Recent Results of D semi-leptonic Decays

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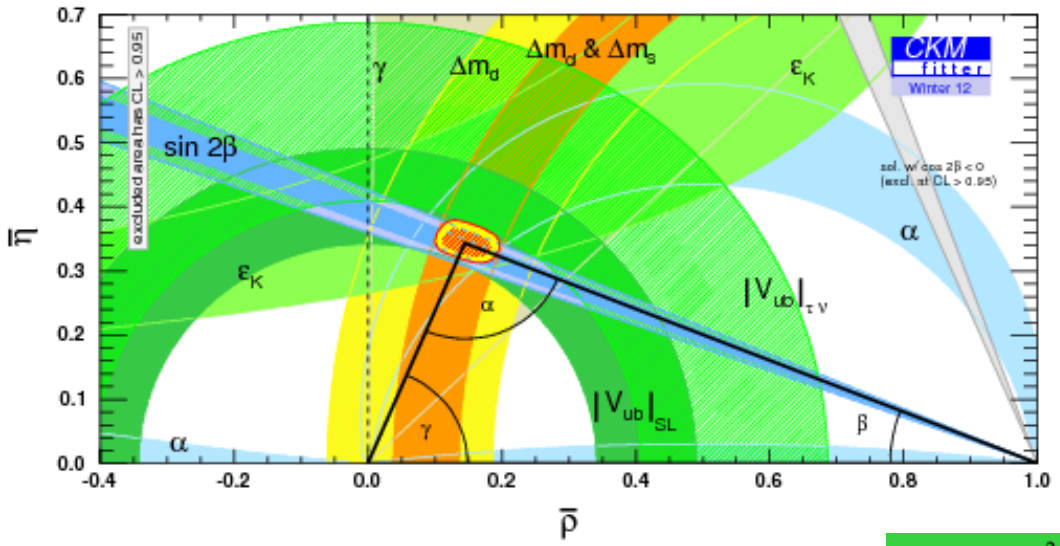
Charm's Role in the Big Picture



Flavor Physics:
* Over-constrain CKM matrix
* Search for New Physics

Difficulties:
* Mixing is not theoretically clean
* V_{ub} is not theoretically clean

Example: V_{ub} from B → π l ν

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

Latest result:

$V_{ub} \times 10^3 = 3.92 \pm 0.09(\text{exp}) \pm 0.45(\text{theory})$

* Needs inputs from Lattice QCD
* Charm physics provides perfect calibration

Why Semi-leptonic D decays

- Large branching fraction, theoretically tractable, experimentally accessible

- P → P transition
  - Measure CKM elements
  - Validate LQCD

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

- P → V transition
  - More factors
  - No unquenched calculations existed

- Rare / forbidden modes
  - New physics, new interactions

Experiment Results

- Exclusive D/D_s decays
  * $P \rightarrow P\, l\, \nu$:
    $D \rightarrow K/\pi\, e\, \nu$ (BF, form factor)
    Results from FOCUS, Belle, Barbar, CLEOc
    Results from BESIII (preliminary)
  * $P \rightarrow V\, l\, \nu$:
    $D^+ \rightarrow K\, \pi\, e\, \nu$ (new)
    $D/D^+ \rightarrow \rho\, e\, \nu$ (new)
  * rare decay /search
    $D^+ \rightarrow \eta/\, \eta'/\phi\, e\, \nu$
    $D_s \rightarrow \omega\, e\, \nu$ (new)

- Inclusive D/D_s Decays

$D^0 \rightarrow K\, e\, \nu$ & $\pi\, e\, \nu$

- BESIII, ~2.9 fb^{-1} data taken at $\psi(3770)$, ~923 pb^{-1}
- Double tag technique (to suppress backgroud) ,
  tag side: fully reconstructed hadronic modes
  signal side: missing neutrino inferred

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

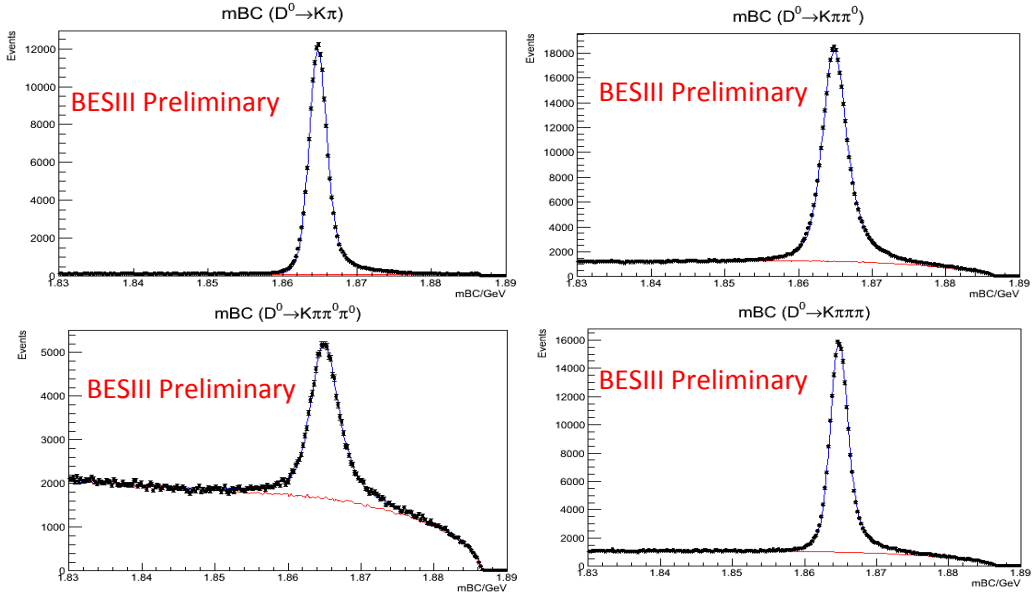
- Simple differential decay rate function (massless lepton assumed)

$$\frac{\Delta\Gamma(D \to \pi(K)e\nu)}{dq^2} = \frac{G_F^2\,|V_{cd(s)}|^2}{24\pi^3}\, p^3\, |f_+(q^2)|^2$$

Tag Mode Reconstruction

- Four tag modes picked
- Best tag mode based minimum ΔE

$$\Delta E \equiv E - E_{beam}$$

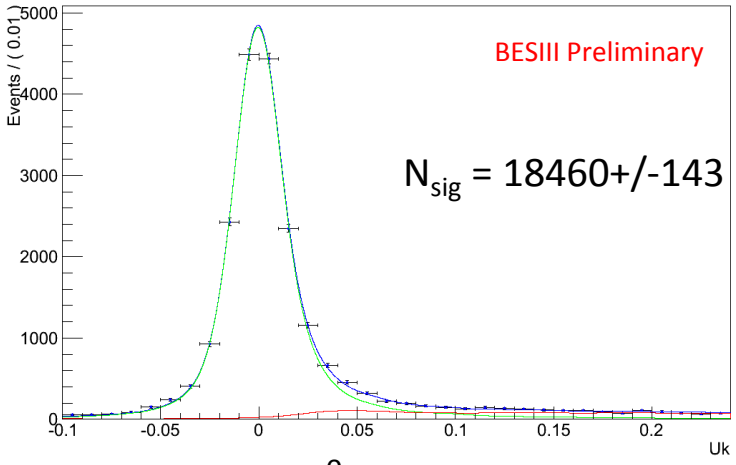


BESIII Preliminary

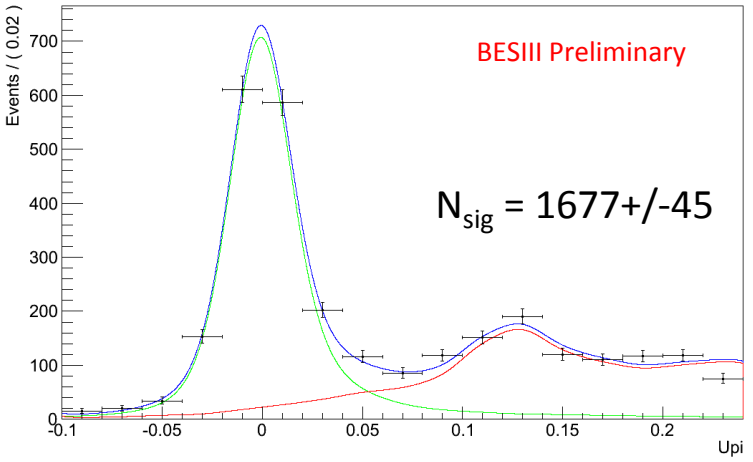
Mode	Data Yield	Fraction of All Tags (%)	Tag Efficiency(%)
$D^0 \to K^-\pi^+$	159,929 ± 413	20.7	62.08±0.07
$D^0 \to K^-\pi^+\pi^0$	323,348 ± 667	41.8	33.56±0.03
$D^0 \to K^-\pi^+\pi^0\pi^0$	78,467 ± 480	10.1	14.93±0.04
$D^0 \to K^-\pi^+\pi^-\pi^+$	211,910 ± 550	27.4	36.80±0.04

Signal Selection

- Two good oppositely-charged tracks
- Kaon/pion and electron PID requirements
- Electron has same charge as the tag side K
- Veto if any unmatched EMC shower is > 250MeV (some background has extra π^0)



D^0 -> K e ν



D^0 -> π e ν

Branching Fraction Results

$$N_{tag}^{obs} = 2N_{D\bar{D}}B_{tag}\epsilon_{tag}$$
$$N_{sig}^{obs} = 2N_{D\bar{D}}B_{tag}B_{sig}\epsilon_{tag,sig}$$

$$\longrightarrow \quad B_{sig} = \frac{N_{sig}^{obs}}{\sum_{\alpha} N_{tag}^{obs,\alpha}\epsilon_{tag,sig}^{\alpha}/\epsilon_{tag}^{\alpha}},$$

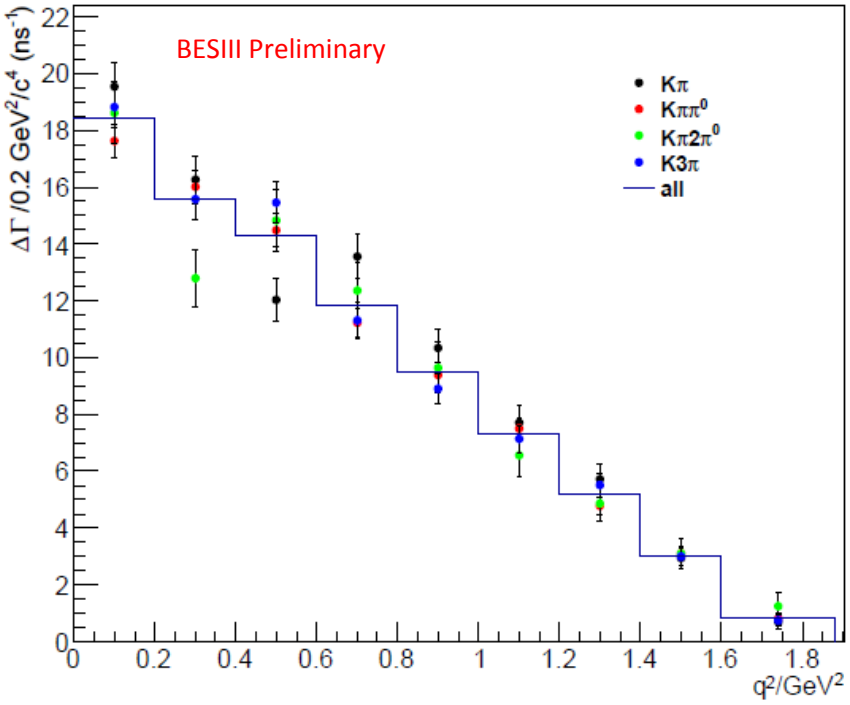
BESIII Preliminary

Mode	measured branching fraction(%)	PDG	CLEOc
$\bar{D}^0 \to K^+e^-\bar{\nu}$	3.542 $\pm$0.030$\pm$0.067	3.55 $\pm$0.04	3.50 $\pm$0.03 $\pm$0.04
$\bar{D}^0 \to \pi^+e^-\bar{\nu}$	0.288 $\pm$0.008$\pm$0.005	0.289 $\pm$0.008	0.288 $\pm$0.008$\pm$0.003

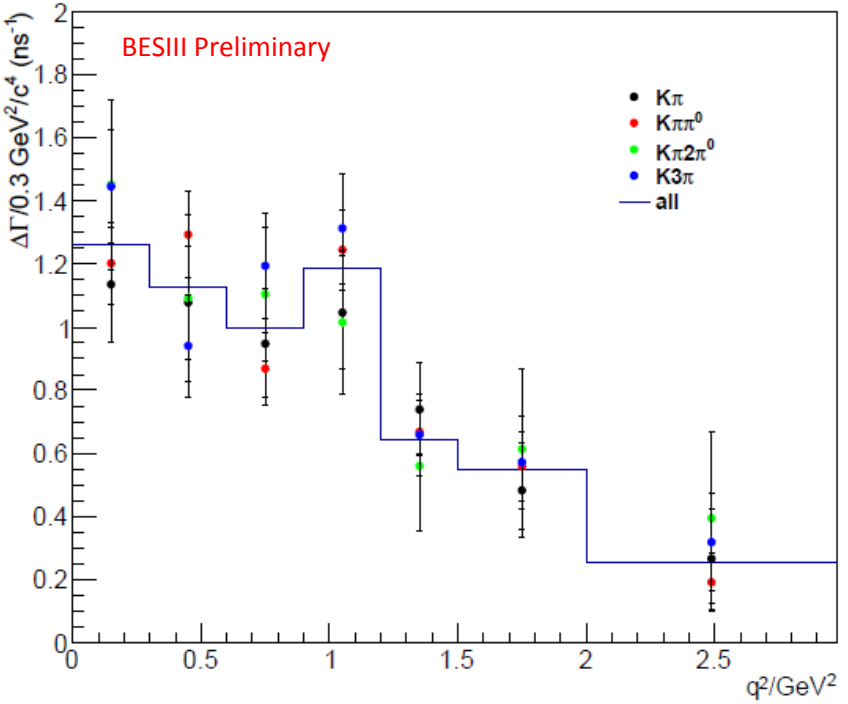
* Systematics are preliminary
* Will improve using full (3x) data set in the near future

Partial Decay Rates Results

- Measured in each q^2 bin, by fitting U distribution
- Compare results from each tag mode



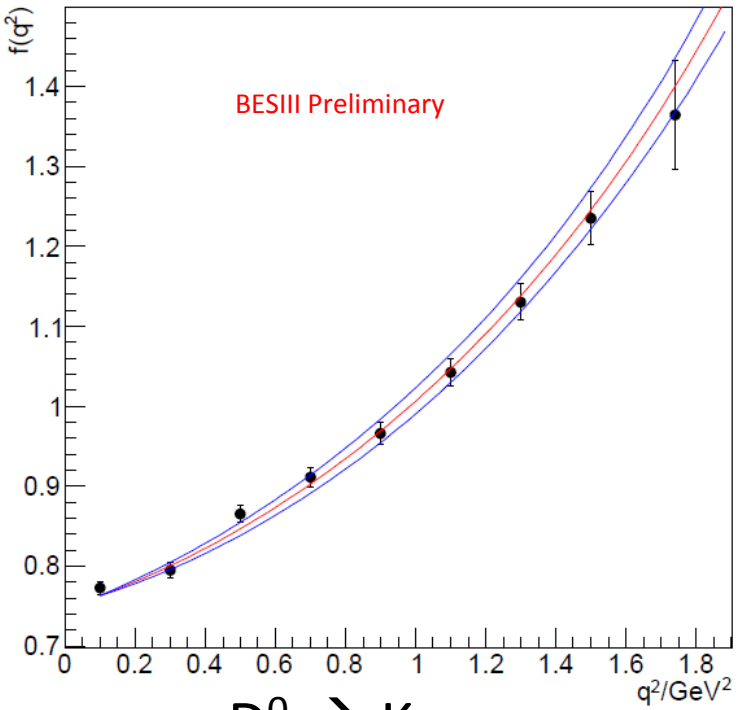
$D^0 \rightarrow K\, e\, \nu$



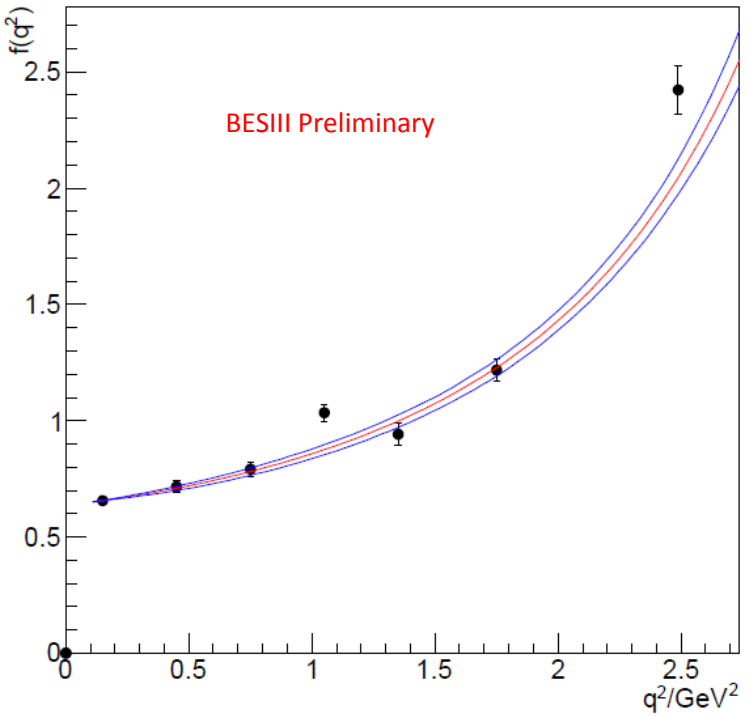
$D^0 \rightarrow \pi\, e\, \nu$

$f(q^2)$ Results

- Points: data with stat. error only
- Curves: from Fermilab-MILC within one stat. error, preliminary, **arXiv:1111.5471** (XXIX International Symposium on Lattice Field Theory);
- Other theoretical work: HPQCD, arXiv:1111.0225
- Comparing shape only here ($f_+(0)$ not known)



$D^0 \rightarrow K\, e\, \nu$



$D^0 \rightarrow \pi\, e\, \nu$

Form Factor Parameterization

Fit to partial decay rates ΔΓ

Simple pole model:

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

Modified pole model:
Beciirevic and Kaidalov
PLB 478, 417 (2000)

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

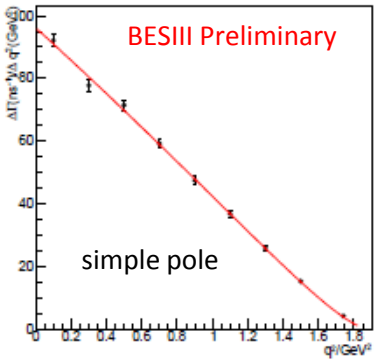
Series expansion:
Becher and Hill
PLB 633, 61 (2006)

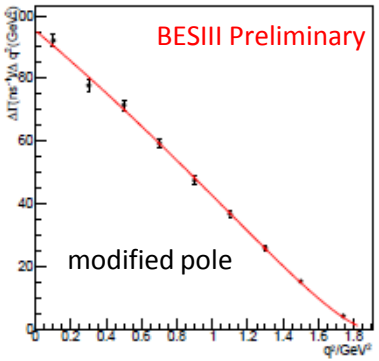
$$f_+(q^2) = \frac{1}{P(q^2)\,\phi(q^2,t_0)} \sum_{k=0}^{\infty} a_k(t_0)\ \left[z(q^2,t_0)\right]^k$$

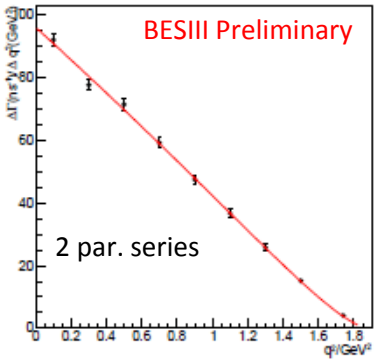
Could fit: $f_+(0)$, $r_1 = a_2/a_1$, $r_2 = a_3/a_1$

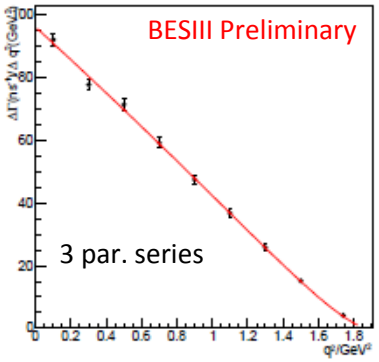
Form Factor Fits

$$\chi^2 = \sum_{i,j=1}^{n} \left(\Delta\Gamma_i - g(q^2)_i\right) C_{ij}^{-1} \left(\Delta\Gamma_j - g(q^2)_j\right)$$

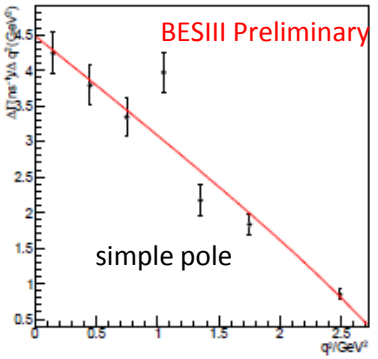


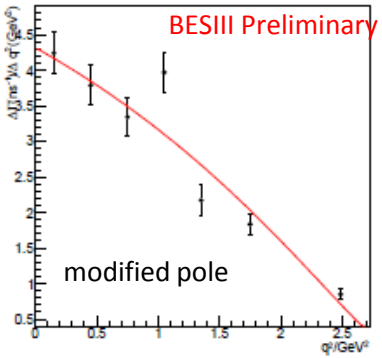


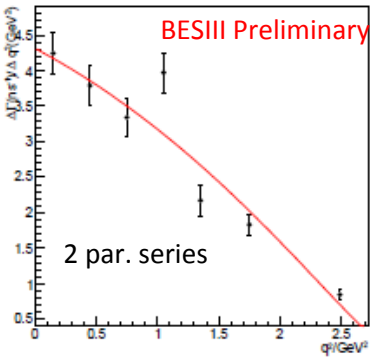


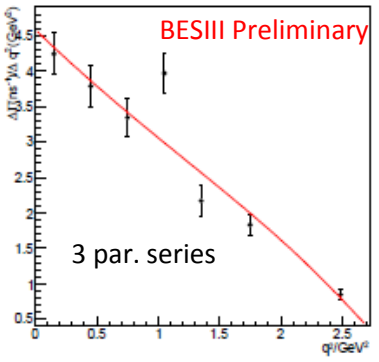


$D^0 \rightarrow K\, e\, \nu$









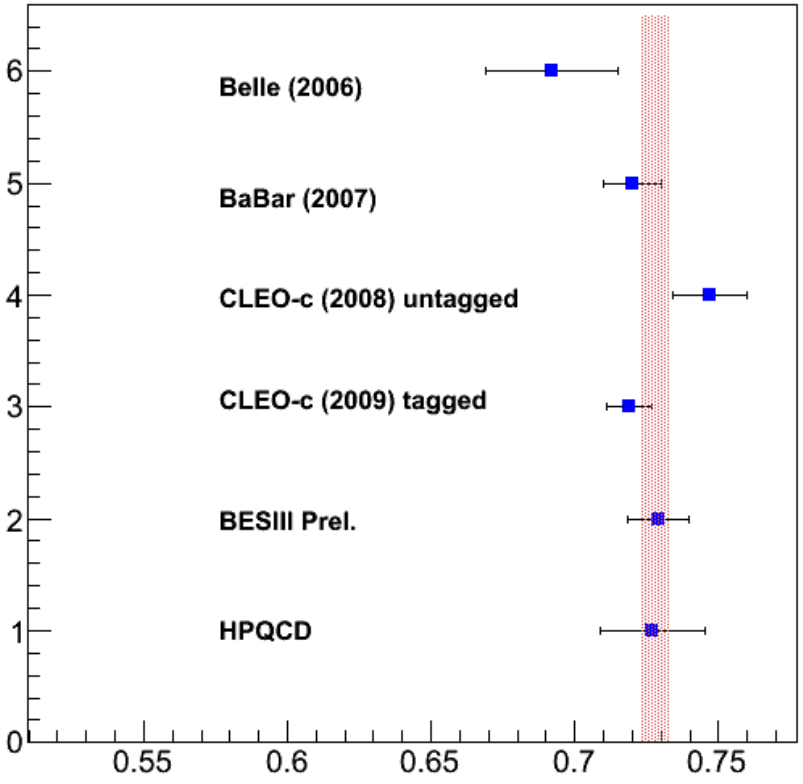
$D^0 \rightarrow \pi\, e\, \nu$

Form Factor Results

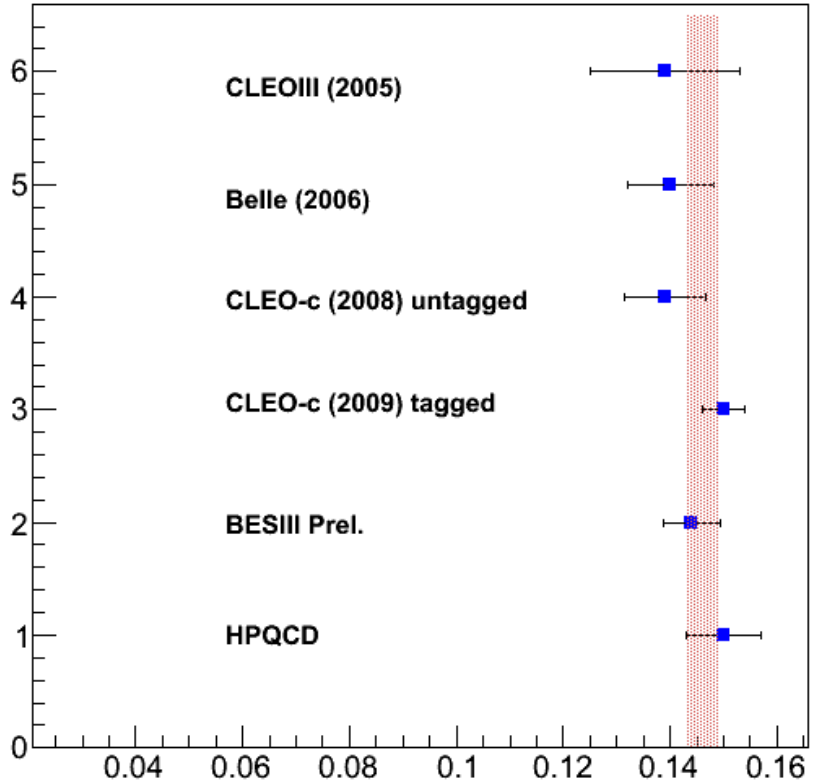
BESIII Preliminary

Simple Pole	$f_+(0)\|V_{cd(s)}\|$	m_{pole}	
$D^0 \to Ke\nu$	$0.729 \pm 0.005 \pm 0.007$	$1.943 \pm 0.025 \pm 0.003$	
$D^0 \to \pi e\nu$	$0.142 \pm 0.003 \pm 0.001$	$1.876 \pm 0.023 \pm 0.004$	
Modified Pole	$f_+(0)\|V_{cd(s)}\|$	α	
$D^0 \to Ke\nu$	$0.725 \pm 0.006 \pm 0.007$	$0.265 \pm 0.045 \pm 0.006$	
$D^0 \to \pi e\nu$	$0.140 \pm 0.003 \pm 0.002$	$0.315 \pm 0.071 \pm 0.012$	
2 par. series	$f_+(0)\|V_{cd(s)}\|$	r_1	
$D^0 \to Ke\nu$	$0.726 \pm 0.006 \pm 0.007$	$-2.034 \pm 0.196 \pm 0.022$	
$D^0 \to \pi e\nu$	$0.140 \pm 0.004 \pm 0.002$	$-2.117 \pm 0.163 \pm 0.027$	
3 par. series	$f_+(0)\|V_{cd(s)}\|$	r_1	r_2
$D^0 \to Ke\nu$	$0.729 \pm 0.008 \pm 0.007$	$-2.179 \pm 0.355 \pm 0.053$	$4.539 \pm 8.927 \pm 1.103$
$D^0 \to \pi e\nu$	$0.144 \pm 0.005 \pm 0.002$	$-2.728 \pm 0.482 \pm 0.076$	$4.194 \pm 3.122 \pm 0.448$

Comparison (3 par. Series)



$f^{K}_{+}(0)|V_{cs}|$



$f^{\pi}_{+}(0)|V_{cd}|$

- Numbers are from HFAG 2012 report(**arXiv:1207.1158**)
- Error bar of BESIII prel. will shrink with full data

$D^+ \rightarrow K \pi e \nu$

- BaBar, 347.5 fb^{-1} $\Upsilon(4s)$, PRD 83, 072001 (2011)
- Measurements of $K\pi$ resonant and non-resonant contributions: S-wave, search of radially excited P-wave and D-wave
- Accurate measurements of $K^*(892)$ modes: resonance parameters, form factors
- $K\pi$ S-wave phase versus the $K\pi$ mass

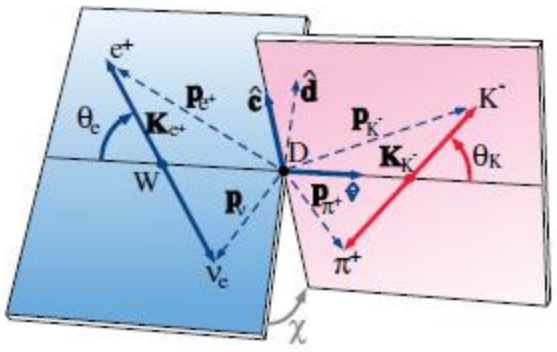


FIG. 3 (color online). Definition of angular variables.

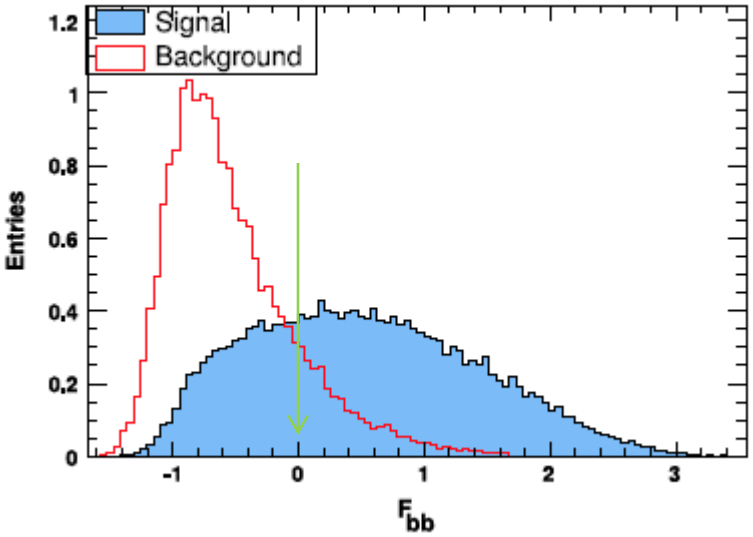
Differential decay rate has 5 degrees of freedom:

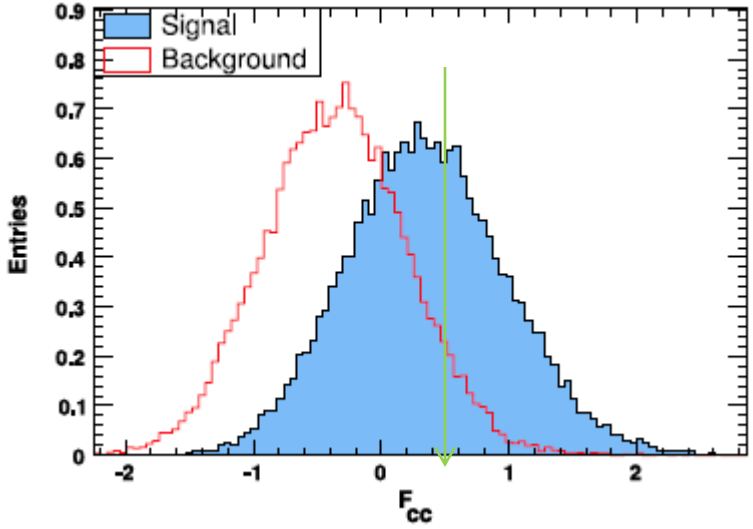
- m^2, of the k π system
- q^2, of the e ν system
- $\cos(\theta_k)$
- $\cos(\theta_e)$
- χ

Event Selection

- Particles boosted to the CM system
- Fisher discrimination variables to reject:

  (1) BB_bar events (2) continuum background (mainly from charm)





Cuts: $F_{bb} > 0$, $F_{cc} > 0.5$

After cuts: 244 x 10^3 signal events left with S/B = 2.3

Form Factor Parameterization

Form factors expanded into partial waves:
F_{10} for S-wave contribution,
F_{i1} and F_{i2} for P and D waves, respectively

$$\mathcal{F}_1 = \mathcal{F}_{10} + \mathcal{F}_{11}\cos\theta_K + \mathcal{F}_{12}\frac{3\cos^2\theta_K - 1}{2};$$

$$\mathcal{F}_2 = \frac{1}{\sqrt{2}}\mathcal{F}_{21} + \sqrt{\frac{3}{2}}\mathcal{F}_{22}\cos\theta_K;$$

$$\mathcal{F}_3 = \frac{1}{\sqrt{2}}\mathcal{F}_{31} + \sqrt{\frac{3}{2}}\mathcal{F}_{32}\cos\theta_K.$$

F_{i1} → Helicity form factors → axial-vector from factor $A_{1,2}(q^2)$
the vector form factor $V(q^2)$

$$\mathcal{F}_{11} = 2\sqrt{2}\alpha q H_0,$$
$$\mathcal{F}_{21} = 2\alpha q(H_+ + H_-),$$
$$\mathcal{F}_{31} = 2\alpha q(H_+ - H_-),$$

Single pole mode:

$$V(q^2) = \frac{V(0)}{1 - \frac{q^2}{m_V^2}},$$
$$A_1(q^2) = \frac{A_1(0)}{1 - \frac{q^2}{m_A^2}},$$
$$A_2(q^2) = \frac{A_2(0)}{1 - \frac{q^2}{m_A^2}},$$

Form Factor Results

Fit the data with different models, the 2nd is the nominal fit:

	$S + \bar{K}^*(892)^0$	$S + \bar{K}^*(892)^0$ $\bar{K}^*(1410)^0$	$S + \bar{K}^*(892)^0$ $\bar{K}^*(1410)^0 + D$
m_A (GeV/c^2)	2.65 ± 0.10	2.63 ± 0.10	2.58 ± 0.09
r_V	1.458 ± 0.016	1.463 ± 0.017	1.471 ± 0.016
r_2	0.804 ± 0.020	0.801 ± 0.020	0.786 ± 0.020

Evaluated at $q^2 = 0$, $r_V = V(0)/A_1(0)$, $r_2 = A_2(0)/A_1(0)$

Final results (with syst. Error) , from 2nd fit

floating $_{mA}$

m_A = 2.63 (0.10) (0.13) GeV

r_V = 1.463 (0.017) (0.032)

r_2 = 0.801 (0.020) (0.020)

fixing m_A = 2.5 GeV

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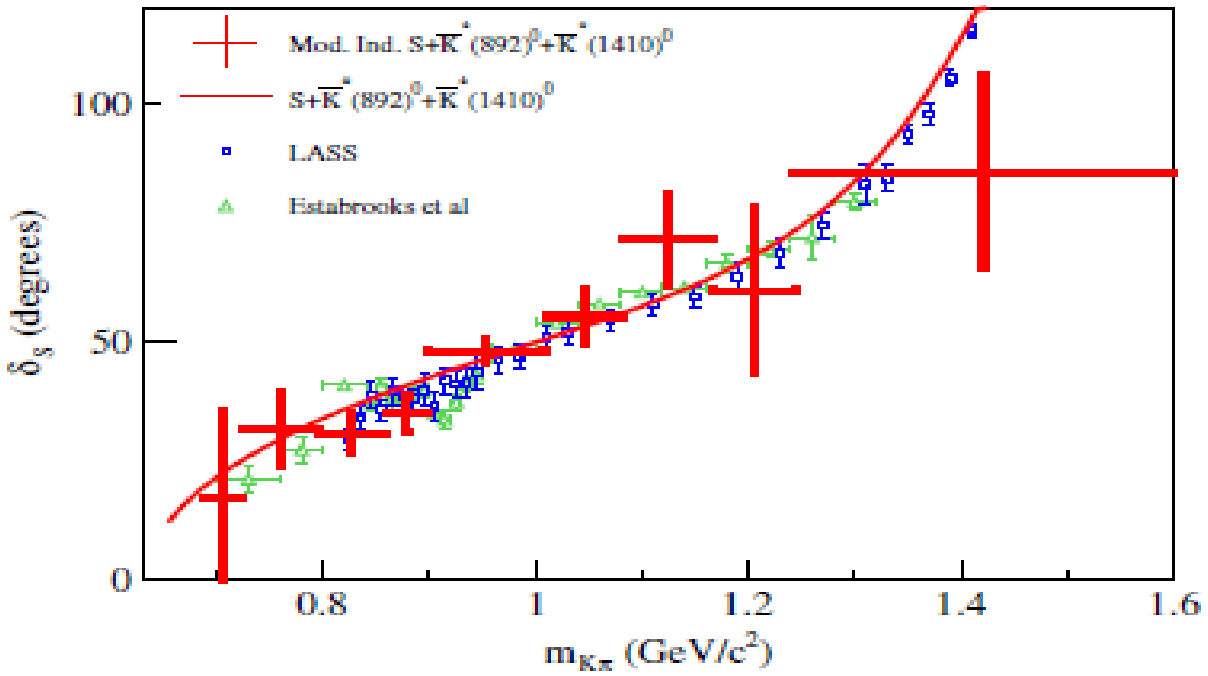
r_V = 1.493 (0.014) (0.021)

r_2 = 0.775 (0.011) (0.011)

Fraction of signal components

Component	$S + \bar{K}^*(892)^0$(%)	$S + \bar{K}^*(892)^0 + \bar{K}^*(1410)^0$(%)	$S + \bar{K}^*(892)^0\ \bar{K}^*(1410)^0 + D$(%)
S wave	$5.62 \pm 0.14 \pm 0.13$	$5.79 \pm 0.16 \pm 0.15$	$5.69 \pm 0.16 \pm 0.15$
P wave	94.38	94.21	94.12
$\bar{K}^*(892)^0$	94.38	$94.11 \pm 0.74 \pm 0.75$	$94.41 \pm 0.15 \pm 0.20$
$\bar{K}^*(1410)^0$	0	$0.33 \pm 0.13 \pm 0.19$	$0.16 \pm 0.08 \pm 0.14$
D wave	0	0	$0.19 \pm 0.09 \pm 0.09$

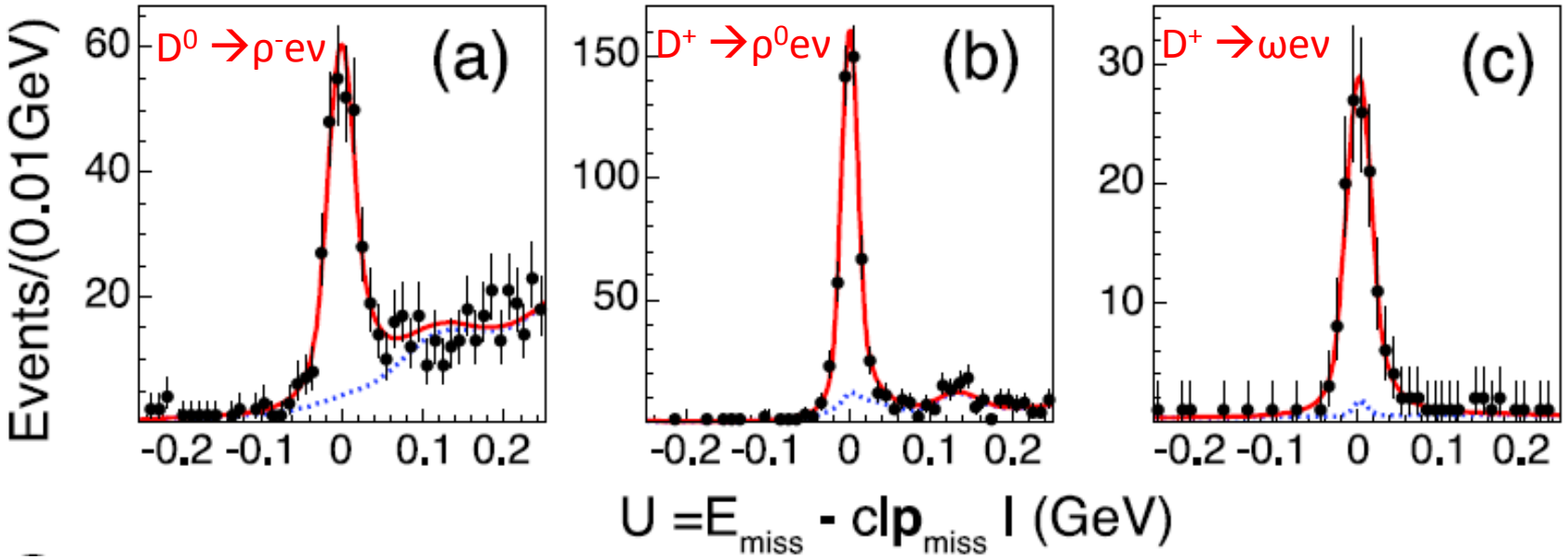
Phase of S-wave Component



- Agreement with K^- p interactions producing $K^-\pi^+$ at small momentum transfer
- Additional negative sign between S and P wave compared with elastic Kπ scattering

$D^0/D^+ \rightarrow \rho\, e\, \nu$
$D^+ \rightarrow \omega\, e\, \nu$

- CLEOc , 818 pb^{-1} , arXiv:1112.2884
- Improved precision on BF on both decays
- First measurement on Cabbio-suppressed P→V Form Factor measurement
- Combined with D→K*e ν and B→V $l^+ l^-$, could extract V_{ub} from B→ ρ e ν
- Double tag technique, extract yields by fitting U = $E_{miss} - P_{miss}$



ρ/ ω e ν Branching Fraction Results

Decay Mode	ϵ (%)	$N_{\rm tag,\ SL}$	$\mathcal{B}_{\rm SL}$	$\mathcal{B}_{\rm SL}$(prev)	$\mathcal{B}_{\rm SL}$(ISGW2)	$\mathcal{B}_{\rm SL}$(FK)
$D^0 \to \rho^- e^+ \nu_e$	26.03 ± 0.02	304.6 ± 20.9	$1.77 \pm 0.12 \pm 0.10$	$1.94 \pm 0.39 \pm 0.13$	1.0	2.0
$D^+ \to \rho^0 e^+ \nu_e$	42.84 ± 0.03	447.4 ± 24.5	$2.17 \pm 0.12^{+0.12}_{-0.22}$	$2.1 \pm 0.4 \pm 0.1$	1.3	2.5
$D^+ \to \omega e^+ \nu_e$	14.67 ± 0.03	128.5 ± 12.6	$1.82 \pm 0.18 \pm 0.07$	$1.6^{+0.7}_{-0.6} \pm 0.1$	1.3	2.5

BF units 10^{-3}, more consistent with FK predictions (PRD 72, 034029, 2005)

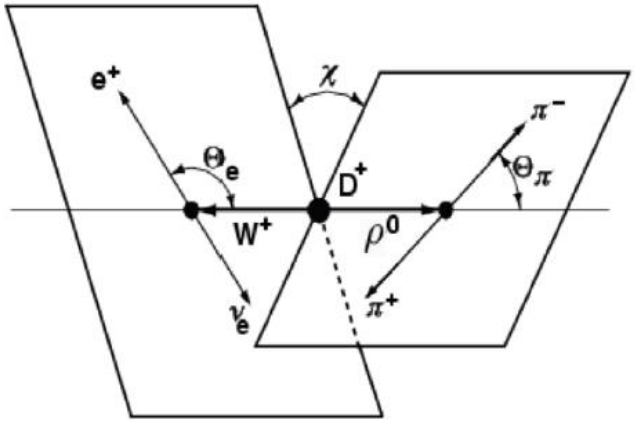
Results consistent with iso-spin invariance :
(Iso-spin symmetry not expected to be exact due to ρ^0-ω interference)

$$\frac{\Gamma(D^0 \to \rho^- e^+ \nu_e)}{2\Gamma(D^+ \to \rho^0 e^+ \nu_e)} = 1.03 \pm 0.09^{+0.08}_{-0.02}$$

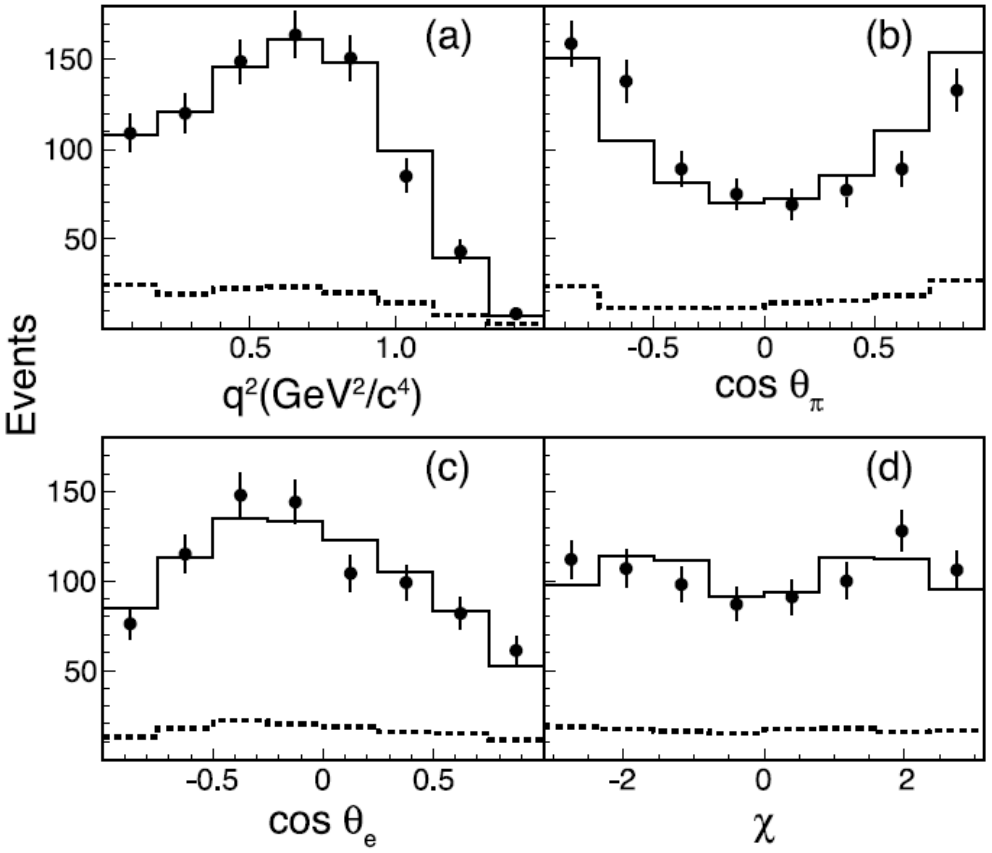
ρ e ν Form Factor Measurement

- Differential decay rate can be expressed in terms of 3 helicity amplitudes
- Helicity amplitudes are related to 2 axial form factors $A_1(q^2)$, $A_2(q^2)$, and 1 vector form factor $V(q^2)$
- Assume simple pole mode, and simultaneous fit to iso-spin conjugate $D^0/D^+ \rightarrow \rho\, e\, \nu$
- extract two FF ratios:

$$r_V = \frac{V(0)}{A_1(0)} \text{ and } r_2 = \frac{A_2(0)}{A_1(0)}.$$



ρ e ν Form Factor Result



Projection of the combined ρ and ρ^0 data

* Difference in $\cos\theta_\pi$ might be due to s-wave interference

*

$r_V = 1.48 \pm 0.15 \pm 0.05$
$r_2 = 0.83 \pm 0.11 \pm 0.04$

*

Using PDG V_{cd}, D^0 and D^+ lifetime:

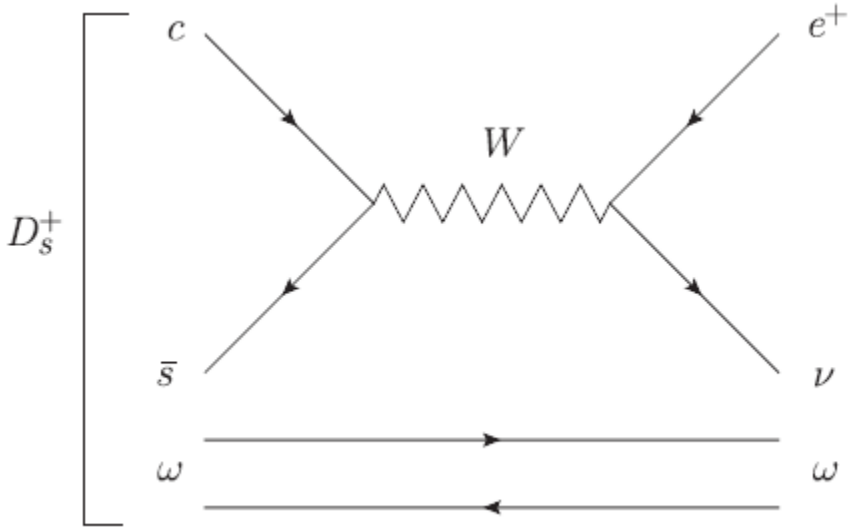
$$A_1(0) = 0.56 \pm 0.01^{+0.02}_{-0.03}$$

$$A_2(0) = 0.47 \pm 0.06 \pm 0.04$$

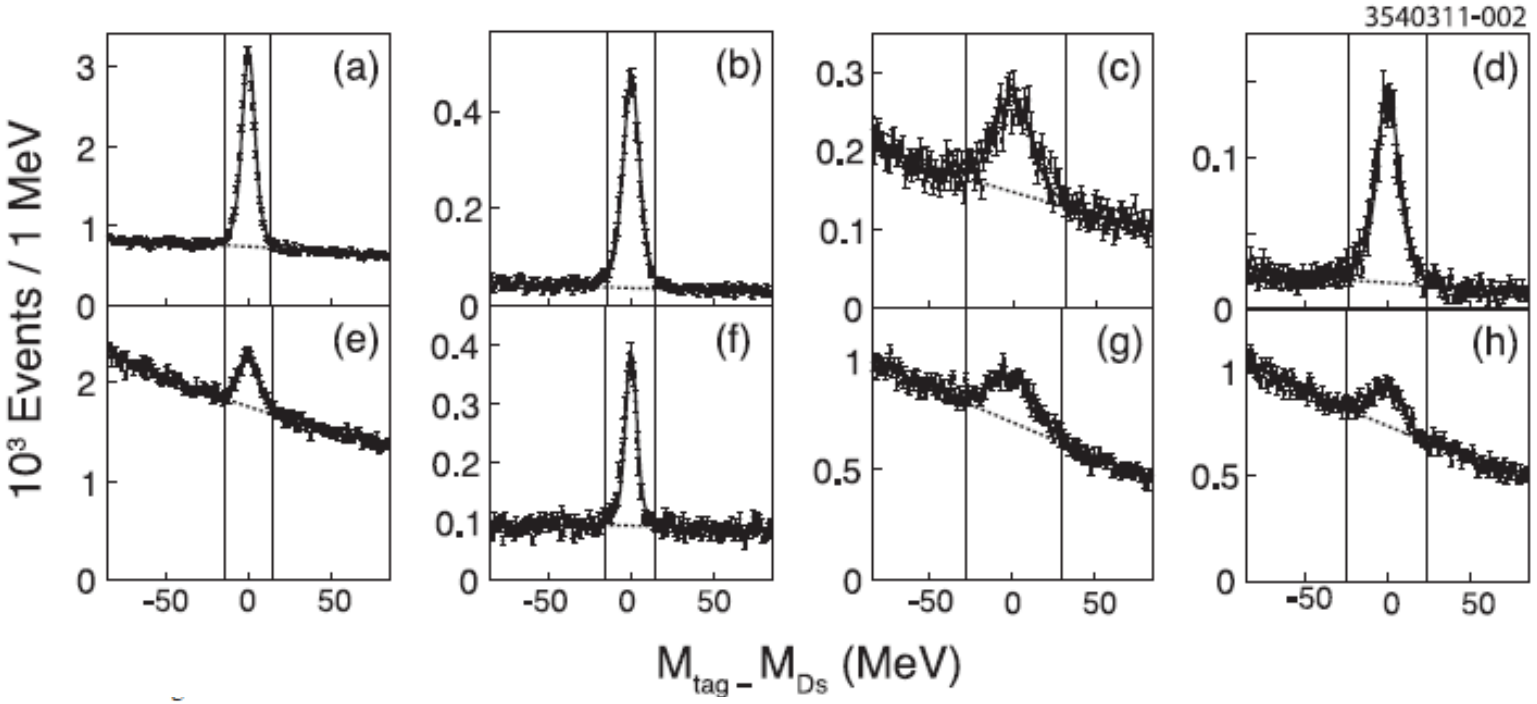
$$V(0) = 0.84 \pm 0.09^{+0.05}_{-0.06}$$

Search for $D^+_s \rightarrow \omega\, e\, \nu$

- CLEOc, 4170 MeV, 586 pb^{-1} (0.6×10^6 $D_s D_s^*$) , PRD 84, 012005 (2011)
- Probe four-quark content of D_s, BF > $2*10^{-4}$ unlikely due to ω-ϕ mixing, evidence for "weak annihilation". (see PRD 79, 074006, 2009)



Tag Modes



Modes	N_{data}	Low sideband	High sideband
$K_S^0 K^-$	5828 ± 92	1 231	958
$K^+ K^- \pi^-$	$25\,990 \pm 285$	22 385	19 452
$K^{*-} \bar{K}^{*0}$	2891 ± 100	2 783	2 647
$\pi^+ \pi^- \pi^-$	8152 ± 369	56 530	43 475
$\eta \pi^-$	3635 ± 160	5 727	3 379
$\eta \rho^-$	6877 ± 330	26 879	14 658
$\pi^- \eta'(\eta \pi^+ \pi^-)$	2344 ± 70	1 040	572
$\pi^- \eta'(\rho \gamma)$	4451 ± 337	42 412	25 476

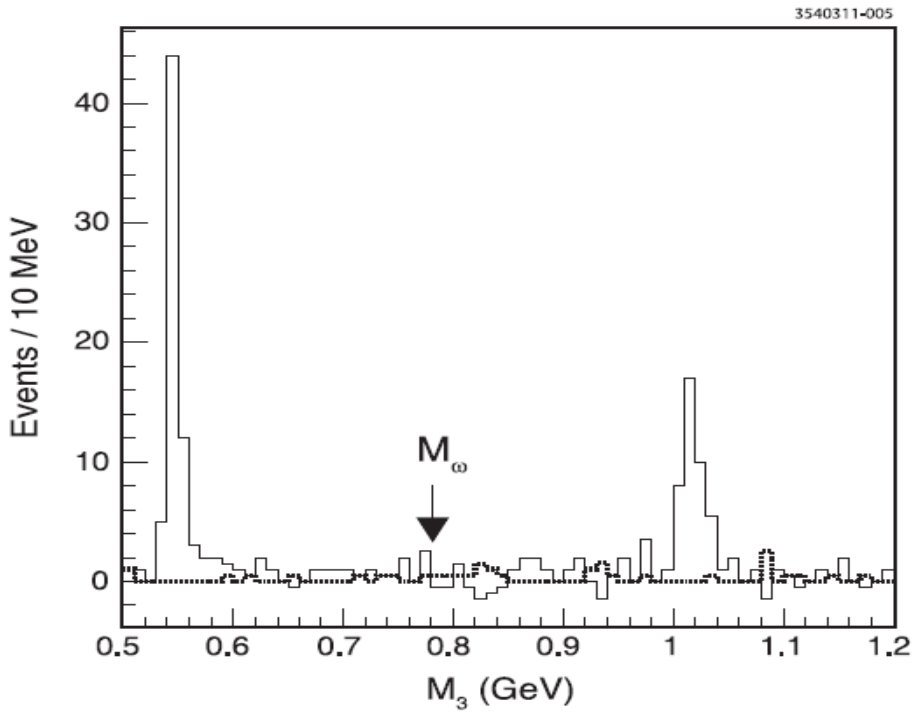
Signal Selection and Results

Missing mass square measured for missing neutrino:

$$MM^2 = (E_b - E_{\text{tag}} - E_\gamma - E_s)^2 - (\mathbf{p}_\text{b} - \mathbf{p}_{\text{tag}} - \mathbf{p}_\gamma - \mathbf{p}_s)^2$$

(E_s, P_s) : from $\omega(\pi\pi\pi^0)$ and electron

Require $-0.05 < MM^2 < 0.05$ GeV2, fit mass of $\pi\pi\pi^0$



No signal found:

Upper limit:

$$\mathcal{B}(D_s^+ \to \omega e^+ \nu) < 0.20\%$$

at 90% C.L.

Summary

- Semi-leptonic D decay analyses have been successful , FOCUS, BELLE, BarBar and CELOc
- 1/3 ψ(3770) data analyzed at BESIII for $D^0 \rightarrow K/\pi\ e\ \nu$, better precision expected
- More new results coming soon from BESIII