D Leptonic and Semi-leptonic Decays

Hailong Ma (IHEP)
For BESIII Collaboration

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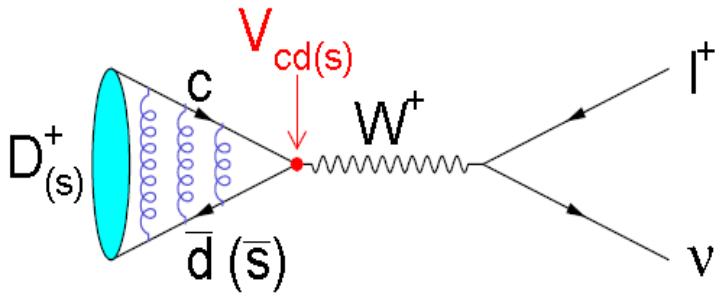
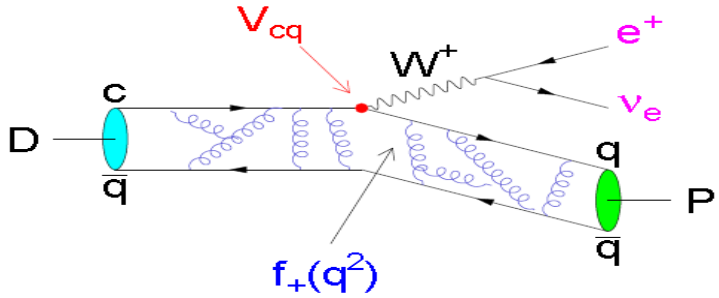
See Fenfen's talk on May 21st for more details

Introduction

D leptonic and semi-leptonic decays are ideal window to probe for weak and strong effects





- **Precision measurements of decay constants f_{D+}, f_{Ds+}, form factors $f_+^{D\to K(\pi)}(q^2)$ of semi-leptonic decays of D mesons will calibrate LQCD calculations at higher accuracy. Once they pass experimental tests, the precise LQCD calculations of f_D/f_B, f_{Ds}/f_{Bs} and form factors will be helpful for measurement in B decay**

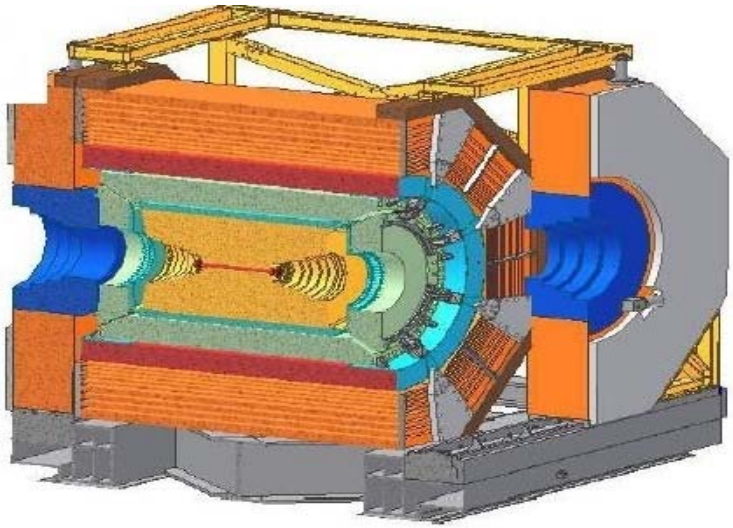
- **Recent LQCD calculations on $f_{D(s)+}$[0.5(0.5)%], $f_+^{D\to K(\pi)}(0)$ [1.7(4.4)%] provide good chance to precisely measure the CKM matrix element $|V_{cs(d)}|$, which are important for the unitarity test of the CKM matrix and search for NP beyond the SM**

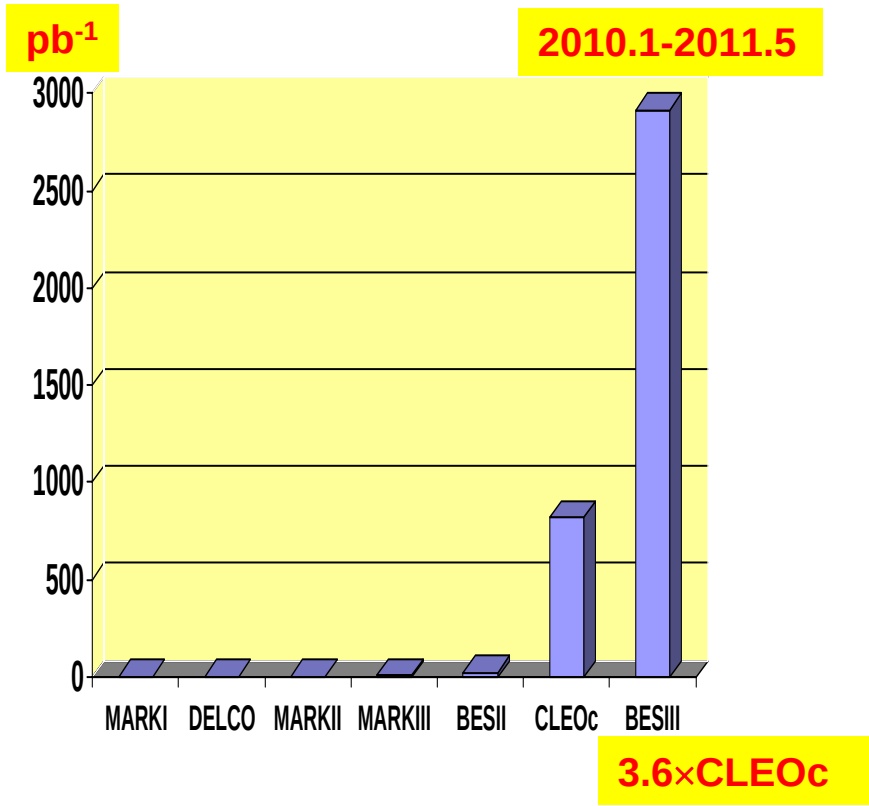
Data Sample

Designed luminosity is 1×10^{33} $cm^{-2}s^{-1}$ at ψ(3770)

Highest luminosity reached 0.85×10^{33} $cm^{-2}s^{-1}$ at ψ(3770) in 2014

2.92 fb^{-1} at ψ(3770)



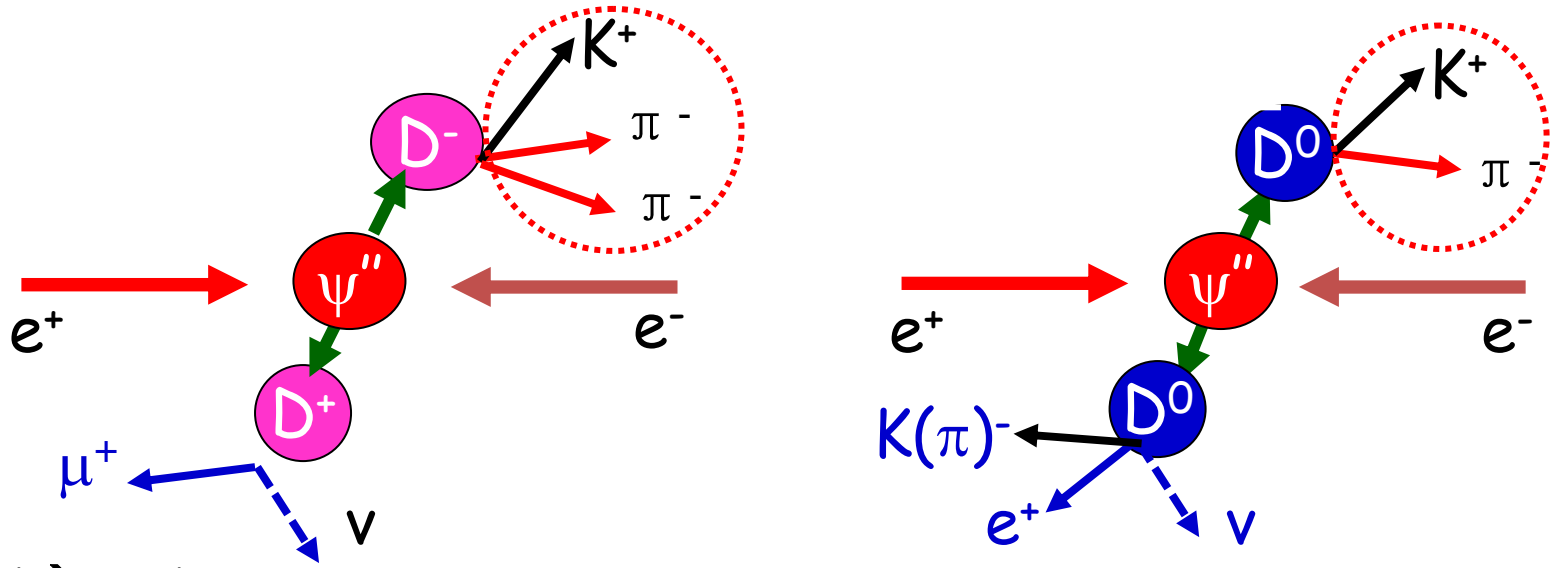


The parameters of each sub-detectors can be found in previous talks

Singly Tagged $\bar{D}^0$ and D^- Mesons

$D^0\bar{D}^0$ and D^+D^- are produced in pair at $\psi(3770)$

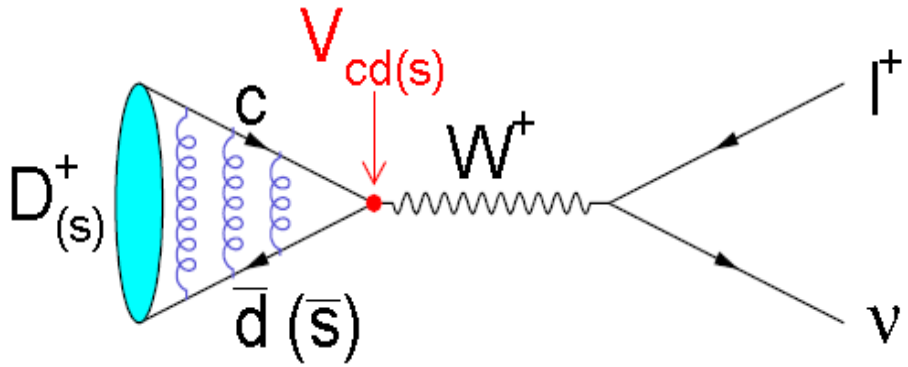
Singly tagged $\bar{D}^0$ and D^- mesons are reconstructed by hadronic decays with large branching fraction and less combinatorial backgrounds



- $D^+ \rightarrow K_L e^+ \nu$
- $D^+ \rightarrow K^- \pi^+ e^+ \nu$
- $D^+ \rightarrow \omega/\phi e^+ \nu$

At the recoil side of singly tagged $\bar{D}^0$ and D^- mesons, leptonic and semi-leptonic decays can be studied

D^+ Leptonic Decays



In the SM:

$$\Gamma(D^+_{(s)} \to \ell^+ \nu_\ell) = \frac{G_F^2 f^2_{D^+_{(s)}}}{8\pi} |V_{cd(s)}|^2 m_\ell^2 m_{D^+_{(s)}} \left(1 - \frac{m_\ell^2}{m^2_{D^+_{(s)}}}\right)^2$$

Bridge to precisely measure

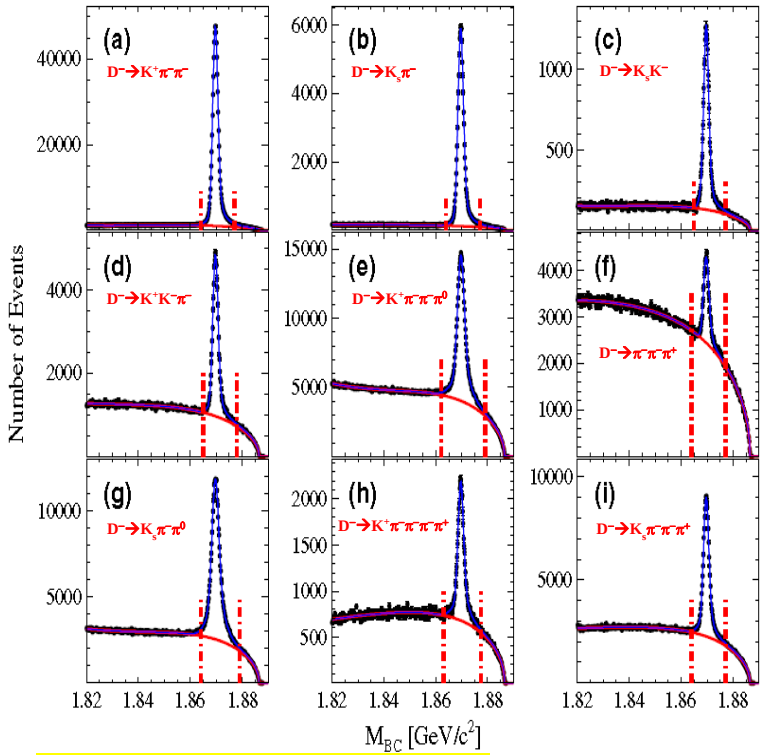
- **Decay constants $f_{D(s)+}$ with input $|V_{cd(s)}|^{CKMfitter}$**
- **CKM matrix element $|V_{cd(s)}|$ with input $f^{LQCD}_{D(s)+}$**

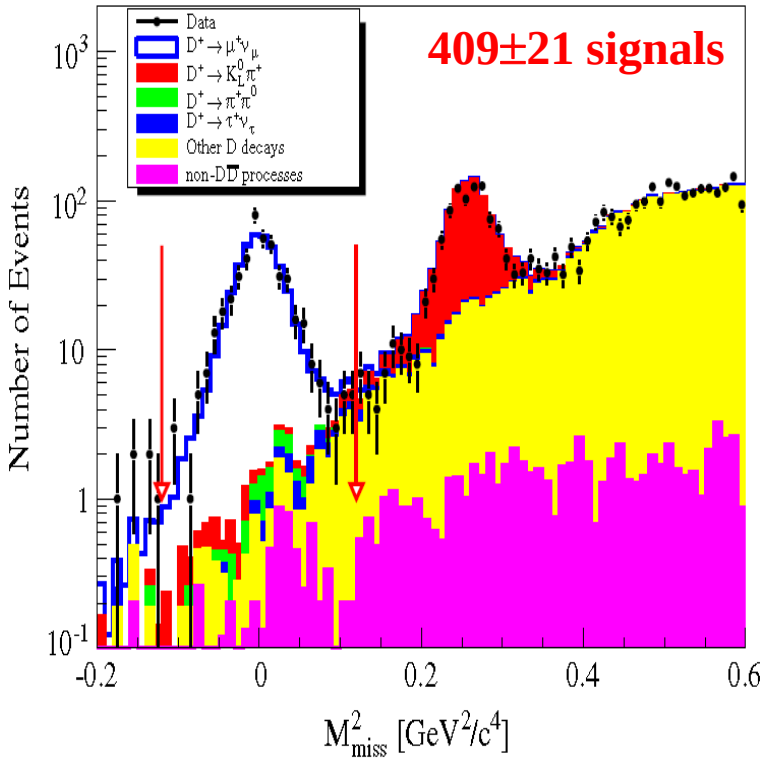
Measurement of $B[D^+ \to \mu^+\nu]$, f_{D^+} and $|V_{cd}|$

$e^+e^- \to \psi(3770) \to D^+D^-$

2.92 fb^{-1} data@ 3.773 GeV

PRD89(2014)051104R





$N_{D^-_{tag}} = (170.31 \pm 0.34) \times 10^4$

$B[D^+ \to \mu^+\nu] = (3.71 \pm 0.19 \pm 0.06) \times 10^{-4}$

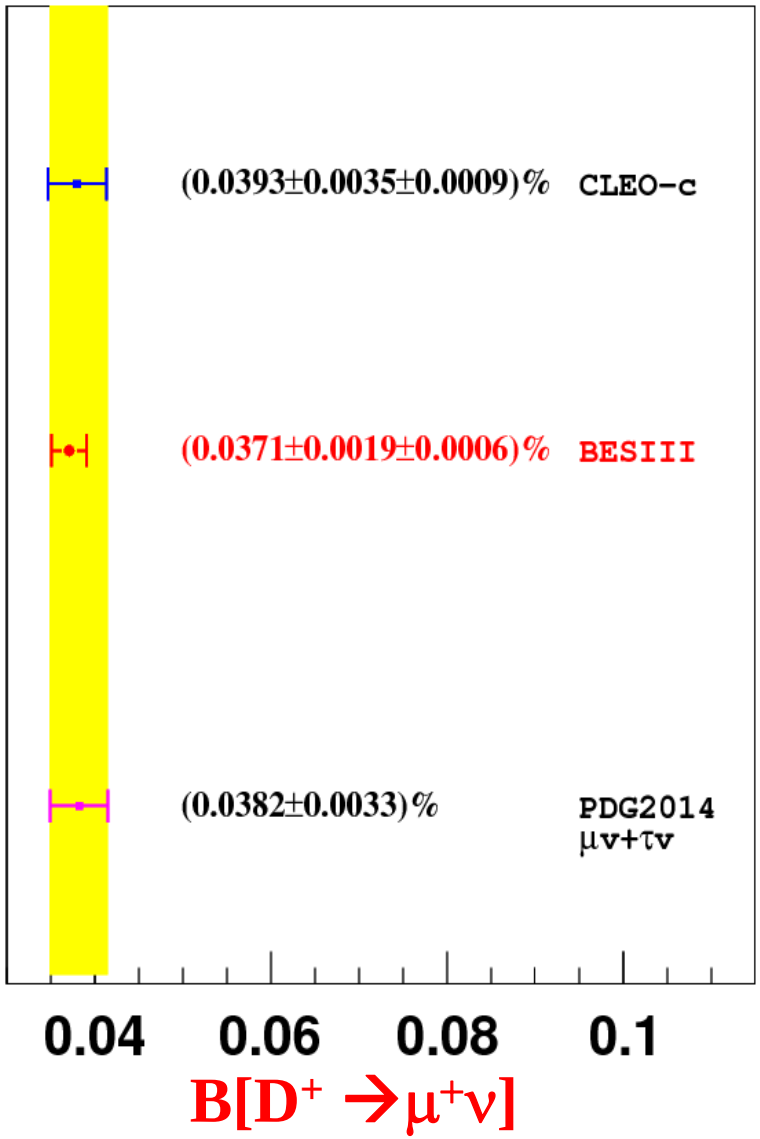
Input t_{D^+}, m_{D^+}, m_{μ^+} on PDG and $|V_{cd}|$ of CKM-Fitter

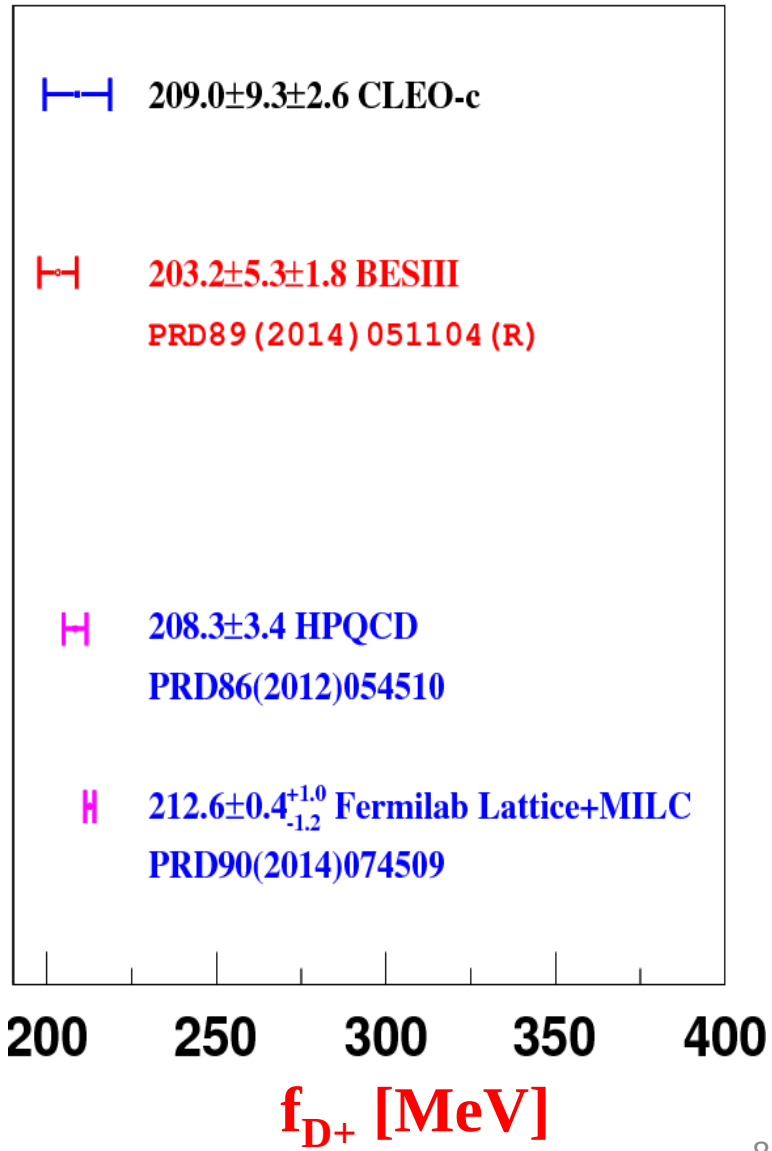
$f_{D^+} = (203.2 \pm 5.3 \pm 1.8)$ MeV

Input t_{D^+}, m_{D^+}, m_{μ^+} on PDG and LQCD calculated $f_{D^+} = 207 \pm 4$ MeV[PRL100(2008)062002]

$|V_{cd}| = 0.2210 \pm 0.0058 \pm 0.0047$

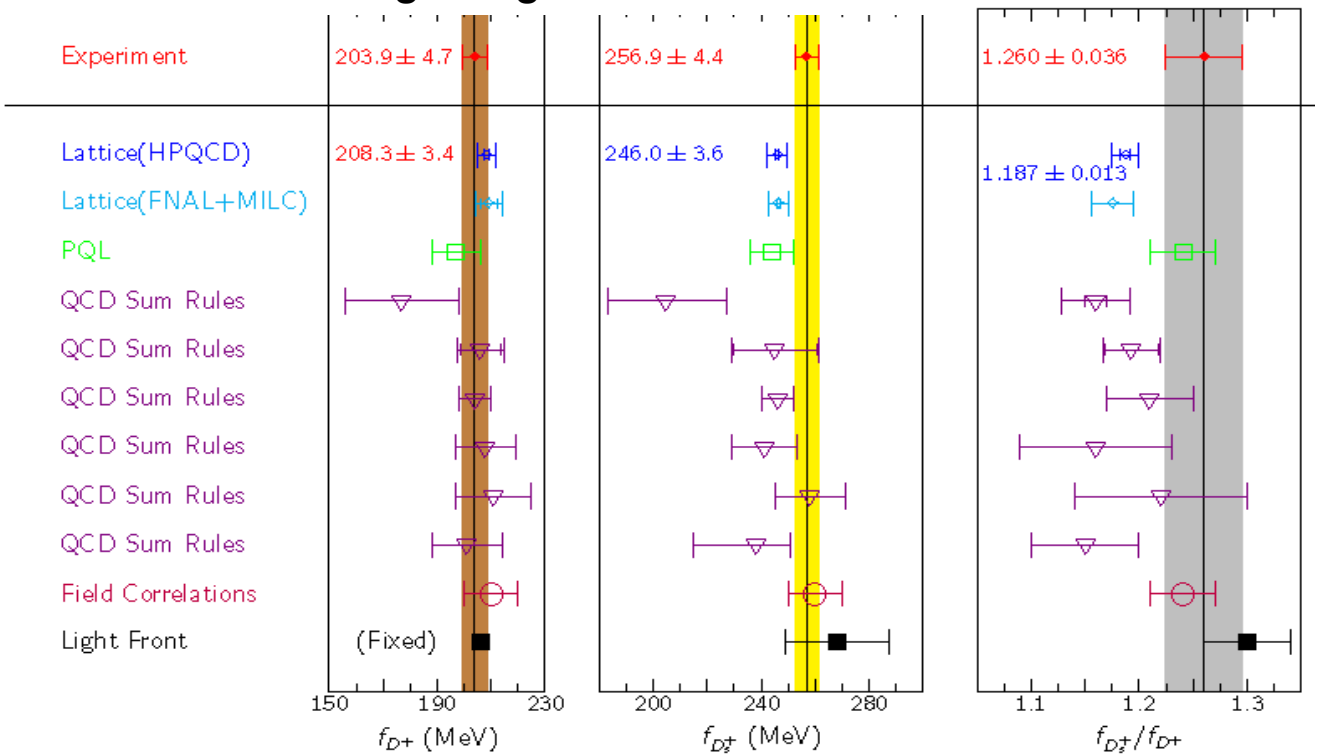
Comparisons of $B[D^+ \to \mu^+ \nu_\mu]$ and f_{D+}





Comparisons of f_{D+}, f_{Ds+} and f_{D+}:f_{Ds+}

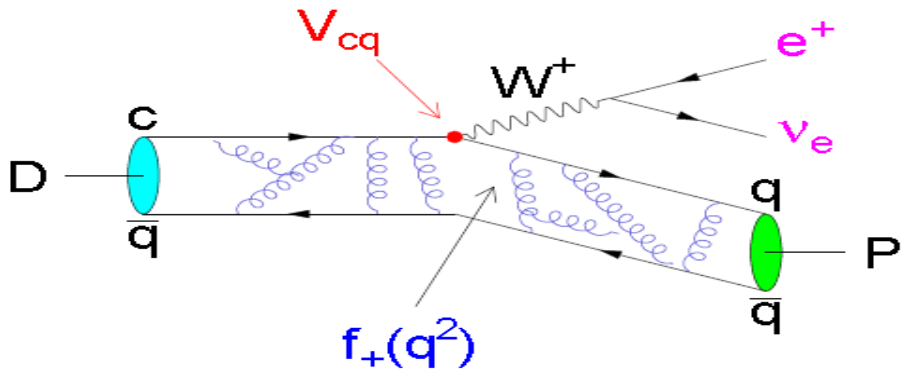
Taken from Gang Rong's talk at CKM2014



- **Precisions of the LQCD calculations of f_{D+}, f_{Ds+}, f_{D+}:f_{Ds} reach 0.5%, 0.5% and 0.3%, which are challenging the experiments**
- **The experimentally measured and the theoretically expected f_{D+}, f_{Ds+}, f_{D+}:f_{Ds+} differ by about 2σ**
- **Improving measurement with larger data sample is expected at BESIII!**

	Experiments	Femilab Lattice+MILC (2014)		HPQCD (2012)	
	Averaged	Expected	Δ	Expected	Δ
f_{D+}(MeV)	203.9±4.7	$212.6\pm0.4^{+1.0}_{-1.2}$	1.8σ	208.3±3.4	0.8σ
f_{Ds+}(MeV)	256.9±4.4	$249.0\pm0.3^{+1.1}_{-1.5}$	1.7σ	246.0±3.6	1.4σ
f_{D+}:f_{Ds+}	1.260±0.036	$1.1712\pm0.0010^{+0.0029}_{-0.0032}$	2.5σ	1.187±0.013	1.9σ

D Semi-leptonic Decays



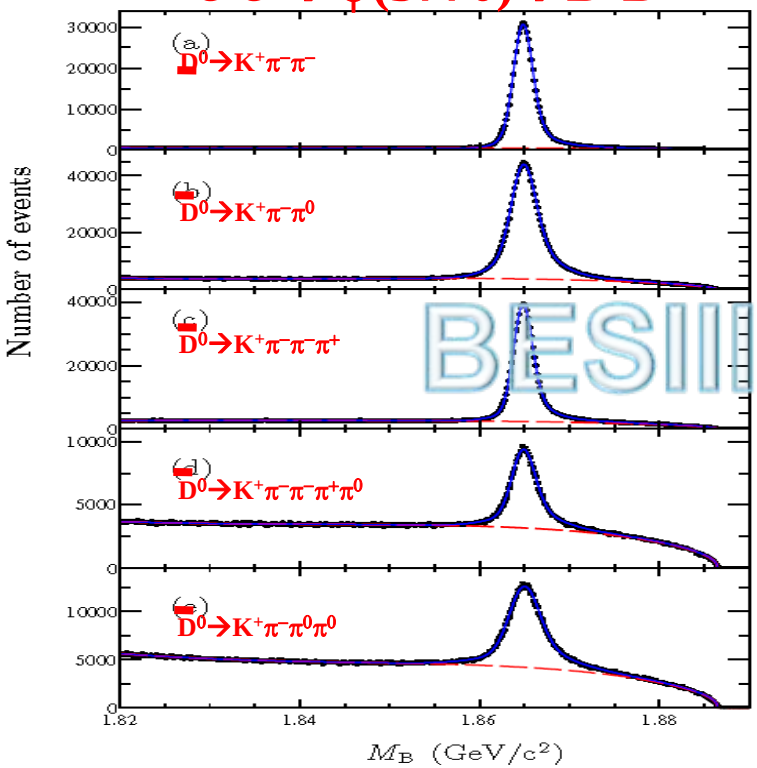
Differential rates: $\frac{d\Gamma}{dq^2} = X\frac{G_F^2|V_{cd(s)}|^2}{24\pi^3}p^3|f_+(q^2)|^2$

Bridge to precisely measure:

- **Form factors $f^{D\to K(\pi)}_+(q^2)$ with input $|V_{cd(s)}|^{CKMfitter}$**
  - **Single pole form**
    $f_+(q^2) = \frac{f_+(0)}{1-\frac{q^2}{M^2_{pole}}}$
  - **Modified pole model**
    $f_+(q^2) = \frac{f_+(0)}{(1-\frac{q^2}{M^2_{pole}})(1-\alpha\frac{q^2}{M^2_{pole}})}$
  - **ISGW2 model**
    $f_+(q^2) = f_+(q^2_{max})\left(1+\frac{r^2_{ISGW2}}{12}(q^2_{max}-q^2)\right)^{-2}$
  - **Series expansion model**
    $f_+(t) = \frac{1}{P(t)\Phi(t,t_0)}a_0(t_0)\left(1+\sum_{k=1}^{\infty}r_k(t_0)[z(t,t_0)]^k\right)$
- **CKM matrix element $|V_{cs(d)}|$ with input $f^{LQCD,D\to K(\pi)}_+(0)$**

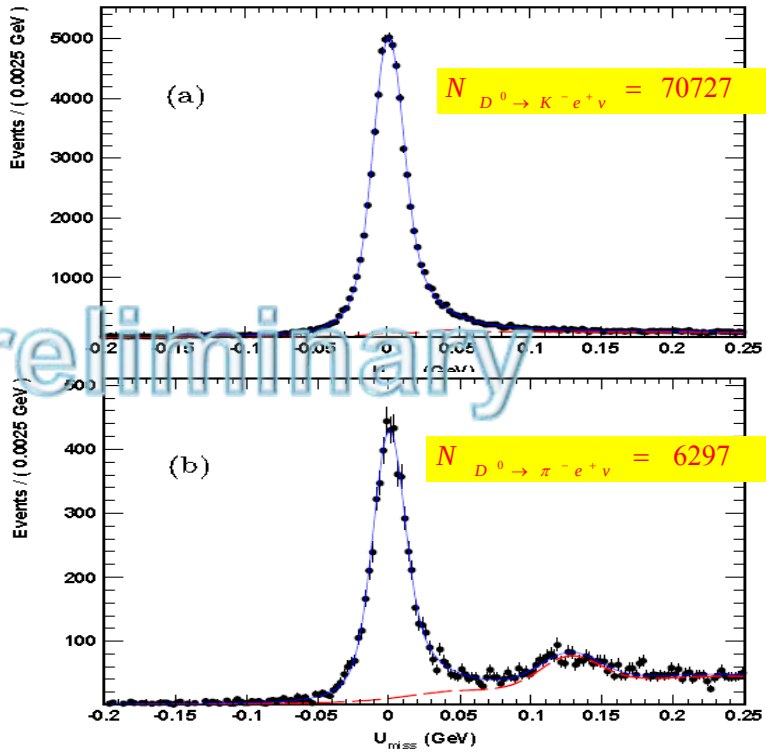
Measurement of $B[D^0 \to K(\pi)^- e^+ \nu]$

$e^+e^- \to \psi(3770) \to D^0\bar{D}^0$



$N_{\bar{D}^0_{tag}} = (279.33 \pm 0.37) \times 10^4$

$U_{miss} = E_{miss} - p_{miss}$



$N_{D^0 \to K^- e^+ \nu} = 70727 \pm 278$

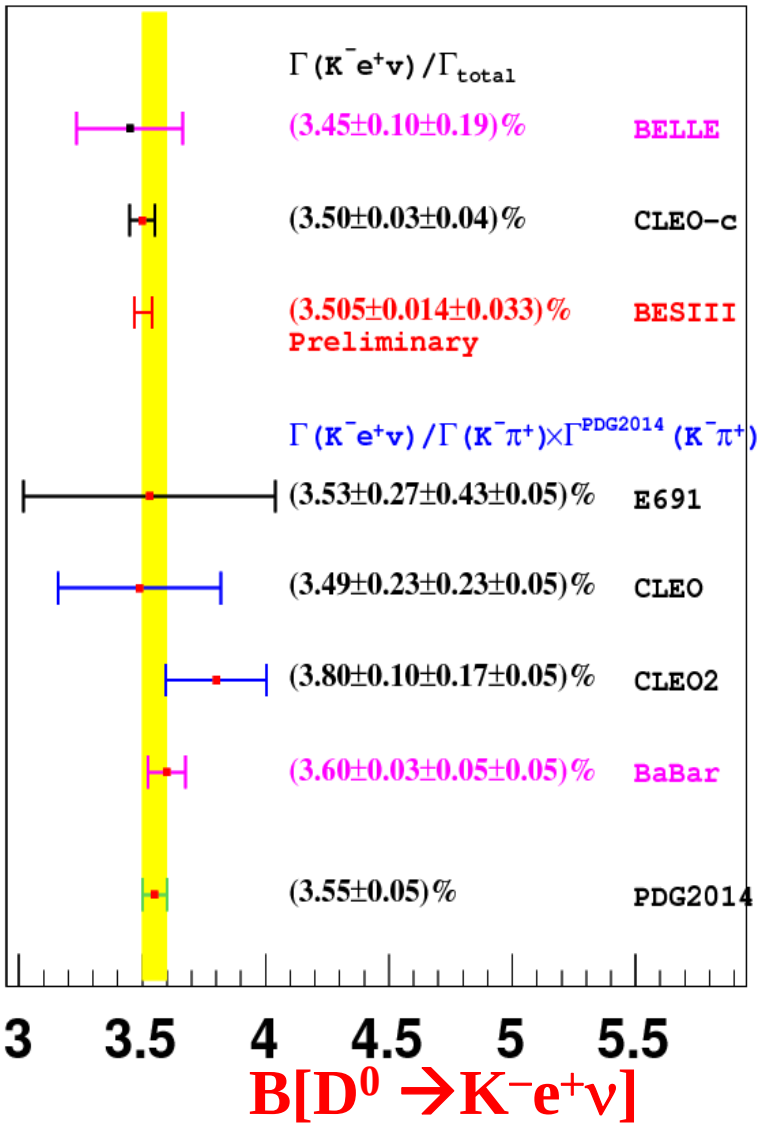
$N_{D^0 \to \pi^- e^+ \nu} = 6297 \pm 87$

BESIII Preliminary

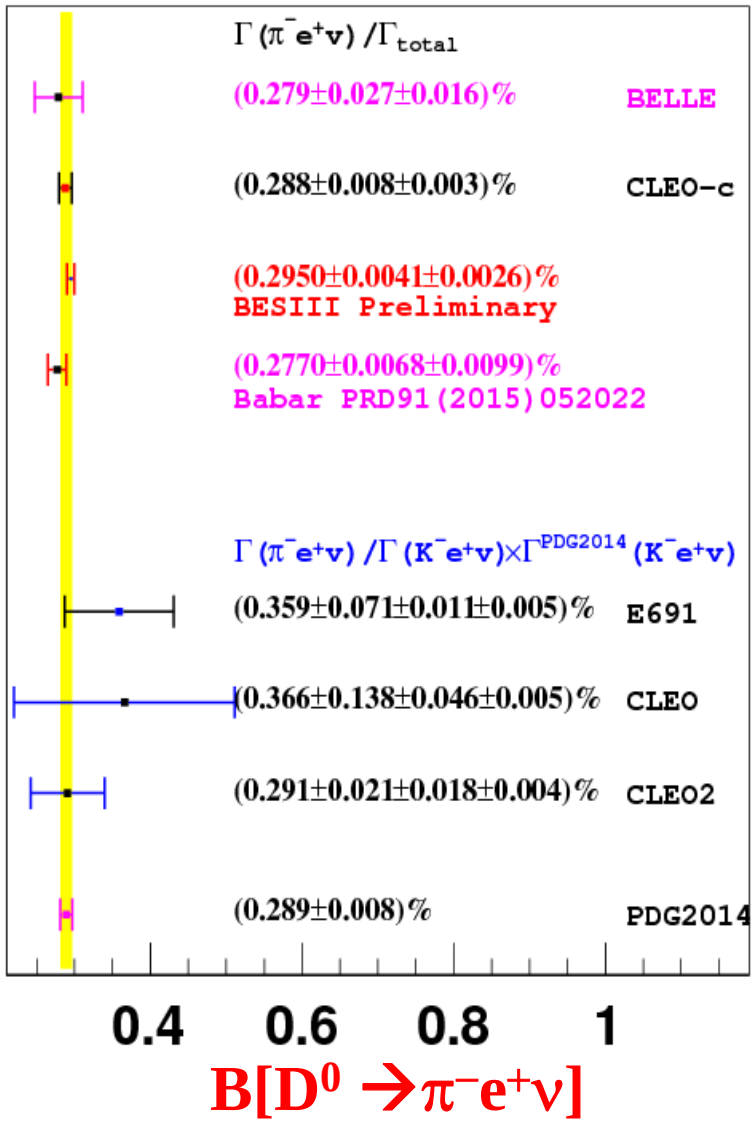
$B_{D^0 \to K^- e^+ \nu} = (3.505 \pm 0.014 \pm 0.033)\%$

$B_{D^0 \to \pi^- e^+ \nu} = (0.2950 \pm 0.0041 \pm 0.0026)\%$

Comparison of $B[D^0 \to K(\pi)^- e^+ \nu]$

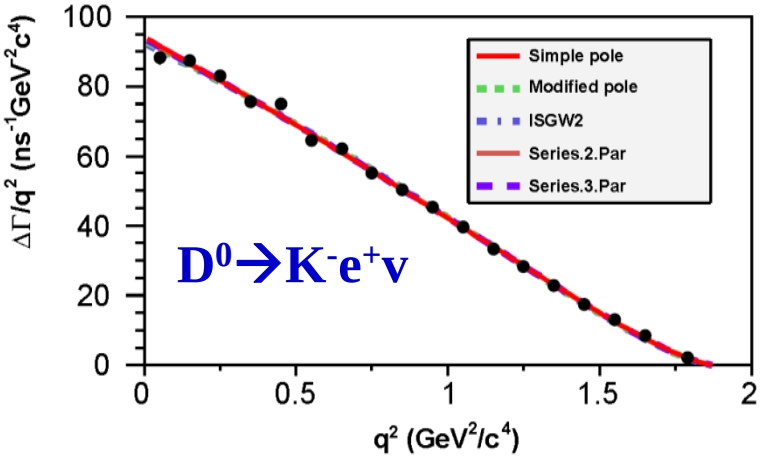


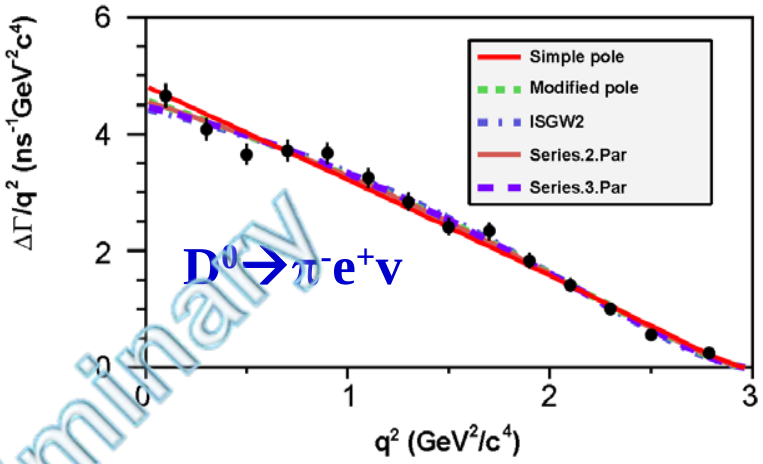
$B[D^0 \to K^- e^+ \nu]$



$B[D^0 \to \pi^- e^+ \nu]$

Extracted Parameters of Form Factors





BESIII Preliminary

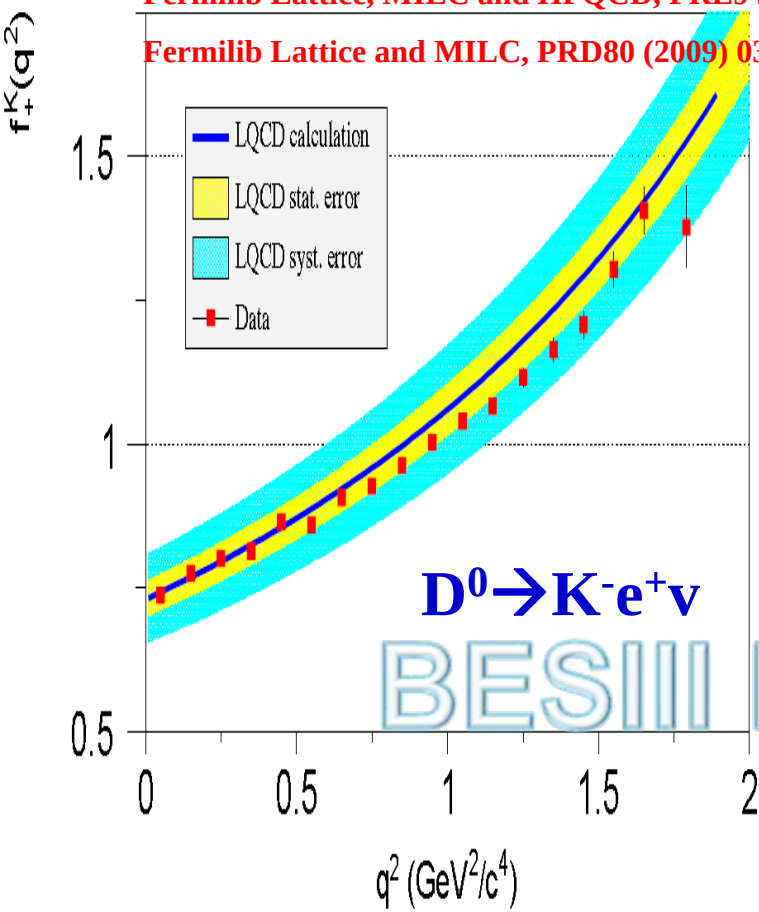
		$D^0 \to K^- e^+ \nu$		$D^0 \to \pi^- e^+ \nu$
Simple Pole	$f_K^+(0)\lvert V_{cs}\rvert$	0.7209±0.0022±0.0033	$f_\pi^+(0)\lvert V_{cd}\rvert$	0.1475±0.0014±0.0005
	M_{pole}	1.9207±0.0103±0.0069	M_{pole}	1.9114±0.0118±0.0038
Mod. Pole	$f_K^+(0)\lvert V_{cs}\rvert$	0.7163±0.0024±0.0034	$f_\pi^+(0)\lvert V_{cd}\rvert$	0.1437±0.0017±0.0008
	α	0.3088±0.0195±0.0129	α	0.2794±0.0345±0.0113
ISGW2	$f_K^+(0)\lvert V_{cs}\rvert$	0.7139±0.0023±0.0034	$f_\pi^+(0)\lvert V_{cd}\rvert$	0.1415±0.0016±0.0006
	r_{ISGW2}	1.6000±0.0141±0.0091	r_{ISGW2}	2.0688±0.0394±0.0124
Series.2.Par	$f_K^+(0)\lvert V_{cs}\rvert$	0.7172±0.0025±0.0035	$f_\pi^+(0)\lvert V_{cd}\rvert$	0.1435±0.0018±0.0009
	r_1	-2.2278±0.0864±0.0575	r_1	-2.0365±0.0807±0.0260
Series.3.Par	$f_K^+(0)\lvert V_{cs}\rvert$	0.7196±0.0035±0.0041	$f_\pi^+(0)\lvert V_{cd}\rvert$	0.1420±0.0024±0.0010
	r_1	-2.3331±0.1587±0.0804	r_1	-1.8434±0.2212±0.0690
	r_2	3.4223±3.9090±2.4092	r_2	-1.3871±1.4615±0.4677

Measurement of $f_+^{K(\pi)}(q^2)$

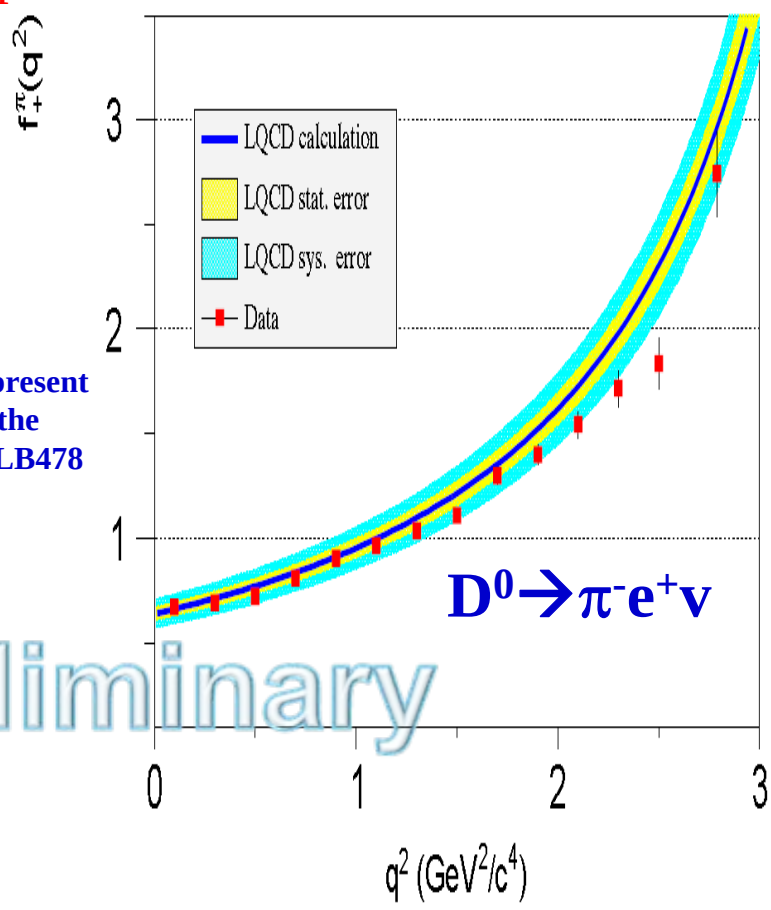
Experimental data calibrate LQCD calculation

Fermilib Lattice, MILC and HPQCD, PRL94 (2005) 011601

Fermilib Lattice and MILC, PRD80 (2009) 034026



Solid lines represent LQCD fits to the BK model, PLB478 (2000)417

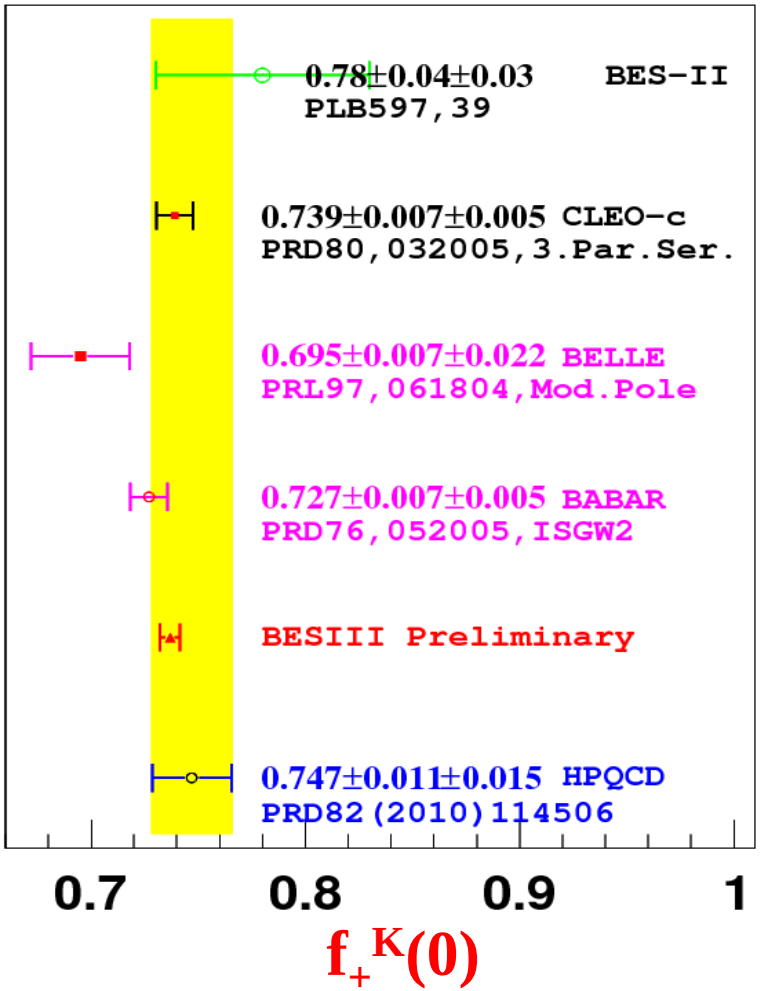


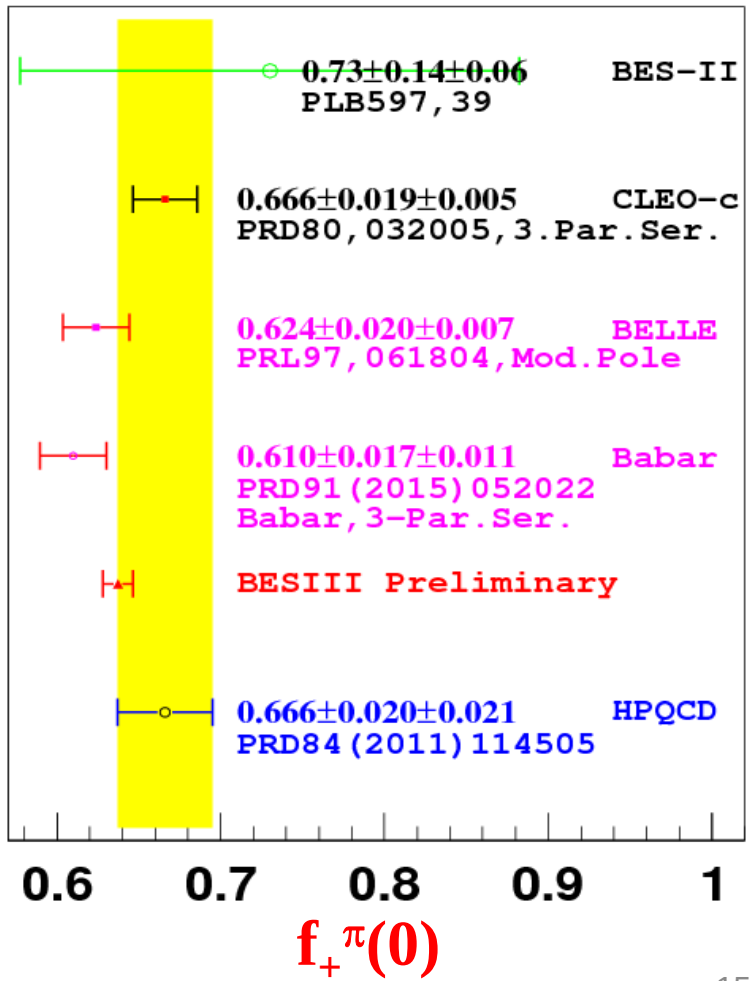
BESIII Preliminary

BESIII

Measurement of $f_+^{K(\pi)}(0)$

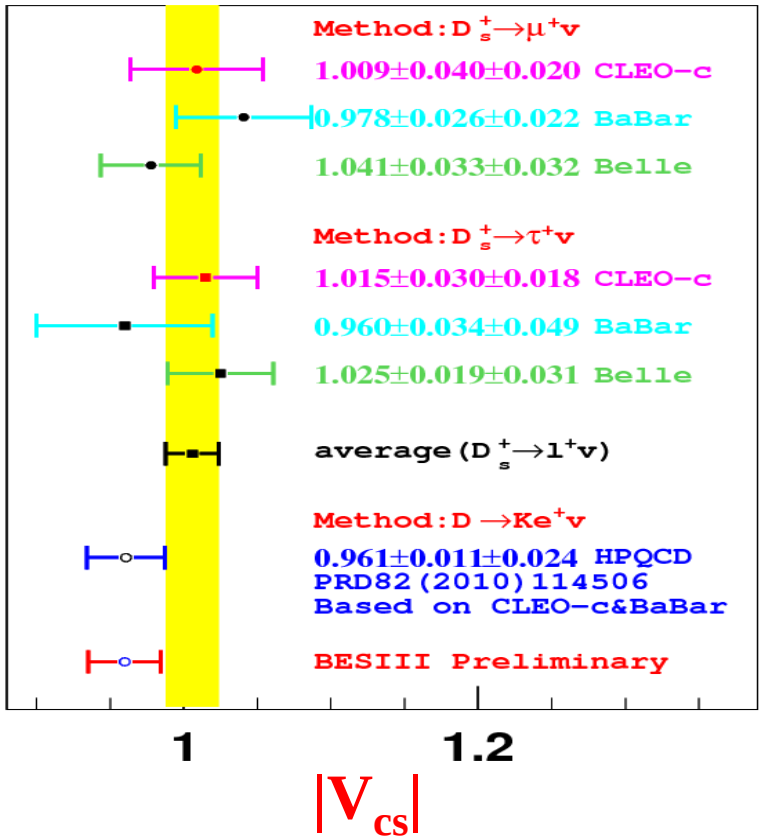
$f^{D\to K(\pi)}_+(0)|V_{cs(d)}|$ → Input $|V_{cs(d)}|$ of CKM-Fitter → $f^{D\to K(\pi)}_+(0)$

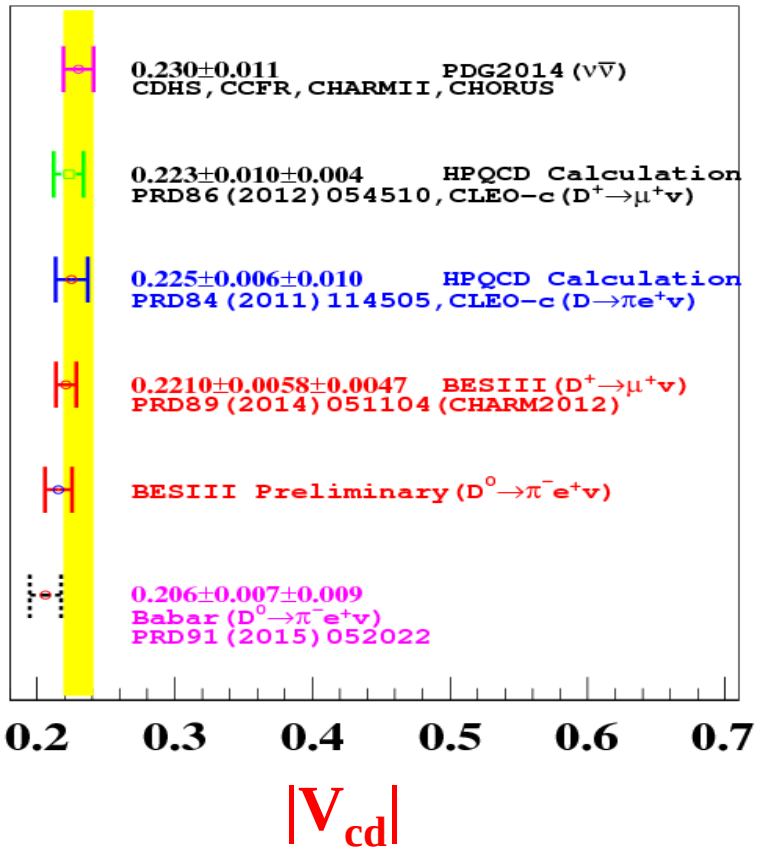




Measurement of $|V_{cs(d)}|$

- **Method 1** $B[D_{(s)}^{+} \to l^{+}\nu]$ → $|V_{cd(s)}|$
  Input t_{D+}, m_{D+}, $m_{\mu+}$ on PDG and LQCD calculated $f_{D(s)+}$
- **Method 2** $f^{D\to K(\pi)}_{+}(0)|V_{cs(d)}|$ → $|V_{cs(d)}|$
  Input $f^{D\to K(\pi)}_{+}(0)$ of LQCD





Method 2 suffers larger theoretical uncertainty in $f_{+}^{D\to K(\pi)}(0)$ [1.7(4.4)%]

Study of $D^+ \to K_L e^+ \nu$

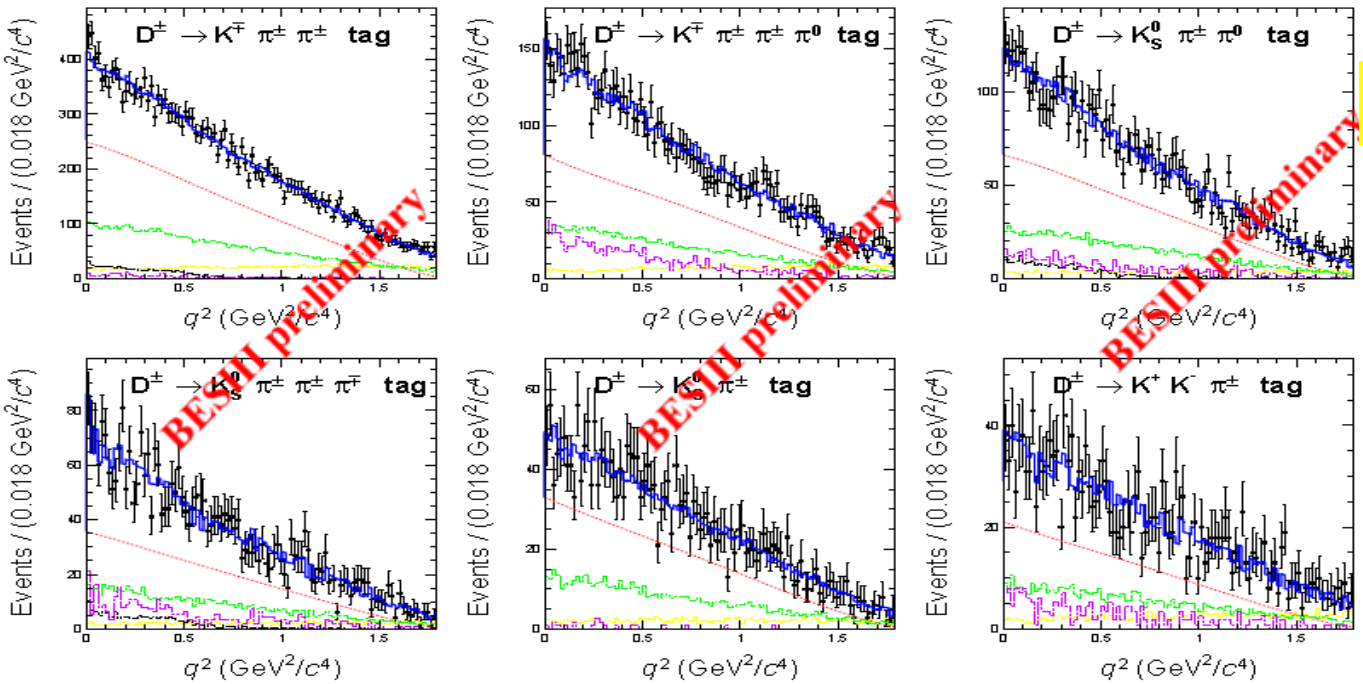
- Regardless of long flight distance, K_L interact with EMC and deposit part of energy, thus giving position information
- After reconstructing all other particles, K_L can be inferred with position information and constraint $U_{miss} \to 0$.

$\bar{B}(D^+ \to K_L e^+ \nu) = (4.482 \pm 0.027 \pm 0.103)\%$

$$A_{CP} \equiv \frac{\mathcal{B}(D^+ \to K_L^0 e^+ \nu_e) - \mathcal{B}(D^- \to K_L^0 e^- \bar{\nu}_e)}{\mathcal{B}(D^+ \to K_L^0 e^+ \nu_e) + \mathcal{B}(D^- \to K_L^0 e^- \bar{\nu}_e)}$$

$A_{CP}^{D^+ \to K L e^+ \nu} = (-0.59 \pm 0.60 \pm 1.50)\%$

Simultaneous fit to event density $I(q^2)$ with 2-par. series Form Factor



First measurements

See Fenfen An's talk for more detail

$f^K_+(0)|V_{cs}| = 0.728 \pm 0.006 \pm 0.011$

$r_1 = a_1/a_0 = -1.91 \pm 0.33 \pm 0.24$

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

- **Fractions with >5σ significance**

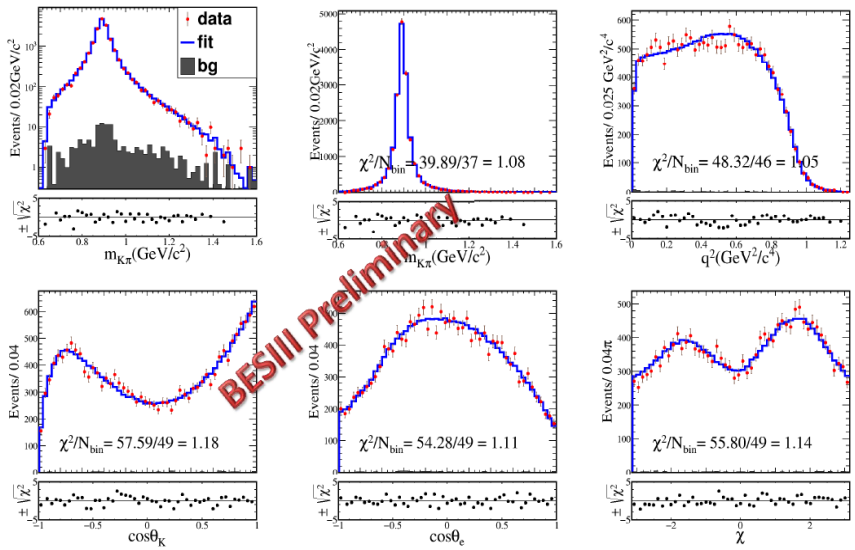
$$f(D^+ \to (K^-\pi^+)_{K^{*0}(892)}\, e^+\nu_e) = (93.93 \pm 0.22 \pm 0.18)\%$$

$$f(D^+ \to (K^-\pi^+)_{S-wave}\, e^+\nu_e) = (6.05 \pm 0.22 \pm 0.18)\%$$

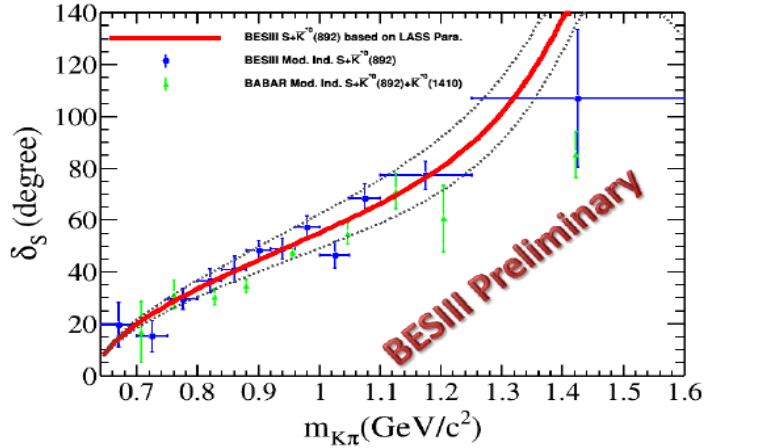
- **Measured parameters of $\bar{K}^*(892)$**

$$m_{K^{*0}(892)} = (894.60 \pm 0.25 \pm 0.08)\ \mathrm{MeV}/c^2$$
$$\Gamma_{K^{*0}(892)} = (46.42 \pm 0.56 \pm 0.15)\ \mathrm{MeV}/c^2$$
$$r_{BW} = (3.07 \pm 0.26 \pm 0.11)\ (\mathrm{GeV}/c)^{-1}$$

- **Comparison of data and fit with S+P in $D^+ \to K^-\pi^+e^+\nu$**



Model independent S-wave phase measurement



Form factors of $D^+ \to \bar{K}^*(892)e^+\nu$ by SPD model

$$V(q^2) = \frac{V(0)}{1-q^2/m_V^2}, \quad A_{1,2}(q^2) = \frac{A_{1,2}(0)}{1-q^2/m_A^2}$$

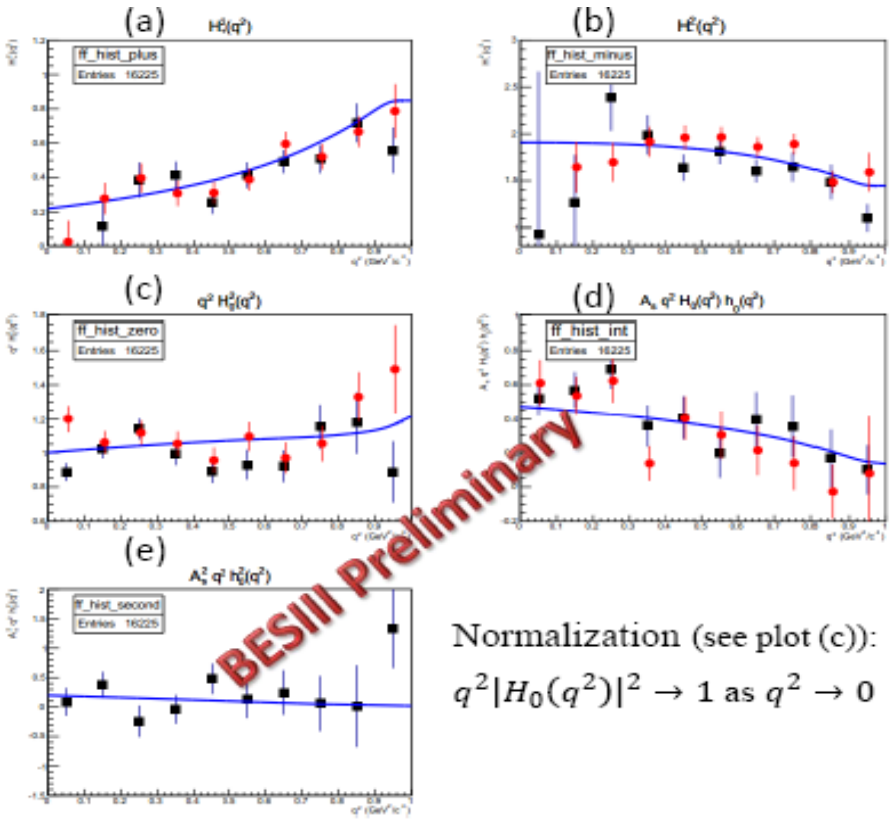
$M_{V/A}$ is expected to $M_{D^*(1-/+)}$

$$m_V = (1.81^{+0.25}_{-0.17} \pm 0.02)\ \mathrm{GeV}/c^2$$
$$m_A = (2.61^{+0.22}_{-0.17} \pm 0.03)\ \mathrm{GeV}/c^2$$
$$A_1(0) = 0.573 \pm 0.011 \pm 0.020$$
$$r_V = V(0)/A_1(0) = 1.411 \pm 0.058 \pm 0.007$$
$$r_2 = A_2(0)/A_1(0) = 0.788 \pm 0.042 \pm 0.008$$

See Fenfen An's talk for more detail

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

- Events located in the $K^{*0}(892)$ window [0.8,1] GeV/c^2, are used to measure the form factors by a Projective Weighting Technique [citation: CLEO collaboration, Phys. Rev. D 81, 112001 (2010)].
- Signal is assumed to be composed of $K^{*0}(892)$ and a non-resonant S-wave.
- Helicity basis form factors include:
  P-wave related: $H_{\pm,0}(q^2)$
  S-wave related: $h_0(q^2)$
- Five weighted q^2 histograms are built. Weight is assigned to each event based on $(q^2, cos\theta_K, cos\theta_e)$.
- Form factors are independently computed in each q^2 bin.
- The model-independent measurements are generally consistent with CLEO's report. And they are also consistent with the predicted trend based on the SPD model from amplitude analysis.



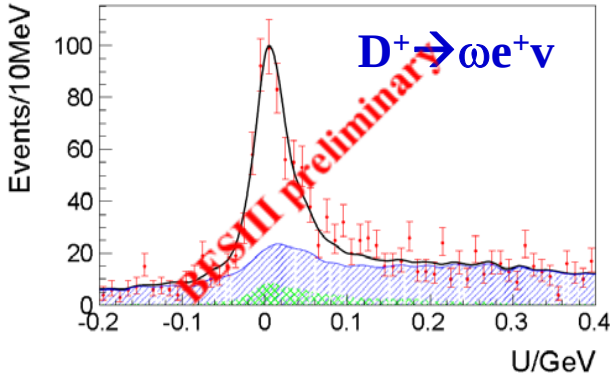
Normalization (see plot (c)):
$q^2|H_0(q^2)|^2 \to 1$ as $q^2 \to 0$

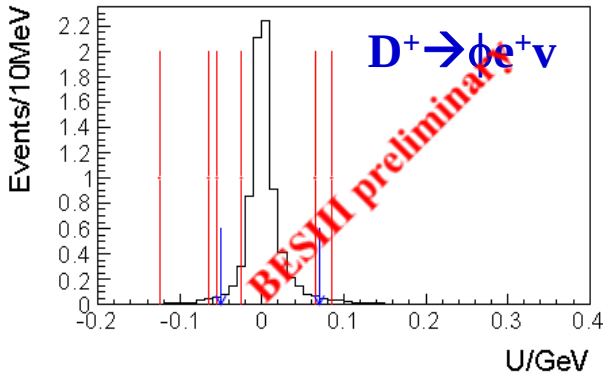
Red dots : BESIII model-independent measurement
Black dots : CLEO model-independent measurement
Blue Line : BESIII result from amplitude analysis, which is based on SPD model and mass-dependent S-wave

Notice: The lines are not simple fits of these dots!

Model independent measurement of form factors in $D^+ \to \bar{K}^{*0}(892)e^+\nu$

Study of $D^+ \to \omega e^+ \nu$ and Search for $D^+ \to \phi e^+ \nu$

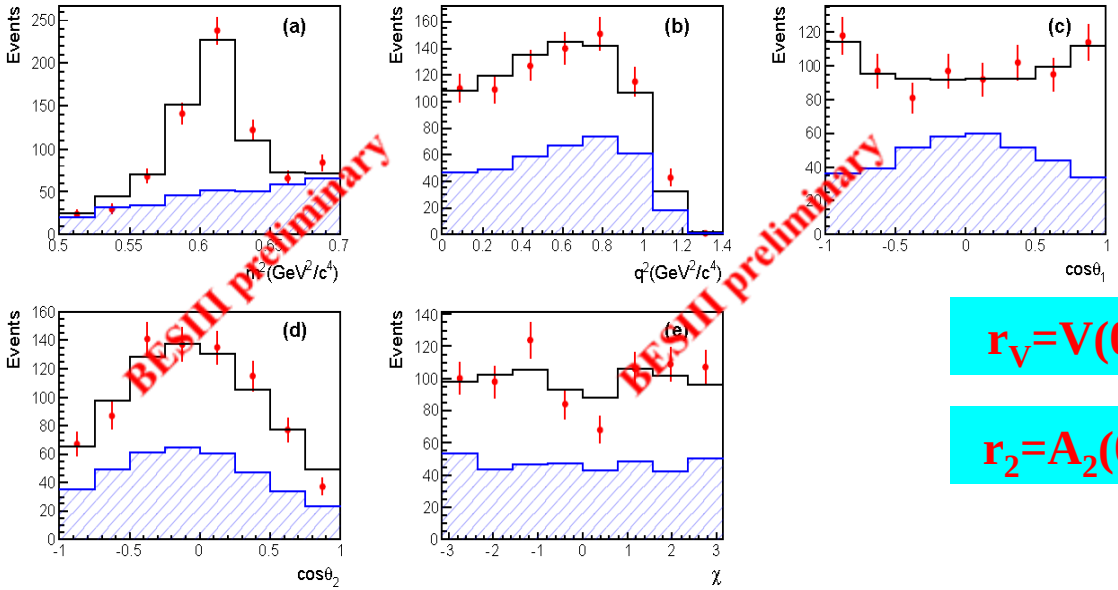




$B[D^+ \to \omega e^+ \nu] = (1.63 \pm 0.11 \pm 0.08) \times 10^{-3}$

$B[D^+ \to \phi e^+ \nu] < 1.3 \times 10^{-5}$ at 90% C.L.

Amplitude analysis is performed



$r_V = V(0)/A_1(0) = 1.24 \pm 0.09 \pm 0.06$

$r_2 = A_2(0)/A_1(0) = 1.06 \pm 0.15 \pm 0.05$

See Fenfen An's talk for more detail

Summary

- With 2.92 fb^{-1} data taken at 3.773 GeV by BESIII, we study the leptonic decay $D^+ \to \mu^+ \nu$, the semi-leptonic decays $D^0 \to K(\pi)^- e^+ \nu$, as well as $D^+ \to K_L e^+ \nu$, $K^- \pi^+ e^+ \nu$ and $\omega/\phi e^+ \nu$
  - Improved decay constant f_{D+}, form factors $f_+^{D \to K(\pi)}(q^2)$ in $D \to K(\pi) e^+ \nu$, as well as form factors in $D^+ \to V e^+ \nu$, which are important to test/calibrate LQCD calculations accurately
  - Improved CKM matrix element $|V_{cs(d)}|$, which is important for unitarity test of the CKM matrix
  - Some other topics are ongoing
- BESIII decide to take 3 fb^{-1} data at 4.17 GeV in 2016, improved f_{Ds+} and $|V_{cs}|$ by $D_s^+ \to l^+ \nu$ are expected in the near future
- 10 fb^{-1} more data at 3.773 GeV will be more helpful for further improving decay constant, form factors, $|V_{cs(d)}|$, as well as strong phases……

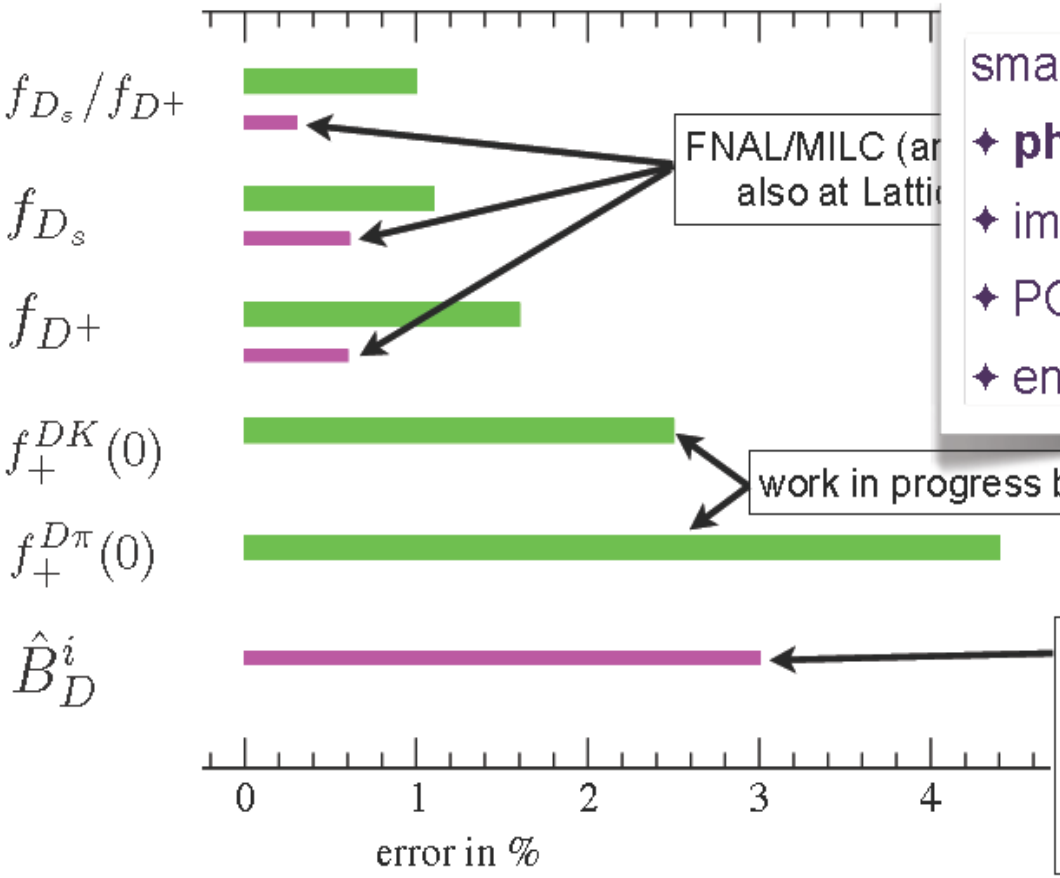
Thank you!

Back-up slides

Progress in LQCD Calculation

Taking from Aida X. EI-Khadra's talk at Beauty2014

errors (in %) comparison: **FLAG-2 averages** vs. **new results**



small errors due to

- **physical light quark masses**
- improved charm-quark action (HISQ)
- PCAC (no renormalization)
- ensembles with small lattice spacings

work in progress by FNAL/MILC (Lattice 2014), ETM, HPQCD, ...

- **First results for D mixing bag parameters** (all five) with local operators only by ETM (2013, 2014) $n_f = 2, 2+1+1$
- work in progress: FNAL/MILC (Lattice 2014)

review by C. Bouchard @ Lattice 2014