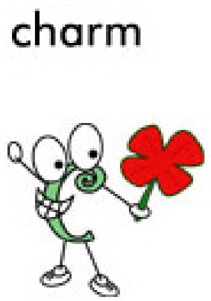
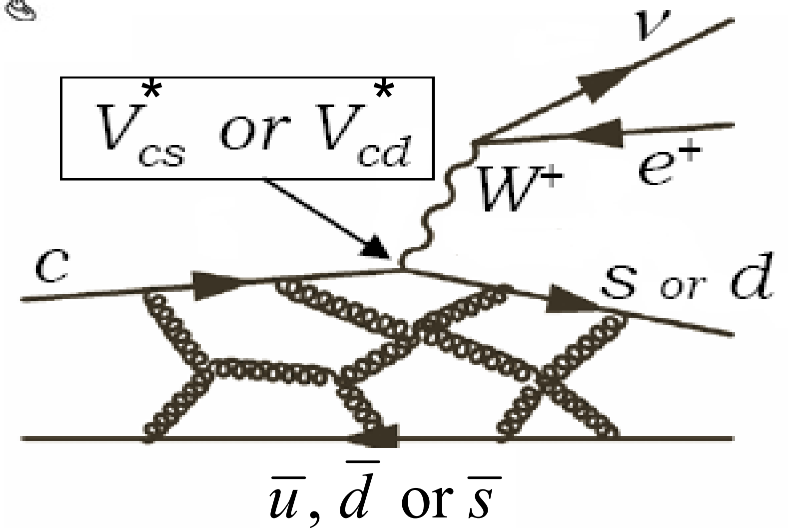
Charm Semileptonic Decays





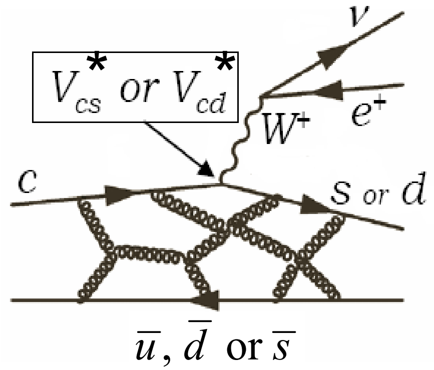
- Introduction
- Analysis techniques
- *D* and D_s Semileptonic:
  Branching fractions
  Semileptonic form factors
  CKM ($|V_{cs}|$, $|V_{cd}|$ and more)
- Summary and prospects

Bo Xin
Purdue University

Flavor Physics and CP Violation
May 27 – June 1, 2009

Importance of Charm Semileptonic Decays

- Golden P→P transitions:



Weak Physics

QCD Physics

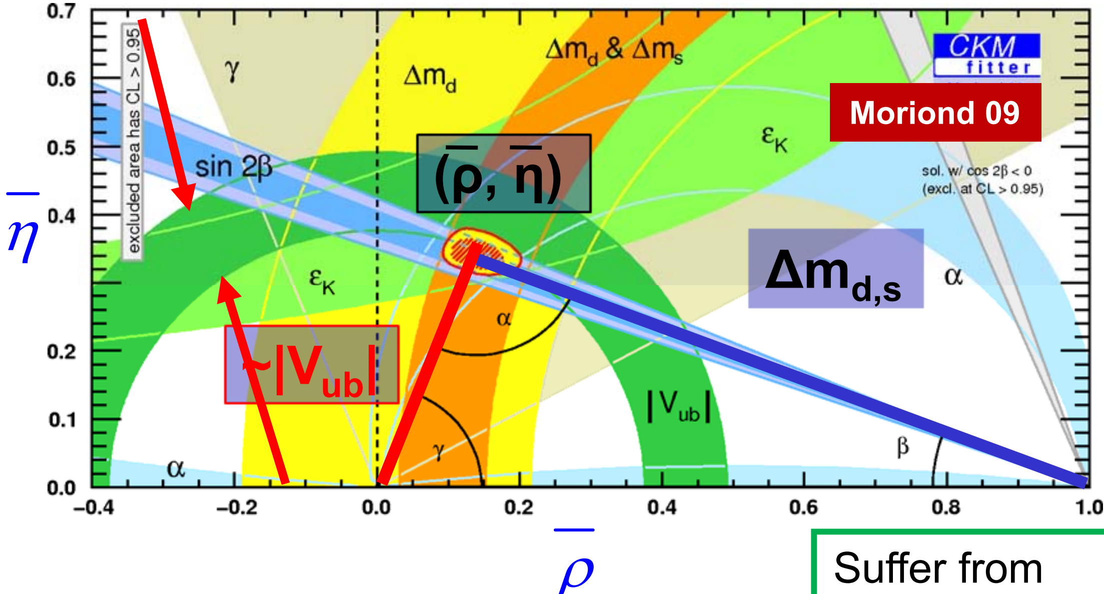
$$\frac{d\Gamma(D\to K(\pi)e\nu)}{dq^2}=\frac{G_F^2\left|V_{cs(cd)}\right|^2 P_{K(\pi)}^3}{24\pi^3}\left|f_+(q^2)\right|^2, where \quad q^2\equiv M_{e\nu}^2$$

  - ✓ Assuming theoretical calculations of form factors, we can extract $|V_{cs}|$ *and* $|V_{cd}|$
  - ✓ Since $|V_{cs}|$ *and* $|V_{cd}|$ are tightly constrained by unitarity, we can check theoretical calculations of the form factors
  - ✓ Tested theory can then be applied to B semileptonic decays to extract $|V_{ub}|$.

- New modes: to gain a complete understanding of charm semileptonic decays

- P→V transitions: 3 hadronic form factors are needed.
  No unquenched LQCD calculation exists.

Theory + Experiment = Precision Flavor Physics



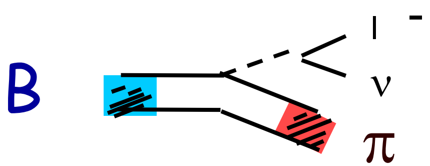
The discovery potential of B physics is limited by systematic errors from QCD (PDG-08):

$$|V_{ub}| = (3.62 \pm 0.22 \pm^{+0.63}_{-0.41}) \times 10^{-3}$$
$$\pm \exp \pm \text{LQCD}$$

One of the most important goals of B physics

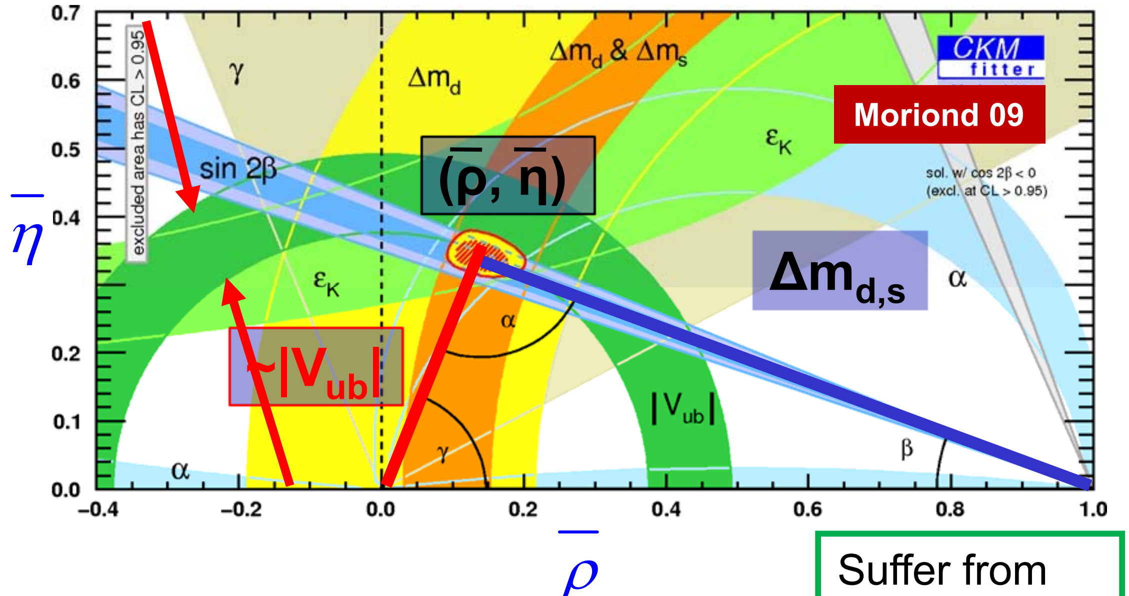
Measured experimentally

Suffer from large theory uncertainty



$$rate \propto [f^{B\to\pi}(q^2)]^2 \quad |V_{ub}|^2$$

Theory + Experiment = Precision Flavor Physics



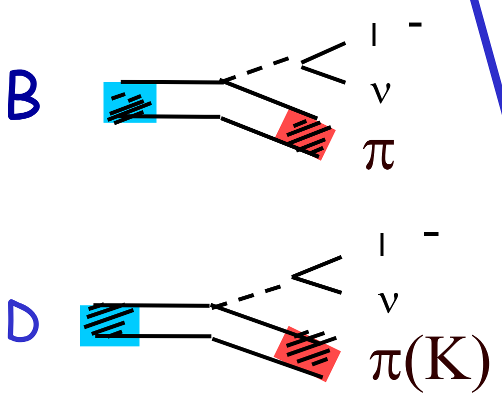
The discovery potential of B physics is limited by systematic errors from QCD (PDG-08):

$$|V_{ub}| = (3.62 \pm 0.22 \pm^{+0.63}_{-0.41}) \times 10^{-3}$$
$$\pm \exp \pm \mathrm{LQCD}$$

One of the most important goals of B physics

Suffer from large theory uncertainty

Measured experimentally



$$rate \propto [f^{B\to\pi}(q^2)]^2 \ |V_{ub}|^2$$

HQS

$$rate \propto [f^{D\to\pi(K)}(q^2)]^2 \ |V_{cd(s)}|^2$$

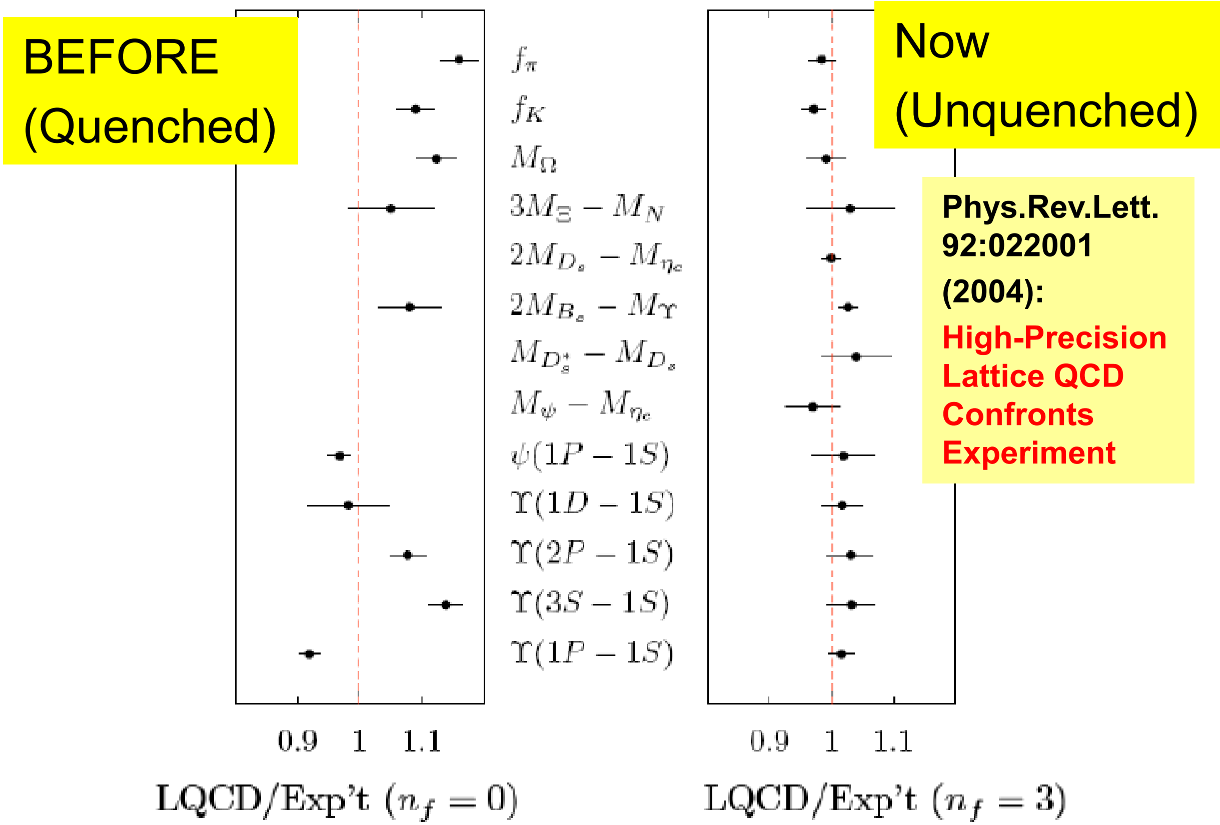
Tightly constrained by CKM unitarity

Theory: A Breakthrough in Lattice QCD

- ❑Revolutionary progress (2003) in algorithms allows inclusion of QCD vacuum polarization.

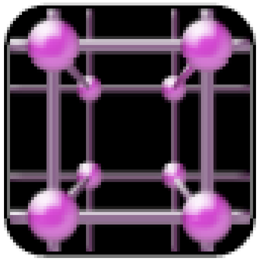
  (Talk by Christine Davies later this morning)
- ❑LQCD demonstrated it can reproduce a wide range of mass differences and decay constants.

These were postdictions



Phys.Rev.Lett. 92:022001 (2004):
High-Precision Lattice QCD Confronts Experiment

- This dramatic improvement needs validation
- *Charm* decay constants f_{D+} & f_{Ds} (next talk by Roy Briere)
- *Charm* semileptonic Form factors



High-Precision Experiments Confront LQCD

e^+e^- collider at charm threshold

- Tagged: $e^+e^- \to \psi(3770) \to D\bar{D}$ or $e^+e^- \to D_s^* D_s$ at 4170 MeV
  - Fully reconstruct one $D(D_s)$ in hadronic final states, study the system recoiling from the D ($D_s + \gamma$)
  - 4-momentum of the semileptonic $D(D_s)$ is known from tagging

    Almost background free, excellent q^2 resolution
- Untagged:(results superseded by tagged results with full dataset)
  - Combine the missing 4-momentum of the events with those of the hadron and lepton to form a D.
  - Larger signal yields, also larger backgrounds

e^+e^- collider at Y(4S)

- Tagged: $e^+e^- \to D_{tag}^{(*)} D_{sig}^{*-} X$, where $X = \pi^{\pm}, \pi^0, K^{\pm}$
  - Fully reconstruct the $D_{tag}^{(*)} X \pi_s^-$, then the 4-momentum of the $\bar{D}_{sig}^0$ is known
- Untagged:
  - Neutrino 4-momentum is estimated from the other particles in the event, the D^0 is then combined with a π^+ to form D^{*+}

Fixed target

D lifetime measurements + Semileptonic decays with D from $D^{*+} \to D^0\pi^+$

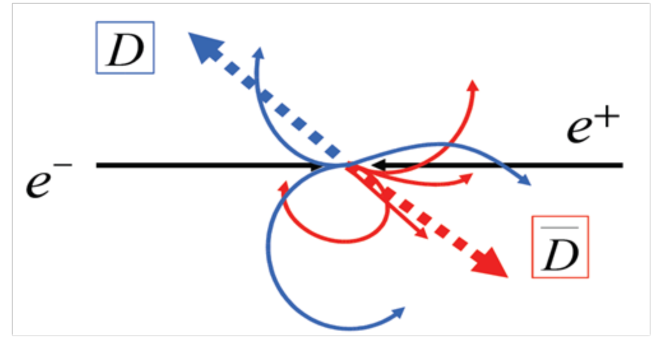
Analysis Technique at 3770 MeV (tagged)

- Candidate events are selected by reconstructing a D, called a tag, in several hadronic modes

- Then we reconstruct the semileptonic decay in the system recoiling from the tag

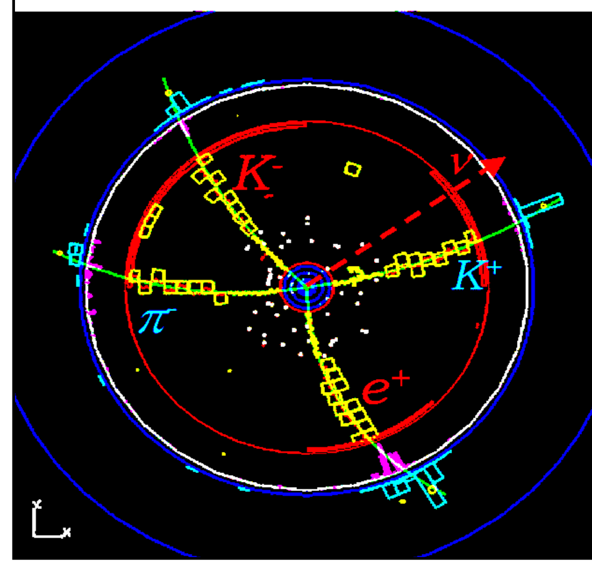
- Two key variables in the reconstruction of a tag: $\Delta E = E_D - E_{beam}$

$$M_{bc} = \sqrt{E_{beam}^2/c^4 - \left|\vec{p}_D\right|^2/c^2}$$



$e^+e^- \rightarrow \psi(3770) \rightarrow D\overline{D}$

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



Tagging creates a single D beam of known 4-momentum

- For semileptonic D : $U = E_{miss} - |\vec{P}_{miss}|$

U peaks at zero for real semileptonic decays

An absolute measurement, independent of the integrated luminosity and number of D mesons in the data sample

D Tagging at 3770 MeV

World's largest data set at 3.770 GeV

$$M_{bc} = \sqrt{E_{beam}^2/c^4 - \left|\vec{p}_D\right|^2/c^2}$$

818 pb^{-1} @3770 (full data set)

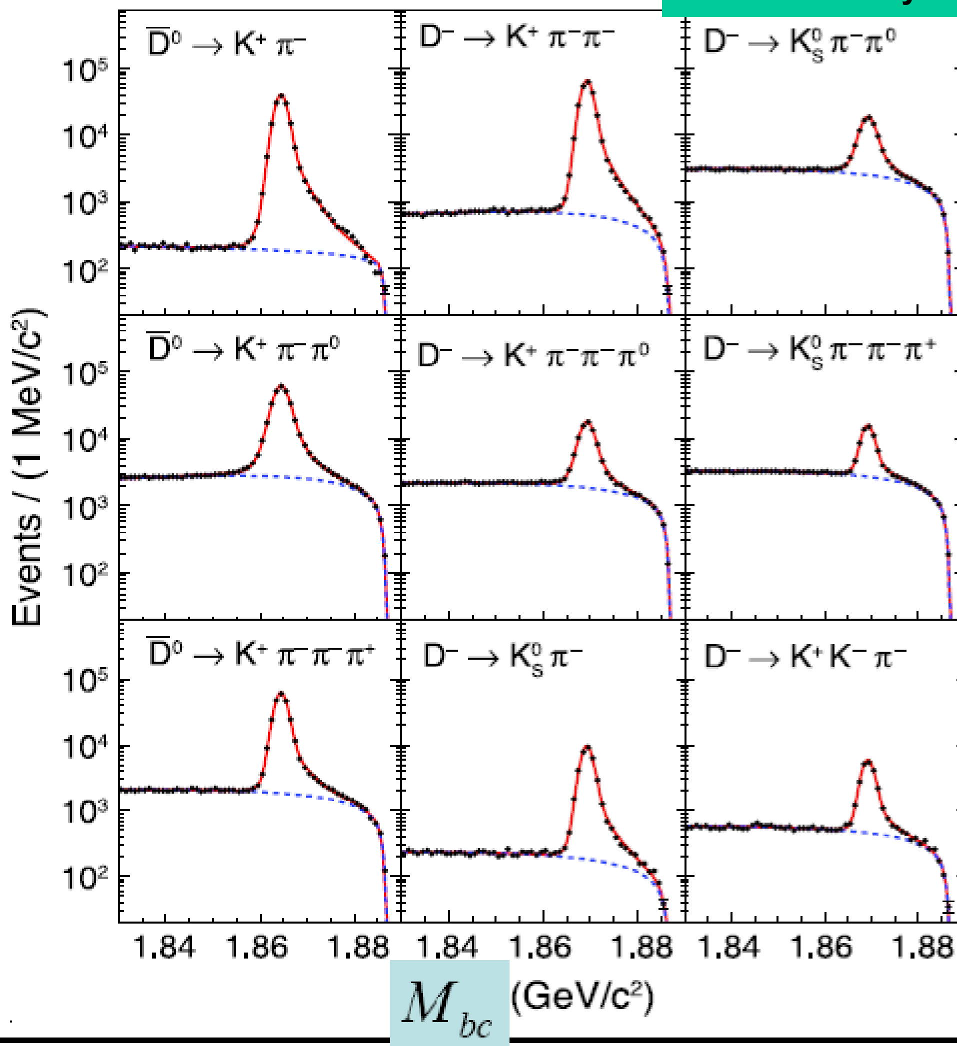
From the 818 pb^{-1}

D→K/πev analysis

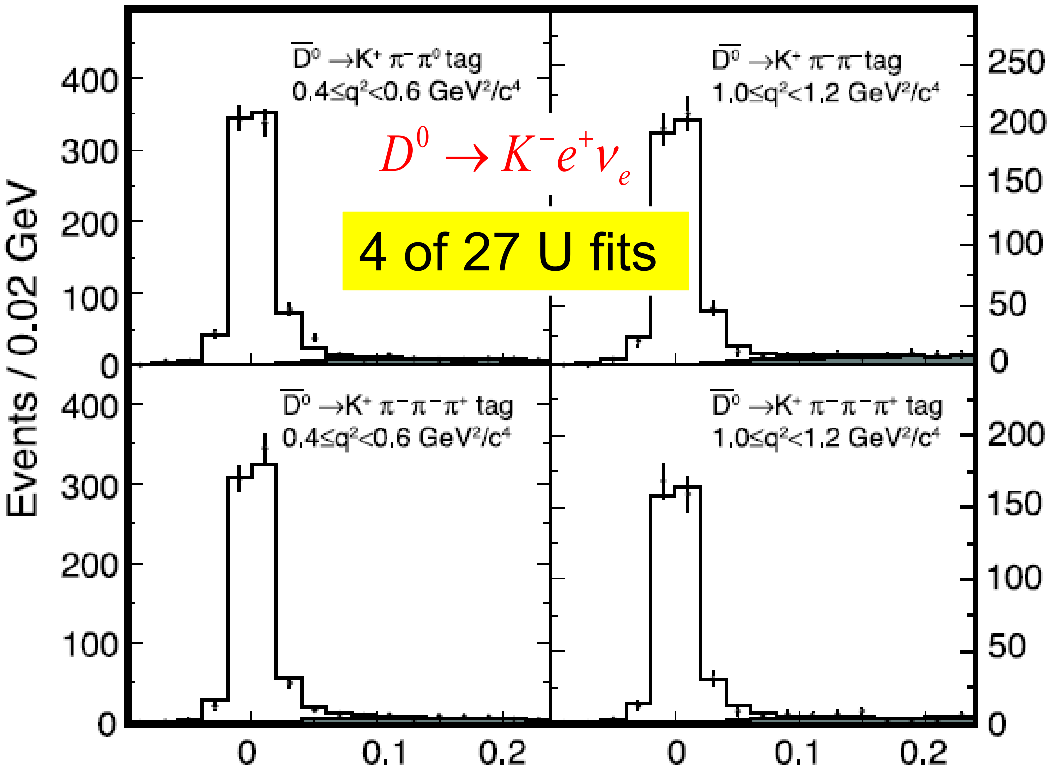
Pure $D\bar{D}$, zero additional particles, ~5-6 charged particles per event

~6.6x 10^5 D^0 and ~4.8 x 10^5 D^+ tags reconstructed from ~5.4 x 10^6 DD events

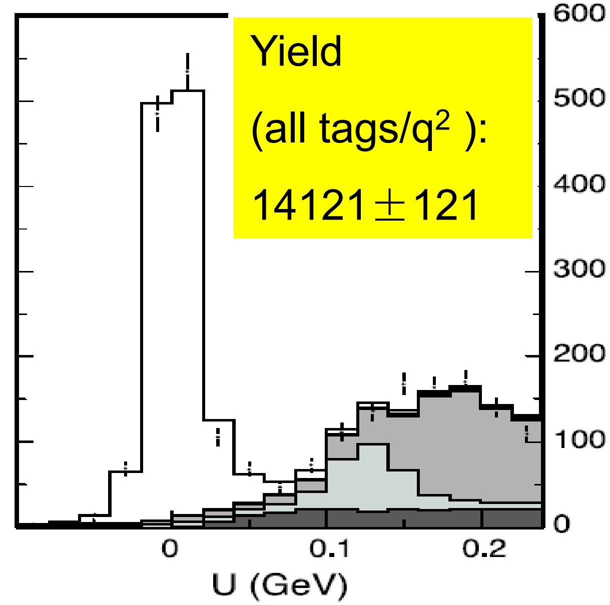
We tag ~20% of the events, compared to ~0.1% of B's at the Υ(4S)



Fits to the U Distributions for $D \to K^- e\nu$



$U = E_{miss} - c\,|\vec{P}_{miss}|$ (GeV)

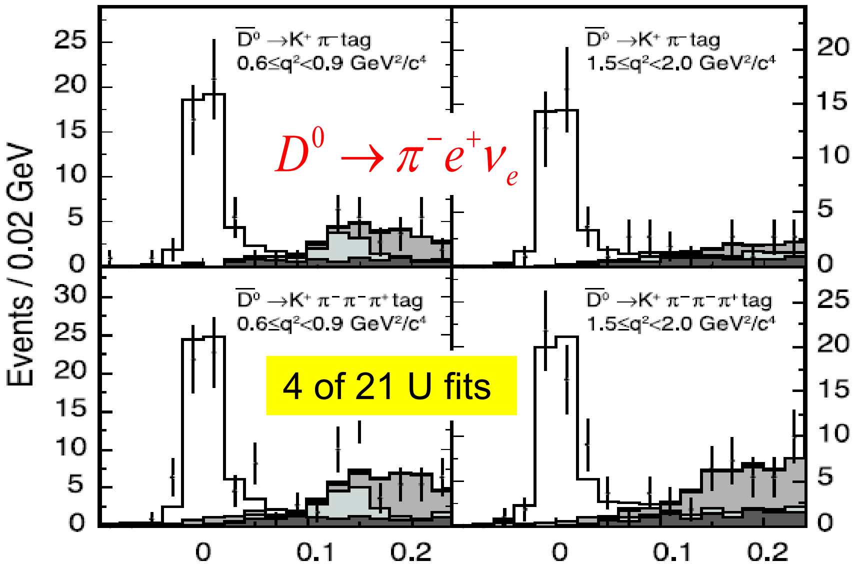


Comparisons with B factories follow

S/N	~300/1
Signal events	~14000
U resolution	~10 MeV
q^2 resolution	~0.008 GeV²/c⁴

- We perform binned likelihood fits to U distributions in each q^2 bin and tag mode
- Signal shapes are taken from signal MC, smeared with double Gaussians
- Background shapes are taken from MC with all $D\overline{D}$ and non-$D\overline{D}$ decays

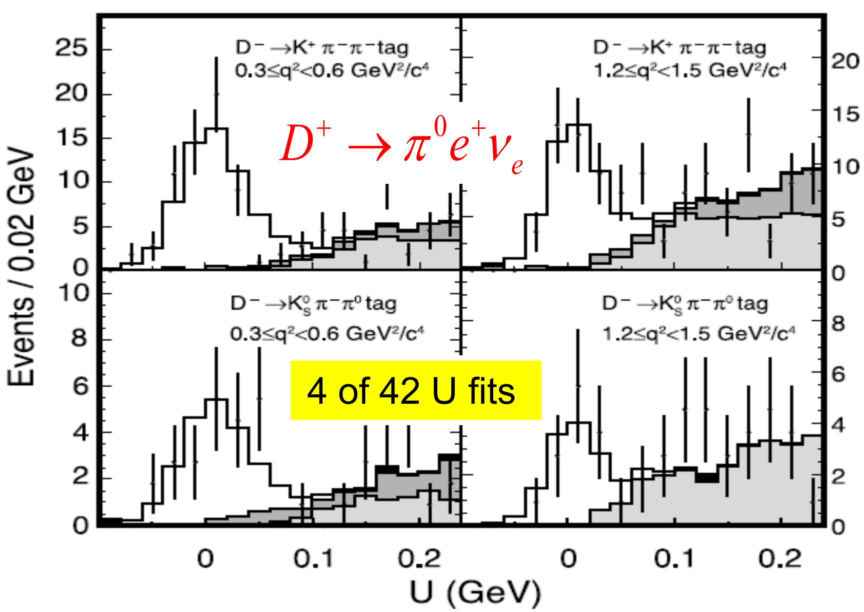
Fits to the U Distributions for $D \to \pi^- / \pi^0 / \bar{K}^0 e\nu$

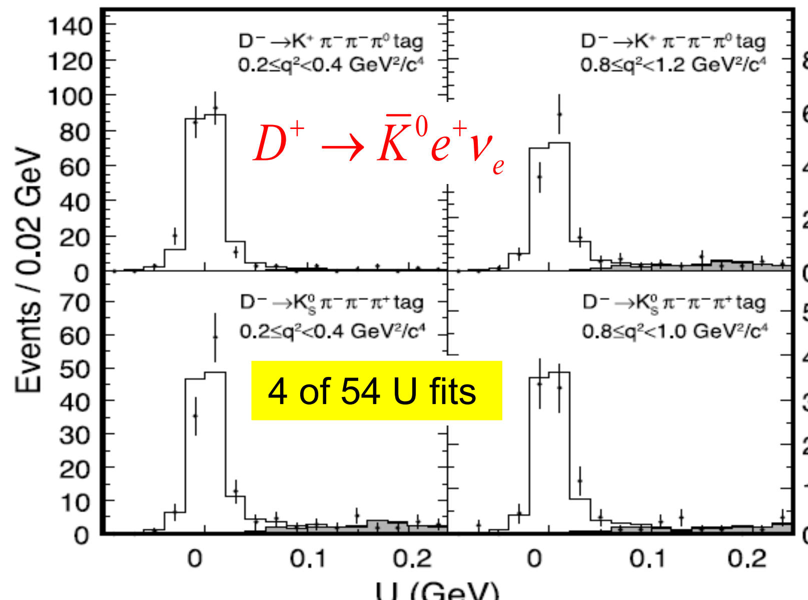


$D^0 \to \pi^- e^+ \nu_e$

S/N	~40/1
Signal events	~1400
U resolution	~10 MeV
q^2 resolution	~0.008 GeV²/c⁴

Comparisons with B factories on the next two slides





$D^0 \to K/\pi\, l^+ \nu$ at Belle

- Tagged Technique:
  [full event reconstruction at Y(4S)]

  $e^+e^- \to D_{tag}^{(*)} D_{sig}^{*-} X$, where $X = \pi^\pm, \pi^0, K^\pm$

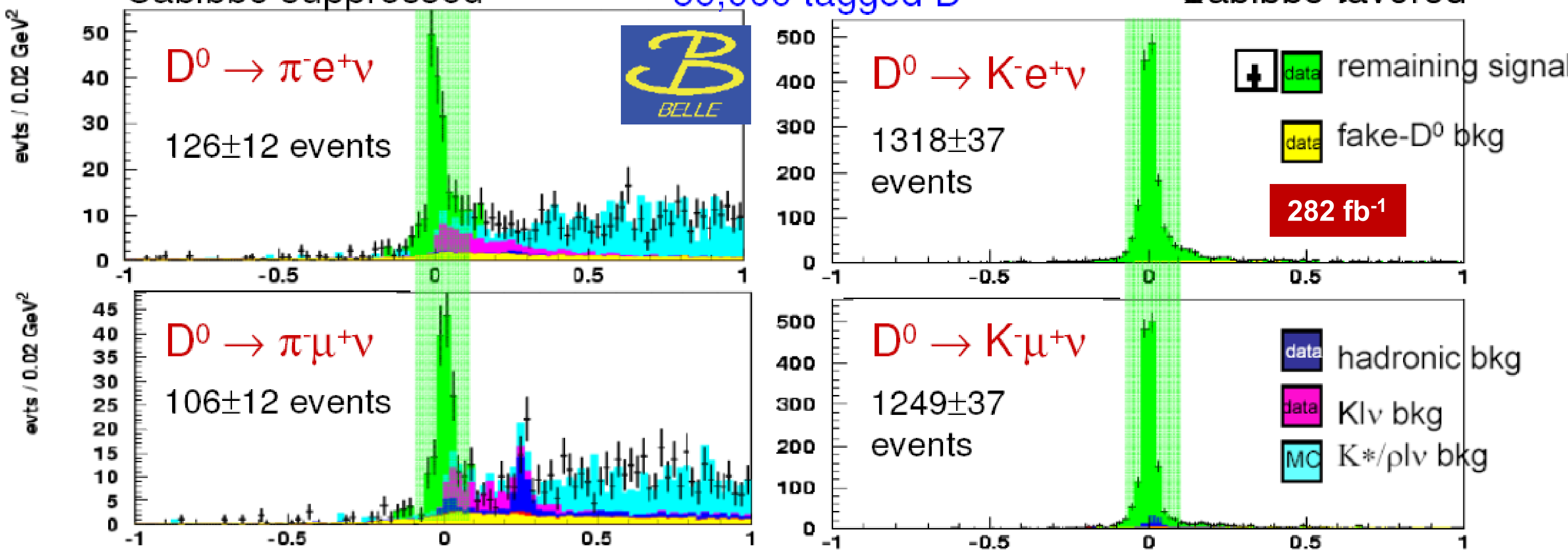
  Fully reconstruct the $D_{tag}^{(*)} X \pi_s^-$,

  then the 4-momentum of the $\bar{D}_{sig}^0$ is known

Compared to CLEO-c (818 pb^{-1} tagged):

- 350 times more luminosity
  5 times fewer signal events
- $\sigma(q^2)$ a factor of 2 larger
- S/N 10 times smaller

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



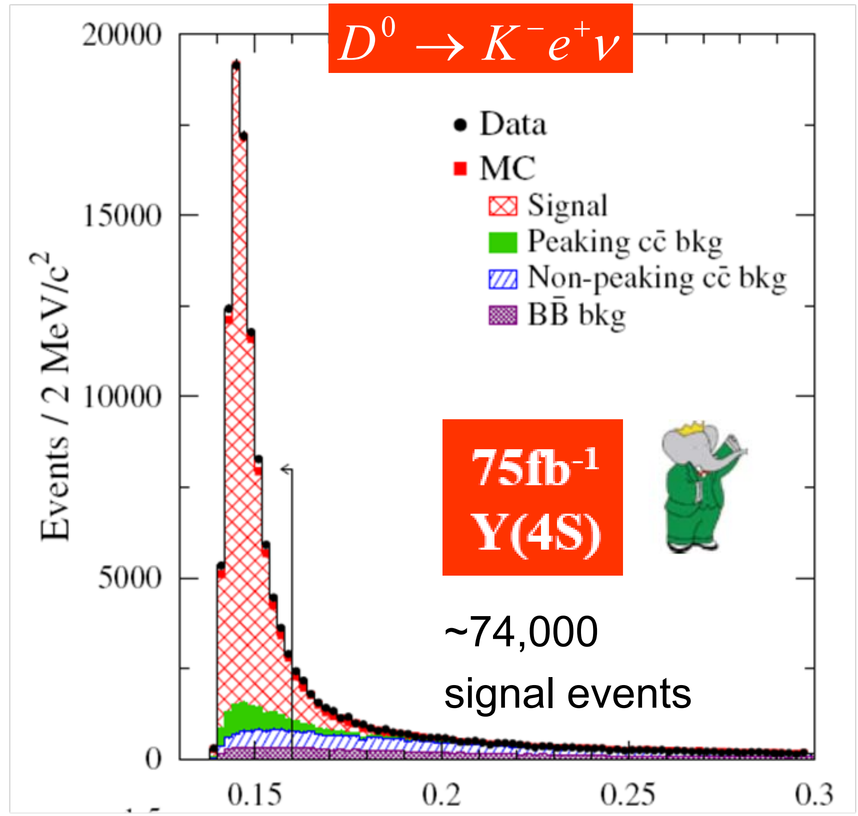
Phys.Rev.Lett.97:061804(2006)

$m_{miss}^2 = E_{miss}^2 - p_{miss}^2$ (GeV)

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

PRD 76, 052005 (2007)

- ❑Untagged Technique: Neutrino 4-momentum is estimated from the other particles in the event.
- ❑ The D^0 originates from $D^{*+} \to D^0\pi^+$
- ❑Normalized to PDG06 $B(D^0 \to K^-\pi^+)$ (dominated by CLEO-c measurement, see Jonas Rademacker talk on Sunday)



$$\delta(m) = m(D^0\pi^+) - m(D^0)$$

Compared to CLEO-c (818 pb^{-1} tagged):

- ❑100 times more luminosity
  5 times more signal events
- ❑$\sigma(q^2)$ a factor of 20 larger
- ❑ S/N 40 times smaller

Measurements for D^+ modes have not been made at B factories!

Method less suitable for Cabibbo suppressed decays

Semileptonic Decay Form Factors

- Form factors relate to the probability of forming final state at given q^2 .
- Theoretical predictions for form factors are needed to turn the measured rates into $|V_{cx}|$ 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, and LQCD.
- LQCD is systematically improvable and aims for several percent precision.

- Assuming zero lepton mass:

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.

Form Factor Parameterizations

In general: $$f_+(q^2) = \frac{f_+(0)}{1-\lambda}\frac{1}{\left(1-q^2/m^2_{pole}\right)} + \frac{1}{\pi}\int_{(m_D+m_P)^2}^{\infty}\frac{\mathrm{Im}(f_+(t))}{t-q^2-i\varepsilon}dt$$

Models

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

Measure $f_+(0)$ & m_{pole}

Modified Pole $$f_+(q^2) = \frac{f_+(0)}{\left(1-q^2/m^2_{pole}\right)\left(1-\alpha\, q^2/m^2_{pole}\right)}$$

Measure $f_+(0)$ & α

$m_{pole} = m(D^*_{(s)})$

(Allows for additional poles)

Model independent

Series Expansion

form factors can be written as: $$f_+(q^2) = \frac{1}{P(q^2)\phi(q^2)}\sum_{k=0}^{\infty} a_k(t_0)[z(q^2,t_0)]^k$$

accounts for D_S^* pole

ensure a_K's good behaviour

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

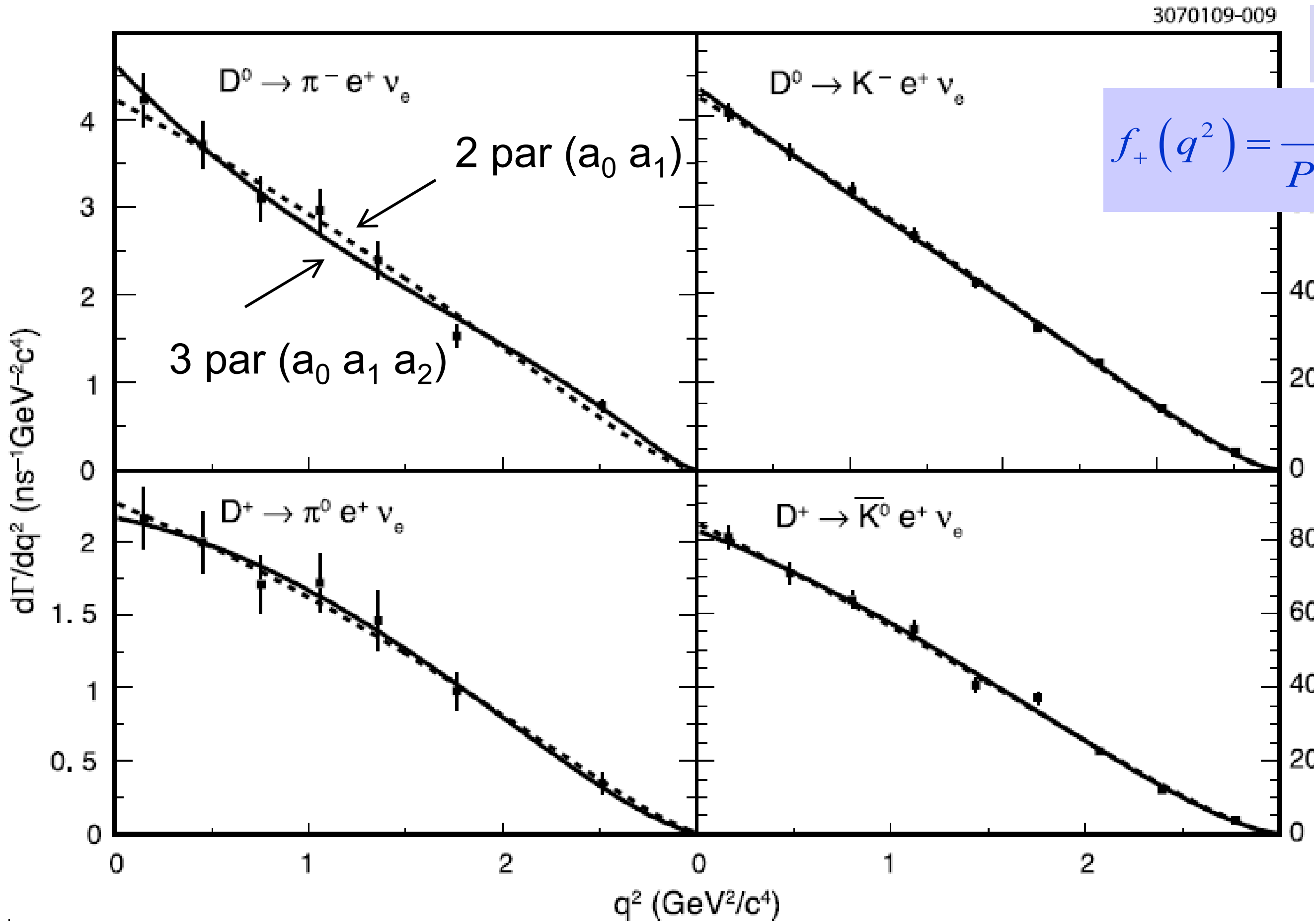
$t_\pm \equiv \left(M_D \pm m_{K,\pi}\right)^2$, t_0: arbitrary q^2 value that maps to z=0

z is small and converges quickly, linear or quadratic is sufficient to describe the data

Measure a_0, $r_1 = a_1/a_0$, and $r_2=a_2/a_0$

Becher & Hill, Phys. Lett. B 633, 61 (2006)

$D \to K/\pi e^+ \nu$: Fits to the $d\Gamma/dq^2$ Distributions



Fit to Becher-Hill Series

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

Other form factor parameterizations exist, but are only used as functional forms as their physical pictures are not supported by the data

Simultaneous fits to isospin conjugate modes are also performed

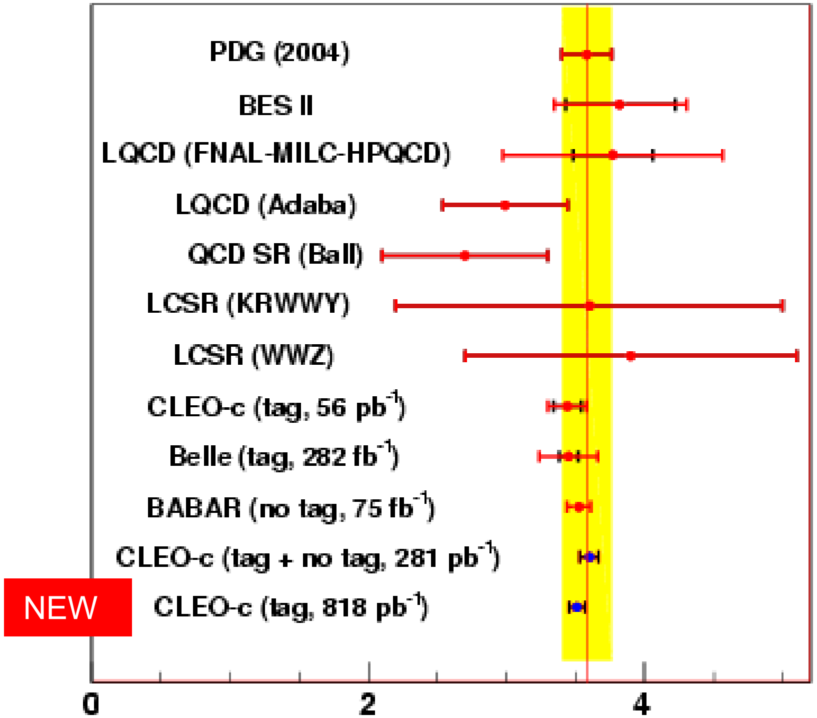
Experimentally measured decay rates $\Gamma_i^{measured}$

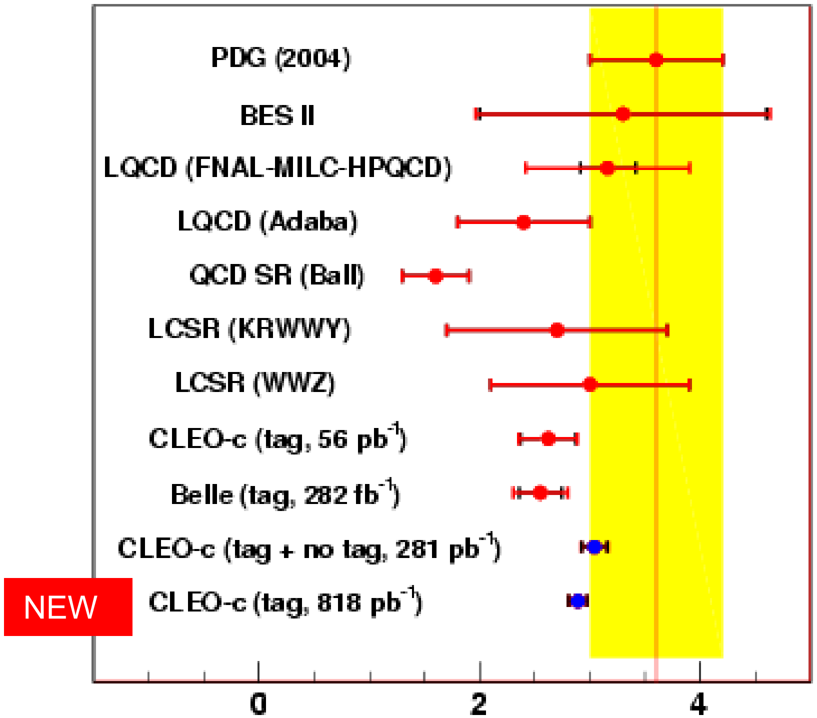
χ^2

Theoretically predicted decay rates

$$\Gamma_i^{predicted} = \int_i d\Gamma = \frac{G_F^2 |V_{Qq'}|^2}{24\pi^3} \int_i |f_+(q^2)|^2 \; p_{P'}^3 dq^2$$

D→K/πe⁺ν Branching fractions





$\mathrm{B}(D^0 \to K^- e^+ \nu) \times 10^{-2}$

$\mathrm{B}(D^0 \to \pi^- e^+ \nu) \times 10^{-3}$

$3.50(3)(4)\,\%$
$(\text{CLEO-c } 818 \text{ pb}^{-1})$

$\sigma(B(Ke\nu))/B(Ke\nu) \sim 1.4\%$
$\sigma(B(\pi e\nu))/B(\pi e\nu) \sim 3.0\%$

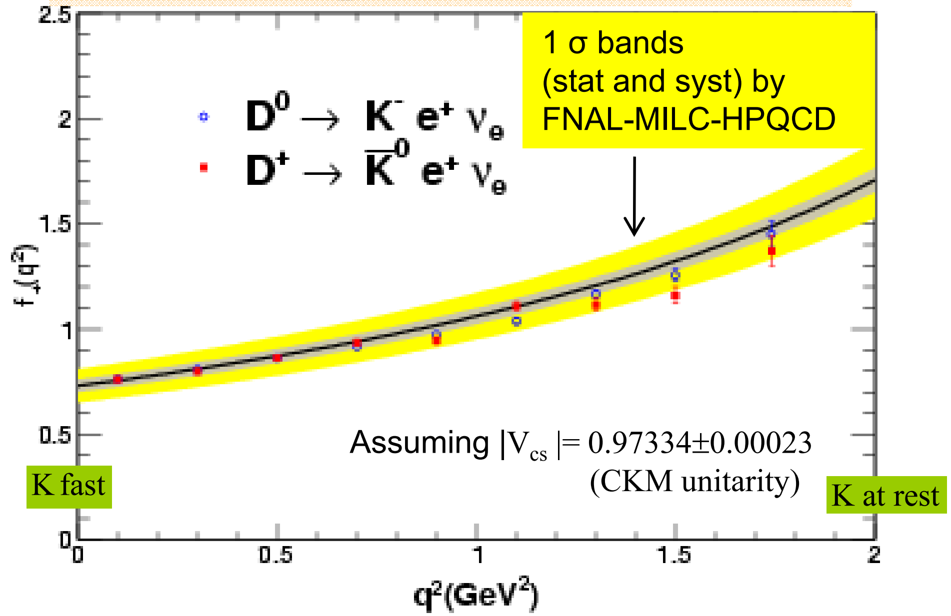
$0.288(8)(3)\%$
$(\text{CLEO-c } 818 \text{ pb}^{-1})$

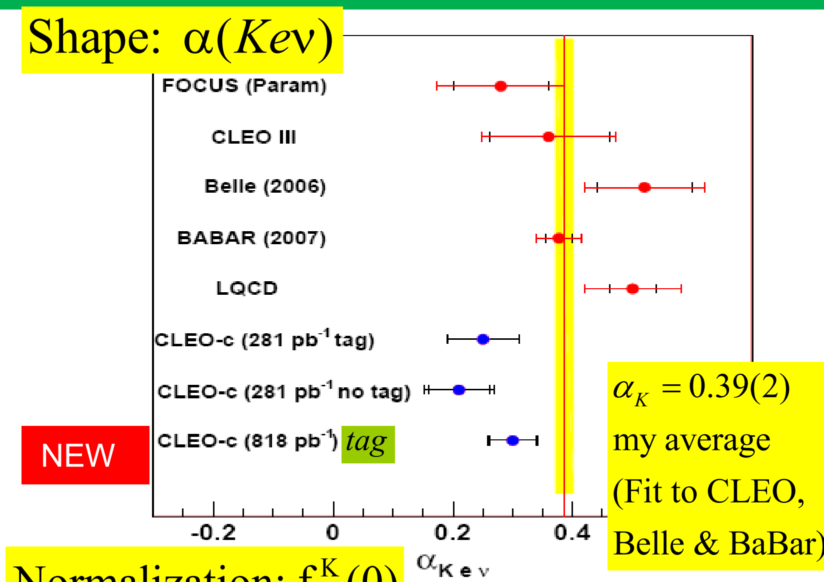
Precision measurements from BABAR/Belle/CLEO-c.
CLEO-c most precise. Theoretical precision lags experiment.

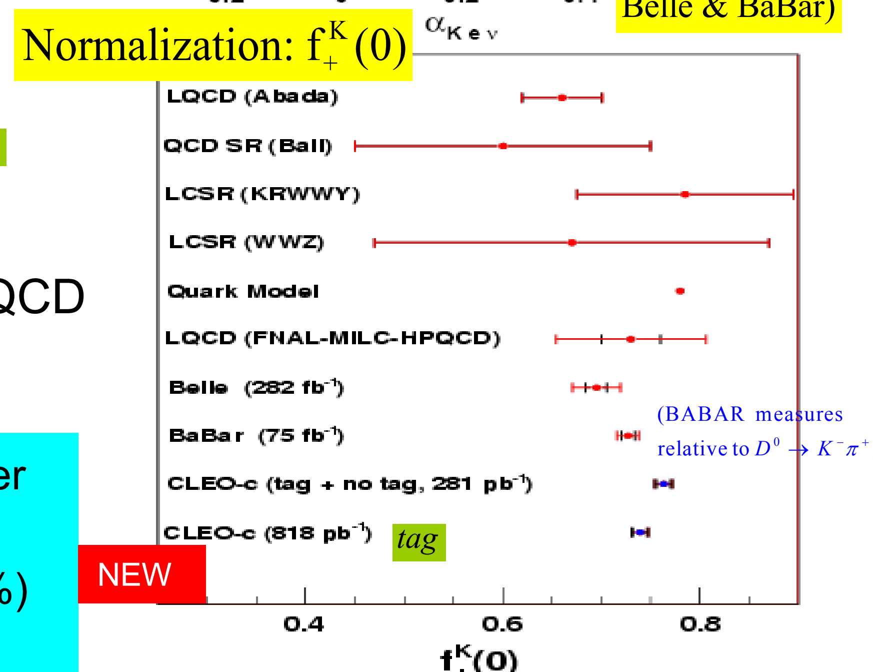
$D \to K e^+\nu$ Form Factor: Test of LQCD

Form factor measures probability hadron will be formed

$$\left|V_{cs(cd)}\right| f_+(q^2) \sim \left[\frac{\Delta\Gamma_i(D \to K(\pi)e\nu)}{\Delta q_i^2} / P^3_{K(\pi)i} \right]^{1/2}$$







Modified pole model used to compare with LQCD

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

α : CLEO-c prefers smaller value for shape parameter than other experiments

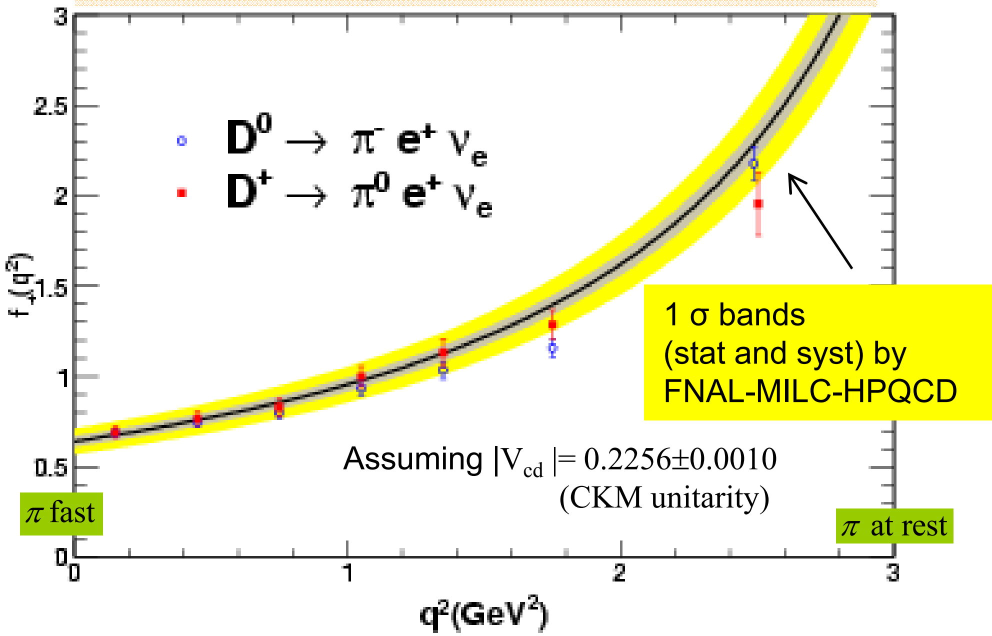
$f_+(0)$: experiments (1.2%) consistent with LQCD (10%)

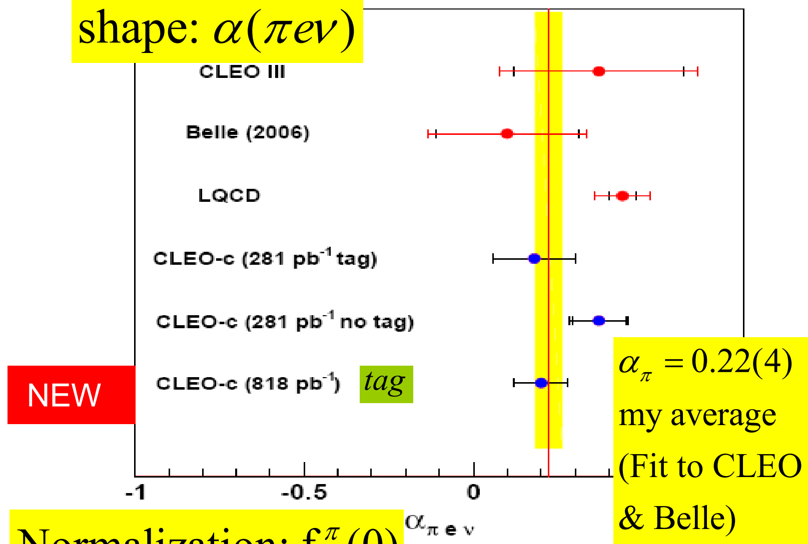
CLEO-c is most precise. *Theoretical precision lags.*

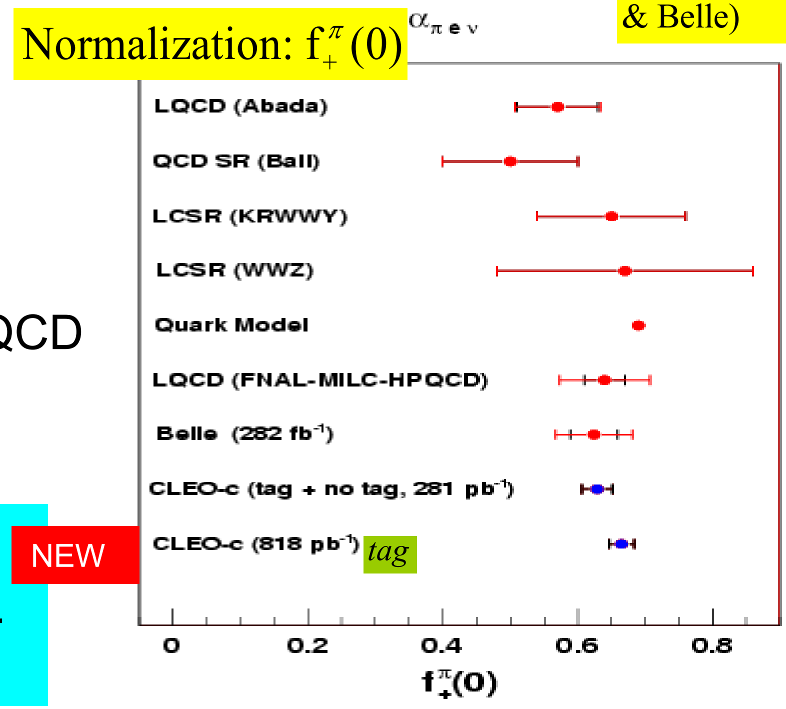
D→πe⁺ν Form Factor: Test of LQCD

Form factor measures probability hadron will be formed

$$|V_{cs(cd)}|\,f_+(q^2) \sim \left[\frac{\Delta\Gamma_i(D\to K(\pi)e\nu)}{\Delta q_i^2} / P^3_{K(\pi)i}\right]^{1/2}$$







Modified pole model used to compare with LQCD

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

α : CLEO-c measurements are compatible with LQCD

$f_+(0)$: experiments (2.9%) consistent with LQCD (10%).

CLEO-c is most precise. *Theoretical precision lags.*

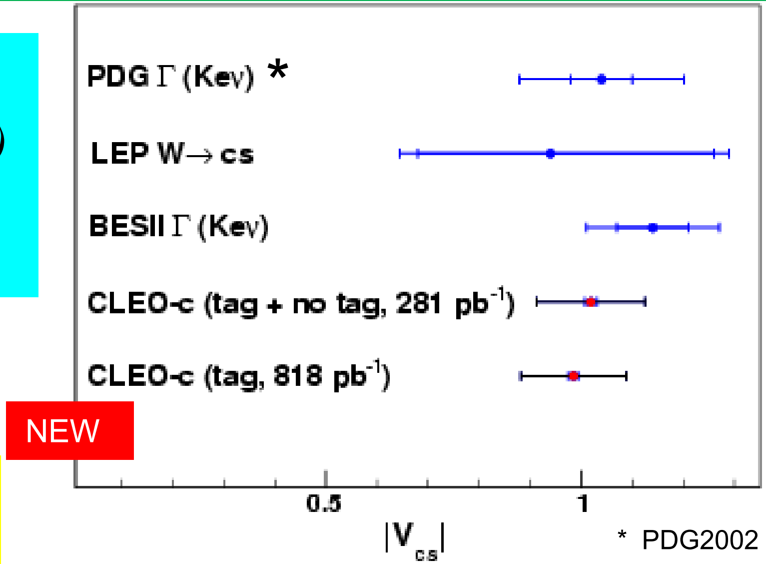
$|V_{cs}|$ and $|V_{cd}|$ Results

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 $|V_{cs}|$ $\sigma(|V_{cs}|)/|V_{cs}| \sim 1.1\%(\text{expt}) \oplus 10\%(\text{theory})$

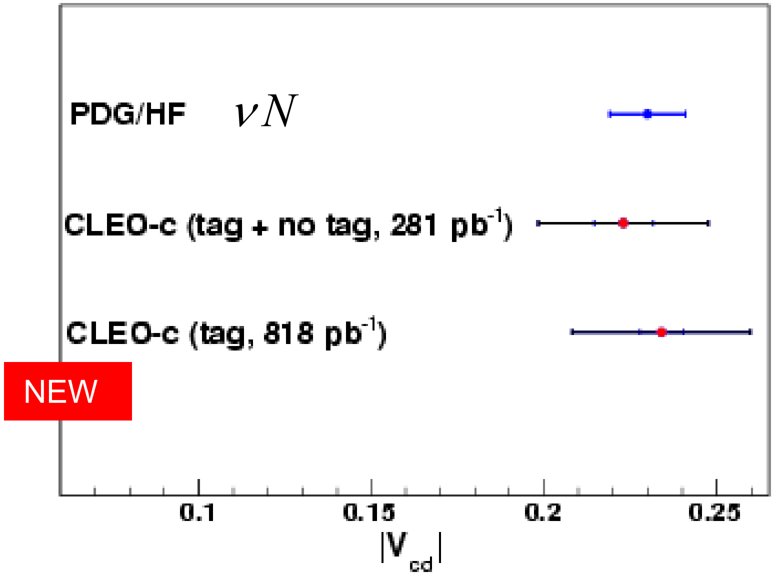
$CLEO-c$	$\lvert V_{cs}\rvert$
(818 pb^{-1})	$0.985 \pm 0.009 \pm 0.006 \pm 0.103$
	stat syst theory



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 pb^{-1})	$0.234 \pm 0.007 \pm 0.002 \pm 0.025$
	stat syst theory



D → ρeν (tagged, 281/pb)

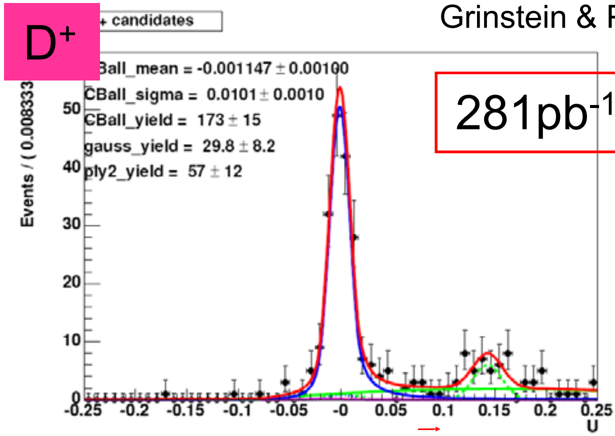
Interest: 1st measurement of FF in Cabibbo suppressed charm P→ V decays +

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

Need $D \to K^* e\nu$, $D \to \rho e\nu$ FF

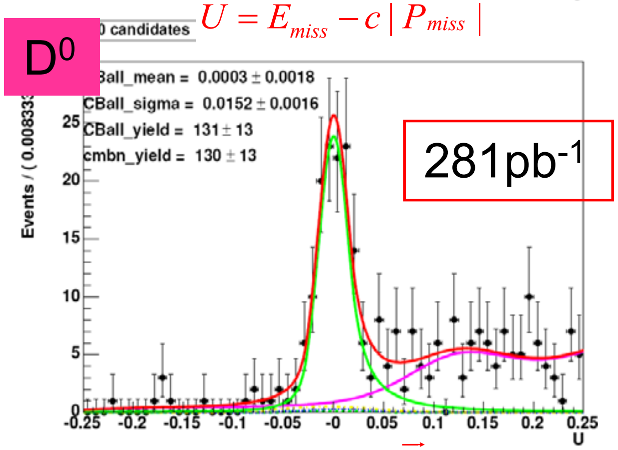
Grinstein & Pirjol [hep-ph/0404250]

D+



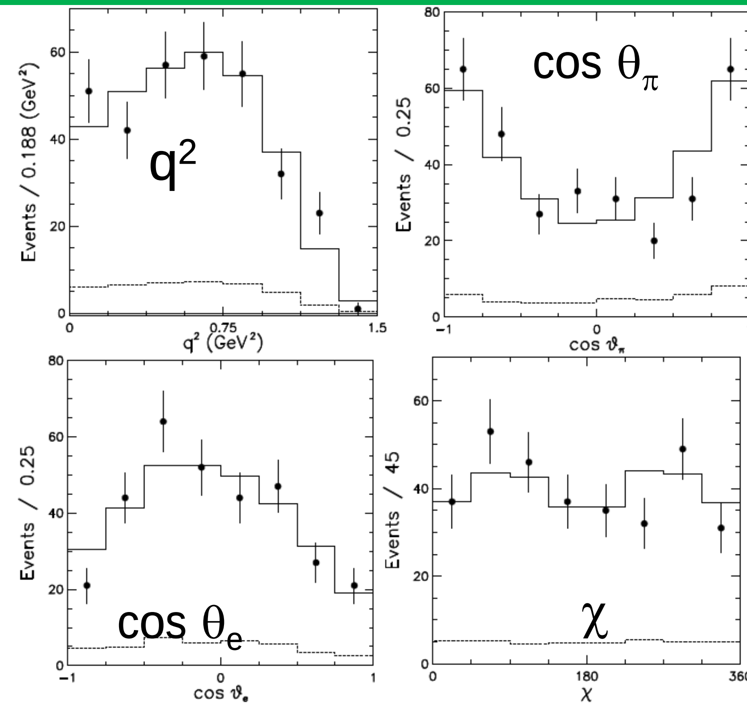
$U = E_{miss} - c|\vec{P}_{miss}|$

D0



$U = E_{miss} - c|\vec{P}_{miss}|$

Fixed background shape and signal tails from MC



Line is projection for fitted R_V, R_2

$B(D^0 \to \rho^- e^+\nu) = (1.56\pm0.16\pm0.09)\times10^{-3}$

$B(D^+ \to \rho^0 e^+\nu) = (2.32\pm0.20\pm0.12)\times10^{-3}$

Isospin average:

$\Gamma(D^0 \to \rho^- e^+\nu) = (0.41\pm0.03\pm0.02)\times10^{-2}\ ps^{-1}$

Simultaneous fit to $D^+ \to \rho^0 e\nu$, $D^0 \to \rho^- e\nu$

$R_V = 1.40 \pm 0.25 \pm 0.03$

$R_2 = 0.57 \pm 0.18 \pm 0.06$

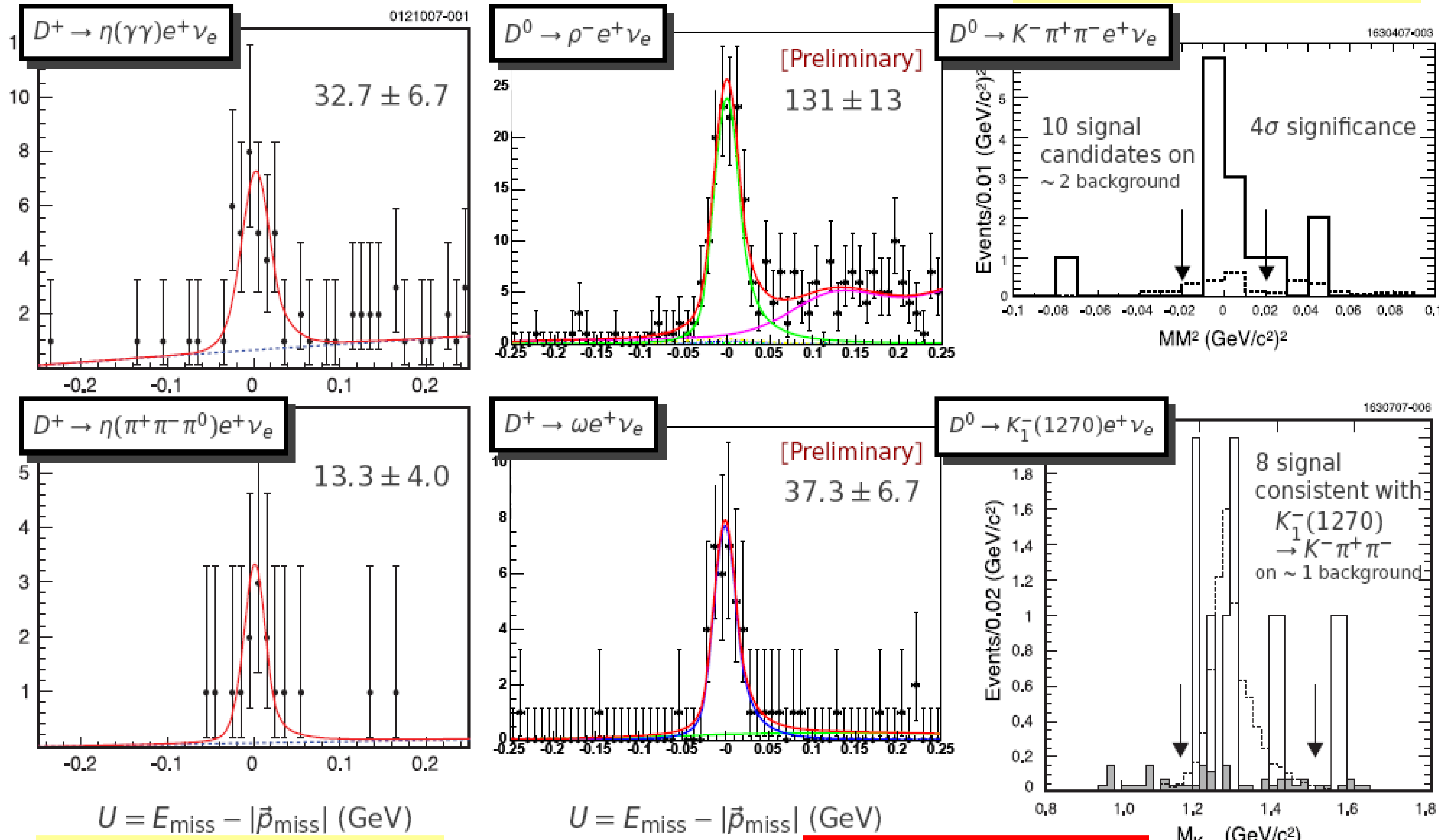
PRELIMINARY

Update to full data set soon

Observations of New D Semileptonic Modes

281 pb^{-1} @3770

Phys.Rev.Lett.99:191801(2007)



Phys.Rev.Lett.102:081801(2009)

Expect more modes soon

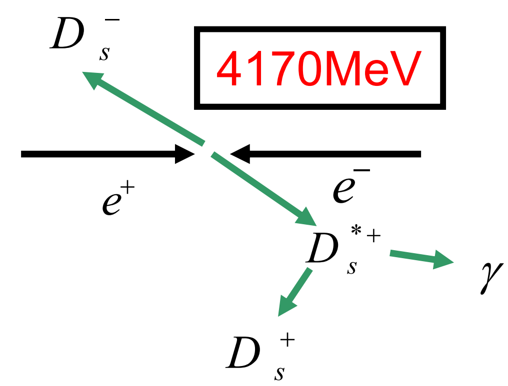
Analysis Technique at 4170 MeV (tagged)

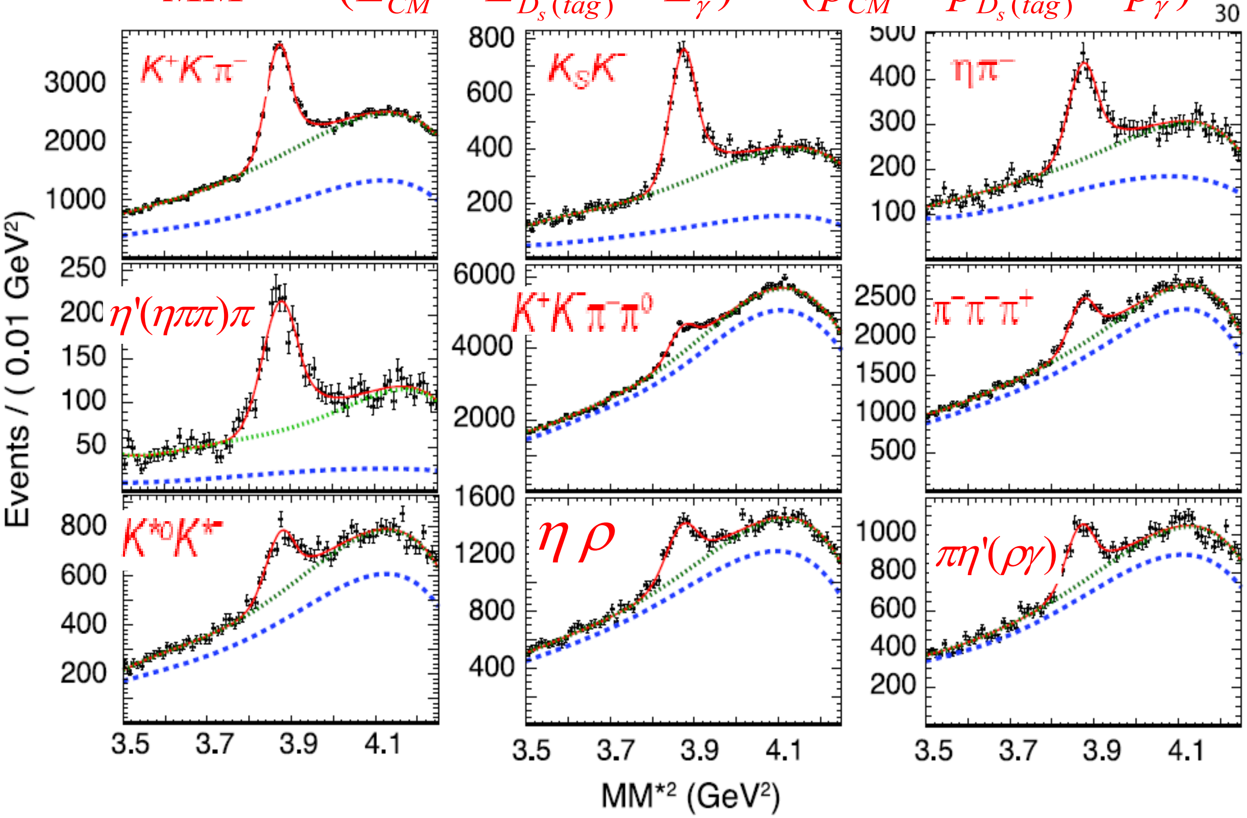
- Candidate events are selected by reconstructing a D_s in several hadronic modes
- The tag is then combined with a well reconstructed γ, The missing mass squared against the γ-tag pair

$$MM^{*2} = (E_{CM} - E_{D_s(tag)} - E_\gamma)^2 - (\vec{p}_{CM} - \vec{p}_{D_s(tag)} - \vec{p}_\gamma)^2$$

$e^+e^- \to D^*_s D_s$

4170MeV





preliminary

9 D_s tag modes:

N(tag)=70514±963

N(tag+γ)=43859±936

reconstructed from ~5.5 x 10^5 D_s^* D_s events

600 pb^{-1} @4170

(CLEO-c full dataset)

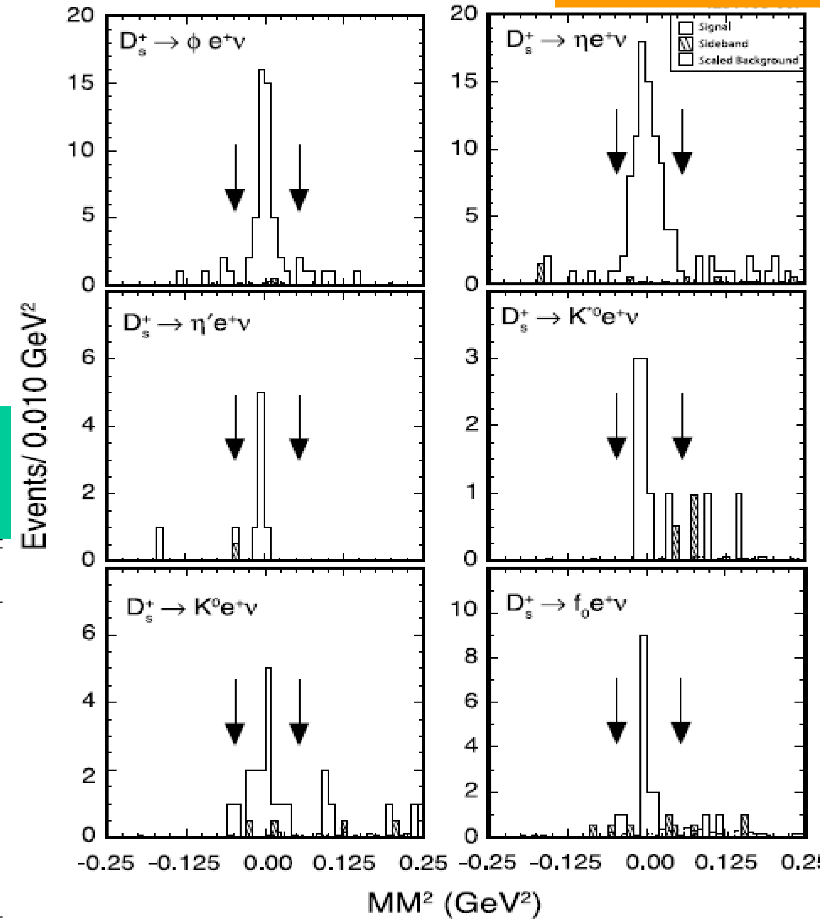
Exclusive D_s Semileptonic Decays

- No other significant D_s semileptonic branching fraction is expected.
- Total width of these exclusive modes is 16% lower than the D^0/D^+ semileptonic widths.
- Shed light on η-η'-glueball mixing
- Direct observation of a semileptonic decay including a scalar meson in the final state.

$$MM^2 = (E_{CM} - E_{D_s(tag)} - E_\gamma - E_e - E_{had})^2$$
$$-(-\vec{p}_{D_s(tag)} - \vec{p}_\gamma - \vec{p}_e - \vec{p}_{had})^2,$$

in the CM system

arXiv:0903:0601



310 pb⁻¹ @4170

(Half of full dataset)

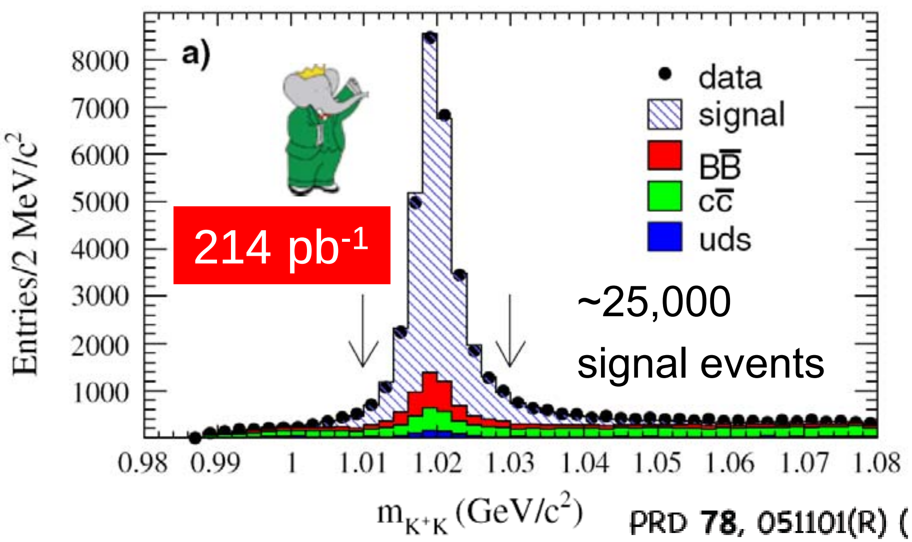
Signal Mode	$\mathcal{B}(\%)$
$D_s^+ \to \phi e^+ \nu_e$	$2.29 \pm 0.37 \pm 0.11$
$D_s^+ \to \eta e^+ \nu_e$	$2.48 \pm 0.29 \pm 0.13$
$D_s^+ \to \eta' e^+ \nu_e$	$0.91 \pm 0.33 \pm 0.05$
$D_s^+ \to K^0 e^+ \nu_e$	$0.37 \pm 0.10 \pm 0.02$
$D_s^+ \to K^{*0} e^+ \nu_e$	$0.18 \pm 0.07 \pm 0.01$
$D_s^+ \to f_0 e^+ \nu_e$	$0.13 \pm 0.04 \pm 0.01$

poster by Koloina Randrianarivony

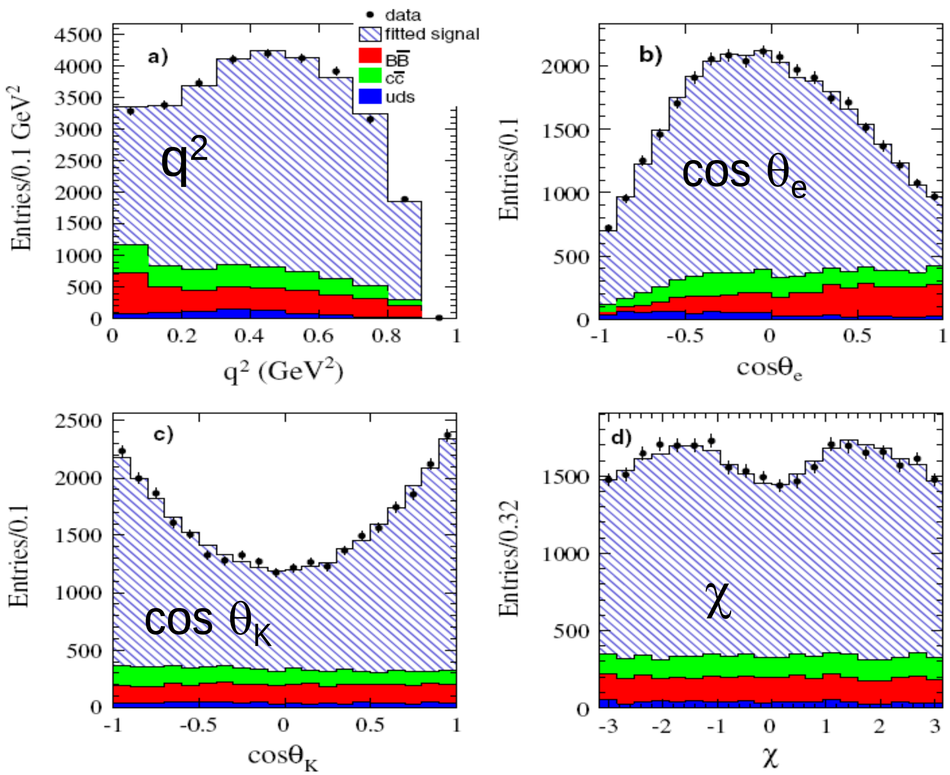
$B(D_s^+ \to f_0(980) e^+ \nu)$
$\times B(f_0 \to \pi^+ \pi^-)$ →

$D_s^+ \to K^+K^-e^+\nu$ at BaBar

- Higher mass of the spectator s-quark → LQCD calculates the form factor more accurately
- Same method as the BaBar $D^0 \to K^-e^+\nu$ analysis, except that no D* is used
- Normalized to CLEO-c $B(D_s^+ \to K^+K^-\pi^+)$ (see Jonas Rademacker talk on Sunday)



PRD 78, 051101(R) (2008)



- $B(D_s^+ \to \Phi e\nu) = (2.61 \pm 0.03 \pm 0.08 \pm 0.15) \times 10^{-2}$

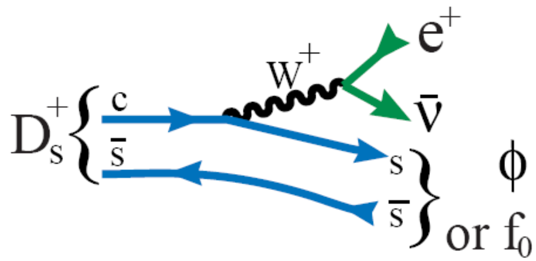
  A small S-wave contribution, possibly $f_0 \to K^+K^-$: $(0.22^{+0.12}_{-0.08} \pm 0.03)\%$ of the $K^+K^-e^+\nu_e$ decay rate.

- r_V is 4σ higher than quenched QCD (hep-lat/0109035) and 2σ higher than r_V from $D^+ \to \bar{K}^* e^+ \nu_e$ (PDG2008)

Dominated by FOCUS

$D_s^+ \to f_0(980) e^+ \nu$

- D_s semileptonic decays provide a very clean environment to study the properties of the $f_0(980)$ meson



600 pb^{-1} @4170
(CLEO-c full dataset)

- It is suggested that $B_s \to J/\Psi f_0$ can be an alternative to $B_s \to J/\Psi \Phi$ to measure CP Violation in the B_s system

Stone & Zhang [PRD79, 074024]

poster by Liming Zhang

NEW

- Many interesting results: PRELIMINARY

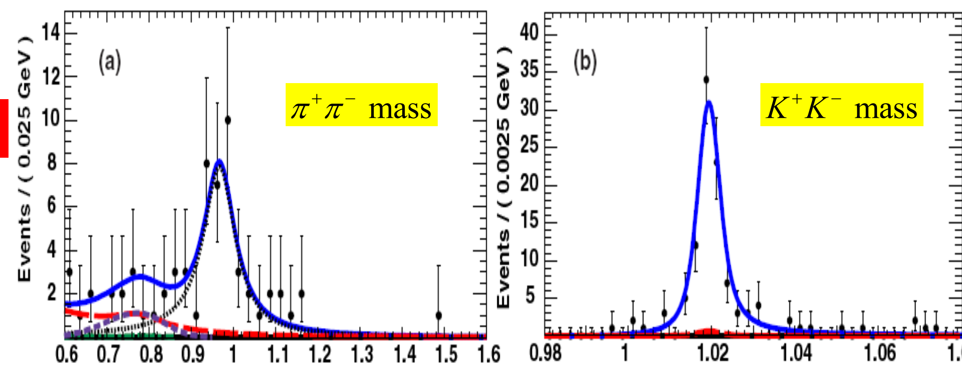
✓ $$\left.\frac{\Gamma(D_s^+ \to f_0(980)e^+\nu, f_0 \to \pi^+\pi^-)}{\Gamma(D_s^+ \to \phi e^+\nu, \phi \to K^+K^-)}\right|_{q^2=0} = (42 \pm 11)\%$$

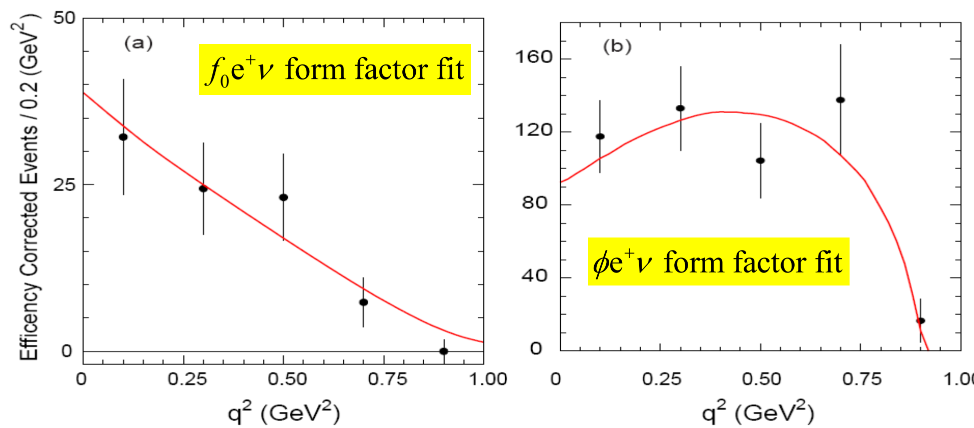
$$\left[\text{Predicted to equal } \frac{\Gamma(B_s \to J/\Psi f_0(980), f_0 \to \pi^+\pi^-)}{\Gamma(B_s \to J/\Psi \phi, \phi \to K^+K^-)}\right]$$

✓ $$B(D_s^+ \to f_0(980)e^+\nu, f_0 \to \pi^+\pi^-) = (0.20 \pm 0.03 \pm 0.01)\%$$
$$B(D_s^+ \to \phi e^+\nu) = (2.36 \pm 0.23 \pm 0.13)\%$$

✓ $$M_{f_0(980)} = (977^{+11}_{-9} \pm 1)\text{ MeV}, \Gamma_{f_0(980)} = (91^{+30}_{-22} \pm 3)\text{ MeV}$$

✓ Simple pole model $M_{\text{pole}} = (1.7^{+4.5}_{-0.7} \pm 0.2)$ GeV





Summary and Prospects

- Charm semileptonic decays are an excellent test ground of LQCD.
- LQCD has been making great progress (talk by Christine Davies later today)
- Experimental precision in charm semileptonic decays has been greatly improved, thanks to contributions from CLEO-c, BaBar, Belle, and FOCUS.
  - Observations of new semileptonic modes in both D and D_s decays.
  - More precise determinations of branching fractions for existing modes.
  - $D \to Ke^+\nu$, $D \to \pi e^+\nu$ form factors in general agreement with LQCD.
  - Form factors in many modes have been studied, including D_s semileptonic modes.
  - Best direct measurement of $|V_{cs}|$, measured to ±1.1%(experimental) ± 10%(theory).
  - $|V_{cd}|$ is measured to ±3.1%(experimental) ± 10%(theory).
- Theoretical precision lags. In particular,
  - CLEO-c measures form factor normalizations for $D \to Ke^+\nu$, $D \to \pi e^+\nu$ to 1% and 3%, respectively, while LQCD predicts them at 10% level.

Summary and Prospects

- Charm semileptonic decays are an excellent test ground of LQCD.
- LQCD has been making great progress (talk by Christine Davies later today)
- Experimental precision in charm semileptonic decays has been greatly improved, thanks to contributions from CLEO-c, BaBar, Belle, and FOCUS.
  - Observations of new semileptonic modes in both D and D_s decays.
  - More precise determinations of branching fractions for existing modes.
  - $D \to Ke^+\nu$, $D \to \pi e^+\nu$ form factors in general agreement with LQCD.
  - Form factors in many modes have been studied, including D_s semileptonic modes.
  - Best direct measurement of $|V_{cs}|$, measured to ±1.1%(experimental) ± 10%(theory).
  - $|V_{cd}|$ is measured to ±3.1%(experimental) ± 10%(theory).
- Theoretical precision lags. In particular,
  - CLEO-c measures form factor normalizations for $D \to Ke^+\nu$, $D \to \pi e^+\nu$ to 1% and 3%, respectively, while LQCD predicts them at 10% level.
- Future prospects:
  - More exciting results from the above mentioned experiments are yet to come.

    Novel event reconstructions are being tried.

    Many results are in the process of being updated using larger data sets.

    Larger data sets enable some measurements previously impossible
  - We are eagerly awaiting more precise LQCD calculations of semileptonic form factors
  - Next big player: BESIII (talk by Roy Briere this afternoon)

Backup Slides

In general: $$f_+(q^2) = \frac{f_+(0)}{1-\alpha}\frac{1}{\left(1-q^2/m_{pole}^2\right)} + \sum_{k=1}^{N}\frac{\rho_K}{1-\frac{1}{\gamma_K}\frac{q^2}{m_{pole}^2}}$$

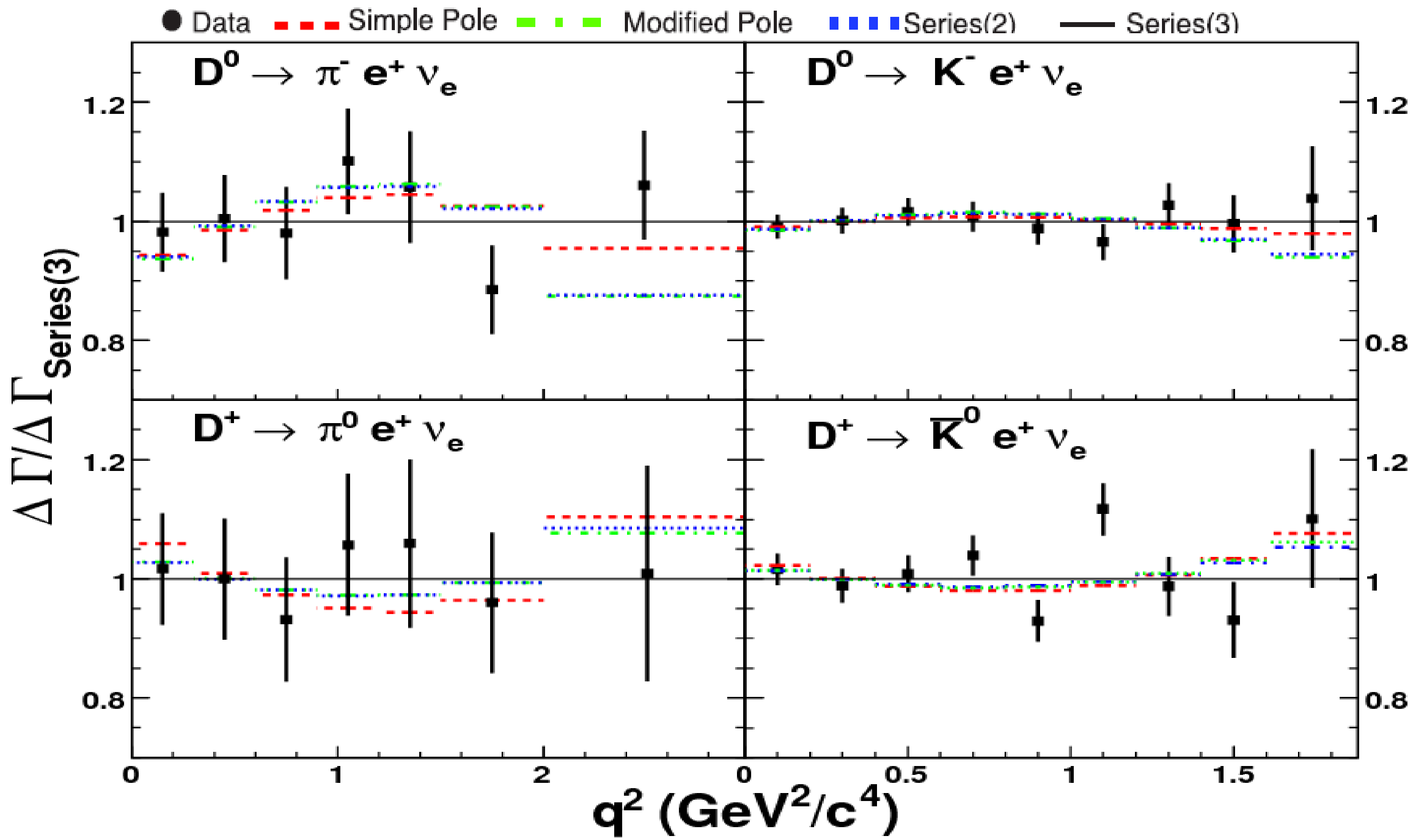
$$\Gamma_i^{measured} = B_i \cdot \Gamma_D = \frac{1}{\tau_D}\frac{\sum_j \varepsilon_{ij}^{-1} N_{tag,SL}^{j}}{N_{tag}}$$

from fits to U

from fits to M_{bc}

Inverse of the efficiency matrix

D→ P e ν, which parameterization to choose?



When the shape parameters are not fixed, each parameterization is able to describe the data with a comparable χ^2 probability.

As data do not support the physical basis for the pole & modified pole models, the model independent Becher-Hill series parameterization is used for **$|V_{cx}|$**.

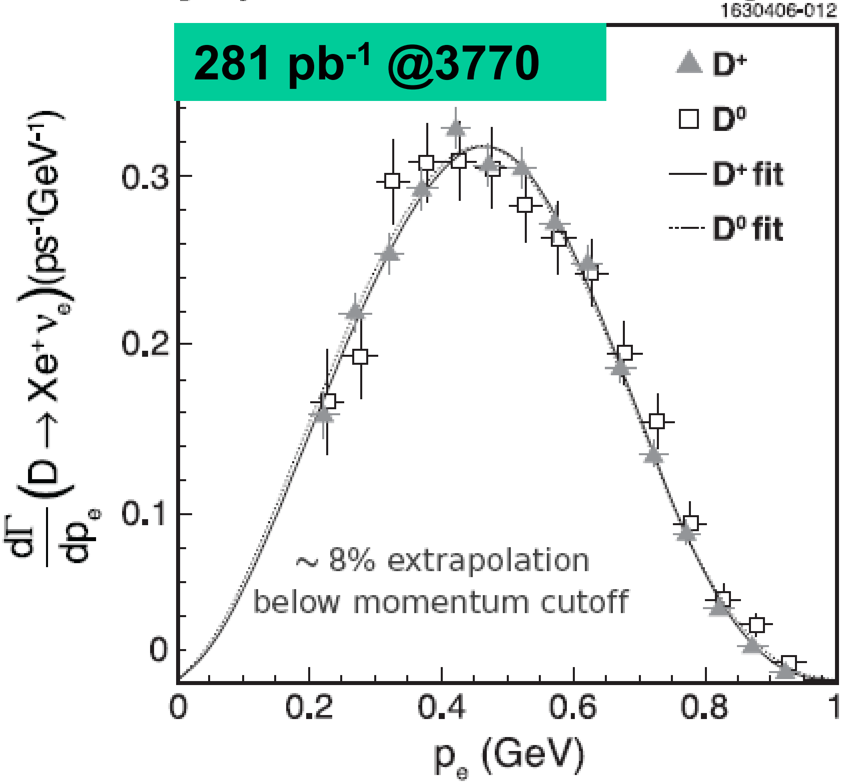
Inclusive $D \to X e \nu$

- Fit observed Lab frame momentum spectra ($d\Gamma/dp_e$) with a shape derived from MC.
- FSR effects are included.
- Use fit results to correct for p<200MeV/c production

- The lightest PS & V resonances saturate the semileptonic width. Any additional exclusive modes will have small branching ratios.

Mode	Branching Fraction
$D^0 \to X e^+ \nu_e$	$(6.46 \pm 0.17 \pm 0.13)\%$
Sum of $\mathcal{B}_{SL}(D^0)$	$(6.1 \pm 0.2 \pm 0.2)\%$
$D^+ \to X e^+ \nu_e$	$(16.13 \pm 0.20 \pm 0.33)\%$
Sum of $\mathcal{B}_{SL}(D^+)$	$(15.1 \pm 0.5 \pm 0.5)\%$

[Phys. Rev. Lett. **97**, 251801 (2006)]



The D^0/D^+ spectra have same shape

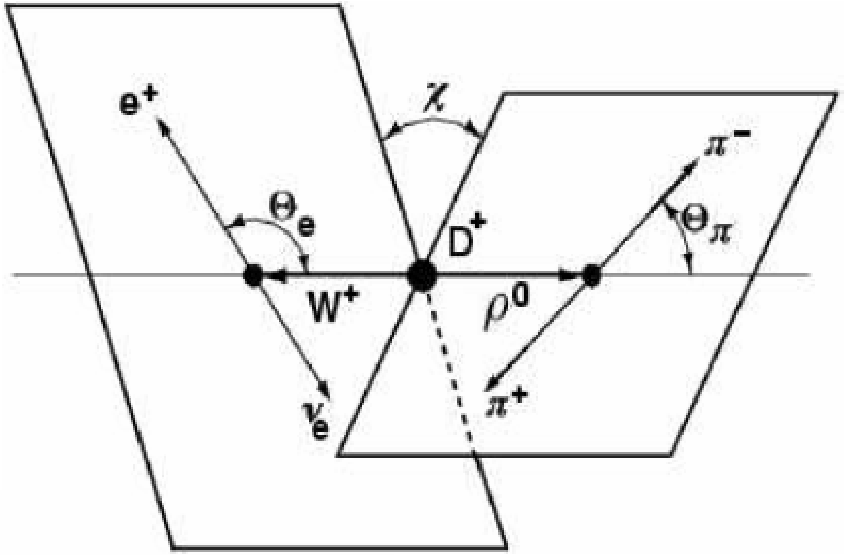
- Consistent with isospin invariance

$$\Gamma^{sl}_{D^+}/\Gamma^{sl}_{D^0} = 0.985 \pm 0.028 \pm 0.015$$

$D \to \rho e \nu$: Kinematic Variables

- Five kinematic variables describe the decay rate (plot):

$$q^2, \cos\theta_e, \cos\theta_\pi, \chi, m(\pi\pi)$$



- The decay rate we make a fit to:

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

$$\{(1+\cos\theta_e)^2\sin^2\theta_\pi\boxed{|H_+(q^2)|^2}$$

$$+(1-\cos\theta_e)^2\sin^2\theta_\pi\boxed{|H_-(q^2)|^2}$$

$$+4\sin^2\theta_e\cos^2\theta_\pi\boxed{|H_0(q^2)|^2}$$

$$+4\sin\theta_e(1+\cos\theta_e)\sin\theta_\pi\cos\theta_\pi\cos\chi\boxed{H_+(q^2)H_0(q^2)}$$

$$-4\sin\theta_e(1-\cos\theta_e)\sin\theta_\pi\cos\theta_\pi\cos\chi\boxed{H_-(q^2)H_0(q^2)}$$

$$-2\sin^2\theta_e\sin^2\theta_\pi\cos 2\chi\boxed{H_+(q^2)H_-(q^2)}\}$$

- Dependence on the form factors enters through $\boxed{H_+, H_- \text{ and } H_0}$.

$D \to \rho e \nu$: Form Factor Ratios R_V and R_2

- The helicity amplitudes are given by

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

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

- Form factors are parameterized using the simple pole model (*i.e.*, vector dominance):

$$A_{1(2)}(q^2) = \frac{A_{1(2)}(0)}{1 - q^2 / M_A^2}; \qquad V(q^2) = \frac{V(0)}{1 - q^2 / M_V^2}$$

- We make a 4D fit to the decay rate for form factor ratios R_V and R_2:

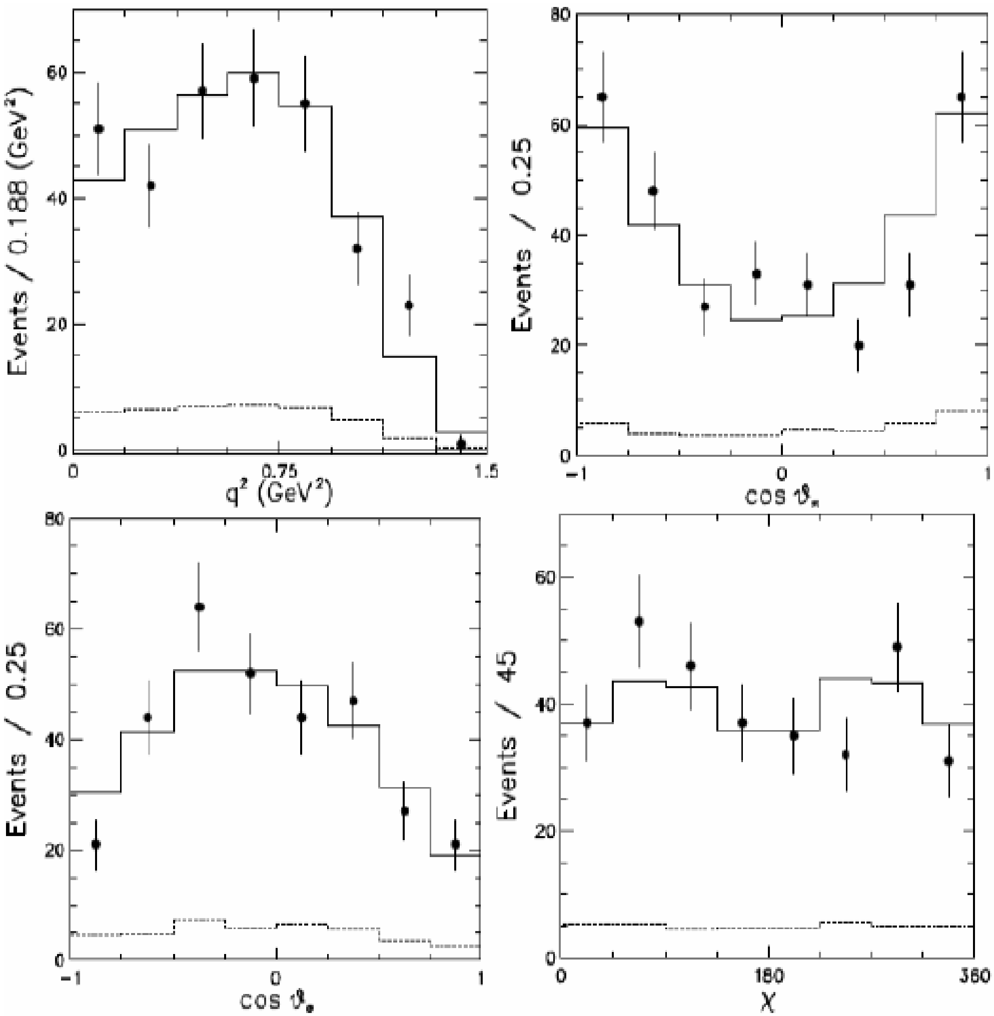
$$R_V \equiv \frac{V(0)}{A_1(0)}; \qquad R_2 \equiv \frac{A_2(0)}{A_1(0)}$$

- We make a fit (Fit B) described in *Nucl. Instr. and Meth.* **A328**, 547 (1993): a multidimensional fit to variables modified by experimental acceptance and resolution taking into account correlations among them

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

- Two isospin conjugate modes

$D^+ \to \rho^0 e \nu$ and $D^0 \to \rho e \nu$ were fit *simultaneously*.



CLEO-c **281 pb^{-1} @3770**

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):

$$R_V = 1.50 \pm 0.07$$

$$R_2 = 0.88 \pm 0.08$$