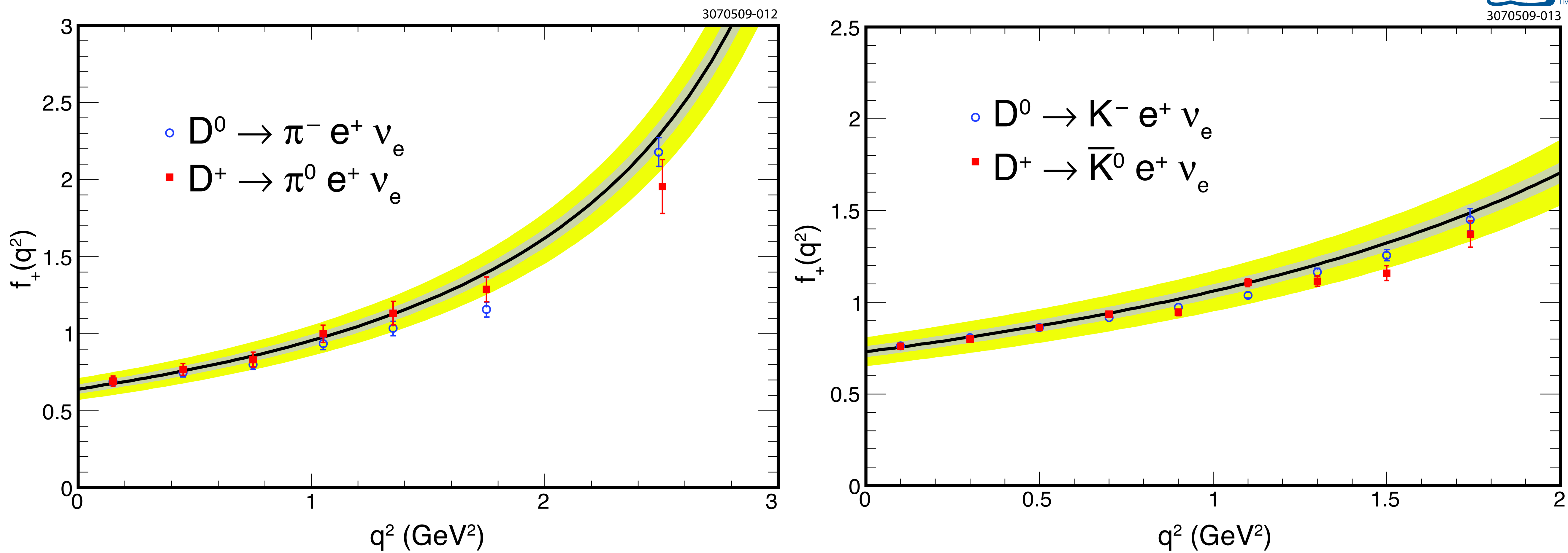
CLEO-c 818 pb^{-1}

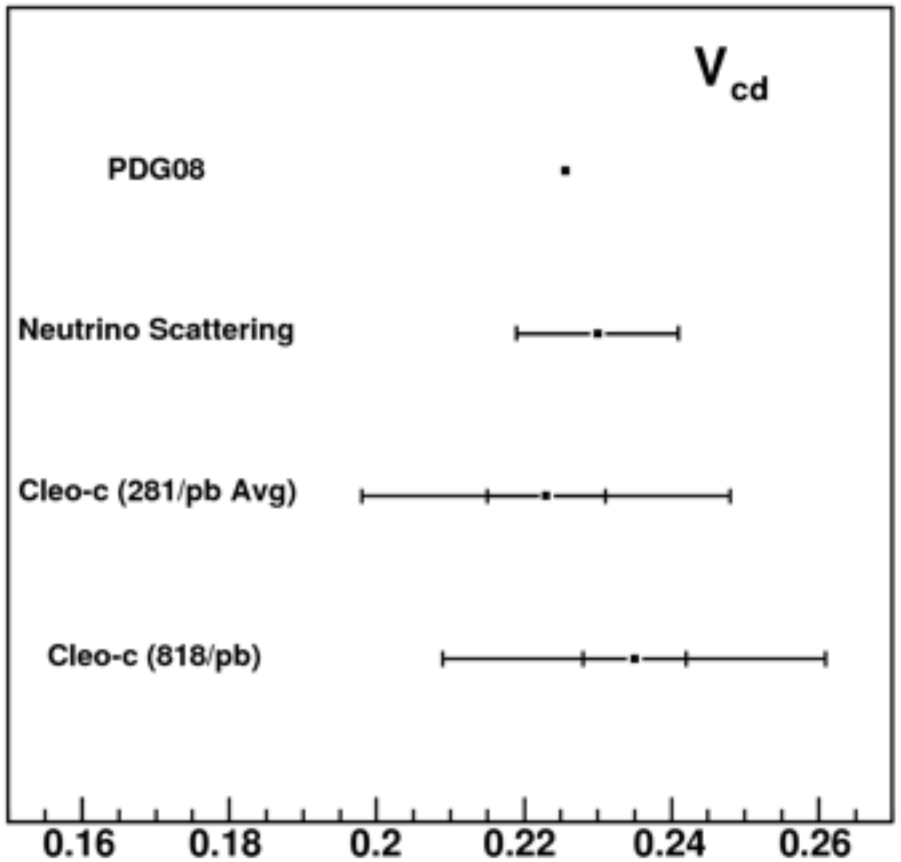
Form factors

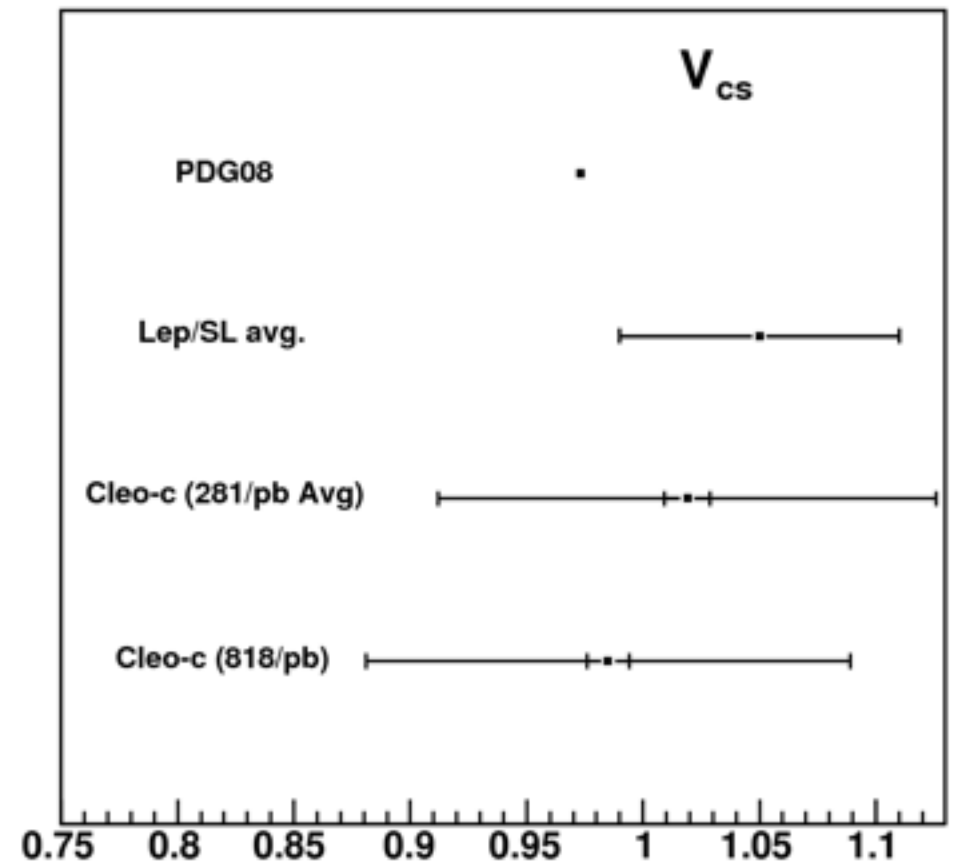


- Extract $f_+(q^2)$ using V_{cd}, V_{cs} from CKM Unitarity (PDG)
- Compare to Lattice QCD
  - Aubin et al. PRL 94, 011601 (2005), C. Bernard et al. PRD 80 034026 (2009)
  - Experimental stat+syst uncertainties smaller than LQCD shown in bands
  - Better agreement at low q^2
  - Isospin symmetry appears to be good
- Curve is modified pole parameterization BK PLB 478 417 (2000)

PRD 80 032005 (2009)
CLEO-c 818 pb^{-1}

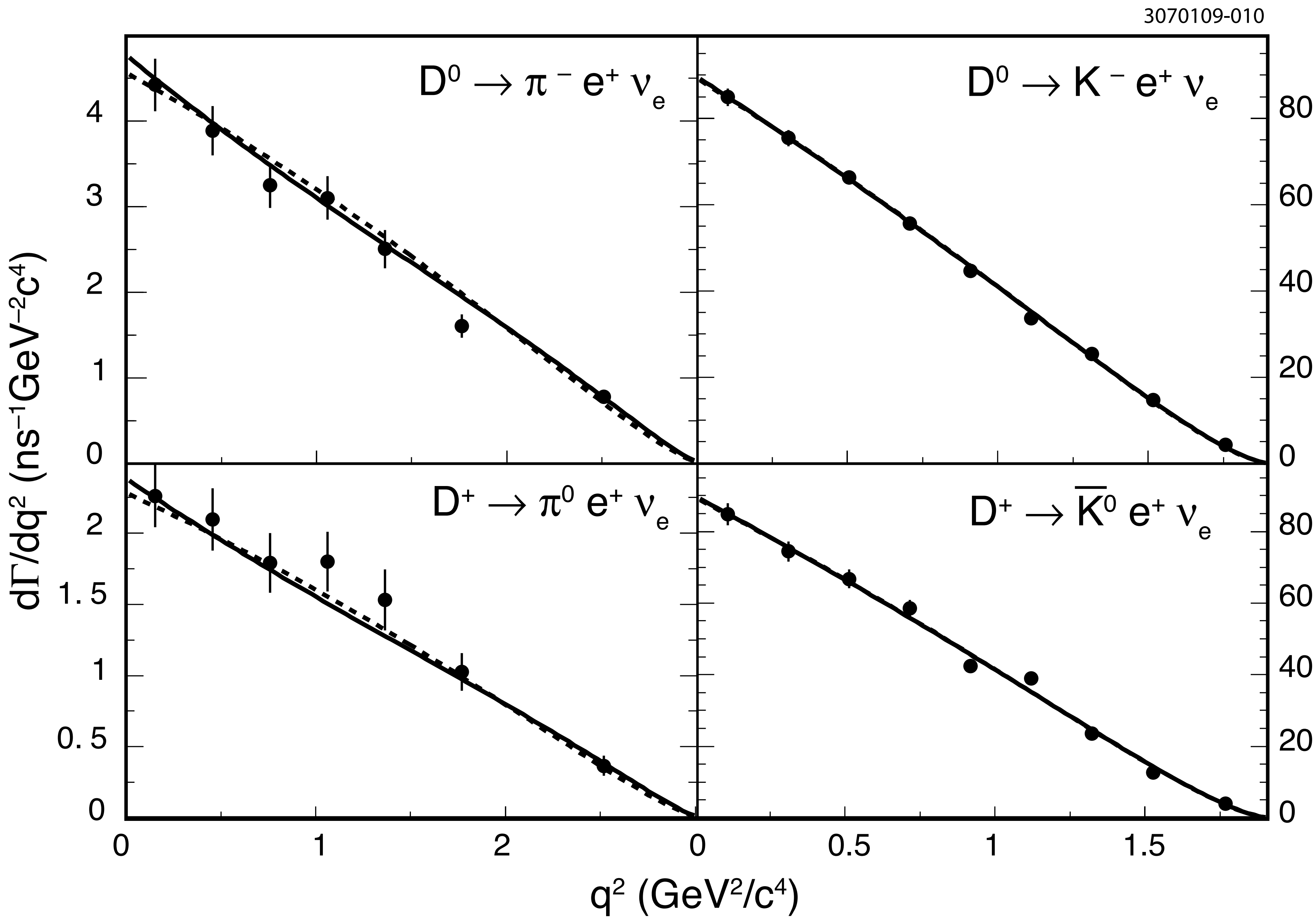
CKM Measurements





- Take $f_+(q^2)$ from LQCD, determine V_{CKM}
- Agreement with CKM unitarity, neutrino scattering, $D_S \to \ell\nu$
- LQCD uncertainty >> experimental stat+syst uncertainty
  -

Form Factor Parameterizations

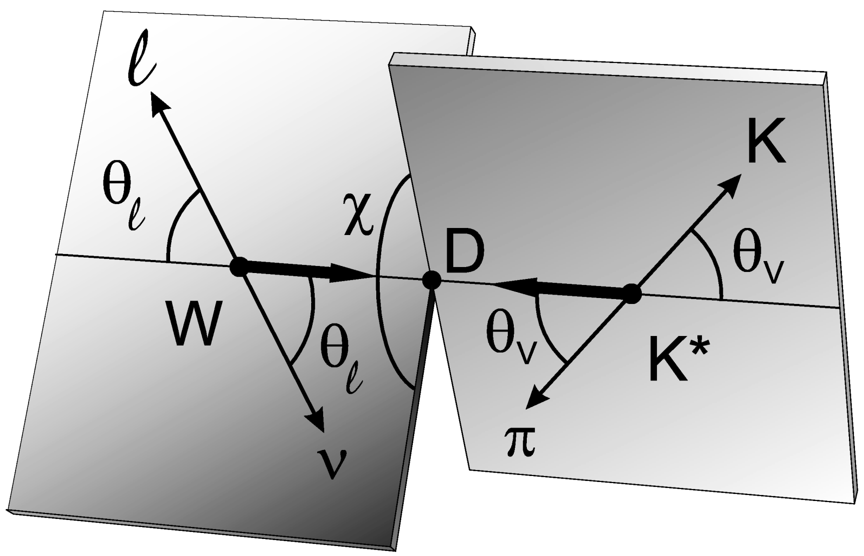


- Comparison of 2 (dashed) and 3 (solid) parameter fits to Becher Hill series
  - There is a slight preference for 3 parameters in $D^0 \to \pi^- e^+ \nu$
- BK, modified pole, simple pole models give similar quality fits
  - when normalization and shape parameter float

arXiv:1004.1954 to appear PRD
CLEO-c 818 pb^{-1}

Study of $D^+ \to K^- \pi^+ \ell^+ \nu$

- Full CLEO-c $\psi(3770)$ dataset
  - Using hadronic D decay tags to fully reconstruct $D\bar{D}$ event
    - excellent resolution on ν from E, p conservation
- Detailed study including resonant K* and non-resonant $K\pi$
  - All 5 kinematic variables used to study 4 helicity amplitudes completely free of model dependence
    - invariant masses: $m(K\pi)$, $q^2 = m^2(\ell\nu)$
    - θ_V & θ_ℓ helicity angles in K* & W rest frames
    - angle χ between decay planes
  - projective weighting technique
    - model independent measurement of form factors
    - pioneered by FOCUS: PLB 633, 183 (2006)
    - exploit the fine kinematic resolution possible at charm threshold



BF($D^+ \to K^- \pi^+ \ell^+ \nu$)

- Six hadronic tag modes:
  - $D^- \to K^+\pi^-\pi^-$, $K^+\pi^-\pi^-\pi^0$, $K_S\pi^-$, $K_S\pi^-\pi^0$, $K_S\pi^-\pi^-\pi^+$, $K^+K^-\pi^-$
- Signal selected with cut on $\left| E_{\text{miss}} - |\mathbf{p}_{\text{miss}}| \right| < 20\,\text{MeV}$
- Both muons and electrons used (novel for CLEO-c)
  - μ's give sensitivity to mass-suppressed form factors

Branching Fraction Results
- full range of $m(K\pi)$

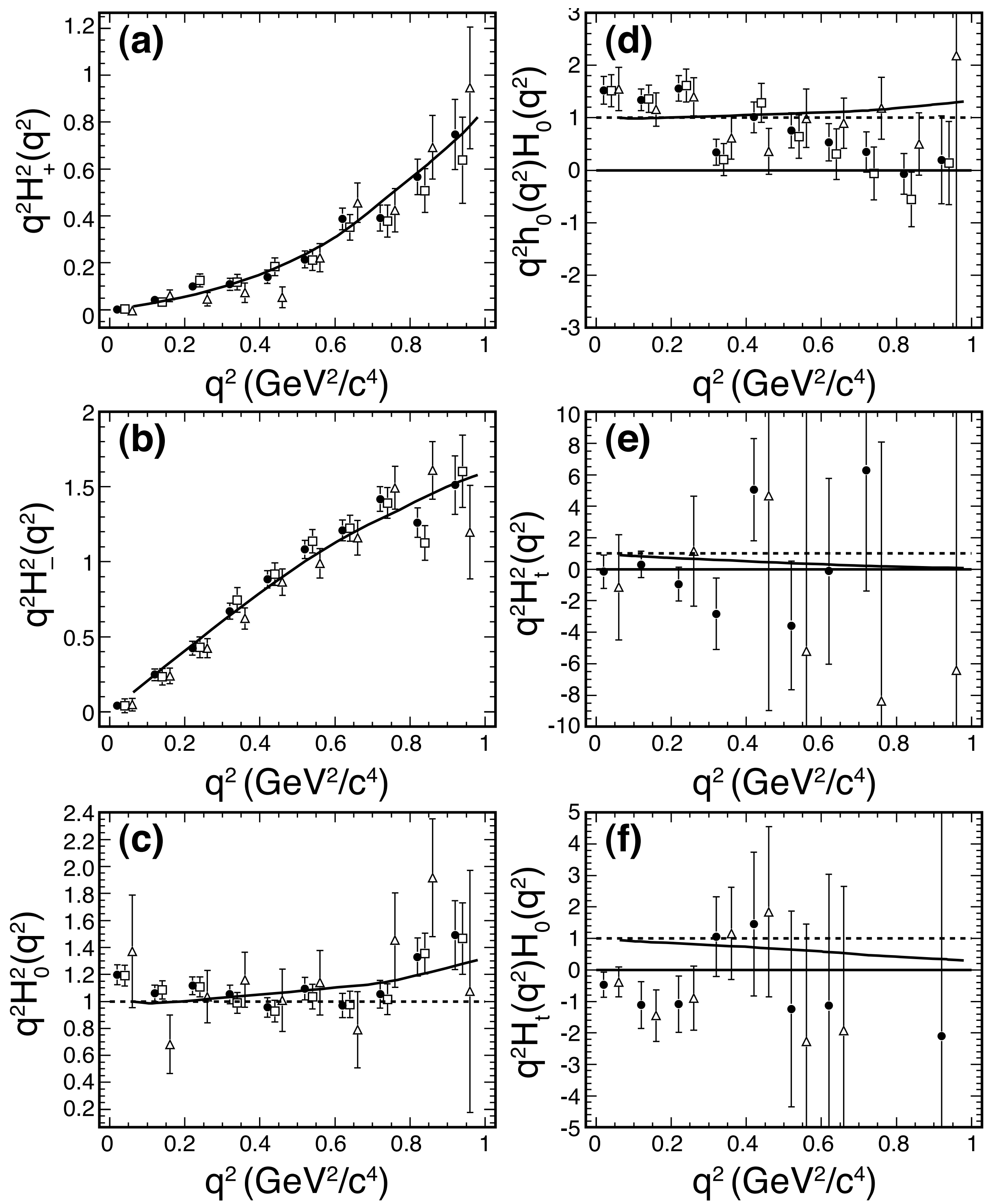
	$\mathcal{L}_{\text{int}}$ (pb^{-1})	$\mathcal{B}_e$ (%)
CLEO-c	818	5.52±0.07±0.13
CLEO-c	56	5.56±0.27±0.23
World Average	PDG 2008	5.49±0.31
		$\mathcal{B}_\mu$ (%)
CLEO-c	818	5.27±0.07±0.14
World Average	PDG 2008	5.40±0.40

- BF reduced by phase space factor $B_\mu / B_e = 0.9598 \pm 0.0193 \pm 0.0130$
- Most precise results, consistent with previous measurements

arXiv:1004.1954 to appear PRD
CLEO-c 818 pb^{-1}

$D^+ \to K^- \pi^+ \ell^+ \nu$ Form Factors

- Analyze 6 helicity FF
- Plot products vs q^2:
  - $H_+^2(q^2)$, $H_-^2(q^2)$, $H_0^2(q^2)$
  - $H_t^2(q^2)$, $H_t H_0(q^2)$, $h_0 H_0(q^2)$
- General agreement with spectroscopic pole-dominated model (curve)
  - (a)-(c) dominant H_0 H_+ H_-
- Confirmed NR s-wave interference with K* (d)
  - no evidence for d- or f-wave
- (e),(f) suggest smaller H_t than expected from LQCD

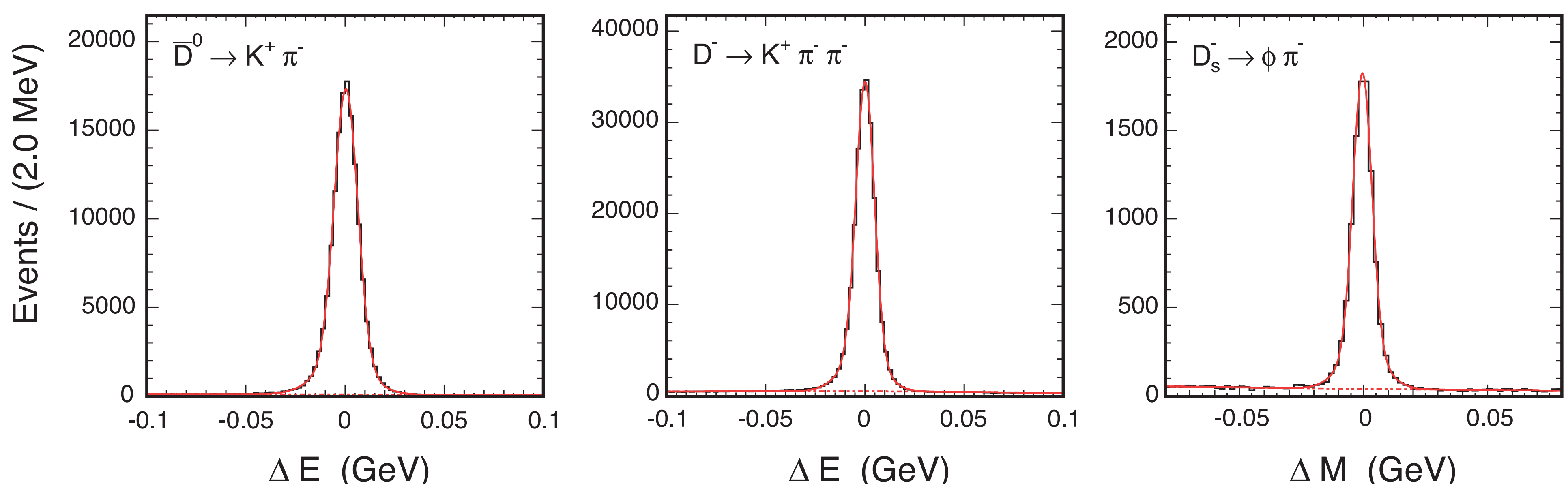


Curves: pole-dominance model
points: data (□e, △μ, ●combined)

PRD 81 052007 (2010)
CLEO-c 818+602 pb^{-1}

Inclusive D and D_s SL decays

- Full CLEO-c open charm samples:
  - 818 pb^{-1} $\psi(3770)$ for $D^0\overline{D}^0$ and D^+D^-
  - 602 pb^{-1} $\sqrt{s}$=4.17 GeV for $D_s \overline{D}{}^*_s$
- Use hadronic $D_{(s)}$ decay on one side as a tag
  - 3 cleanest tags: $D^0 \to K^-\pi^+$, $D^+ \to K^-\pi^+\pi^+$, $D_s^+ \to \phi\pi^+$

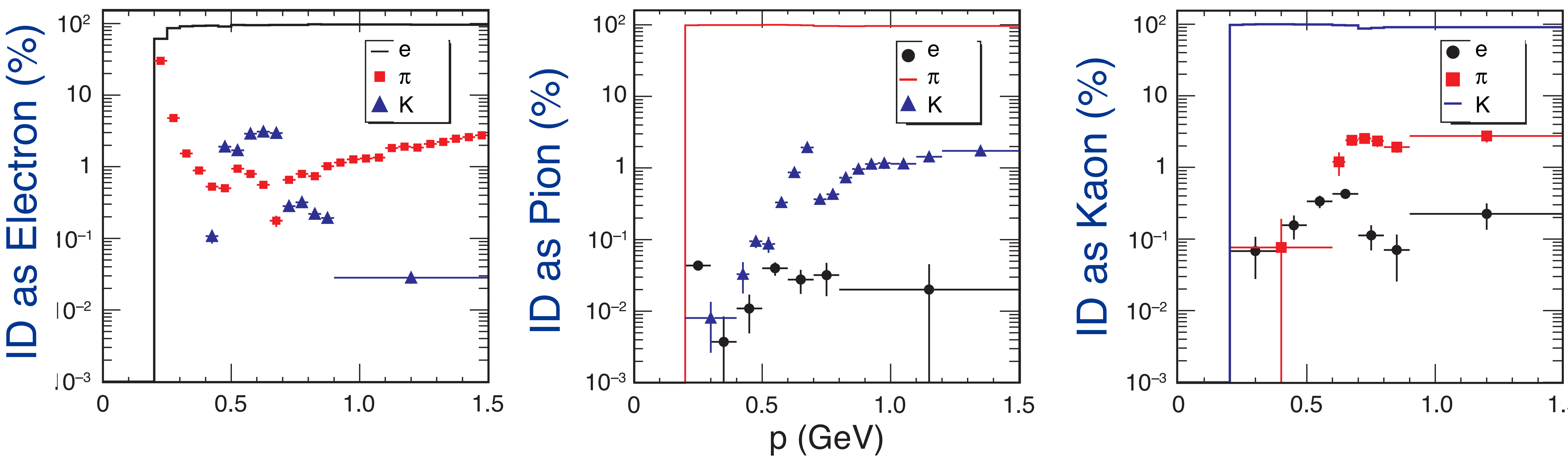


- Accompanying electron spectrum gives inclusive S.L. branching fraction
  - fit spectrum to extrapolate below p = 200 MeV/c

PRD 81 052007 (2010)
CLEO-c 818+602 pb^{-1}

Electron Identification

- Tracks above 200 MeV/c and $|\cos\theta|<0.8$
  - electrons identified with dE/dx, E/p and RICH
  - efficiency and fake rates measured using data
    - π from $K_S \to \pi\pi$;
    - K from reconstructed $D^+ \to K^-\pi^+\pi^+$ decays
    - electrons from radiative Bhabha events embedded in data

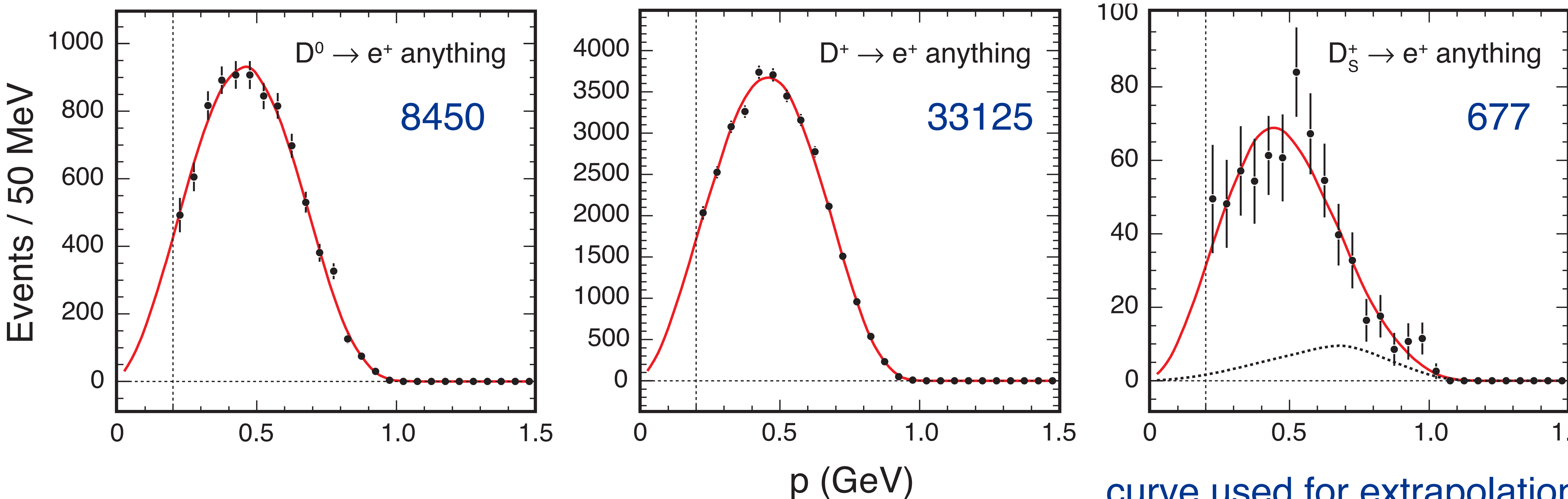


  - High efficiency and low fake rates

PRD 81 052007 (2010)
CLEO-c 818+602 pb^{-1}

Electron Spectra

- Unfold true electron spectrum from π, K & e spectra using PID efficiency matrix binned in momentum
  - Matrix accounts for smearing from finite momentum resolution
- Subtract backgrounds ($\gamma \rightarrow ee, \pi^0 \rightarrow \gamma ee$) using wrong sign candidates (9% correction for D^0)



curve used for extrapolation
dashed = $D_s \rightarrow \tau\nu, \tau \rightarrow e\nu\nu$

PRD 81 052007 (2010)
CLEO-c 818+602 pb^{-1}

Extrapolation & Results

- Sum of exclusive modes used to extrapolate below electron ID threshold at 200 MeV
  - use BF and Form factors from other measurements
    - normalizations float within uncertainties
  - higher resonances added to complete inclusive BF
    - Use ISGW2 predictions & 100% uncertainties for unobserved modes

	$\mathcal{B}(eX)_{trunc}$ (%)	$\mathcal{B}(eX)$ (%)	$\mathcal{B}(Xe\nu)$ (%)
D^0	5.958±0.084	6.460±0.091	6.46±0.09±0.11
D^-	14.863±0.092	16.147±0.100	16.13±0.10±0.29
D_s	7.002±0.361	7.525±0.387	6.52±0.39±0.15

- $\mathcal{B}(eX)$ is extrapolated to all electron momentum
- $\mathcal{B}(Xe\nu)$ is corrected for $D_{(s)}\to\tau\nu, \tau\to e\nu\nu$ using measured BFs

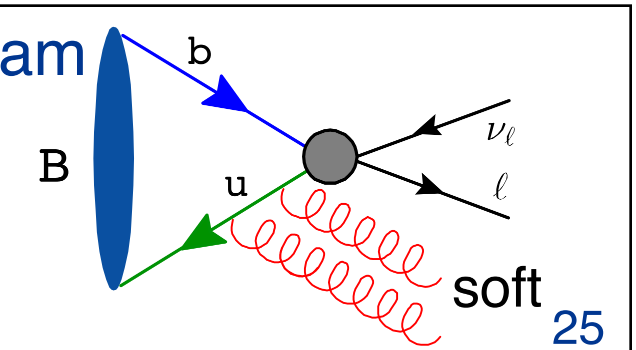
PRD 81 052007 (2010)
CLEO-c 818+602 pb^{-1}

Interpretation

- Compare decay rates under
  - Isospin $D^0 \leftrightarrow D^+$ $$\frac{\Gamma(D^+ \to Xe^+\nu)}{\Gamma(D^0 \to Xe^+\nu)} = 0.985 \pm 0.015 \pm 0.024$$
    - consistent with unity as expected
  - SU(3) ($D_s \leftrightarrow D^+$) $$\frac{\Gamma(D_s^+ \to Xe^+\nu)}{\Gamma(D^0 \to Xe^+\nu)} = 0.828 \pm 0.051 \pm 0.025$$
    - Rate not expected to be equal under SU(3)
    - May shed light on heavy quark SL decays in Heavy Quark expansion
    - Weak Annihilation* contributions impact extraction of V_{ub} from inclusive $b \to u\ell\nu$, estimated ~3% of the total rate concentrated at q^2_{max}
    - Voloshin suggested $\frac{\Gamma(D_s^+ \to Xe^+\nu)}{\Gamma(D^0 \to Xe^+\nu)}$ can constrain B^+ & B^0 differences in the kinematic regions used to measure $b \to u\ell\nu$ and V_{ub}
    - Expectations for WA in D_s are larger by ~$(m_b/m_c)^3$
    - CLEO-c measurement suggests the WA contribution to B decays is smaller than 3%, perhaps < 1%
      - Recent analysis in Ligeti et al. arXiv:1003.1351 Gambino& Kamenik arXiv:1004.0114 presentation tomorrow

Voloshin PLB 515, 74 (2001)

* "WA" diagram



Summary & Outlook for Charm SL

- Full CLEO-c statistics are partially analyzed
  - Form factors and BF in $D \to Ke\nu$, $D \to \pi e\nu$, $D^+ \to K^-\pi^+\ell^+\nu$
    - $D \to \pi e\nu$ gives a challenge for LQCD FF needed for V_{ub} from $B \to \pi e\nu$
    - V_{cs} and V_{cd} consistent with CKM unitarity (leading uncertainty from LQCD FF)
  - Inclusive D^0, D^+, D_s branching fraction & electron spectrum
    - provides some constraints on weak annihilation in V_{ub} extraction
- Additional analysis underway at CLEO-c
  - $D \to \rho e\nu, \eta e\nu, \omega e\nu$ with full statistics
  - D_s exclusive decays: $\phi e\nu, \eta e\nu, \eta' e\nu, K_S e\nu, K^{*0} e\nu, f_0 e\nu$
    - (not shown: 310 pb^{-1} published PRD 80, 052007 (2009); 600 pb^{-1} on tape)
- B factories have potential to add here
  - not shown: preliminary $D^+ \to K^-\pi^+\ell\nu$ form factors from BaBar
- BES III is now running at $\psi(3770)$ with upgraded detector
  - $\mathcal{L}_{int} > 700$ pb^{-1}, aiming for 1 fb^{-1} by June 2010 $\psi(3770)$
  - See BES III status talk by H. Li: goal of ~4xCLEO-c statistics