Semileptonic D Decays

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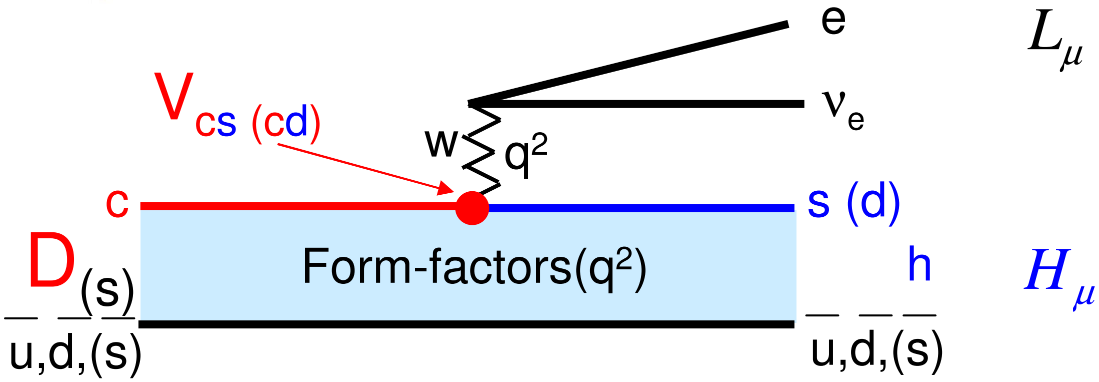
Motivation



$$M(D \rightarrow h\, e\, \nu) = -i\frac{G_F}{\sqrt{2}}\ V_{cs\ (cd)}\ L_\mu H^\mu$$

Factorization!

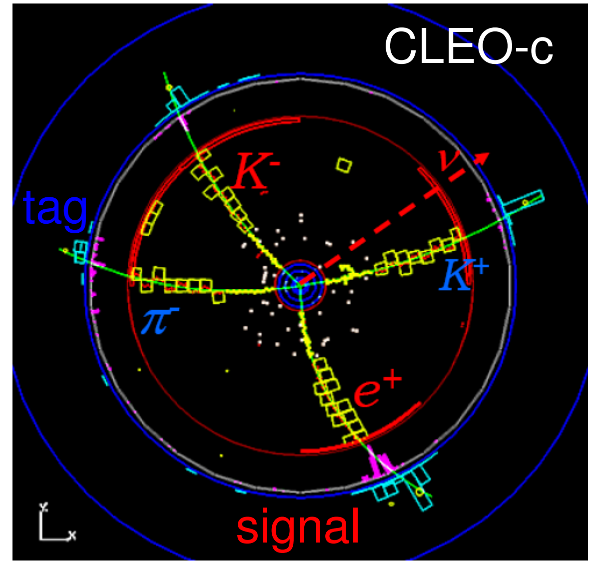
- Direct determination of $|V_{cs\ (cd)}|$.
- Theoretical (Lattice QCD) errors on the form-factor predictions dominate.
- Taking $|V_{cs\ (cd)}|=|V_{ud\ (us)}|$ can turn data into form-factor measurements (normalization and q^2 dependence) to test/develop LQCD.
- Potentially, lead to improved predictions for the form-factors in semileptonic b decays and improved determination of $|V_{ub}|$.

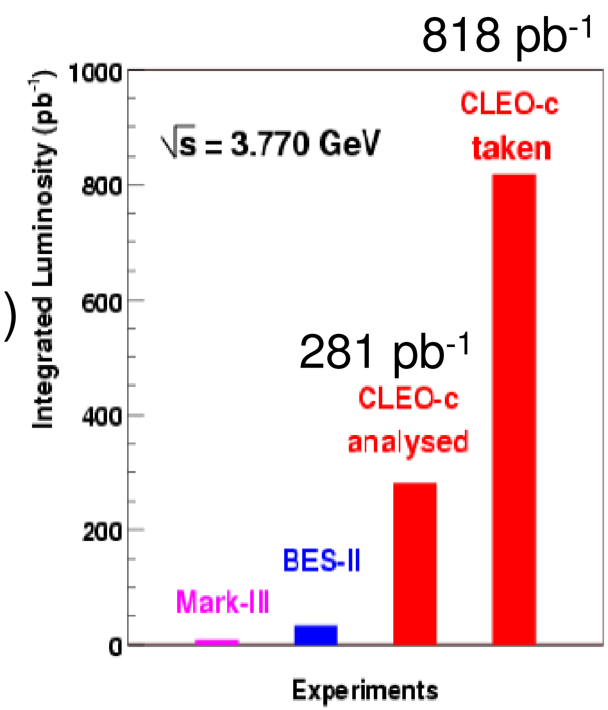
Experimental challenges

- Neutrino escapes detection.
- Indirect measurement of neutrino four-momentum necessary to identify decay mode and to suppress backgrounds.
- Experimental handles at e^+e^- experiments:
  - Inclusive reconstruction of all detectable particles in the event. The missing energy and momentum give neutrino four-vector ("neutrino reconstruction").
    - Reconstruction failures degrade sensitivity, thus hermeticity, lepton and hadron identification and detection of photons are important.
  - Further background suppression tools:
    - $D^* \rightarrow D\pi_{slow}$. Heavily used by measurements above the D* production threshold. Works the best for $D^{*-} \rightarrow D^0\pi^-$.
    - Full reconstruction of the other D in the event ("tagging"). Provides also robust rate normalization.
- Other experiments (e.g. FOCUS):
  - D lifetime + $D^{*-} \rightarrow D^0\pi^-$

Tagging technique

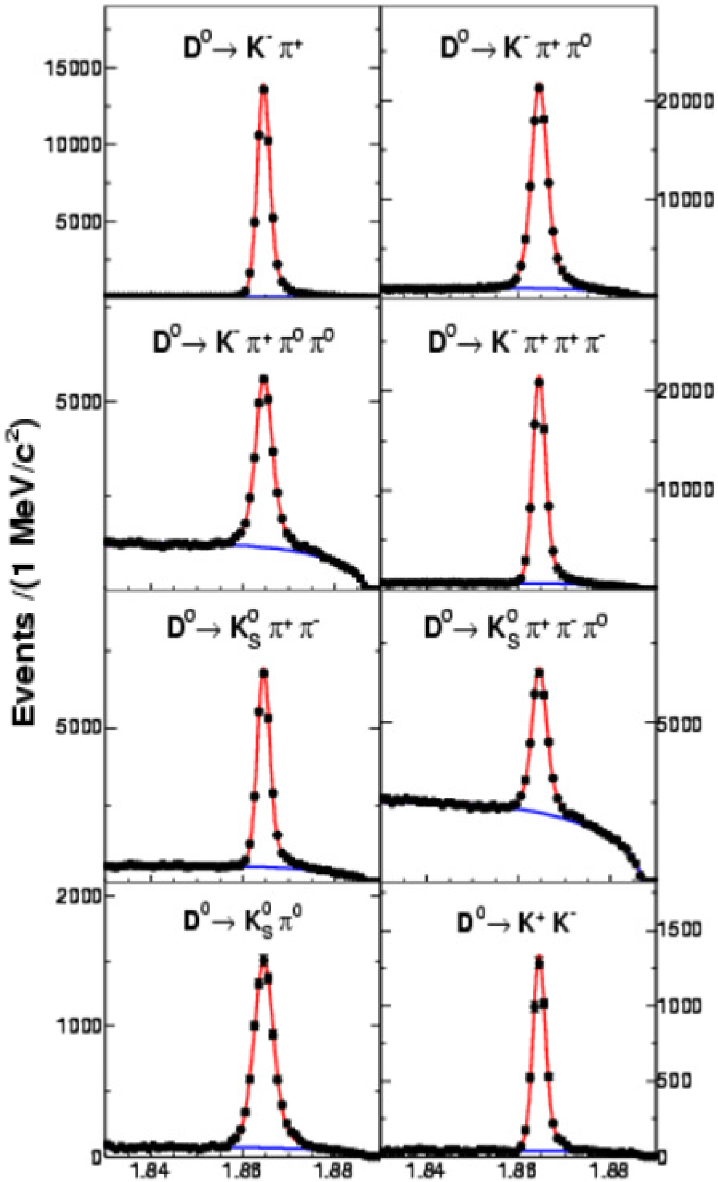
- Most effective for $e^+e^- \rightarrow \psi(3770) \rightarrow D\bar{D}$:
  - No fragmentation particles produced
- Reconstruct one D (tag) in several clean hadronic decay modes:
  - Cut on $\Delta E = E_D - E_{beam}$
  - Fit $M_{bc} = \sqrt{E_{beam}^2 - \mathbf{p}_D^2}$ to determine N_{tag}
  - The tag determines momentum of the other D: $\mathbf{p}_{D\ signal} = -\mathbf{p}_{D\ tag}$
- Find subsample in which the rest of reconstructed particles consists of an electron (e) and desired hadron (h) from semileptonic D-decay.
  - Calculate missing energy ($E_{miss} = E_{beam} - E_e - E_h$) and momentum ($\mathbf{p}_{miss} = -\mathbf{p}_{D\ tag} - \mathbf{p}_e - \mathbf{p}_h$). Fit $U_{miss} = E_{miss} - |\mathbf{p}_{miss}|$ to extract N_{signal}.
  - $BR = (N_{signal} / \varepsilon_{signal}) / (N_{tag} / \varepsilon_{tag})$
  - Also determine differential rates in $q^2 = (E_{beam} - E_h)^2 - (-\mathbf{p}_{D\ tag} - \mathbf{p}_h)^2$





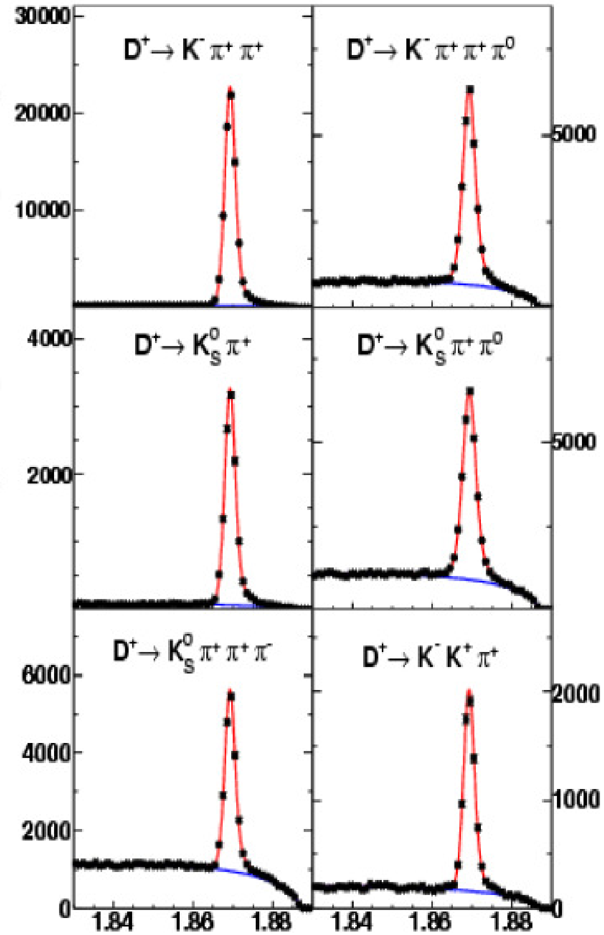
Tag

~310,000 D^0



M_{bc} (GeV)

~160,000 D^+

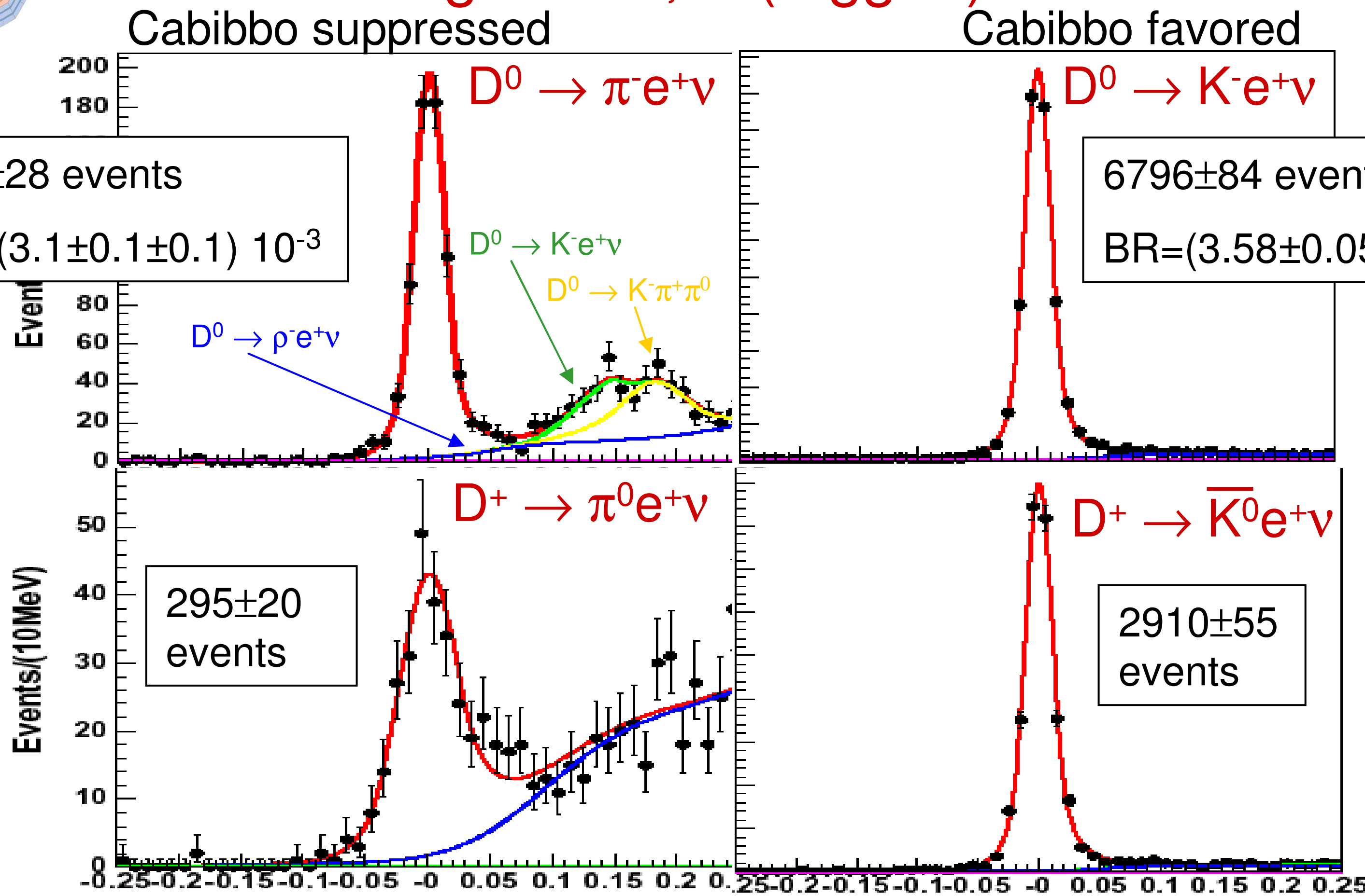


M_{bc} (GeV)

CLEO-c 281 pb^{-1}

- CLEO-c reconstructs a tag in about ~25% of all $D\overline{D}$ events
- Compared to ~0.1% tagging B efficiency at Y(4S)

Signal – π, K (tagged)



CLEO-c
281 pb^{-1}
Preliminary

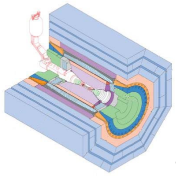
$U_{miss} = E_{mis} - |\mathbf{p}_{mis}|$ (GeV)

$$\frac{\Gamma\left(D^0 \to \pi^- e^+ \nu\right)}{2 \cdot \Gamma\left(D^+ \to \pi^0 e^+ \nu\right)} = 0.975 \pm 0.075$$

(isospin symmetry)

$$\frac{\Gamma\left(D^0 \to K^- e^+ \nu\right)}{\Gamma\left(D^+ \to \bar{K}^0 e^+ \nu\right)} = 1.024 \pm 0.024$$

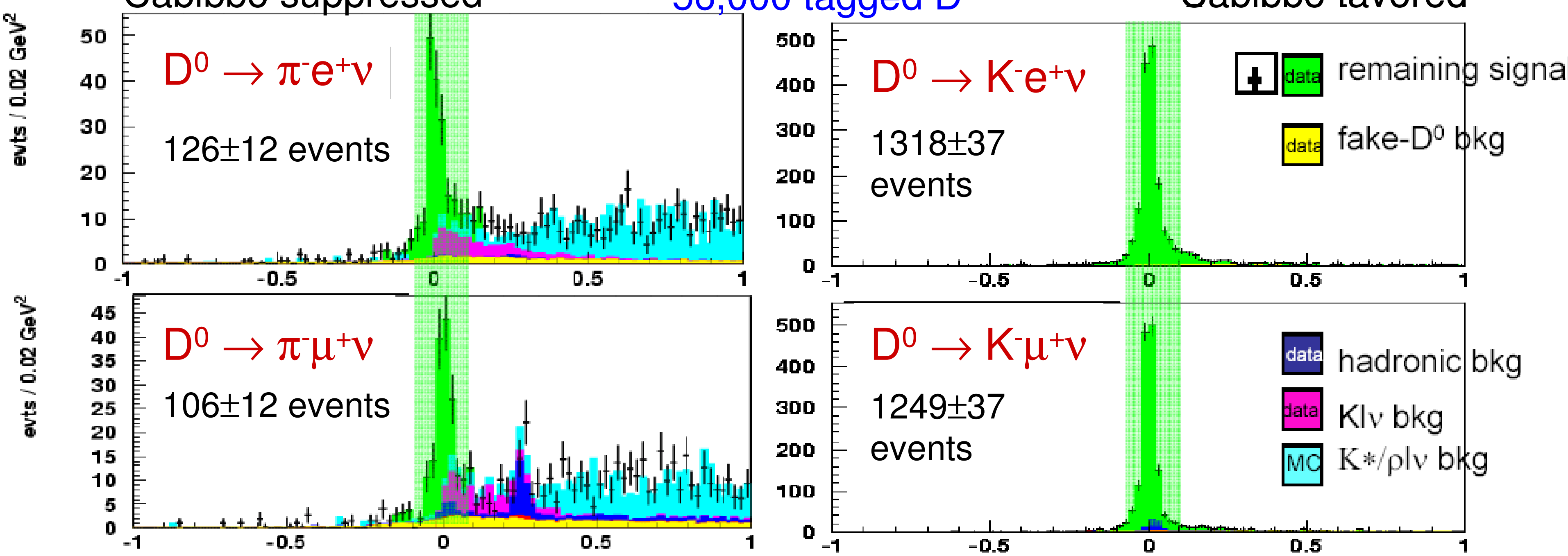
- Excellent background suppression. Small feed-across due to threshold kinematics.



Signal – π, K (tagged) at Belle

- Continuum production at E_{cm}~10 GeV (282 fb^{-1}).
- Reconstruct all particles (except for neutrino) and tag the other D in $e^+e^- \to D^{(*)}_{tag}\, D^*_{signal}\, X$.
- Tagging provides absolute normalization of the measured rates.

Cabibbo suppressed ~56,000 tagged D^0 Cabibbo favored



$$m_{miss}^2 = E_{miss}^2 - \mathbf{p}_{miss}^2 \quad (GeV)$$

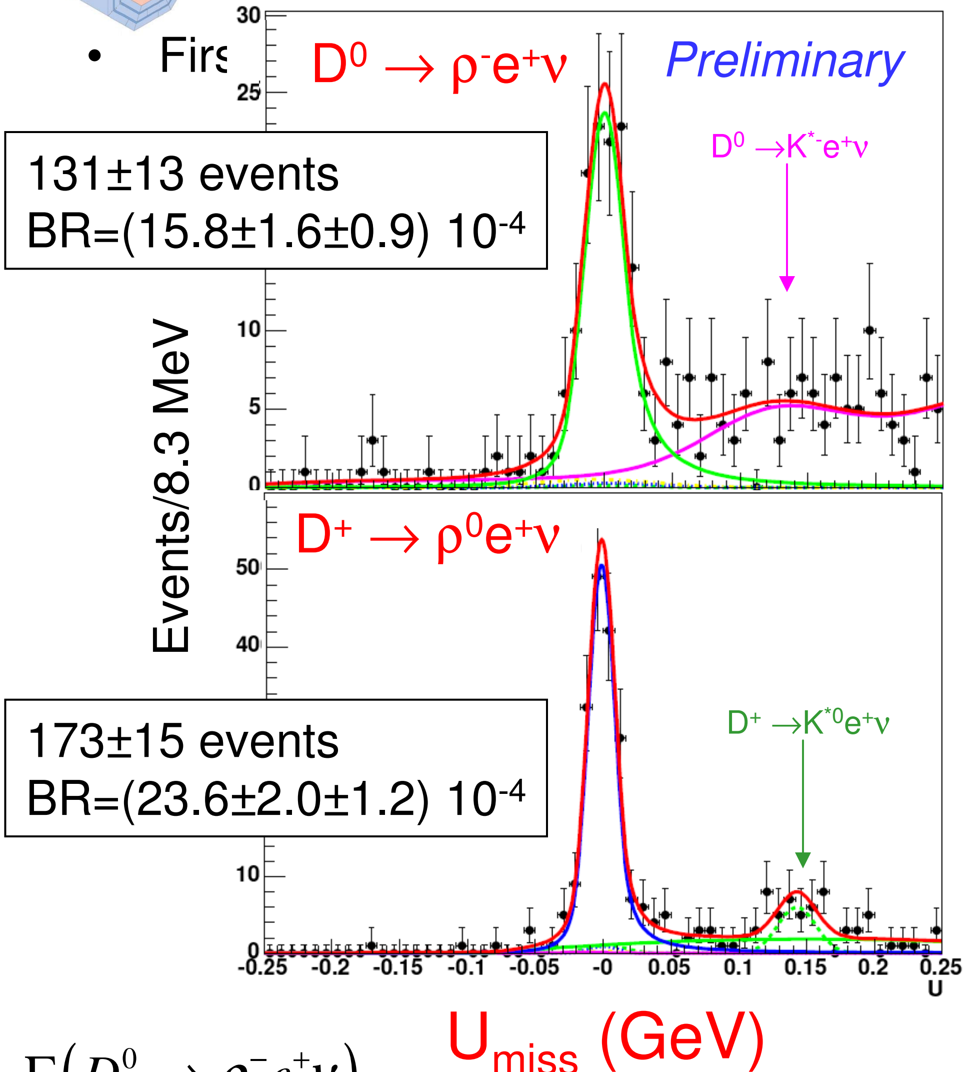
- Impressive results in difficult production environment! Both e and μ measured.
- Compared to CLEO-c results:
  - Factor ~1000 more luminosity
  - Factor ~3 less signal events
  - Factor ~10 worse signal/noise

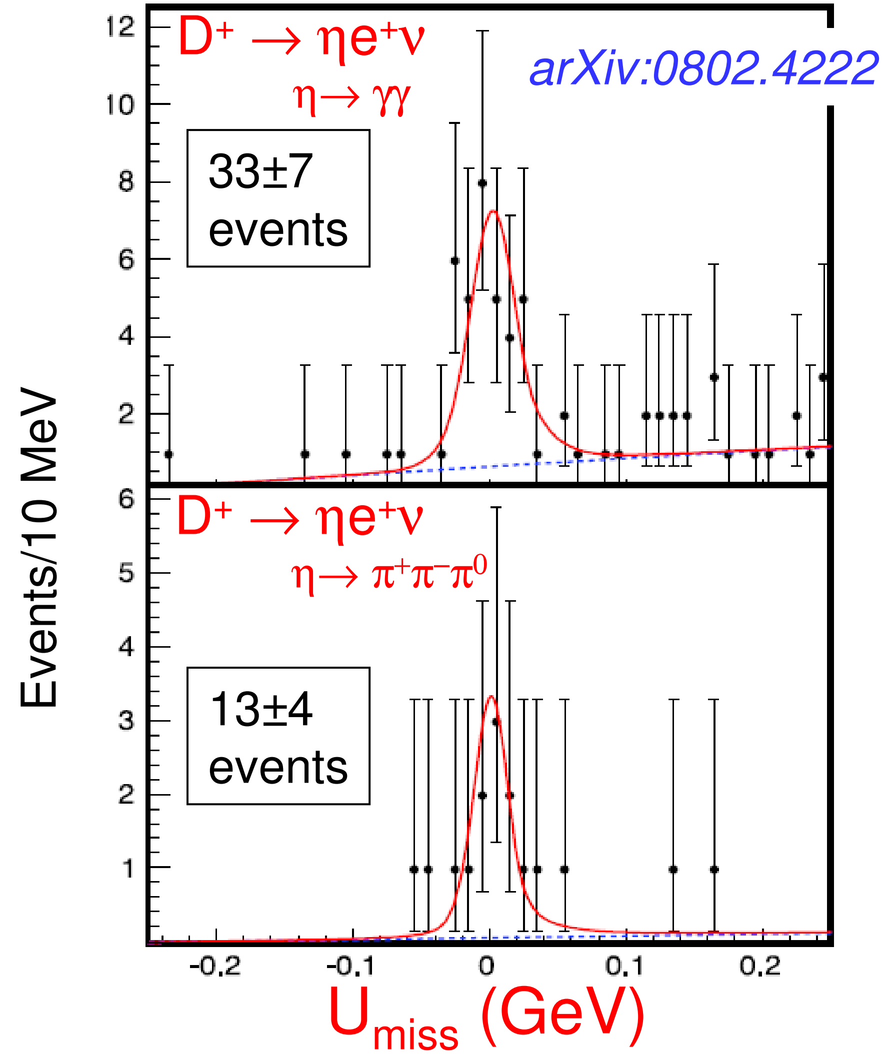
Belle, PRL 97, 061804 (2006)

Signal - ρ, η (tagged) Cabibbo suppressed

CLEO-c 281 pb^{-1}

- Firs





$$\frac{\Gamma\left(D^0 \to \rho^- e^+ \nu\right)}{2 \cdot \Gamma\left(D^+ \to \rho^0 e^+ \nu\right)} = 0.85 \pm 0.11$$ *(isospin symmetry)*

BR=(13.3±2.0±0.6) 10^{-4}

See also PRL 99, 191801 (2007) for first observation of $D^0 \to K^- \pi^+ \pi^- e^+ \nu$

"Neutrino reconstruction" technique (in CLEO-c)

- Same data. Same selection goal – reconstruct all decay products of both D mesons except for the neutrino (semileptonic decay of one D, hadronic decay of the other D). Missing energy and momentum give neutrino four-vector.
- Do not restrict hadronic decays of the other D to a few clean decay channels – allow any number of charged tracks ($\Sigma Q=0$) and photons. No D-mass constraint for D decaying hadronicly (no D-tagging). This leads to higher efficiency but also higher backgrounds and larger systematic uncertainty.

$$E_{miss} = 2\,E_{beam} - \Sigma \sqrt{m_{e,\pi,K}^2 + p_{charged}^2} - \Sigma\, E\gamma$$

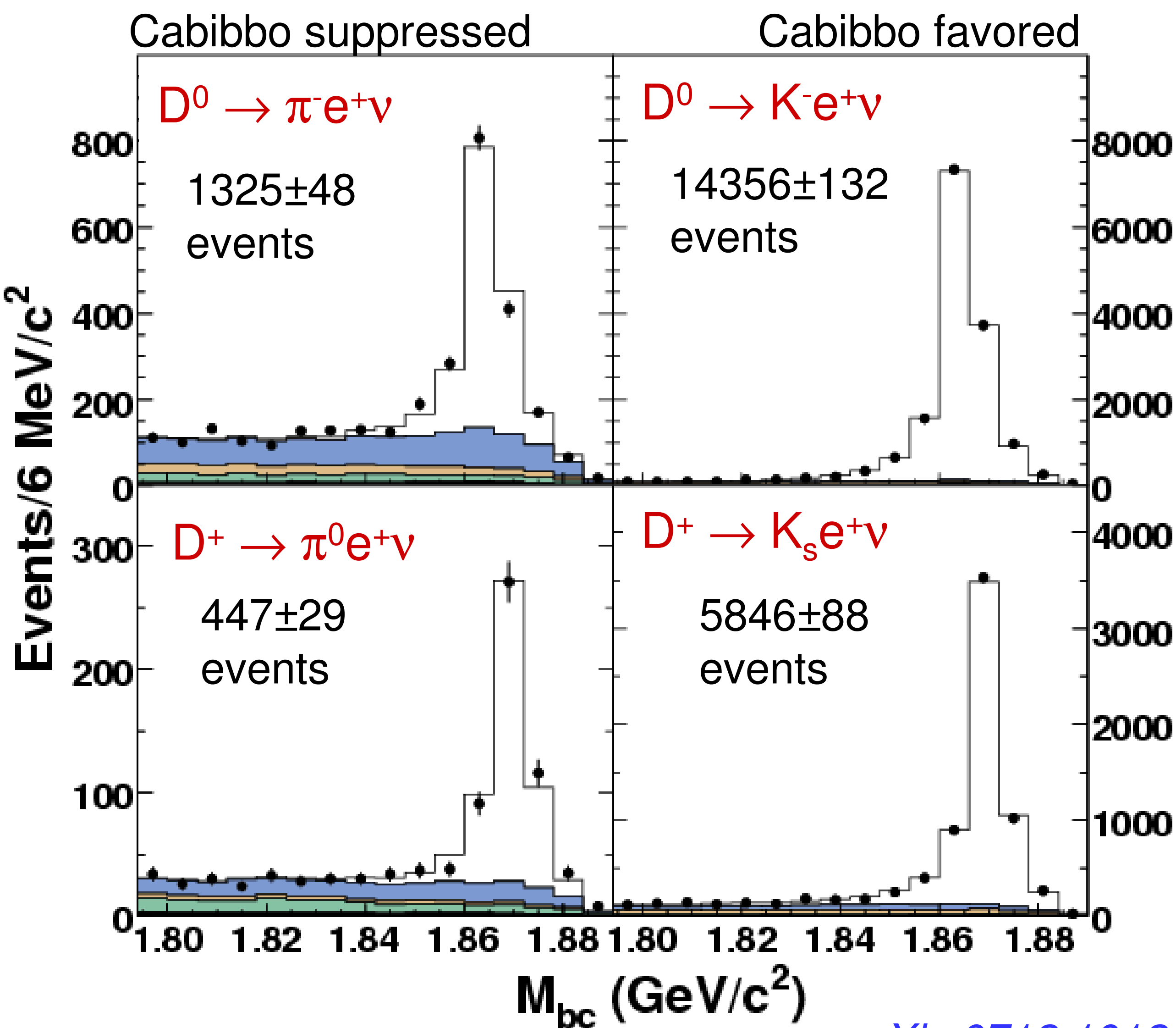
$$\mathbf{p}_{miss} = - \Sigma\, \mathbf{p}_{charged} - \Sigma\, \mathbf{p}\gamma$$

$$m_\nu^2 = E_{miss}^2 - \mathbf{p}_{miss}^2 < 0.4\, |\mathbf{p}_{miss}|$$

- Pick a combination of the electron (only one allowed) and a hadron, that minimizes $|\Delta E| = |\, E_h + E_e + |\mathbf{p}_{miss}| - E_{beam}\,|$.

  Fit $M_{bc} = \sqrt{E_{beam}^2 - (\mathbf{p}_h + \mathbf{p}_e + \mathbf{p}_{miss})^2}$ to extract N_{signal}.
  - $BR = N_{signal} / (\,\varepsilon_{signal}\, N_{DD})$
  - Also determine differential rates in $q^2 = (\mathbf{p}_e + \mathbf{p}_{miss})^2$
- The two techniques are strongly correlated.

Signal – π, K (untagged)



CLEO-c 281 pb^{-1}

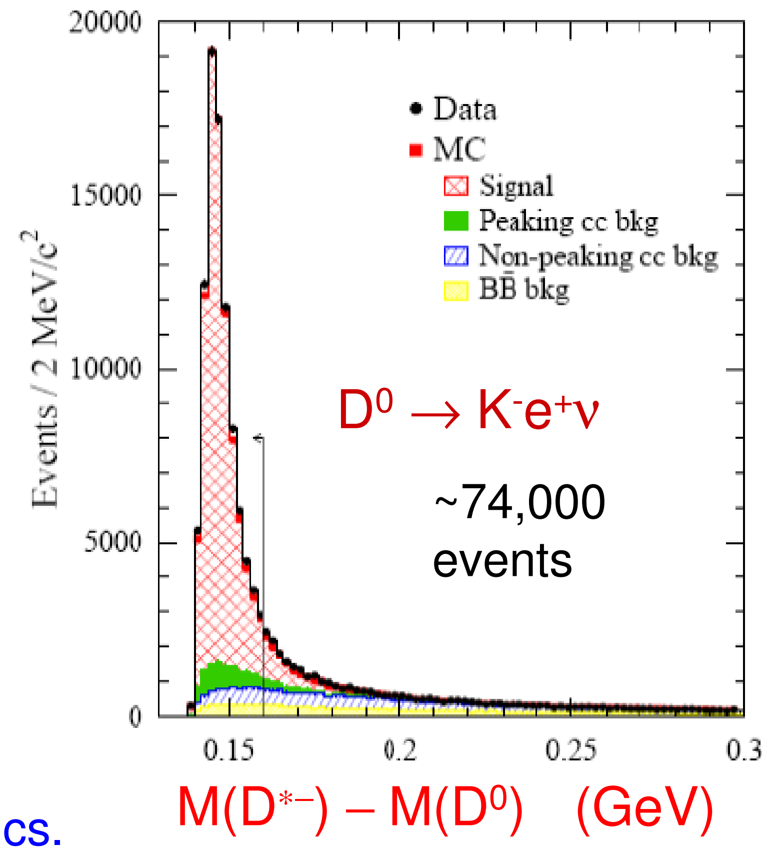
arXiv:0712.1012
and
arXiv:0712.0998 (accepted by PRL)

- Compared to the tagged analysis:
  - Factor ~2 increase in the signal statistics.

Signal – K (untagged) at BaBar

- Neutrino "reconstruction" technique together with $D^{*-} \to D^0 \pi^-$

Cabibbo favored



PRD 76, 052005 (2007)

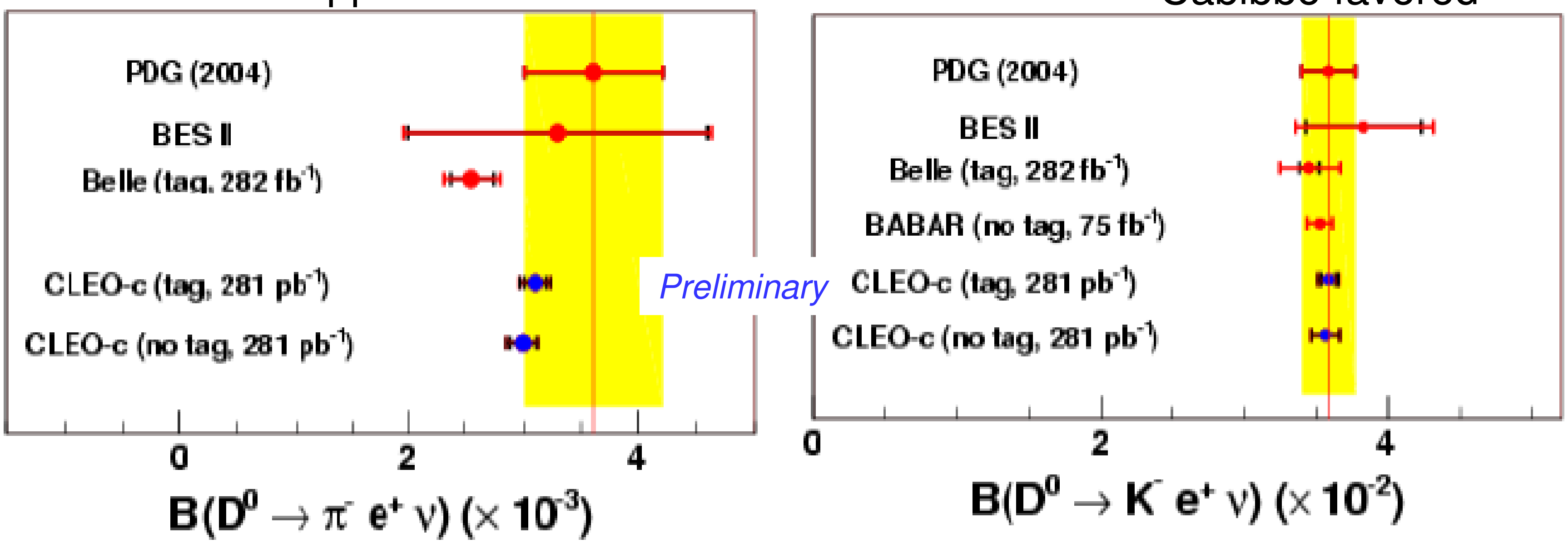
BaBar 75 fb^{-1}

- Very large signal statistics.
- Compared to CLEO-c results:
  - Factor ~300 more luminosity
  - Factor ~5 more signal events
  - Normalization to $BR(D^0 \to K^- \pi^+)$ [determined by CLEO-c]
  - Poor q^2 resolution (unfolding needed for form factor measurements)
  - Much worse signal/noise (method not suitable for Cabibbo suppressed decays)

Branching Ratio Results - Comparison

Cabibbo suppressed

Cabibbo favored



- Significant improvement in precision by recent BaBar/Belle/CLEO-c measurements (CLEO-c most precise).

Form factors

- Form factors are related to probability of forming final state hadron at given q^2.
- Theoretical predictions for form factors needed to turn the measured rates into $V_{cs\ (cd)}$ determinations.
- Theory often calculates this probability at fixed q^2 and uses parameterizations to extrapolate to full q^2 range.
- Theoretical approaches include phenomenological models, QCD sum rules, LQCD.
- Only the latter is systematically improvable.

h – pseudoscalar:

$$H^{\mu} = f_{+}(q^2)(P_D + P_h)^{\mu}$$

h – vector:

$$H^{\mu} = \frac{2i\varepsilon^{\mu\nu\alpha\beta}}{m_D + m_h} e_{\nu}^{*} P_{h\alpha} P_{D\beta} V(q^2) - (m_D + m_h) e^{\mu *} A_1(q^2) + \frac{e^{*\alpha} q_{\alpha}}{m_D + m_h} (P_D + P_h)^{\mu} A_2(q^2)$$

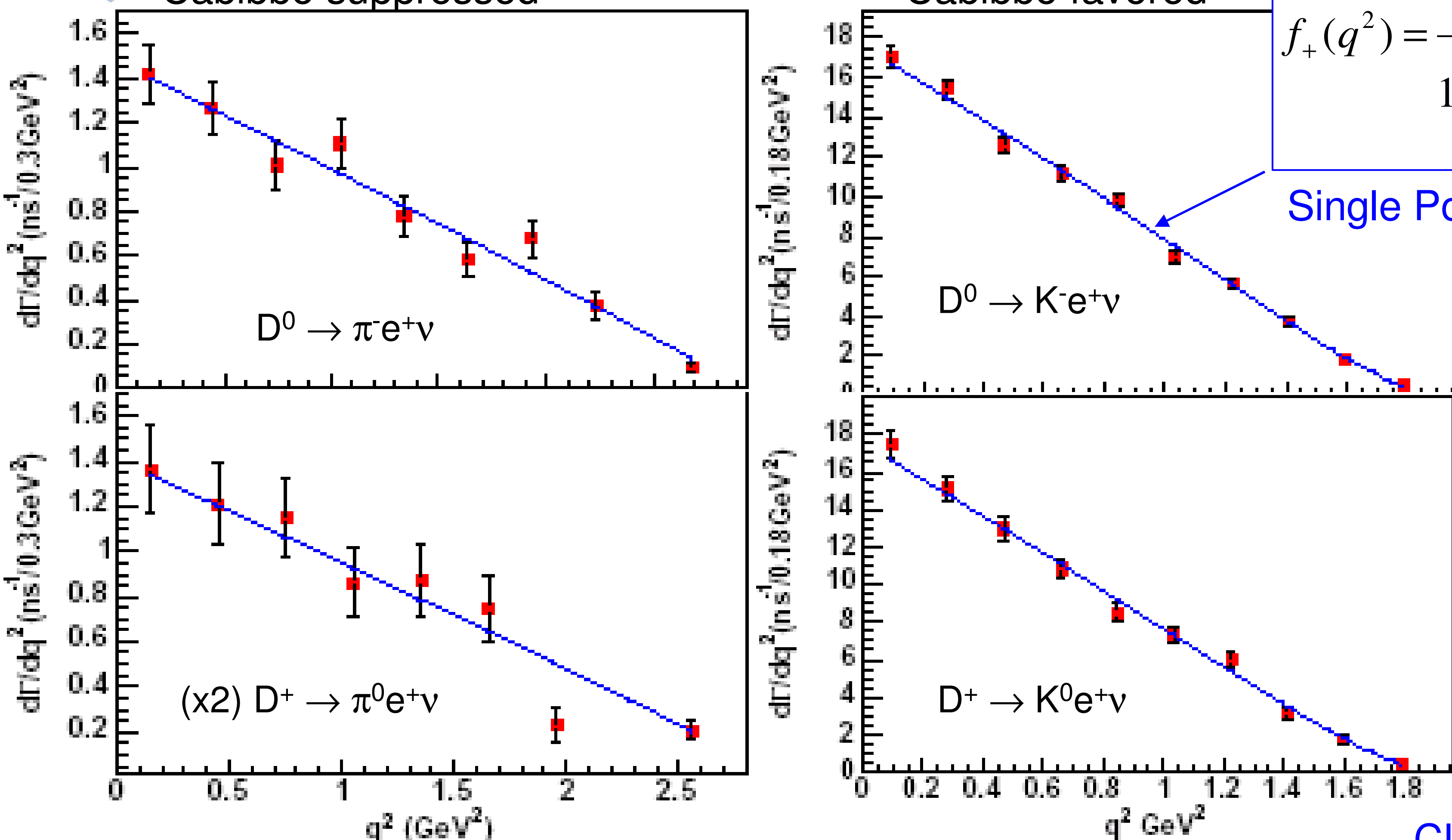
Simplicity favors pseudoscalar decay modes.

Pseudoscalar Form Factors

Cabibbo suppressed Cabibbo favored

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

Single Pole Model

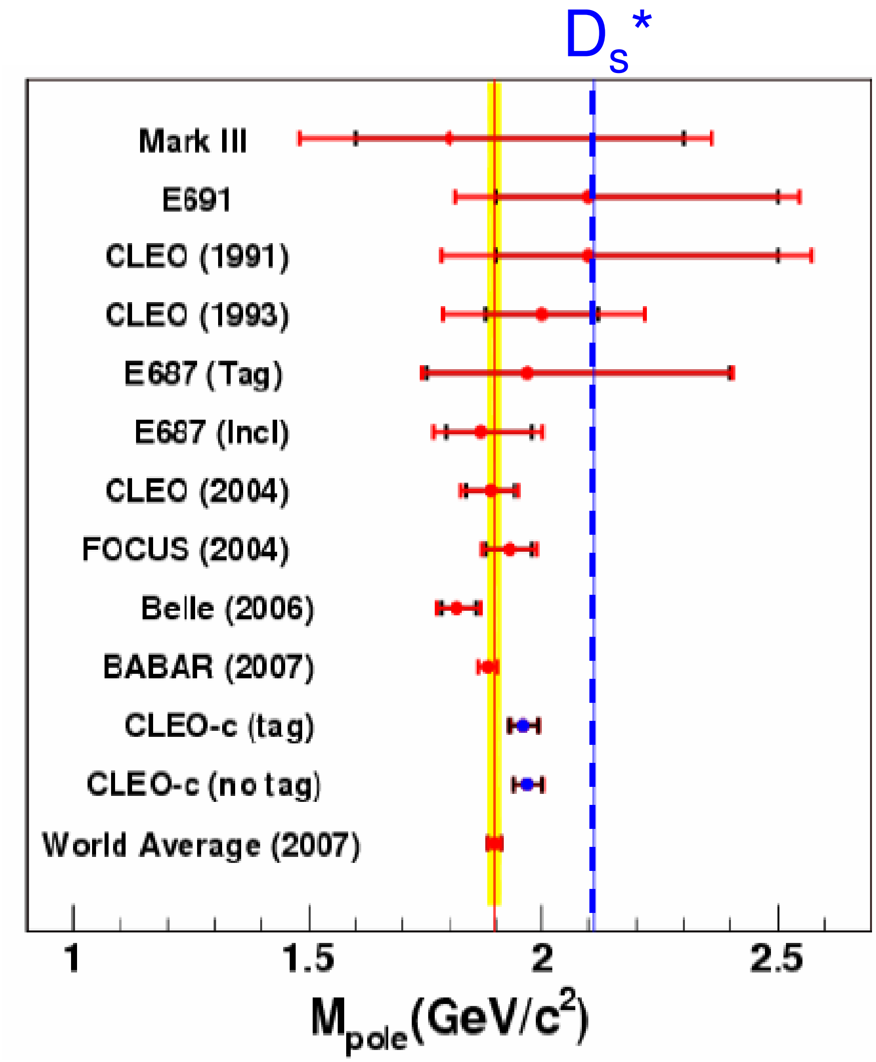


CLEO-c
Tagged
281 pb^{-1}
Preliminary

$$\frac{d\Gamma}{dq^2} = \frac{G_F}{24\pi^3} P^3_{K(\pi)} \left|V_{cs(cd)}\right|^2 \left|f_+(q^2)\right|^2$$

- Much of the visible variation is due to the phase-space factor (P^3).

$D \to K e \nu$ Form Factor

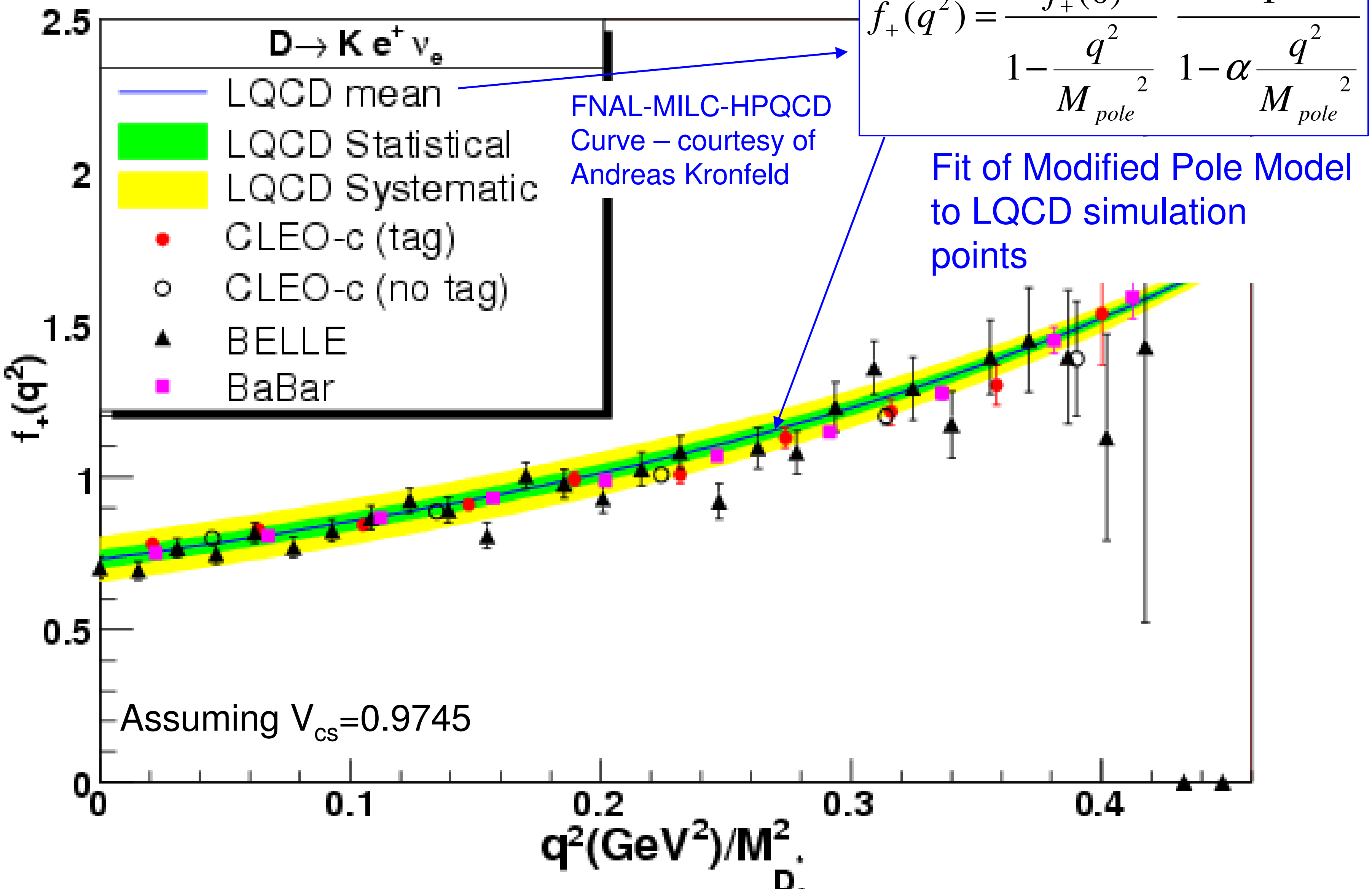


- Single Pole Model describes data reasonably well, but not with spectroscopic D_s^* mass

(from Ian Shipsey's talk at LQCD workshop, FNAL, Dec 2007 – see for more extensive discussion of form factor results)

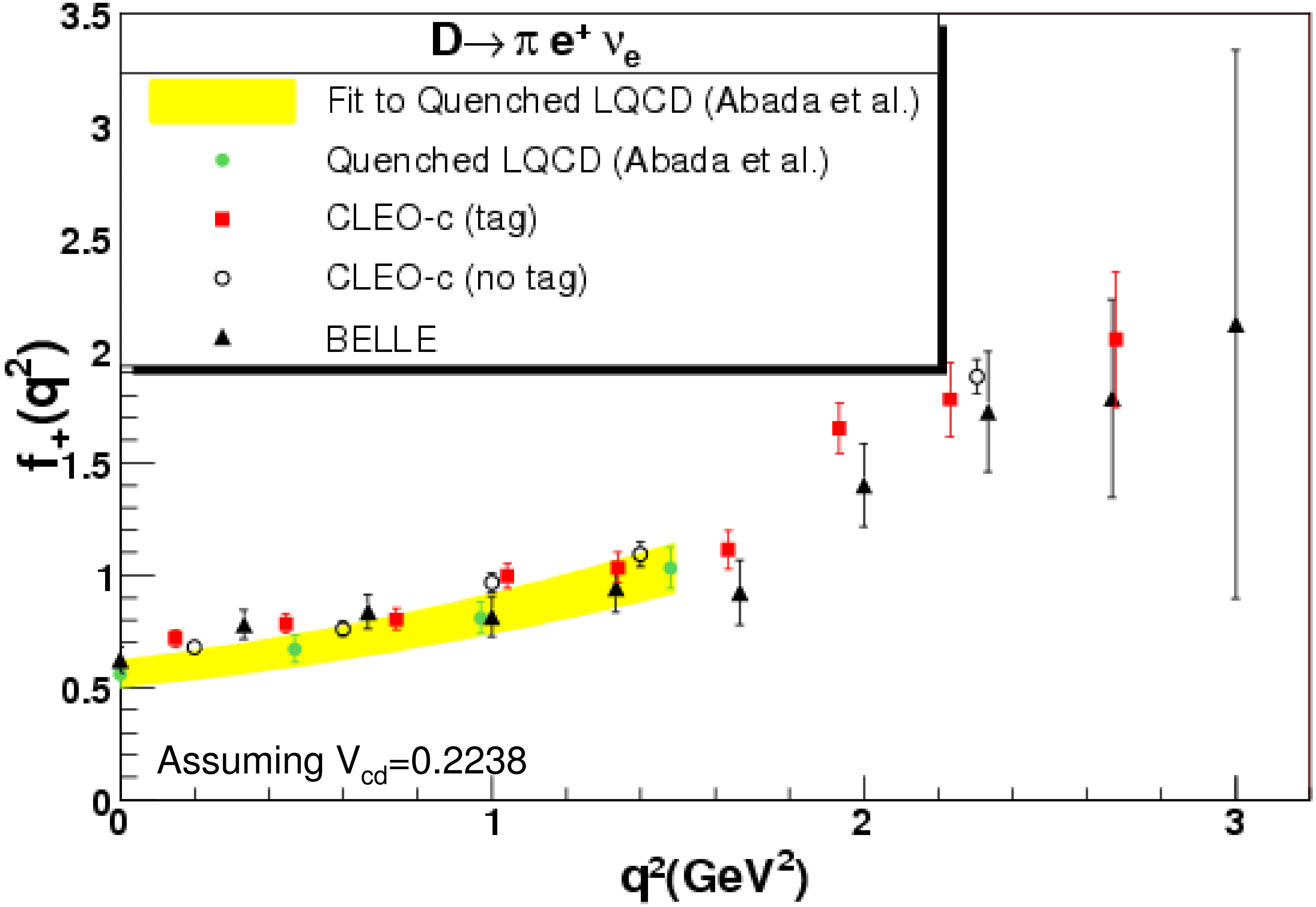
Pseudoscalar form-factor: LQCD vs experiments

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



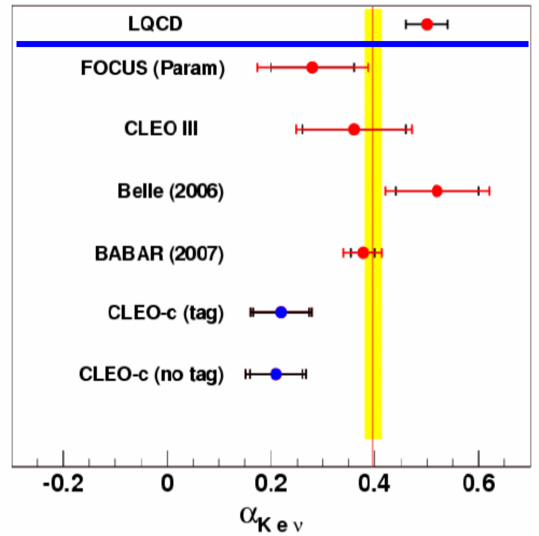
- Theoretical errors larger than experimental

Pseudoscalar form-factor: LQCD vs experiments

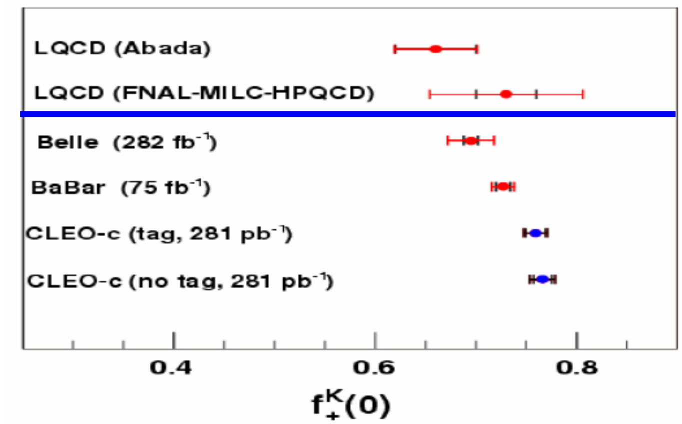


Tests of LQCD

Slope



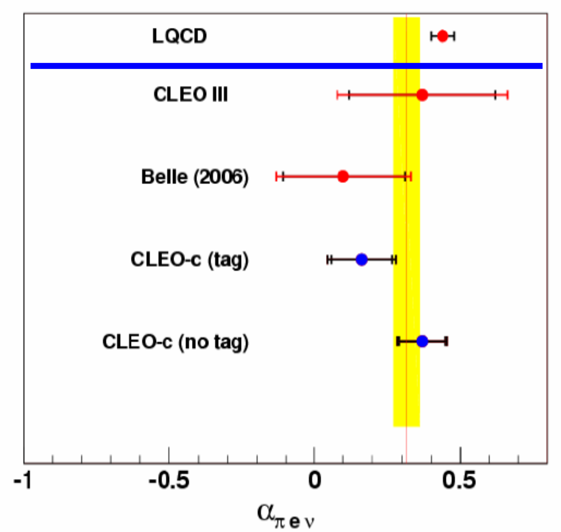
Normalization (assuming $|V_{cs\ (cd)}|=|V_{ud\ (us)}|$)

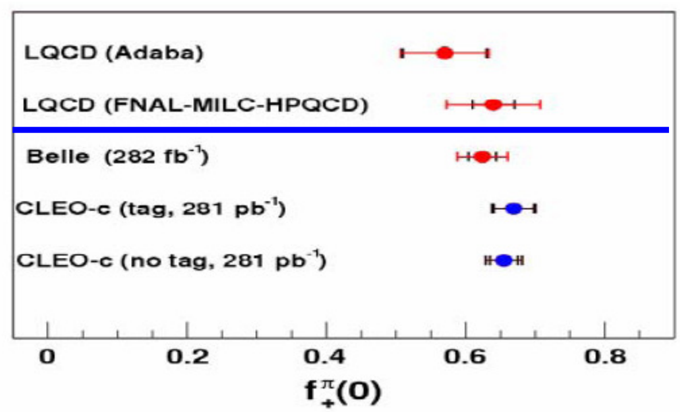


$D \to Ke\nu$

Normalization errors

Channel	Experi-ments	theory
$D \to Ke\nu$	2%	10%
$D \to \pi e\nu$	4%	10%

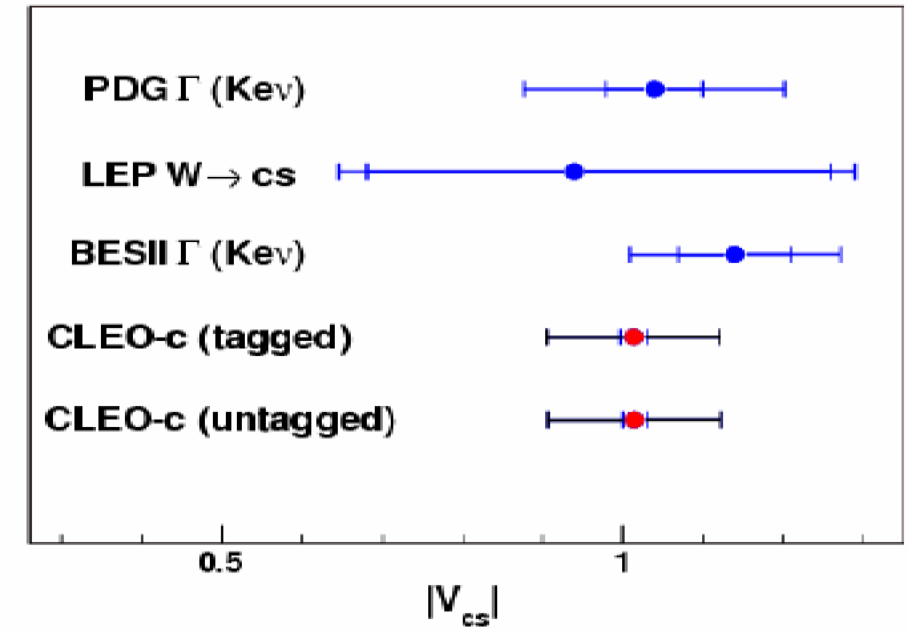


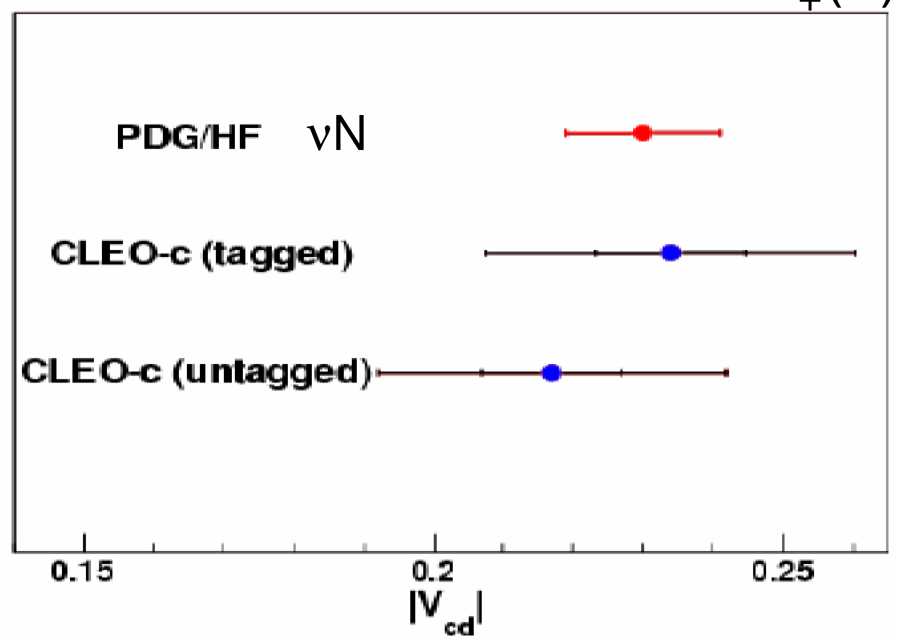


$D \to \pi e\nu$

CKM results

Combine measured $|V_{cx}|f_+(0)$ values (*fit of Hill&Becher f.f. parameterization)* with FNAL-MILC-HPQCD calculations for $f_+(0)$





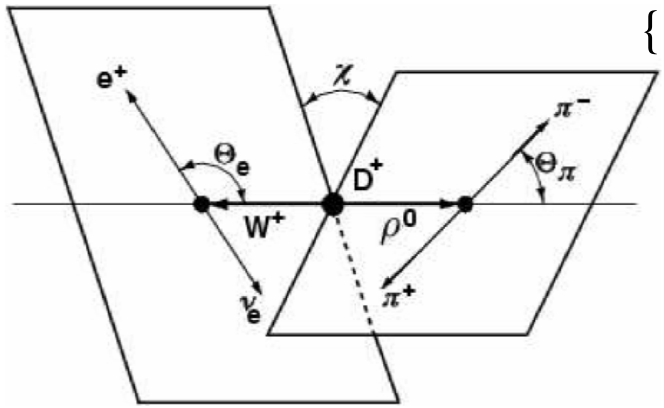
CLEO-c (results are strongly correlated – do not average)

	$\lvert V_{cs}\rvert$	$\lvert V_{cd}\rvert$
(tagged *prelim*)	1.014±0.013±0.009±0.106	0.234±0.010±0.004±0.024
(untagged *final*)	1.015±0.010±0.011±0.106	0.217±0.009±0.004±0.023
	stat syst LQCD	stat syst LQCD

- Improvements in LQCD calculations are needed

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

$$\frac{d\Gamma}{dq^2 d\cos\theta_\pi d\cos\theta_e d\chi} = BR(\rho^0 \to \pi\pi)\frac{3G_F^2}{8(4\pi)^4}|V_{cs}|^2 \frac{P_\rho q^2}{M_D^2}\times$$



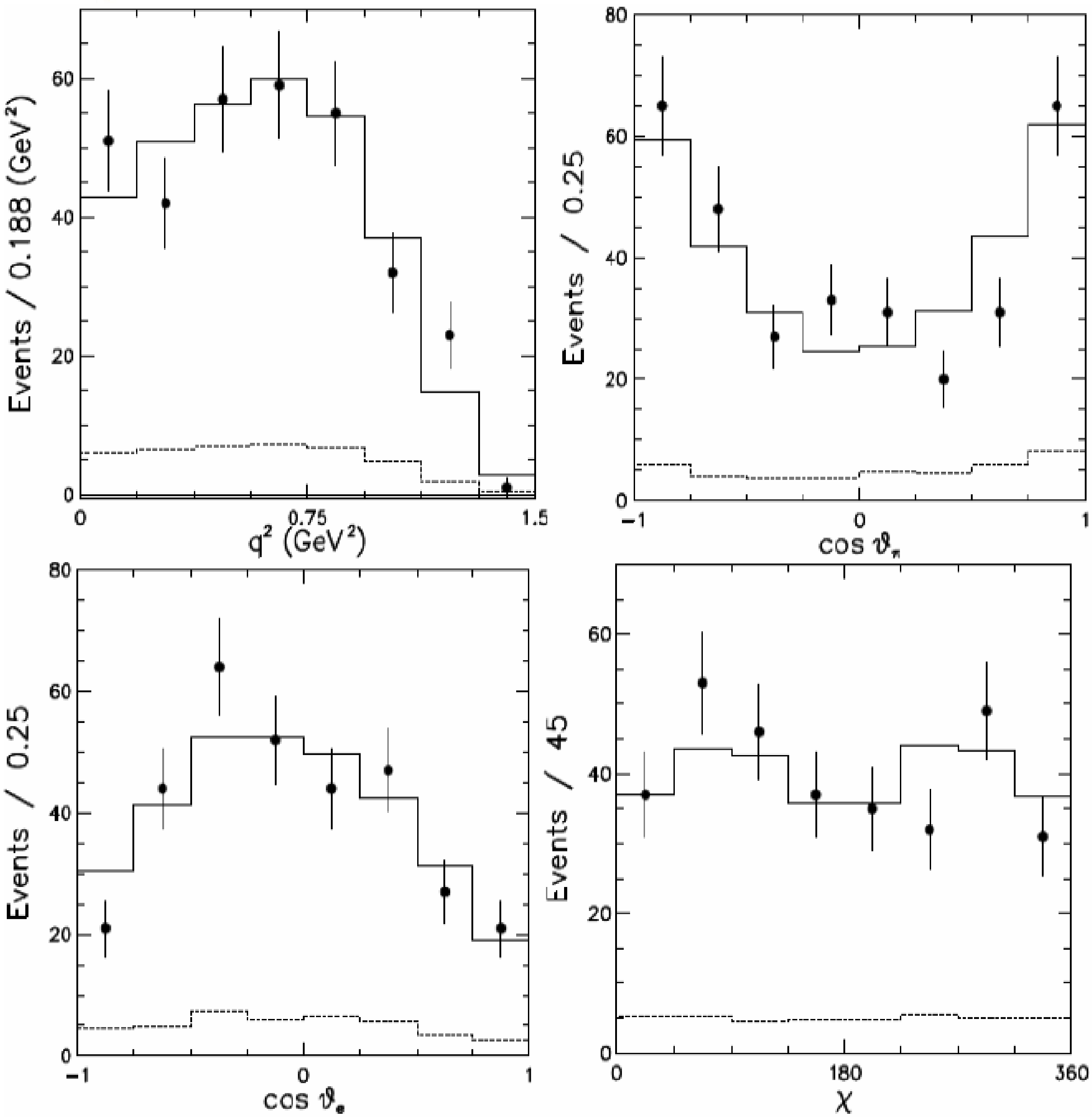
$$\begin{aligned}\{ \quad & (1+\cos\theta_e)^2 \sin^2\theta_\pi \left|H_+(q^2,m_{\pi\pi})\right|^2 \\ + \; & (1-\cos\theta_e)^2 \sin^2\theta_\pi \left|H_-(q^2,m_{\pi\pi})\right|^2 \\ + \; & 4\sin^2\theta_e \cos^2\theta_\pi \left|H_0(q^2,m_{\pi\pi})\right|^2 \\ + \; & 4\sin\theta_e(1+\cos\theta_e)\sin\theta_\pi\cos\theta_\pi\cos\chi H_+(q^2,m_{\pi\pi})H_0(q^2,m_{\pi\pi}) \\ - \; & 4\sin\theta_e(1-\cos\theta_e)\sin\theta_\pi\cos\theta_\pi\cos\chi H_-(q^2,m_{\pi\pi})H_0(q^2,m_{\pi\pi}) \\ - \; & 2\sin^2\theta_e\sin^2\theta_\pi\cos 2\chi H_+(q^2,m_{\pi\pi})H_-(q^2,m_{\pi\pi}) \quad \}\end{aligned}$$

$$H_\pm(q^2,m_{\pi\pi}) = (M_D+m_{\pi\pi})A_1(q^2) \mp 2\frac{M_D P_{\pi\pi}}{M_D+m_{\pi\pi}}V(q^2)$$

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

- Use Simple Pole Model for $V(q^2)$,$A_1(q^2)$ and $A_2(q^2)$
- Fit data (in 4D) for ratios of form factor normalizations:
  - $R_V = V(0)/A_1(0)$
  - $R_2 = A_2(0)/A_1(0)$

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



CLEO-c 281 pb^{-1}

Preliminary

~300 events

$$R_V = 1.40 \pm 0.25$$

$$R_2 = 0.57 \pm 0.19$$

(first measurement in Cabibbo suppressed mode)

Not much different from Cabibbo favored $D \to K^* \mu \nu$ form factor ratios (FOCUS):

$$R_V = 1.50 \pm 0.07$$

$$R_2 = 0.88 \pm 0.08$$

$D_s \to K^+K^-e\nu$ Form Factors

- Untagged

BaBar 214 fb^{-1}

(David Kirkby, Hot Topics session)

$D_s \to \phi e\nu$

$$R_V = 1.87 \pm 0.06 \pm 0.08$$

$$R_2 = 0.76 \pm 0.07 \pm 0.06$$

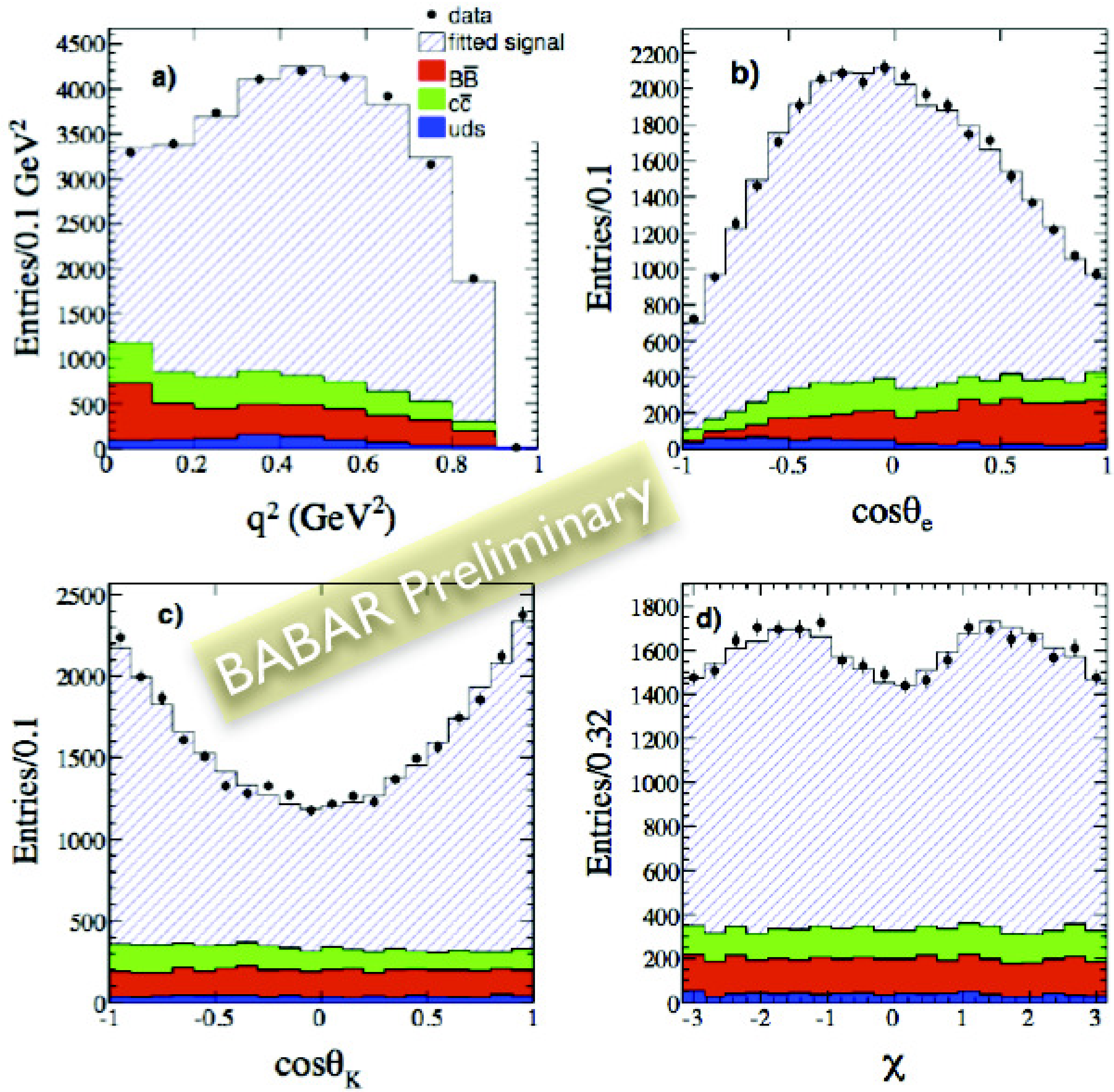
$$R_0 = 15.3 \pm 2.6 \pm 1.0$$

$D_s \to f_0 e\nu$

(first evidence)

Expect CLEO-c tagged results for D_s this summer.

~25,200 events



Summary and outlook

- Our knowledge of semileptonic D-decays and related parameters has been significantly improved thanks to high luminosities at B-factories (BaBar, Belle) and data taken at the charm threshold (CLEO-c). CLEO-c most precise.
  - BR($D \to K e \nu$) 6% error $\to$ 2%
  - combined with LQCD calculations (10% errors) leads to best direct determination of V_{cs}
  - BR($D \to \pi e \nu$) 45% error $\to$ 4%
  - Potential for best direct determination of V_{cd} if LQCD errors are improved
  - First measurements of many decays with small BRs
  - Many new and improved form factor measurements.
- CLEO-c $\psi(3770)$ statistics has been recently increased by a factor of 3. Expectations from analysis of the full data sample (in progress):
  - More stringent tests of theory on form factor normalizations and slopes.
  - Improved determinations of CKM elements:
    - V_{cs} ~ 0.9-1.2% (systematics limited) + theory error
    - V_{cd} ~ 2.3-3.5% (statistics limited) + theory error
- Expect CLEO-c results for tagged semileptonic decays of D_s this summer.