Charm Physics at BESIII

(Leptonic and semi-leptonic D decays)

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- $D^0 \to K(\pi)^- e^+ \nu$
- Summary

- What happen in the past 26 years?
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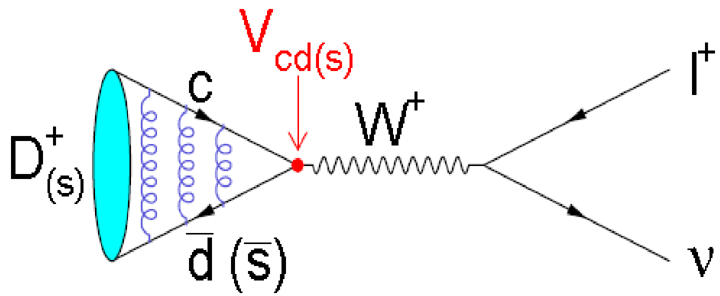
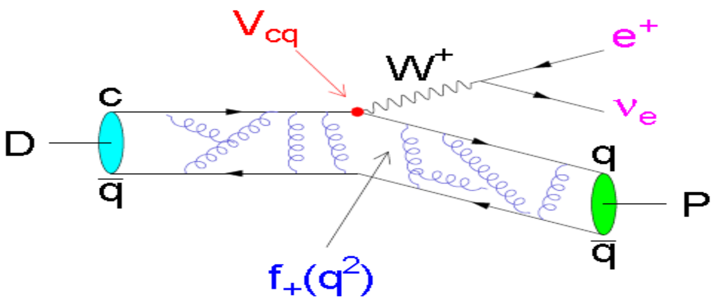
- Opportunity in the next 20 years?

I would like to thank Prof. Steve Olsen for his helpful suggestions to improve my slides!

Why they are important?

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



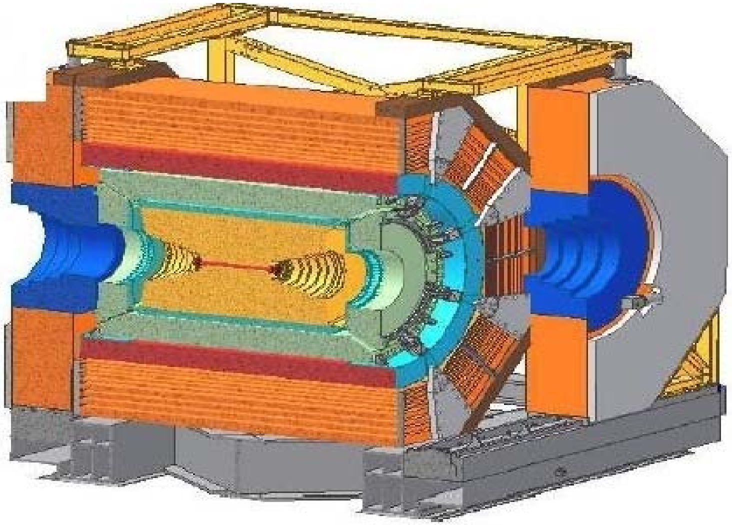


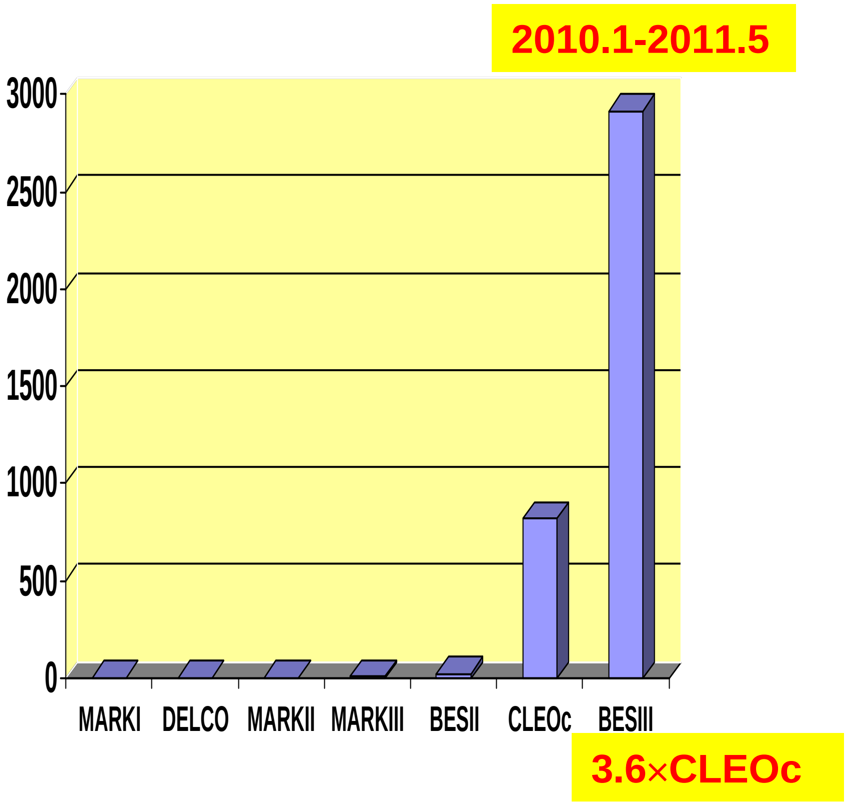
- **Precision measurements of decay constants f_{D+}, f_{Ds+}, form factors $f_+^{D\to K(\pi)}(q^2)$ of semi-leptonic decays of $D_{(s)}$ mesons will calibrate LQCD calculations at higher accuracy. Once they pass experimental tests, the precisely LQCD calculated f_D/f_B, f_{Ds}/f_{Bs} and $f_+^{D\to K(\pi)}(0)/f_+^{B\to K(\pi)}(0)$ will be helpful for measurements in B decays**

- **Recently improved LQCD calculations on $f_{D(s)+}$[0.5(0.5)%], $f_+^{D\to K(\pi)}(0)$ [2.4(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

2.92 fb^{-1} data were taken around 3.773 GeV

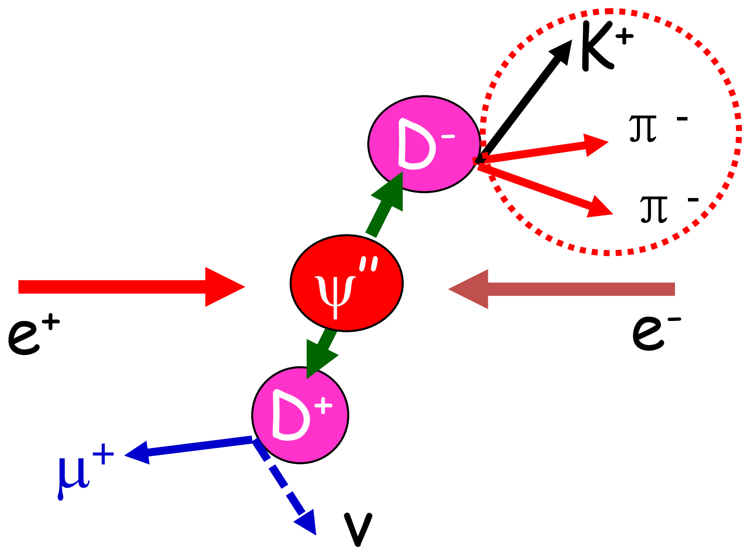


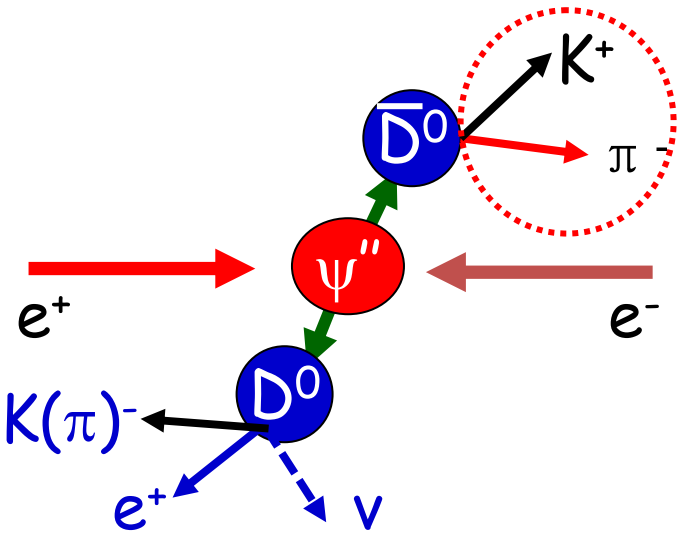


Singly Tagged $\bar{D}^0$ and D^- Mesons

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

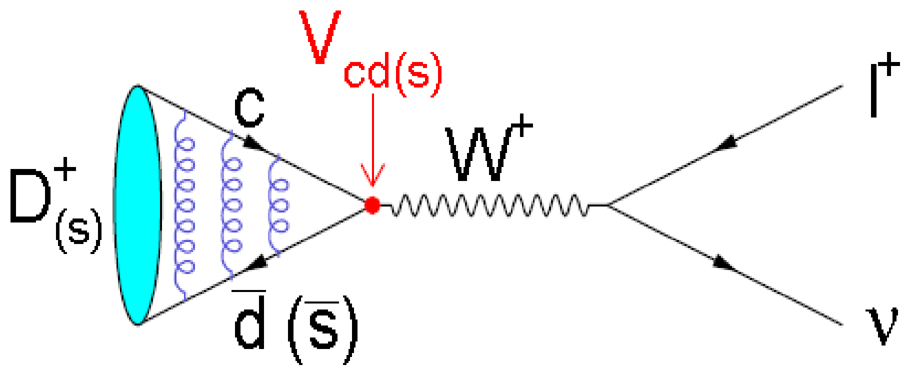
Singly tagged $\bar{D}^0$ and D^- mesons are reconstructed by hadron decays with large branching fraction and less combinatorial backgrounds





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:

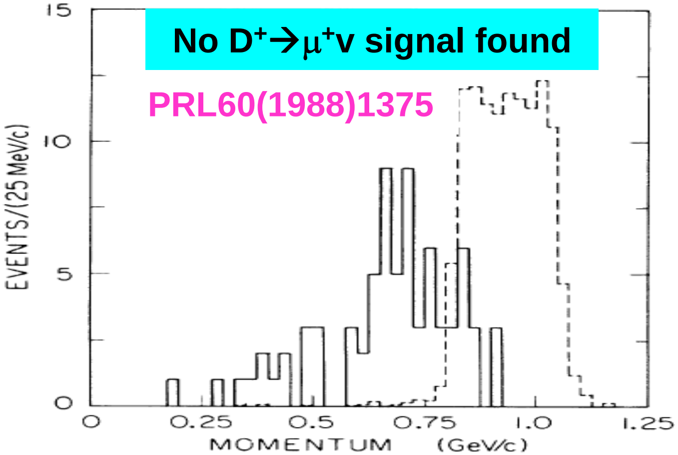
$$\Gamma(D^+_{(s)} \to \ell^+ \nu_\ell) = \frac{G_F^2 f_{D^+_{(s)}}^2}{8\pi} |V_{cd(s)}|^2 m_\ell^2 m_{D^+_{(s)}} \left(1 - \frac{m_\ell^2}{m_{D^+_{(s)}}^2}\right)^2$$

Bridge to precisely measure

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

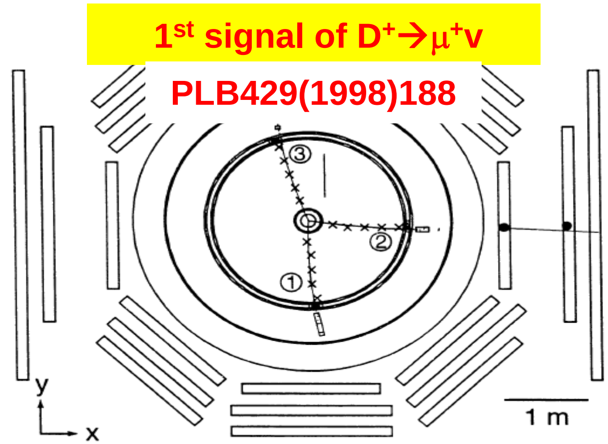
Progress of Measuring f_{D+} in past 26 years

- MARKIII, 9.6 pb^{-1} at ψ''



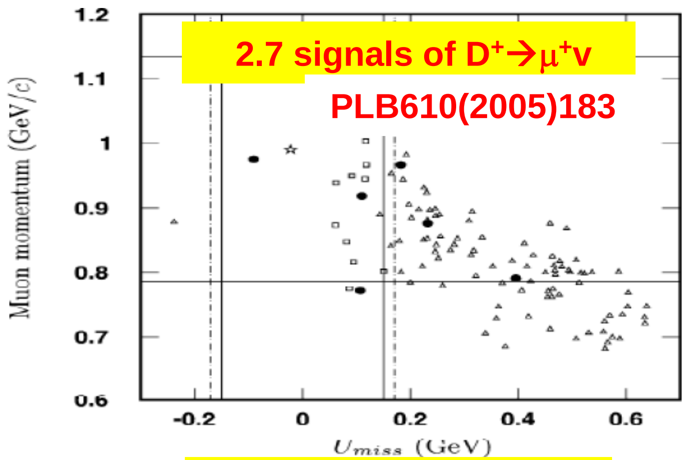
f_{D+}<290 MeV @ 90% C.L.

- BESI, 22.3 pb^{-1} at 4.03 GeV



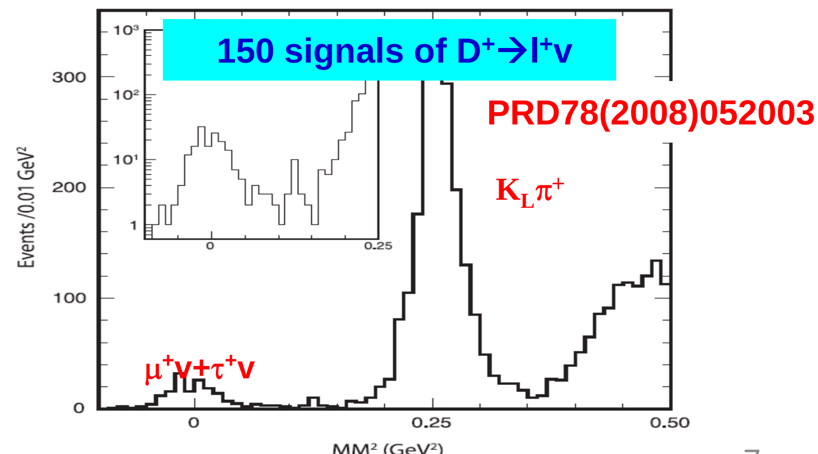
$f_{D^+} = (300^{+180+80}_{-150-40})$ MeV

- BESII, 33 pb^{-1} data at ψ''



$f_{D^+} = (371^{+129}_{-119} \pm 25)$ MeV

- 2004-2008, CLEO-c, 818 pb^{-1} at ψ''



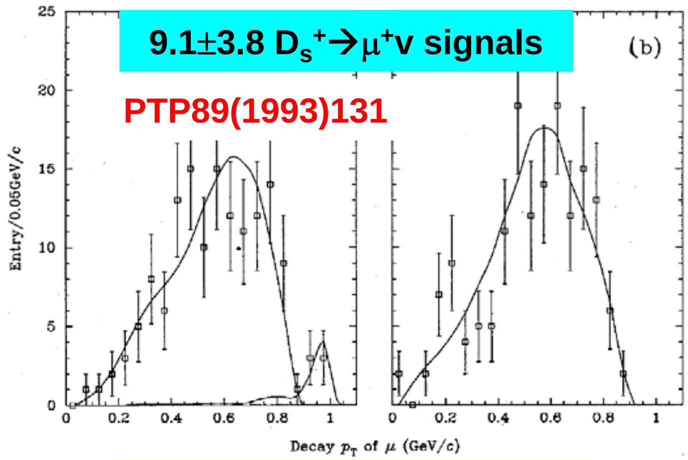
f_{D+}=205.8±7.5±2.5 MeV

Progress of Measuring f_{D_s+} in past 21 years

- WA75, Fixed target experiment

9.1±3.8 $D_s^+ \to \mu^+ v$ signals

PTP89(1993)131

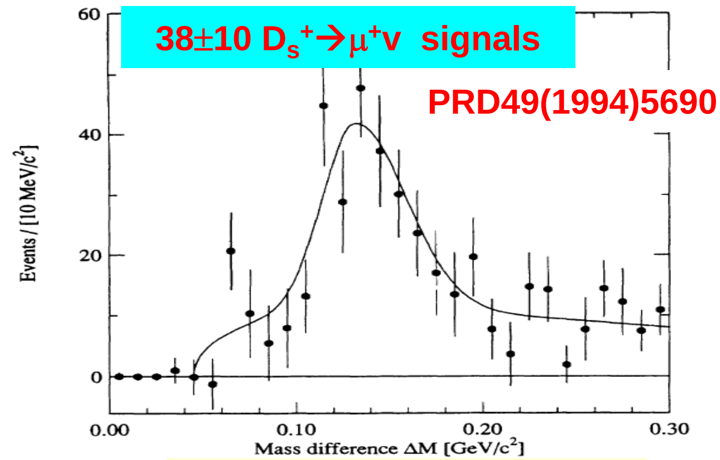


f_{Ds+}=232±45±20±48 MeV

- CLEOII, 2.13 fb^{-1} at 10.6 GeV

38±10 $D_s^+ \to \mu^+ v$ signals

PRD49(1994)5690

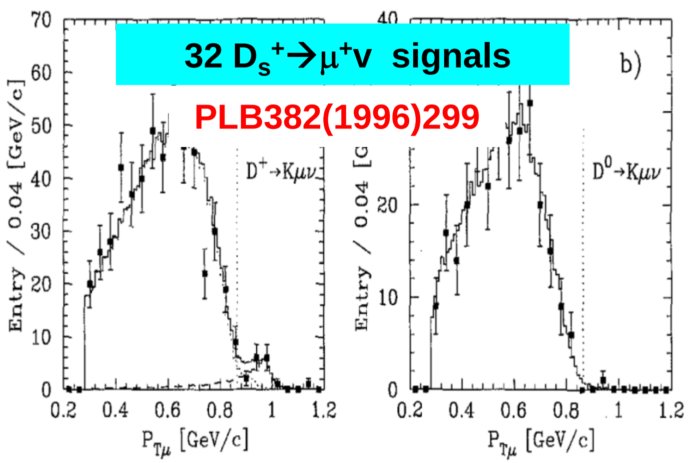


f_{Ds+}=344±37±52±42 MeV

- E653, Fermilab fixed target experiment

32 $D_s^+ \to \mu^+ v$ signals

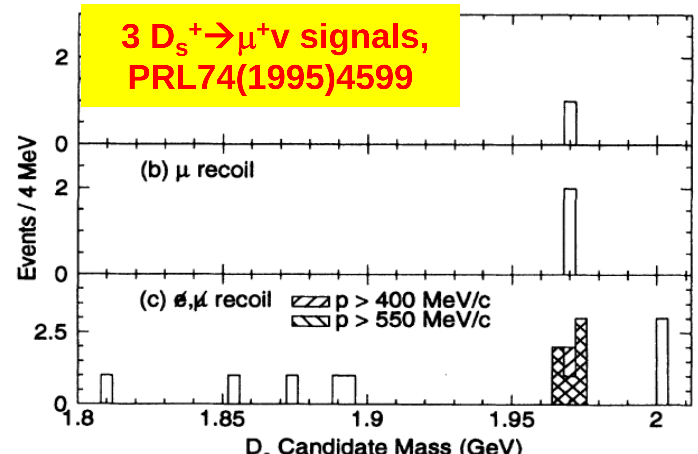
PLB382(1996)299



f_{Ds+}=194±35±20±14 MeV

- BESI, 22.3 pb^{-1} at 4.03 GeV

3 $D_s^+ \to \mu^+ v$ signals,
PRL74(1995)4599



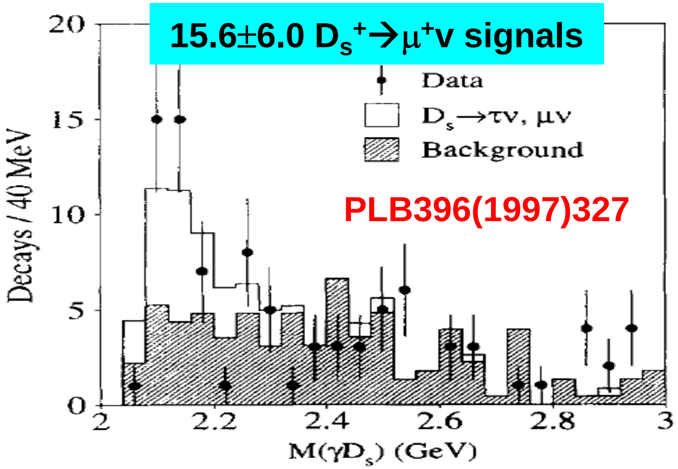
$$f_{D_s^+} = (430^{+150+40}_{-130-40})\ \text{MeV}$$

First absolute measurement

Progress of Measuring f_{Ds+} in past 21 years

- L3, $Z \to q\bar{q}$, 49.6 pb^{-1} at 91.2 GeV

15.6±6.0 $D_s^+ \to \mu^+ v$ signals

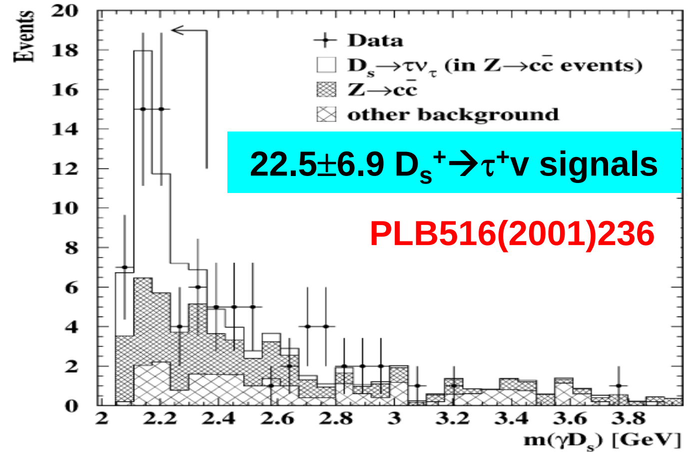


PLB396(1997)327

f_{Ds+}=309±58±33±38 MeV

- OPAL, 3.9×10^6 $e^+e^- \to q\bar{q}$

22.5±6.9 $D_s^+ \to \tau^+ v$ signals

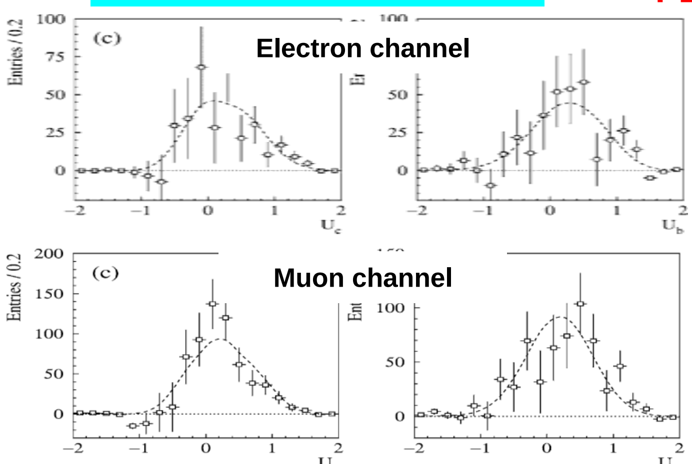


PLB516(2001)236

f_{Ds+}=286±44±41 MeV

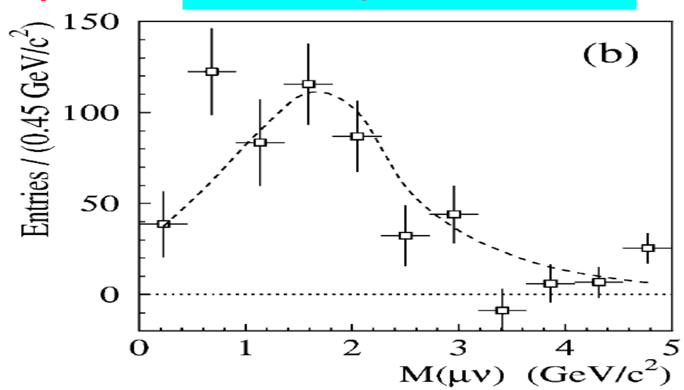
- ALPHA, 3.97×10^6 Z hadronic decay

306±62 $D_s^+ \to \tau^+ v$ signals



PLB528(2002)1

575±84 $D_s^+ \to \mu^+ v$ signals



f_{Ds+}=285±19±40 MeV

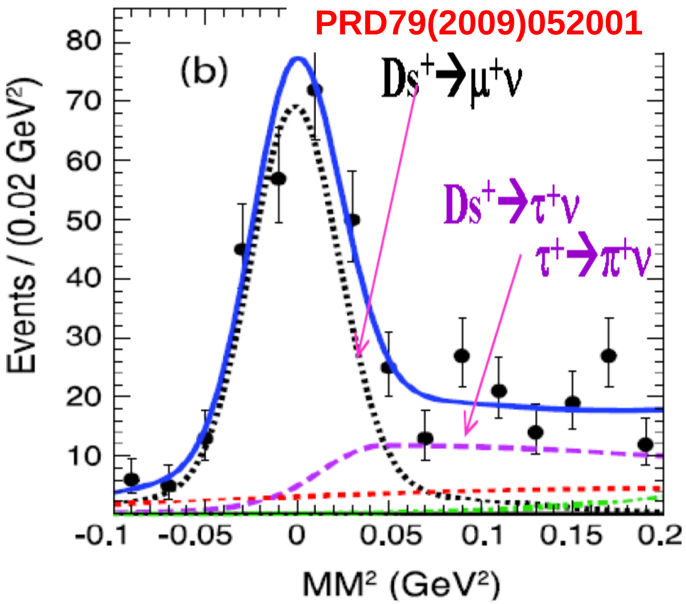
Progress of Measuring f_{Ds+} in past 21 years

- **CLEO-c, 600 pb^{-1} at 4.17 GeV**

Absolute measurement

235±14 $D_s^+ \to \mu^+ v + \tau^+ v$ signals

126±16 $D_s^+ \to \tau^+ v$ signals

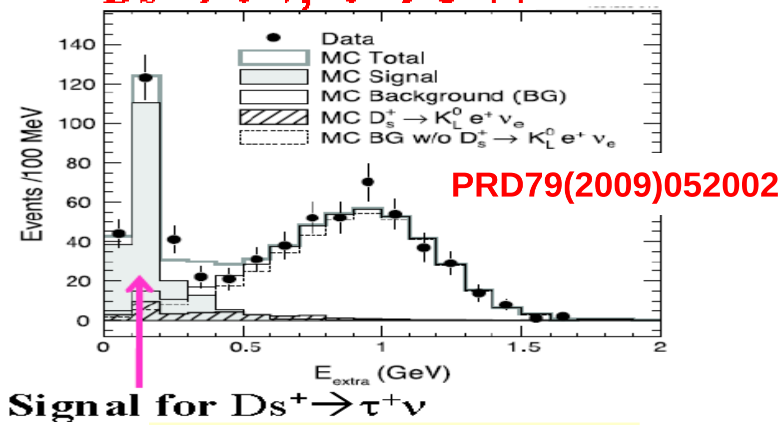


f_{Ds+}=263.3±8.2±1.9 MeV

Improved statistical and systematic errors

181±16 $D_s^+ \to \tau^+ v$ signals

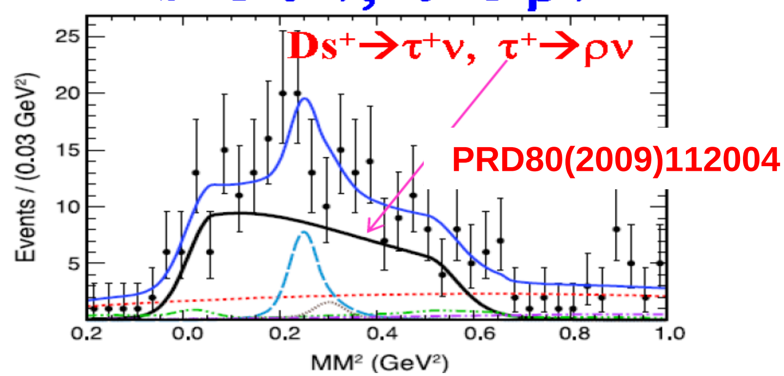
$Ds^+ \to \tau^+\nu,\ \tau^+ \to e^+\nu\nu$



f_{Ds+}=252.2±11.1±5.2 MeV

155±17 $D_s^+ \to \tau^+ v$ signals

$Ds^+ \to \tau^+\nu,\ \tau^+ \to \rho\nu$



f_{Ds+}=257.8±13.3±5.2 MeV

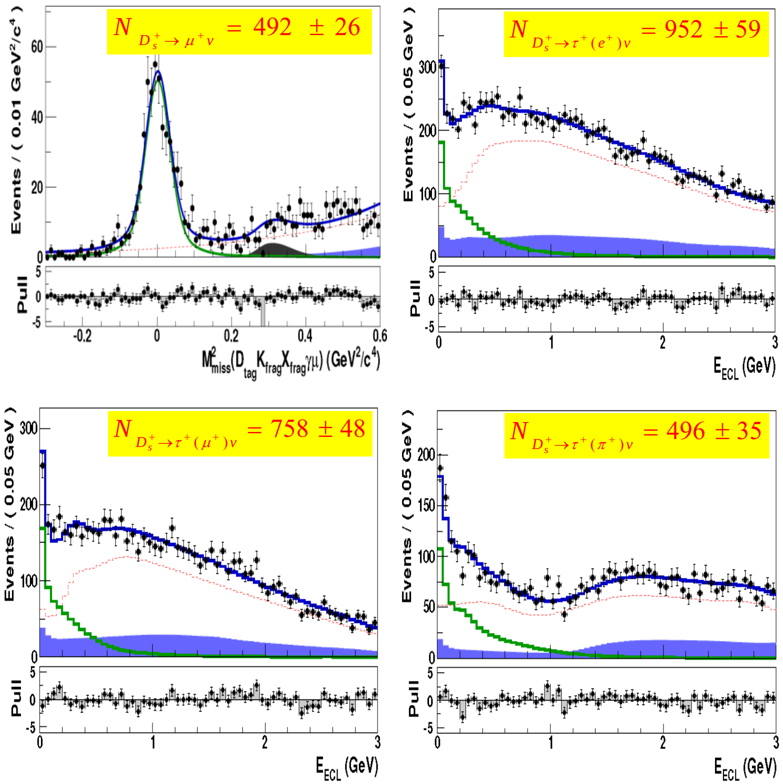
Progress of Measuring f_{Ds+} in past 21 years

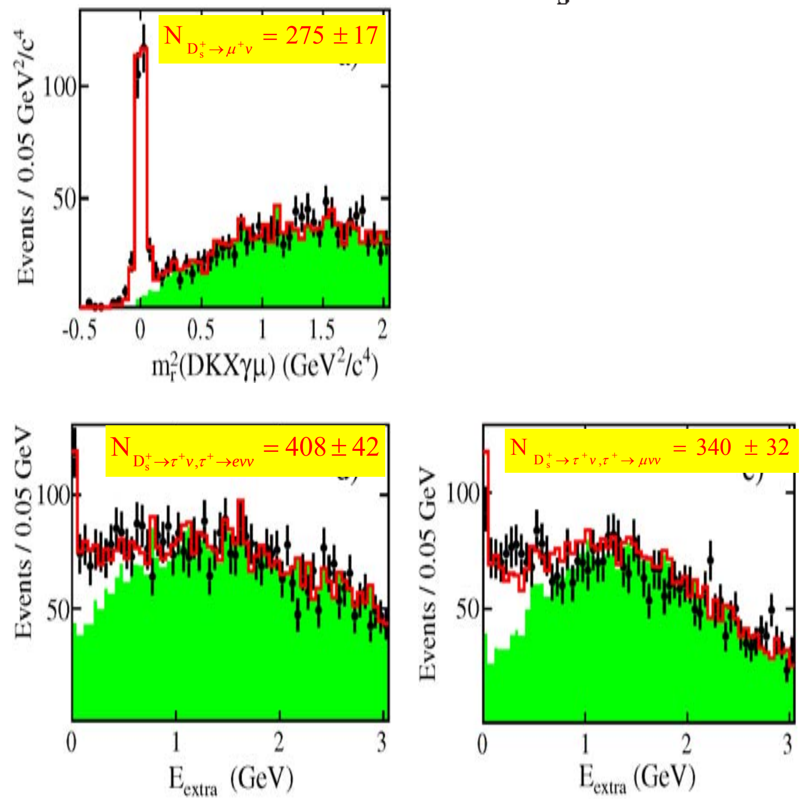
- Belle, 913 fb^{-1} at 10.58 GeV
- Babar, 521 fb^{-1} at 10.58 GeV

Absolute measurements

$$e^+e^- \to c\bar{c} \to D_{\rm tag}K_{\rm frag}X_{\rm frag}D_s^{*-}$$

$$e^+e^- \to DKXD_s^{*-}$$





f_{Ds+}=255.5±4.2±5.1 MeV

2698 signals, JHEP1309(2013)129

f_{Ds+}=258.6±6.4±7.5 MeV

1023 signals, PRD82(2010)091103

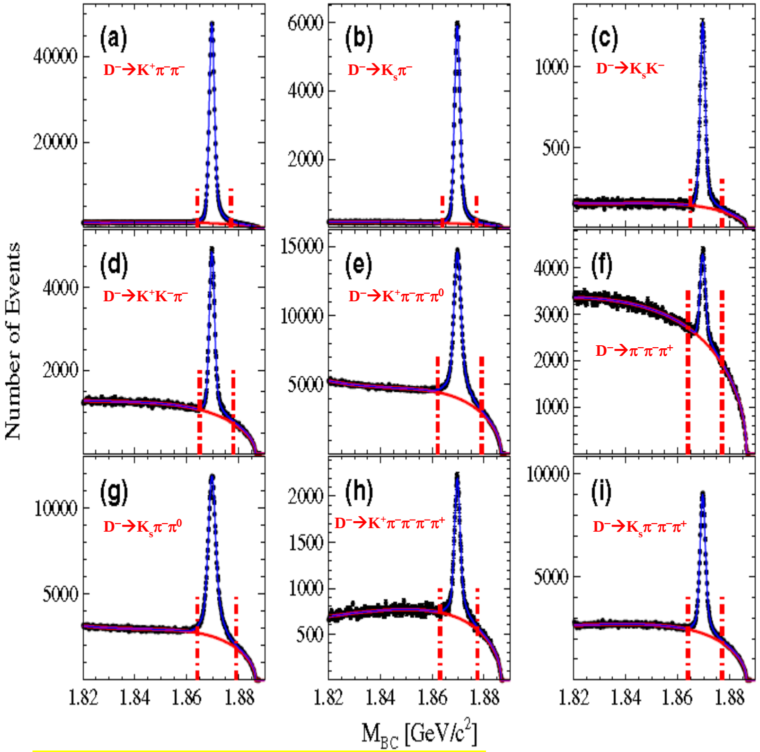
Better statistical but worse systematic errors at B factory

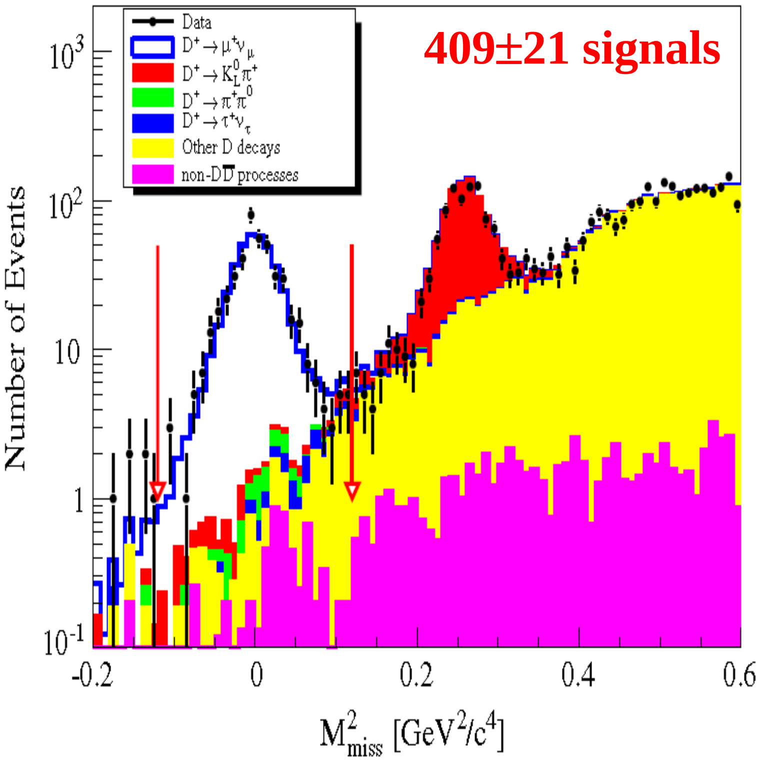
Improved $B[D^+ \to \mu^+ \nu]$, f_{D+} and $|V_{cd}|$ at BESIII

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

2.92 fb^{-1} data@ 3.773 GeV

PRD89(2014)051104R





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

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

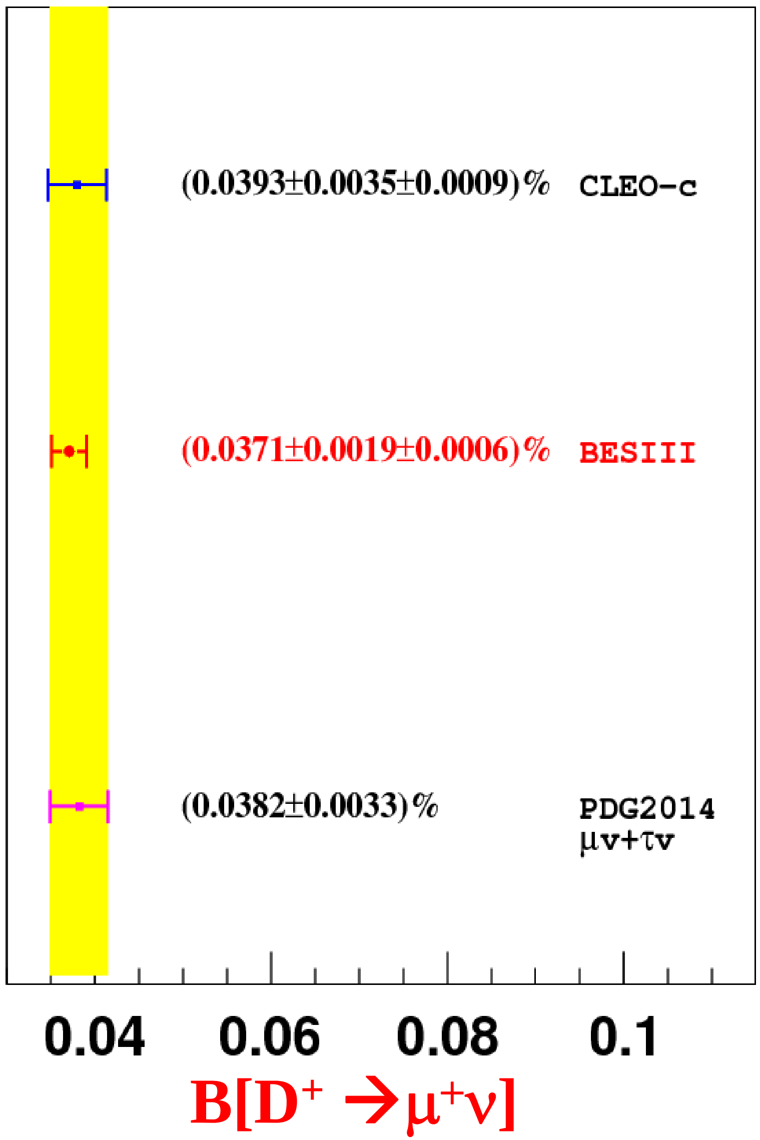
Input t_{D+}, m_{D+}, $m_{\mu+}$ on PDG and $|V_{cd}|$ of CKM-Fitter

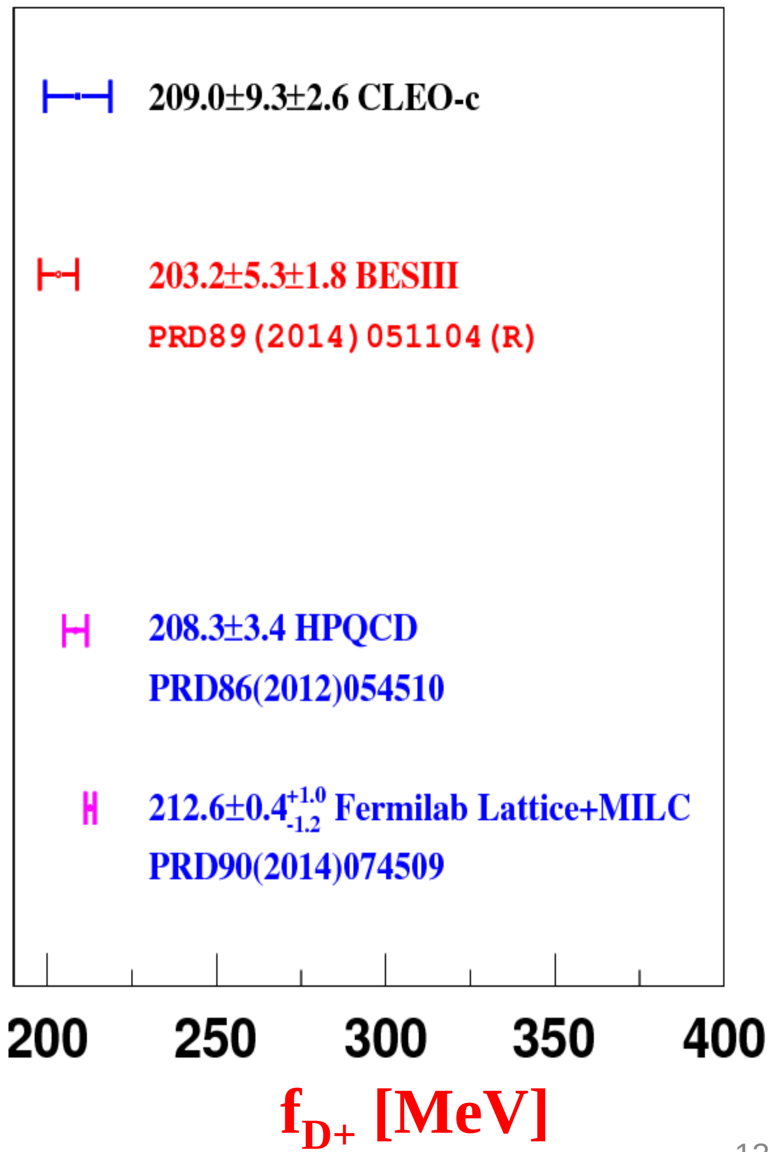
$f_{D+} = (203.2 \pm 5.3 \pm 1.8)$ MeV

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

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

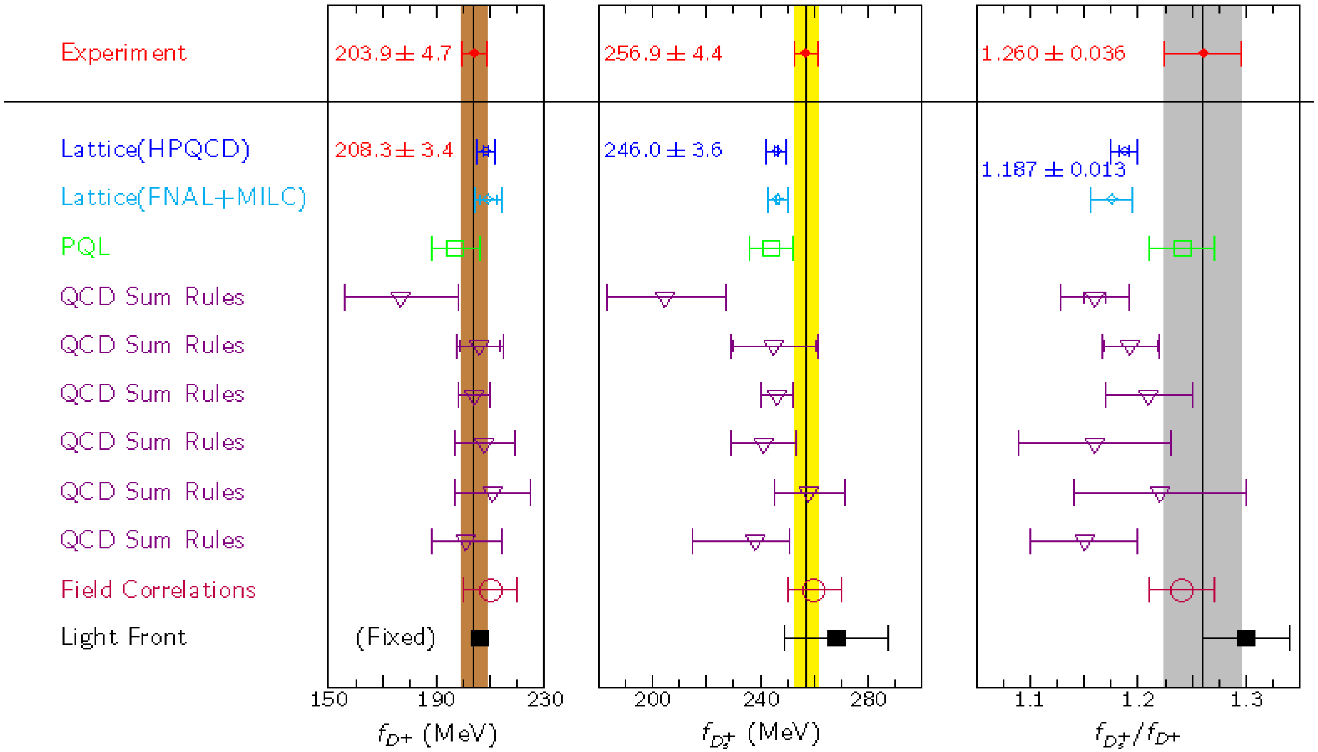
Comparisons of $B[D^+ \rightarrow \mu^+ \nu_\mu]$ and f_{D^+}





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

Taken from Gang Rong's talk at CKM2014

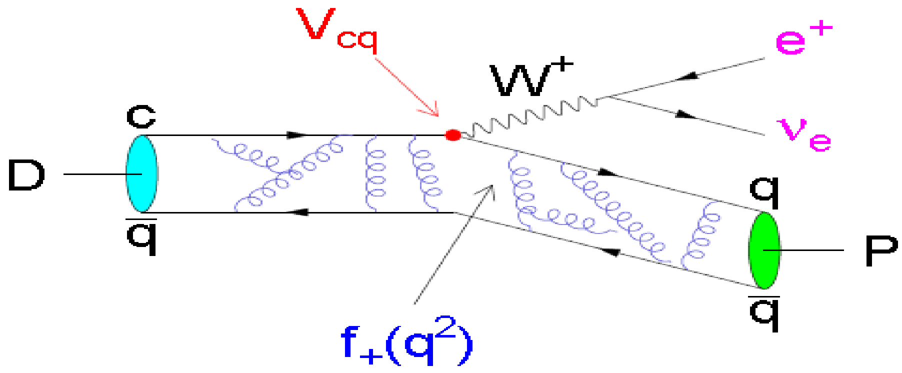


- Precisions of the LQCD calculations of f_{D+}, f_{Ds+}, $f_{D+}:f_{Ds}$ reach 0.5%, 0.5% and 0.3%, which are challenging the experiments
- The experimentally measured and the theoretically calculated f_{D+}, f_{Ds+}, $f_{D+}:f_{Ds+}$ differ by about 2σ

	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

- Improving measurement with larger data sample is necessary!

Semi-leptonic Decay $D^0 \rightarrow K(\pi)^- e^+ \nu$



Differential rates:

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

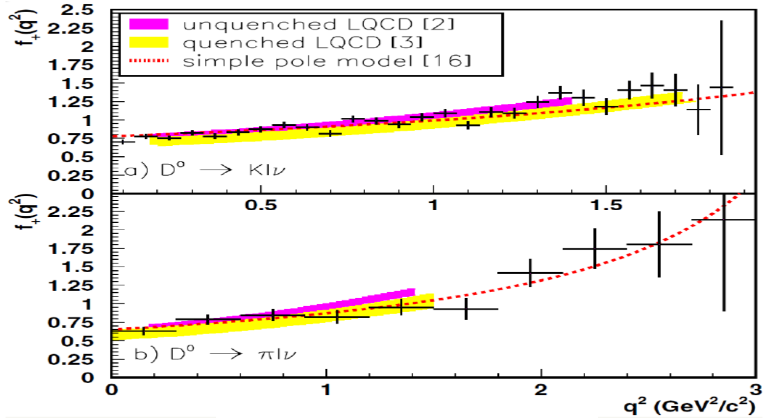
Bridge to precisely measure:

- **Form factors $f_+^{D\rightarrow K(\pi)}(0)$ with input $|V_{cd(s)}|^{CKMfitter}$**
  - **Single pole form**
    $$f_+(q^2) = \frac{f_+(0)}{1 - \frac{q^2}{M_{pole}^2}}$$
  - **Modified pole model**
    $$f_+(q^2) = \frac{f_+(0)}{(1 - \frac{q^2}{M_{pole}^2})(1 - \alpha \frac{q^2}{M_{pole}^2})}$$
  - **ISGW2 model**
    $$f_+(q^2) = f_+(q_{max}^2) \left(1 + \frac{r_{ISGW2}^2}{12}(q_{max}^2 - q^2)\right)^{-2}$$
  - **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 $f_+^{LQCD,D\rightarrow K(\pi)}(0)$**

Progress of Extracting $f_+^{D\to K(\pi)}(0)|V_{cs(d)}|$

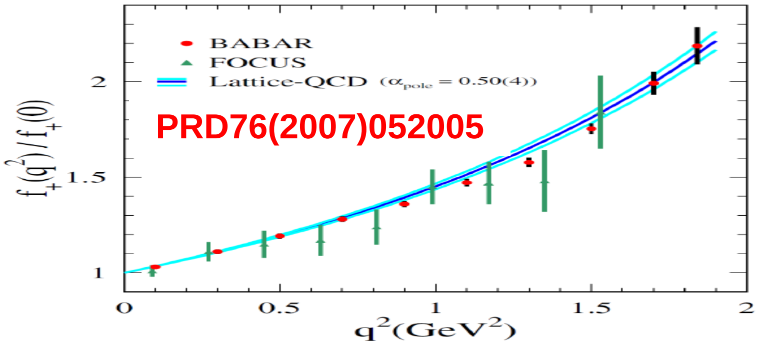
During the past 26 years, studies of $D\to K(\pi)l^+\nu$ are made by MARKIII, E691, CLEO, CLEOII, BESII, FOCUS, BELLE, Babar and CLEO-c

- **BELLE, 282 fb^{-1} at 10.58 GeV**



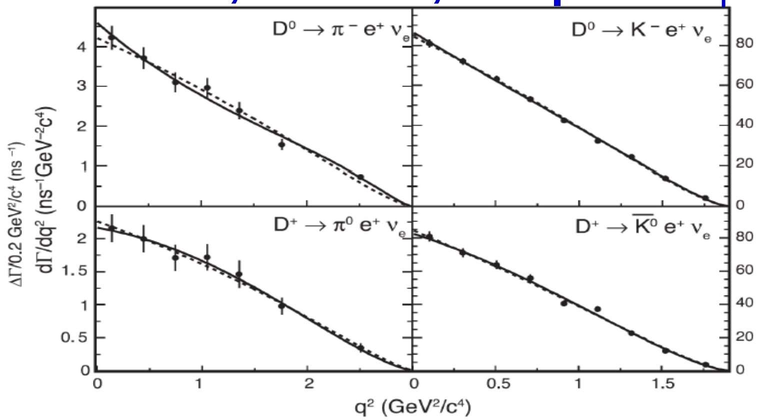
PRL97(2006)061804

- **Babar, 75 fb^{-1} at 10.58 GeV**



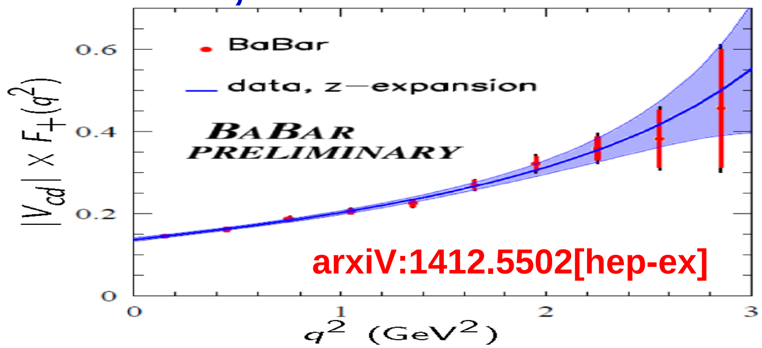
PRD76(2007)052005

- **2004-2009, CLEO-c, 818 pb^{-1} at ψ''**



PRD80(2009)032005

- **Babar, 347.2 fb^{-1} at 10.58 GeV**



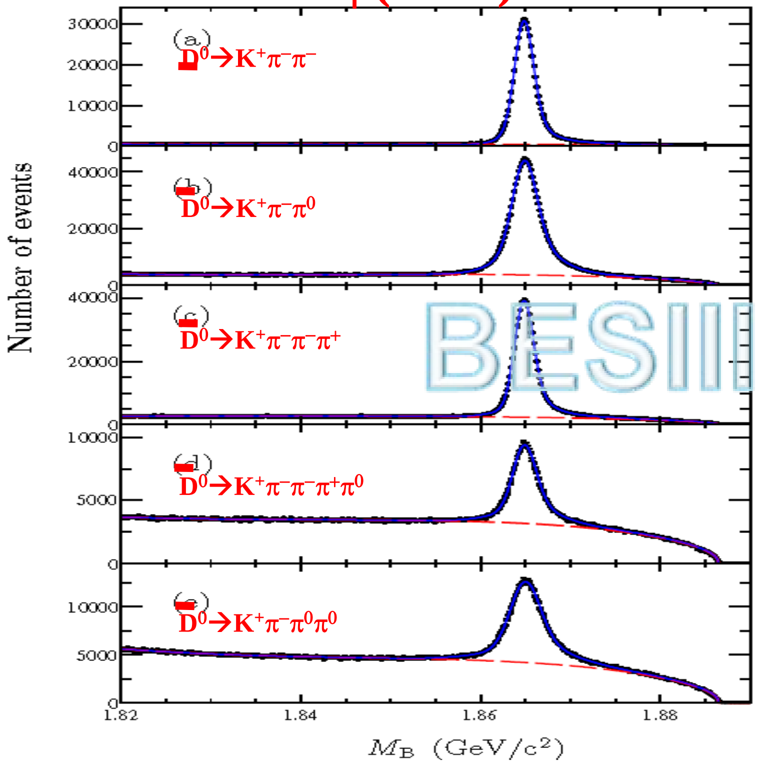
arxiV:1412.5502[hep-ex]

Before 2010, the LQCD calculated $f_+^{D\to K(\pi)}(0)$ precision is at 10% level, thus limiting $|V_{cs(d)}|$ measurement

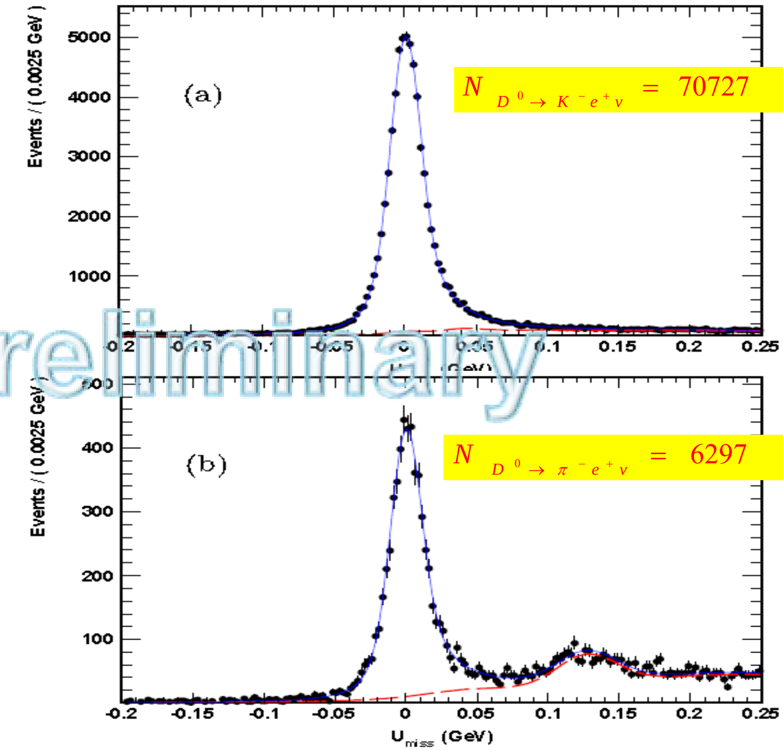
Improved B[$D^0 \to K(\pi)^- e^+ \nu$] at BESIII

2.92 fb^{-1} data@ 3.773 GeV

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



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



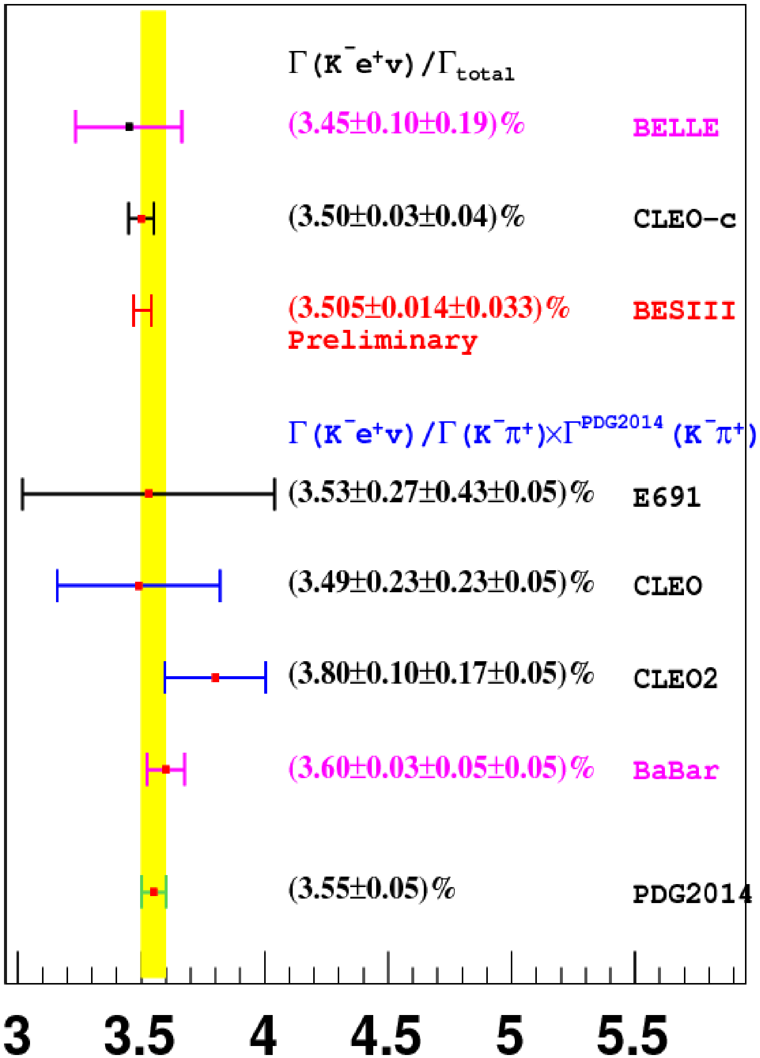
$N_{\bar{D}^0_{tag}} = (279.33 \pm 0.37) \times 10^4$

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

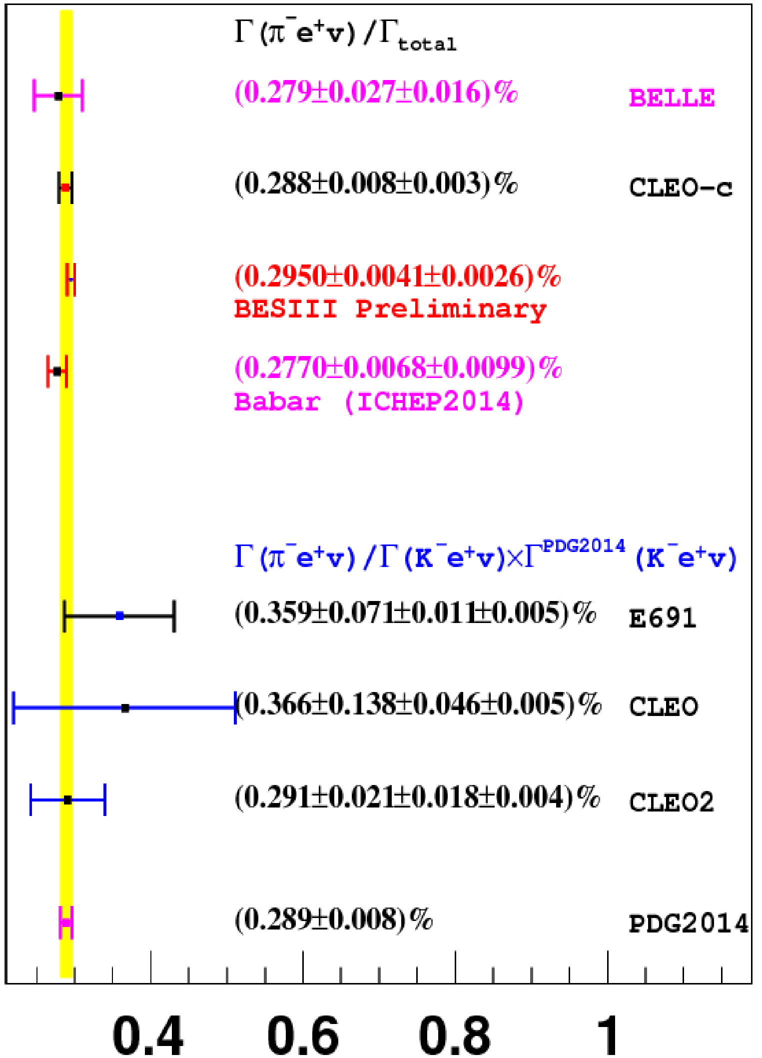
$B_{D^0 \to \pi^- e^+ \nu} = (0.2950 \pm 0.0041 \pm 0.0026)\%$

BESIII

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

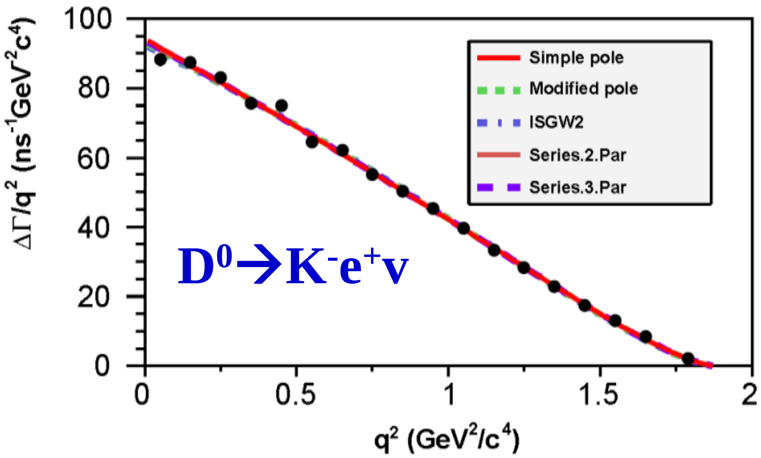


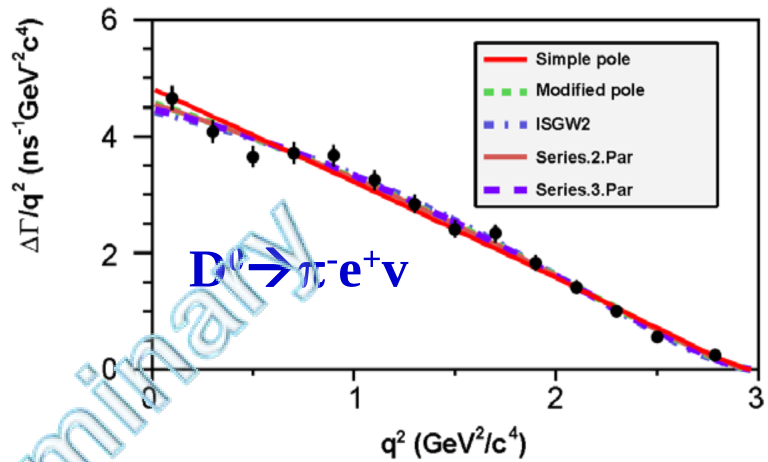
$B[D^0 \rightarrow K^- e^+ \nu]$



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

Extracted Parameters of Form Factors

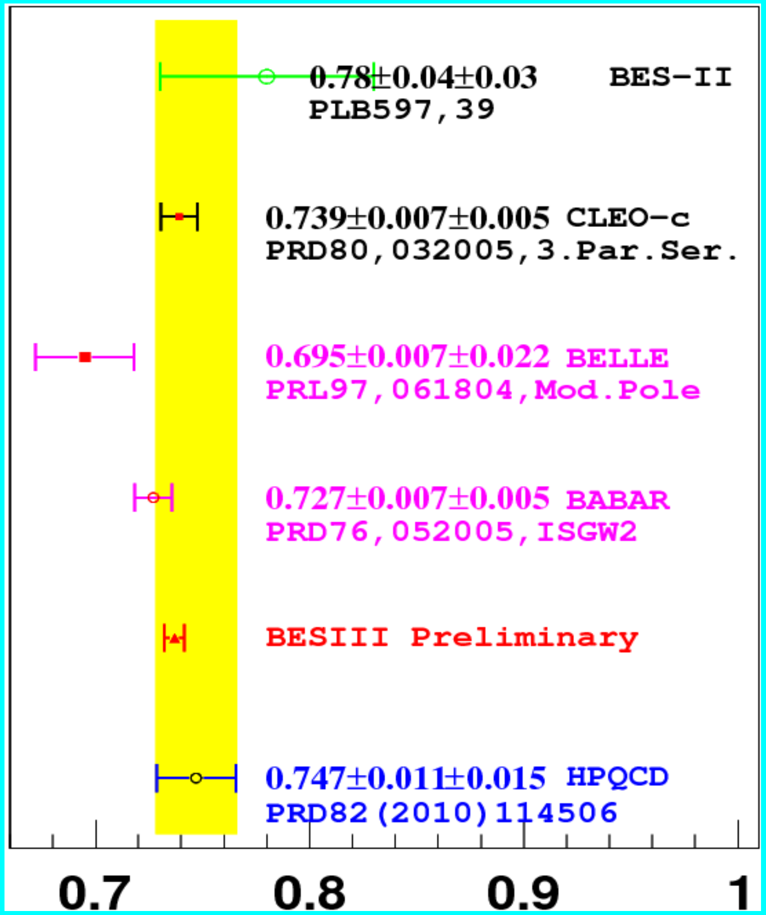




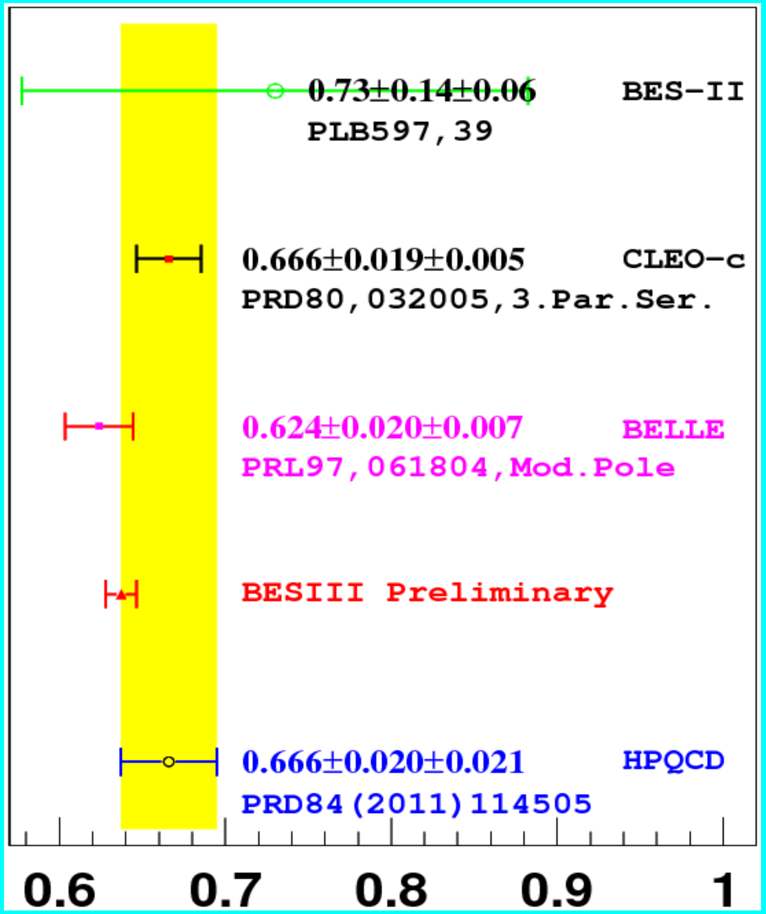
		$D^0 \to K^- e^+ \nu$		$D^0 \to \pi^- e^+ \nu$
Simple Pole	$f_K^+(0)\lvert V_{cs}\rvert$	0.7209±0.0022±0.0033	$f_\pi^+(0)\lvert V_{cd}\rvert$	0.1475±0.0014±0.0005
	M_{pole}	1.9207±0.0103±0.0069	M_{pole}	1.9114±0.0118±0.0038
Mod. Pole	$f_K^+(0)\lvert V_{cs}\rvert$	0.7163±0.0024±0.0034	$f_\pi^+(0)\lvert V_{cd}\rvert$	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

Improved Form factor $f_+^{D\to K(\pi)}(0)$ at BESIII

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



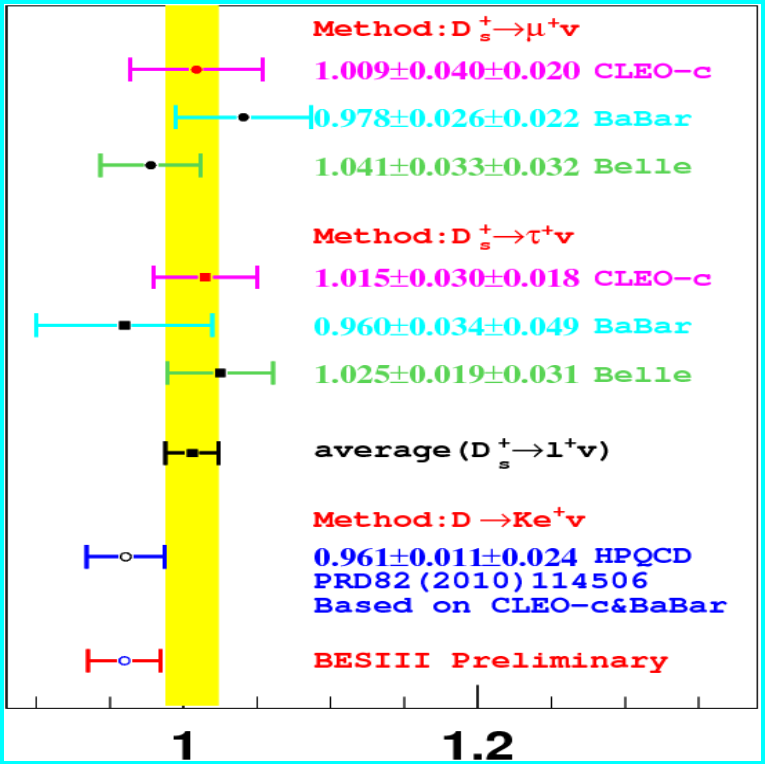
$f_+^{D\to K}(0)$



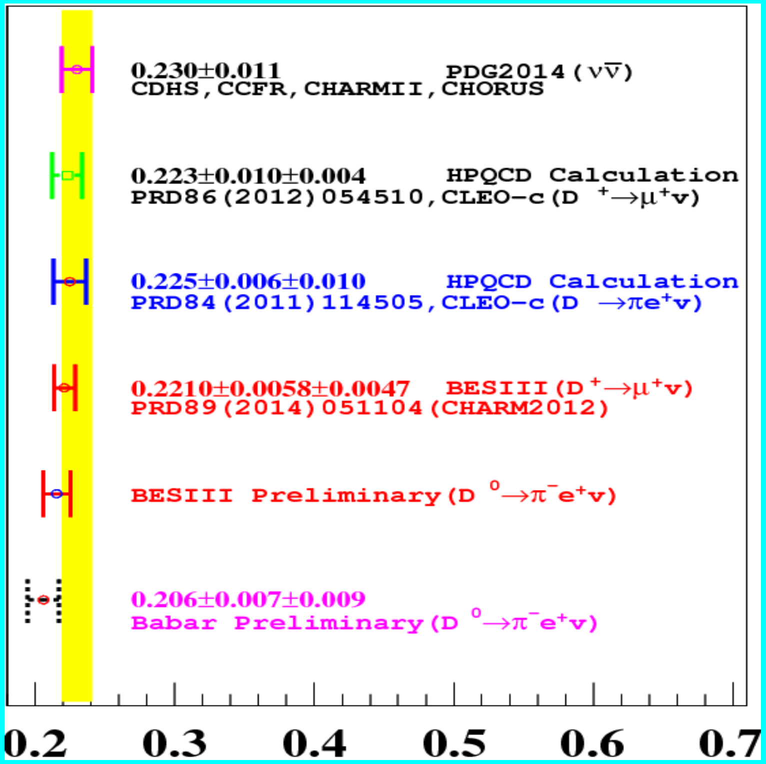
$f_+^{D\to \pi}(0)$

Improved $|V_{cs(d)}|$ at BESIII

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



$|V_{cs}|$



$|V_{cd}|$

Method 2 suffers larger theoretical uncertainty in $f_+^{D\to K(\pi)}(0)$ [2.4(4.4)%]

Summary of BESIII results

- With 2.92 fb^{-1} data taken at 3.773 GeV by BESIII, we study the leptonic decay of $D^+ \rightarrow \mu^+ \nu$ and the semi-leptonic decay $D^0 \rightarrow K(\pi)^- e^+ \nu$

- We provide improved measurement of decay constant f_{D+} and form factor $f_+^{D \rightarrow K(\pi)}(q^2)$, which are important to test and calibrate LQCD calculations accurately

- We provide improved measurement of CKM matrix element $|V_{cs(d)}|$, which is important for unitarity test of the CKM matrix

- BESIII will take 3 fb^{-1} data at 4.17 GeV in 2016, improved measurement of f_{Ds+} and $|V_{cs}|$ by $D_s^+ \rightarrow l^+ \nu$ is expected in the near future

Why HIEPA is expected?

Leptonic decay $D_{(s)}^{+} \to l^{+}v$

- Measurement of $f_{D(s)+}$ and $|V_{cd(s)}|$ is limited by data size
- More precise f_{D+}, f_{Ds+}, $f_{D+}:f_{Ds}$ is expected

1. Challenge from LQCD calculation with 0.5%, 0.5% and 0.3% precisions
2. ~2σ difference between experiment and theoretical calculation

Semi-leptonic decay $D^{0} \to K(\pi)^{-}e^{+}v$

- Measurement of $f_{+}^{D\to\pi}(0)$ is limited by data size
- Measurement of $|V_{cs(d)}|$ is limited by $f_{+}^{LQCD,D\to K(\pi)}(0)$

Improving $|V_{cs(d)}|$, $f_{D(s)+}$, $f_{+}^{D\to K(\pi)}(0)$ statistical precisions by an order of magnitude at HIEPA?

Prospects at HIEPA?

Opportunity: If we have 300 fb^{-1} data at 3.773 GeV and 300 fb^{-1} data at 4.17/4.03 GeV, what precisions we can reach?

Roughly estimate based on BESIII and CLEO-c experiments

	Systematic error	Statistical error		
		~3 fb^{-1}	12 fb^{-1}	300 fb^{-1}
$\Delta f_{D+}/f_{D+}$	~0.9%^{BESIII}	2.6%	1.3%	0.26%
$\Delta f_{Ds+}/f_{Ds+}$	~1.5%$^{CLEO-c}$	1.1%/2.0%	0.6%/1.0%	0.11%/0.20%
$\Delta f_{D\to K}/f_{D\to K}$	~0.5%^{BESIII}	0.35%	0.18%	0.04%
$\Delta f_{D\to\pi}/f_{D\to\pi}$	~0.7%^{BESIII}	1.26%	0.63%	0.13%
$\lvert V_{cs}\rvert^{Ds+\to l+v}$	~2.0%$^{CLEO-c}$	1.8%/3.0%	0.9%/1.5%	0.18%/0.30%
$\lvert V_{cs}\rvert^{D0\to K-e+v}$	2.5%^{BESIII}(2.4%^{LQCD})	0.35%	0.18%	0.04%
$\lvert V_{cd}\rvert^{D+\to\mu+v}$	2.1%^{BESIII}(1.9→0.5%^{LQCD})	2.6%	1.3%	0.26%
$\lvert V_{cd}\rvert^{D0\to\pi-e+v}$	4.5%^{BESIII}(4.4%^{LQCD})	1.26%	0.63%	0.13%

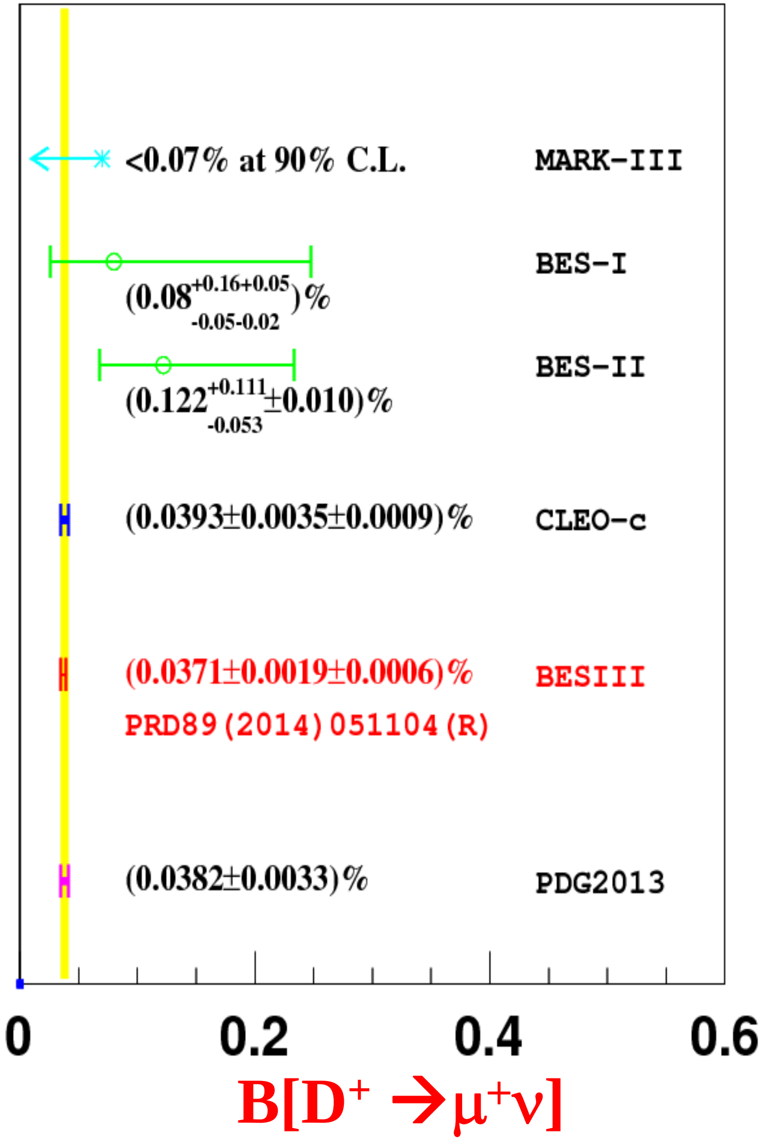
Challenges:

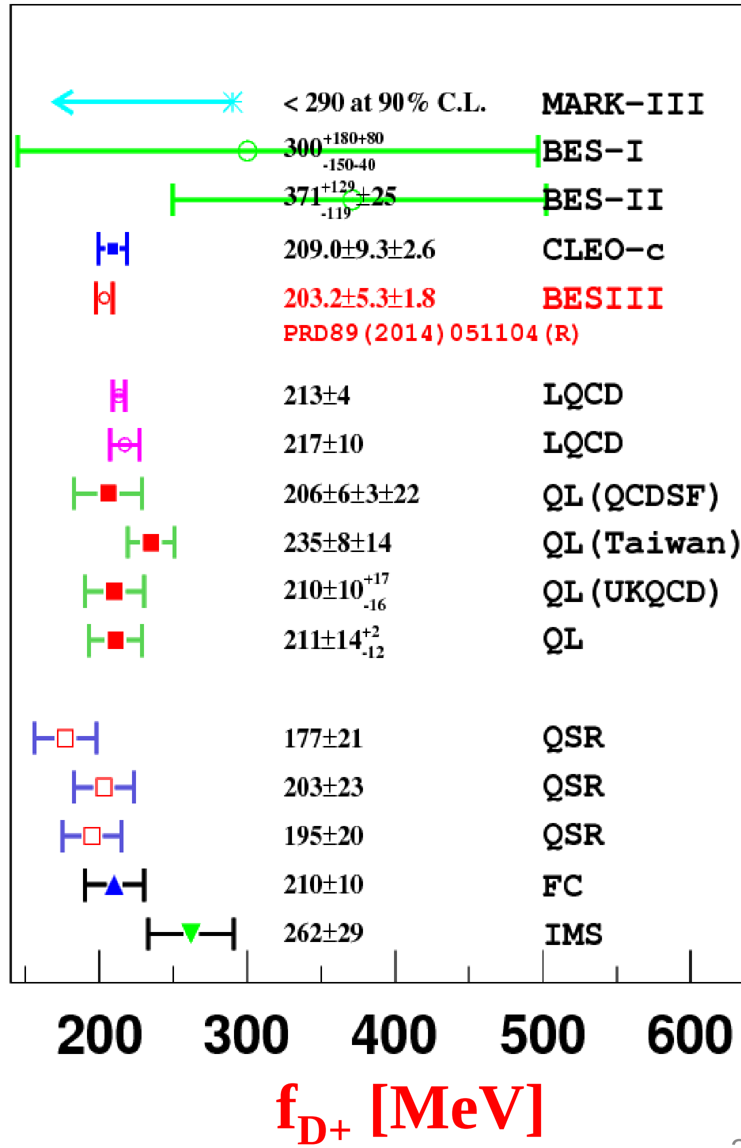
- Measuring $|V_{cs(d)}|$ by $D\to K(\pi)e^+v$ will be limited by LQCD calculation precision of $f_+^{D\to K(\pi)}(0)$, whether it can reach 0.5% level?
- Measuring f_{Ds+} and $|V_{cs}|$ will be limited by systematic error of selecting $D_s^+\to l^+v$, whether it can reach 1.0% level?

Thank you!

Back-up slides

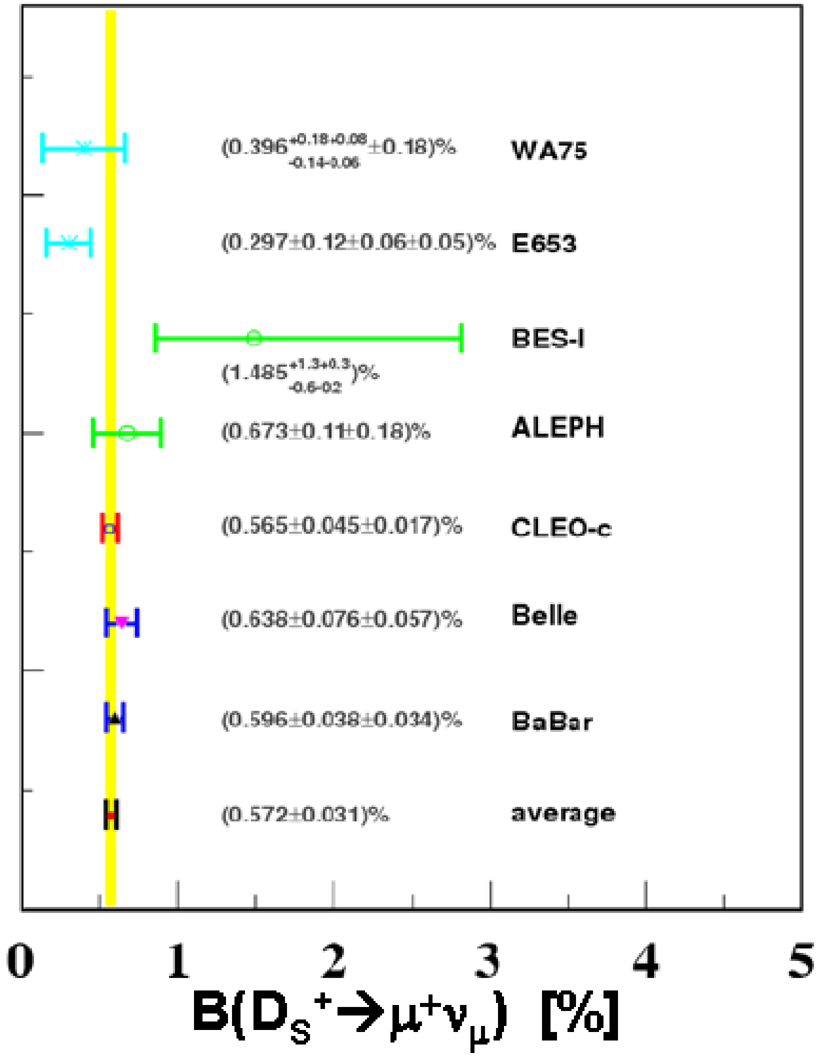
Comparisons of $B[D^+ \to \mu^+ \nu_\mu]$ and f_{D^+}

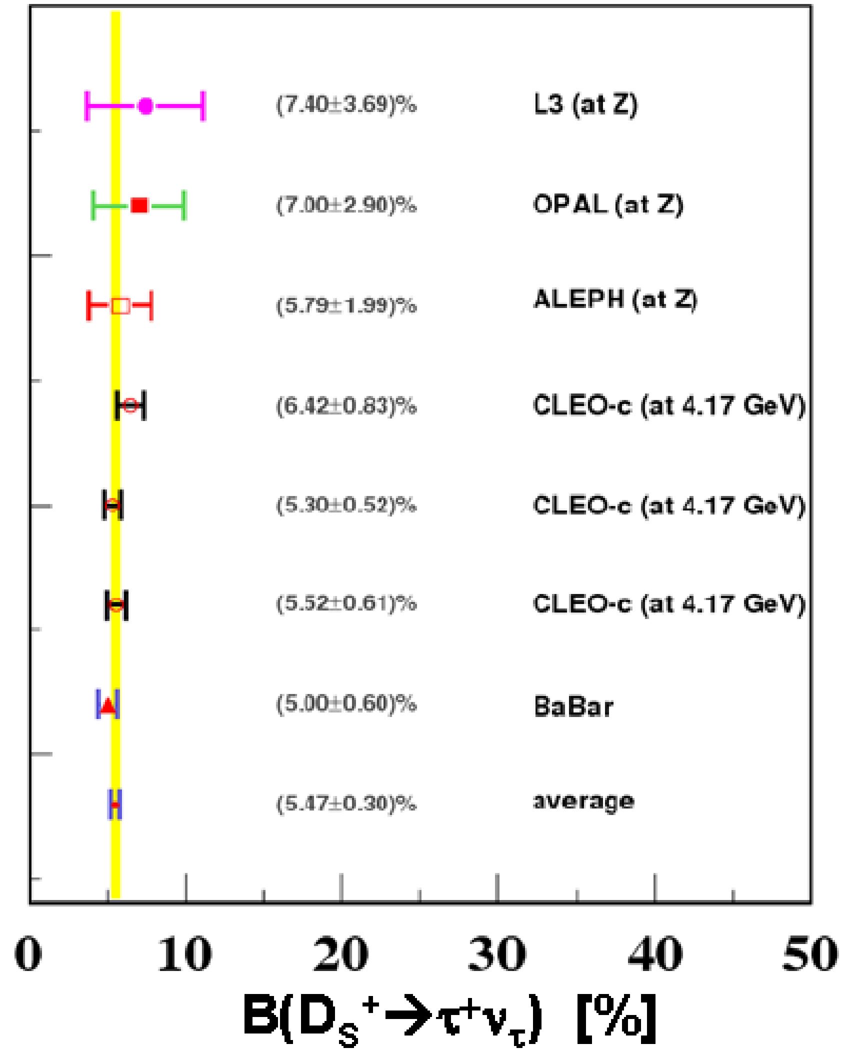




Comparisons of $B[D_{(s)}^+ \to l^+ \nu]$

Taking from Gang Rong's talk at CHARM2012

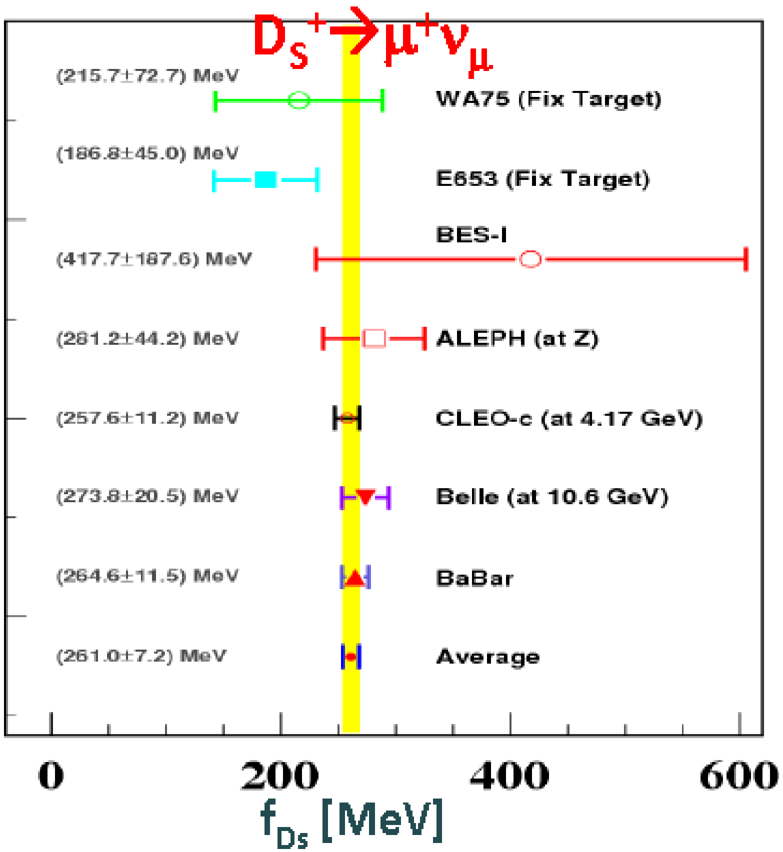


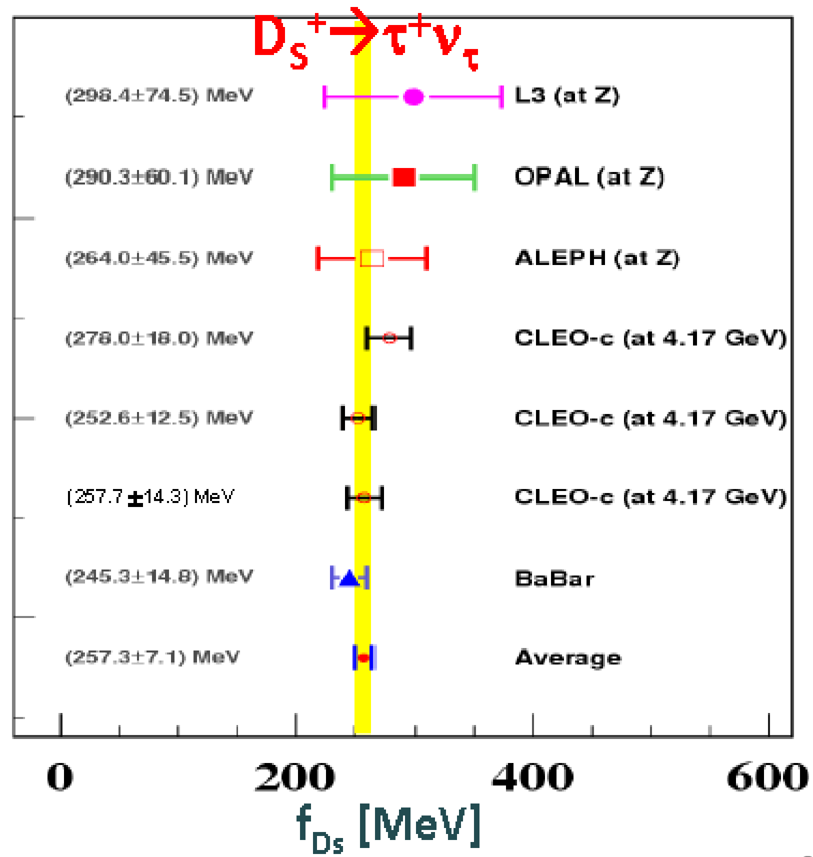


Comparisons of $B[D_{(s)}^+ \to l^+ \nu]$ and f_{D+}

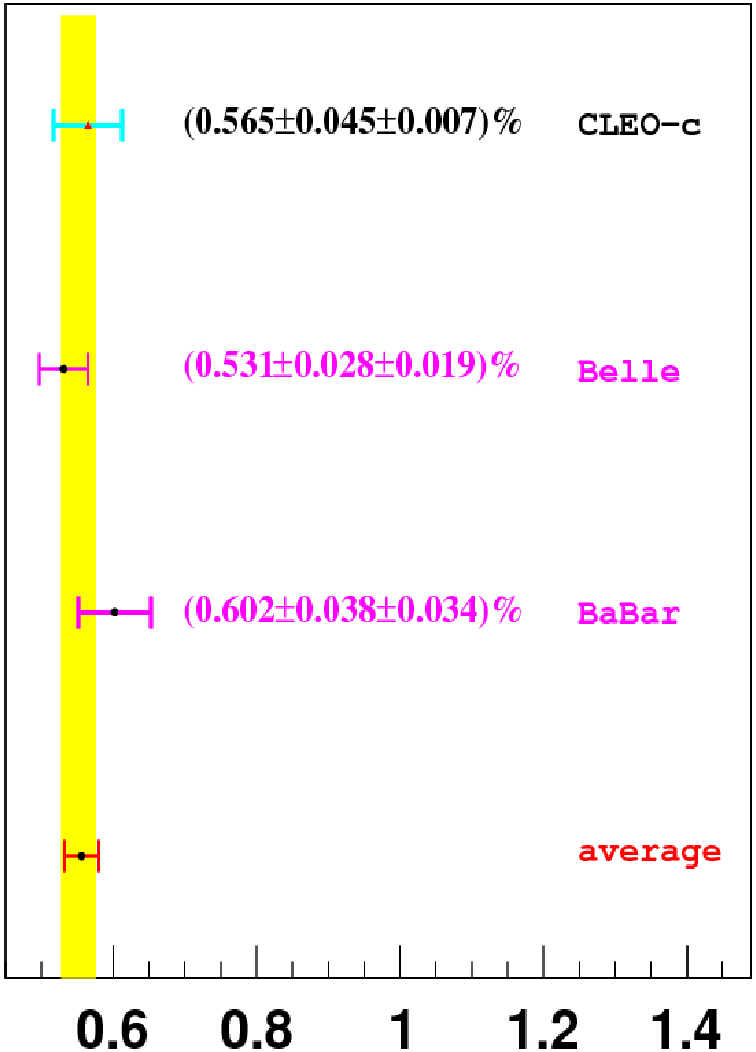
Taking from Gang Rong's talk at CHARM2012

Based on the measured branching factions of D_S^+ leptonic decays (after radiative correction), and with inputs of D_S^+ mass, lepton mass, D_S^+ lifetime and $|V_{cs}|$=0.97345 from CKMfiter, we calculate the f_{Ds} .

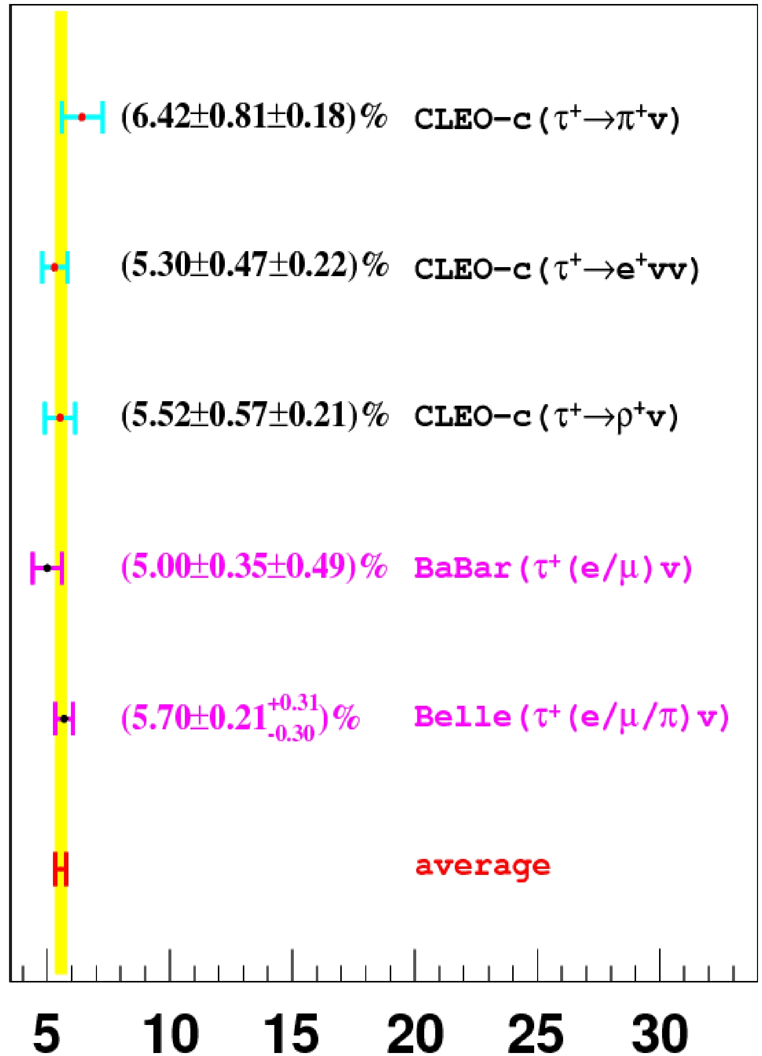




Comparisons of existing $B[D_s^+ \to \mu(\tau)^+ \nu]$

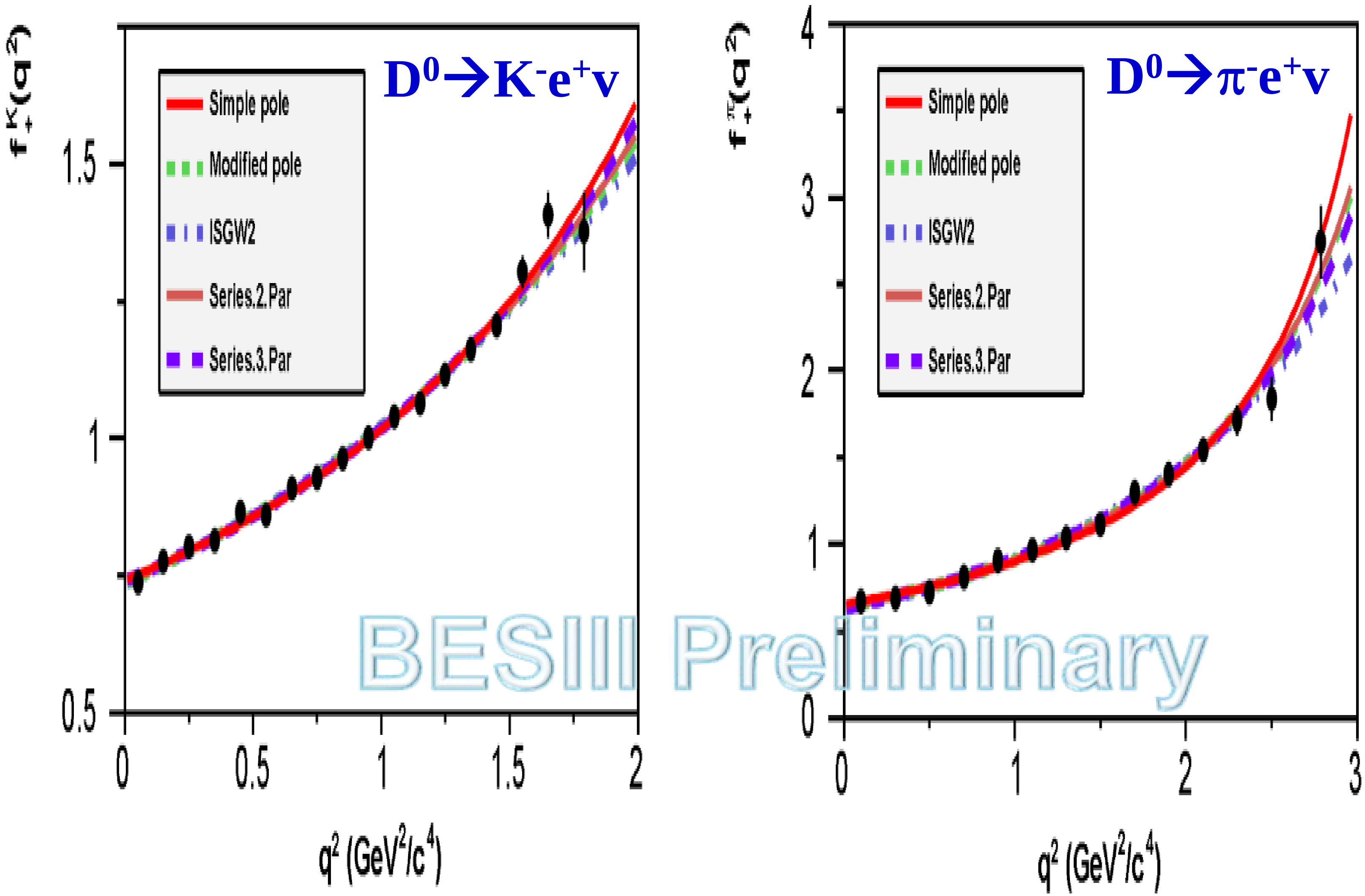


$B[D_s^+ \to \mu^+ \nu]$



$B[D_s^+ \to \tau^+ \nu]$

Projections on Form Factors $f^{K(\pi)}_{+}(q^2)$

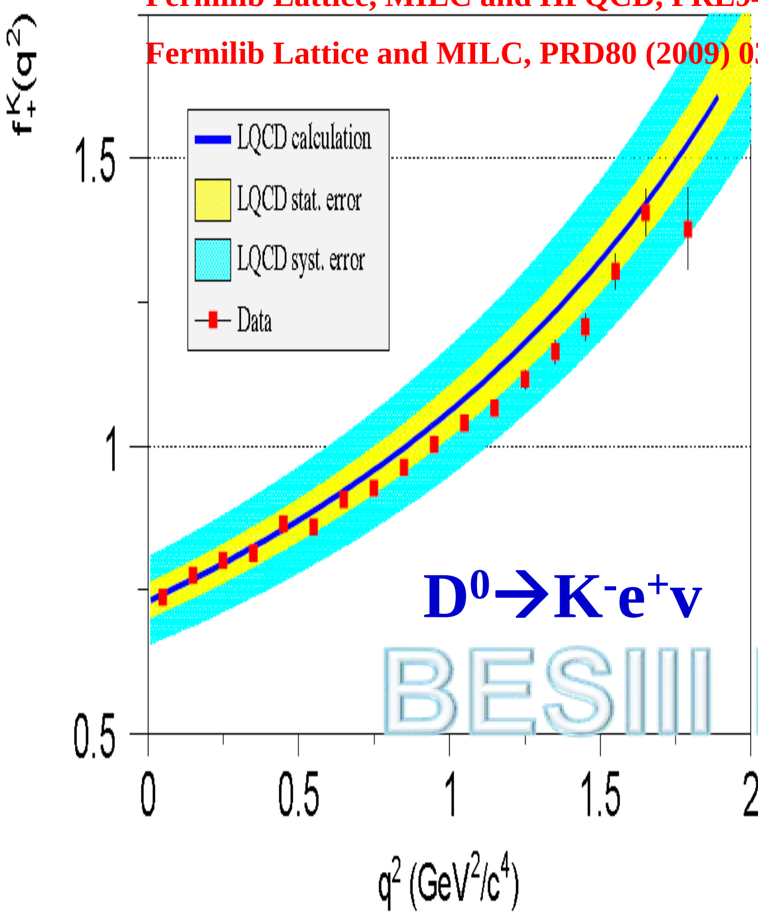


Comparisons of Form Factors

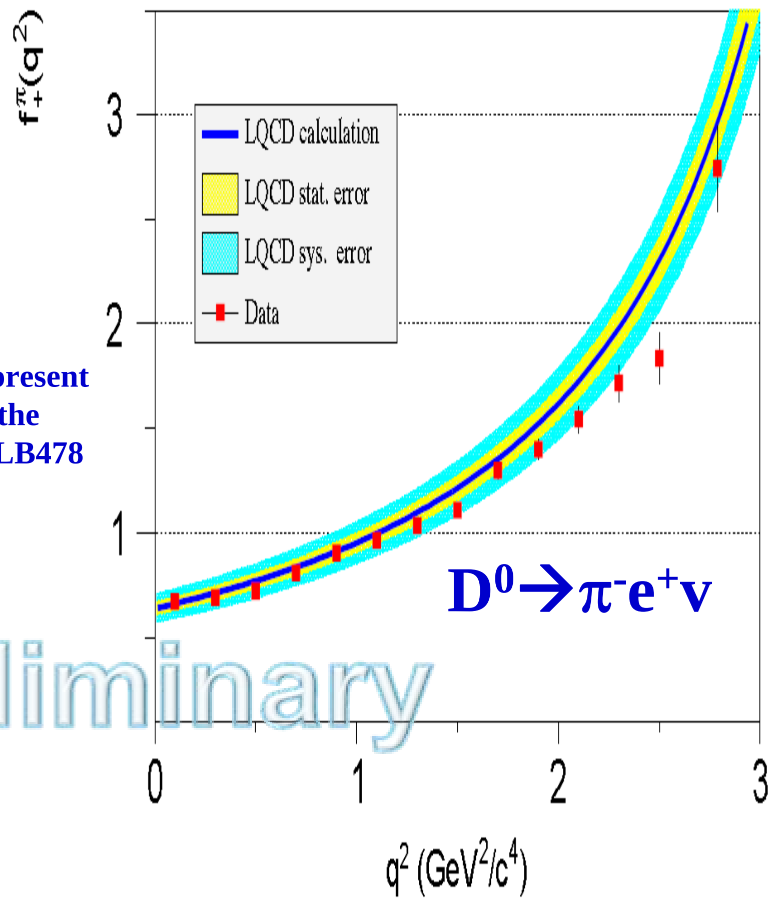
Experimental data calibrate LQCD calculation

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

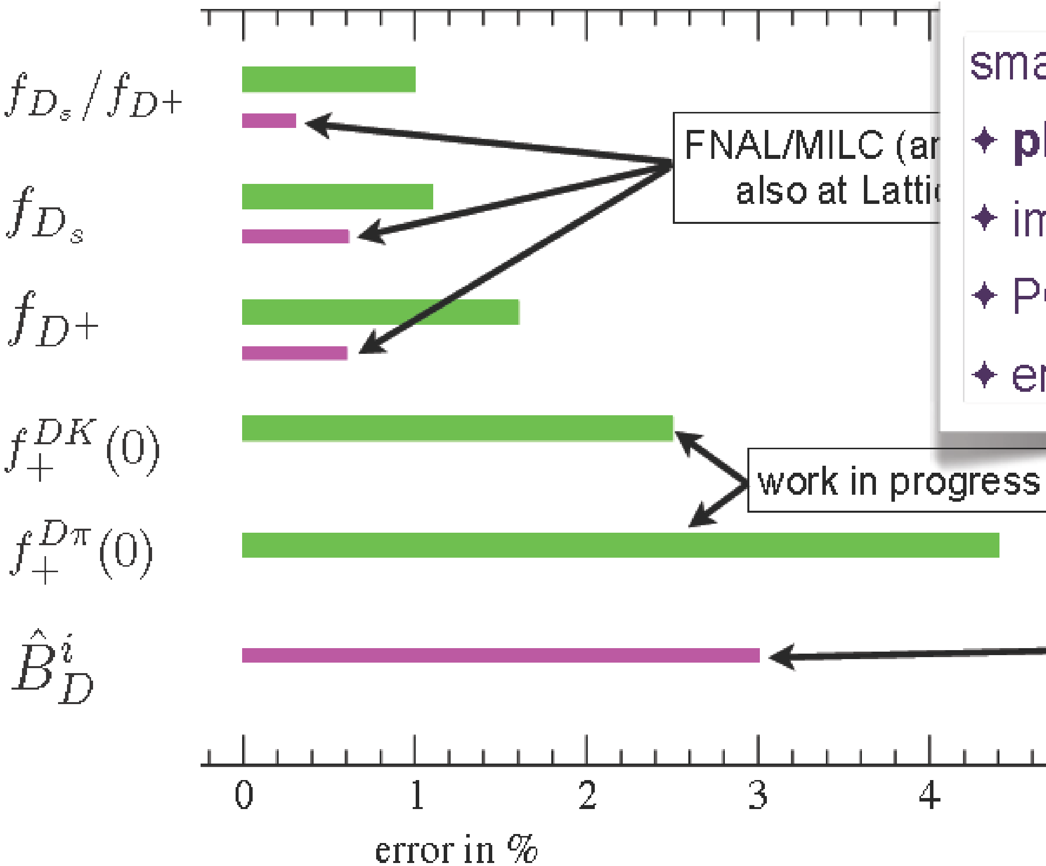


BESIII Preliminary

Progress in LQCD Calculation

Taking from Aida X. El-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