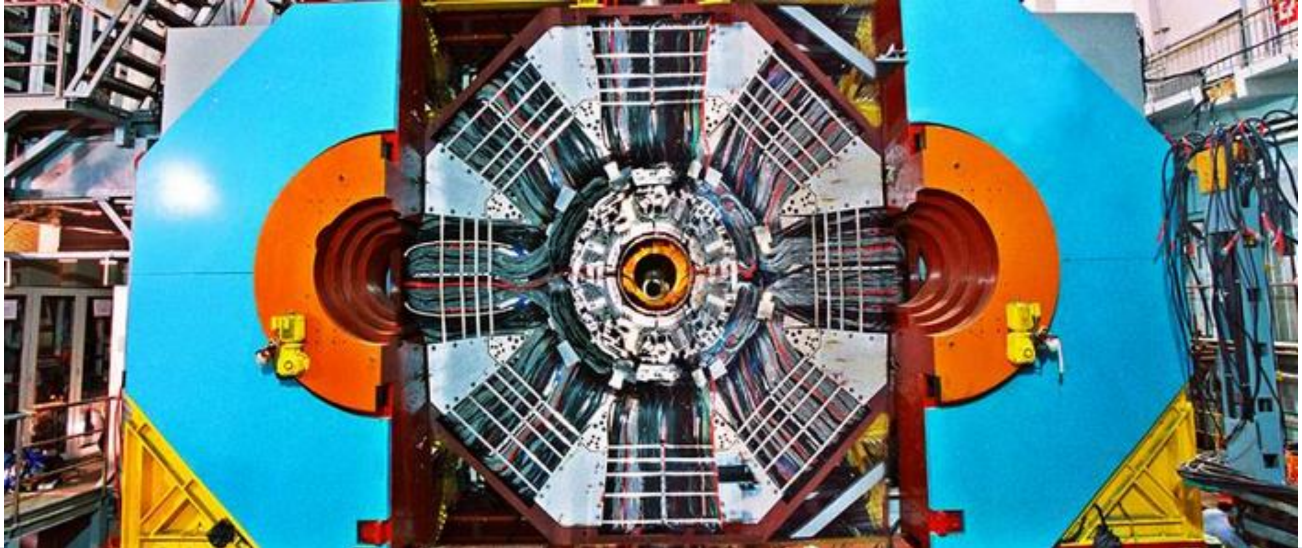


Charmed Meson Leptonic and Hadronic decays at BESIII

Dan Ambrose

University of Minnesota

CIPANP 2015

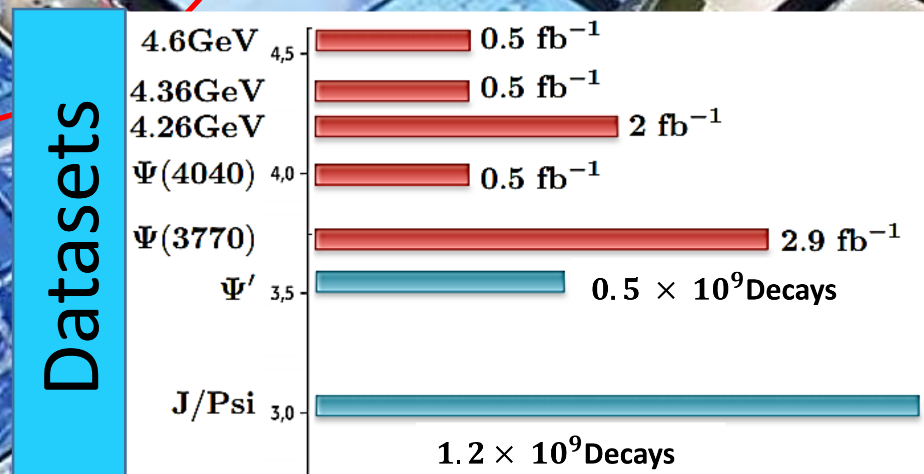
May 24, 2015

Overview

- BESIII experiment
- Leptonic decays
  - $D^+ \to \mu\nu$
- Semi-leptonic decays
  - $D^0 \to K(\pi)^- e^+ \nu$
  - Measurement of $\mathrm{Y_{CP}}$ in $\mathrm{D^0\overline{D^0}}$ oscillation
- Hadronic decays
  - GGSZ strong-phase measurements for $\mathrm{D^0} \to K^0\pi^+\pi^-$
- More upcoming BESIII measurements
- Summary

BEPCII and BESIII

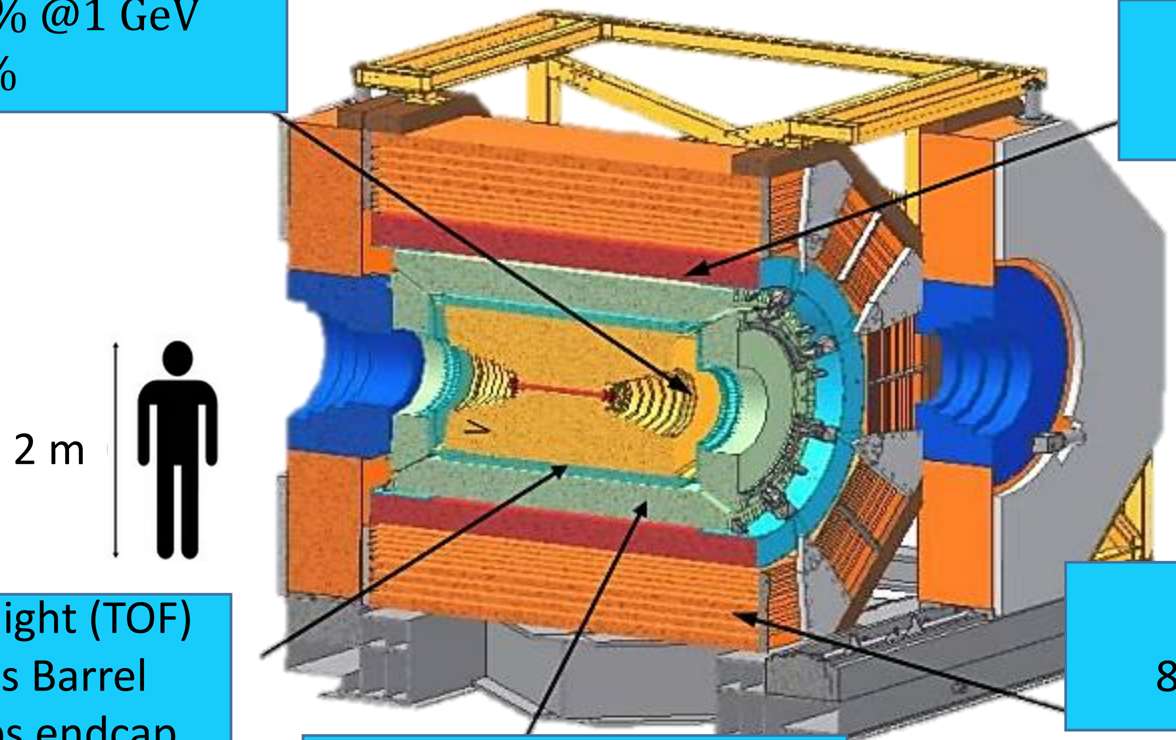
Taking Physics Data since 2009



BESIII Detector

Drift Chamber (MDC)
$\sigma_P/P = 0.5\%$ @1 GeV
$\sigma_{dE/dx} = 6\%$

Super-conducting magnet (1.0 tesla)



Time Of Flight (TOF)
σ_T : 90 ps Barrel
110 ps endcap

EMC :
σ_E/E = 2.5%@1GeV
σ_Z = 0.6cm

μ Counter
8- 9 layers RPC

M. Ablikim et al., (BESIII Collaboration), Nucl. Instrum. Meth. A 614, 345 (2010).

BESIII Collaboration

53 institutions, more than 400 physicists

USA
Carnegie Mellon University, Indiana University, University of Hawaii, University of Minnesota, University of Rochester.

Sweden
Uppsala University

Nederland
KVI/University of Groningen

Russia
Budker Institute of Nuclear Physics, Joint Institute for Nuclear Research

Japan
Tokyo University

China
31 institutions

Germany
Bochum University, GSI Darmstadt, Helmholtz Institute Mainz, Johannes Gutenberg University of Mainz, Universitaet Giessen

Italy
Ferrara University, Laboratori Nazionali di Frascati, University of Turin, Perugia

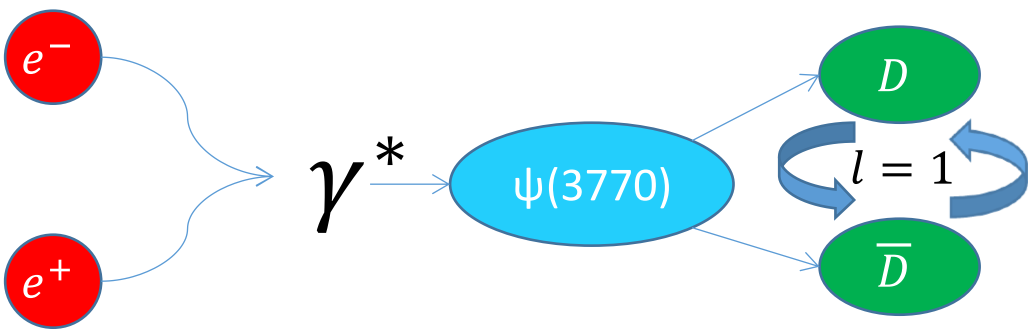
Turkey
Turkish Accelerator Center Particle Factory Group

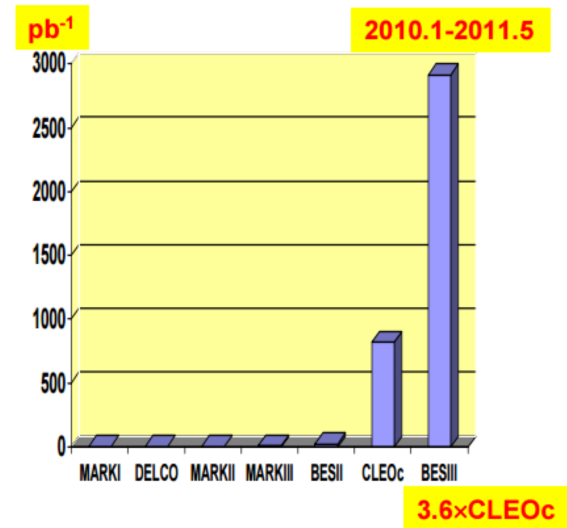
Pakistan
Institute of Information Technology, University of the Punjab.

ψ(3770) Dataset

2.9 fb^{-1} is the largest set of at this type in the world by 3.6 times.

ψ(3770) excited $c\bar{c}$ state which decays primarily into a $D\bar{D}$ pair.





The ability to fully reconstruct most events allows us to determine the presence of particles that don't interact in our detector(ν, K_L).

$D\bar{D}$ pair created in a quantum-correlated state, unique compared to generic D decays.

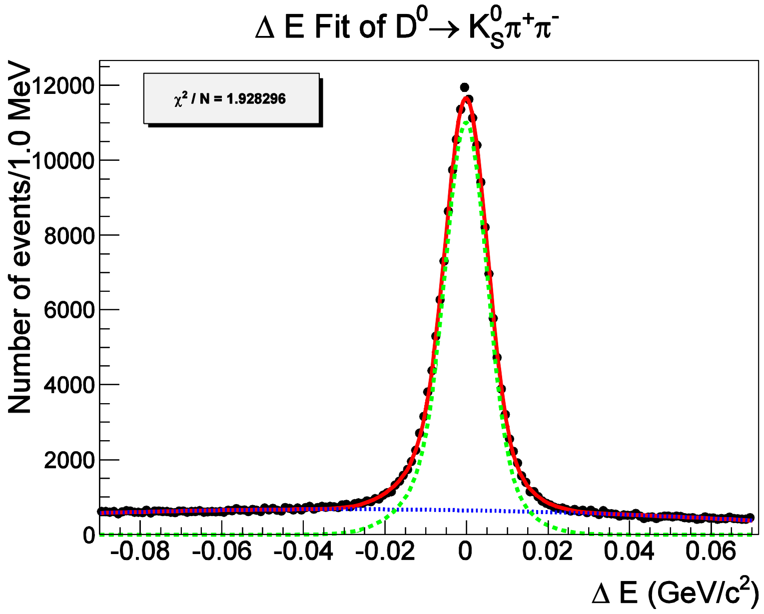
Single D Tagging

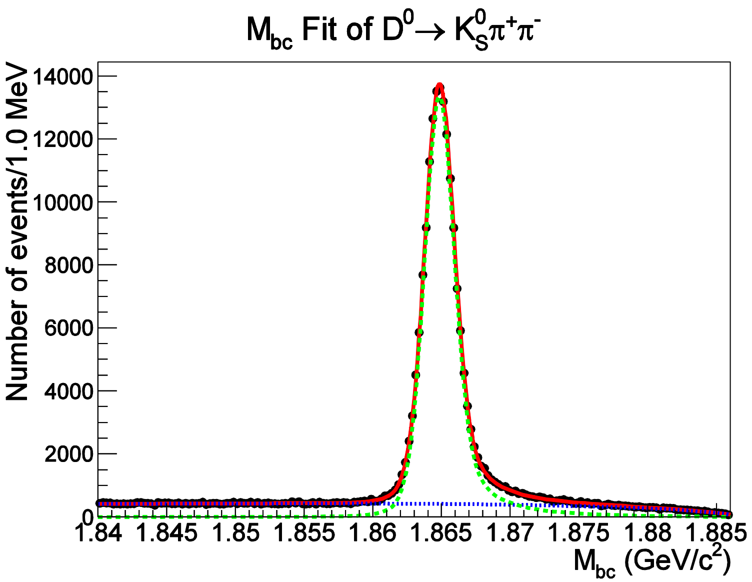
Single Tagging

Reconstruct particles from a single D decay.

$$\Delta E = E_{D\ Rec} - E_{Beam}$$

$$M_{bc} = \sqrt{E_{beam}^2 - |\vec{P}_{D\ Rec}|^2}$$





Double D Tagging

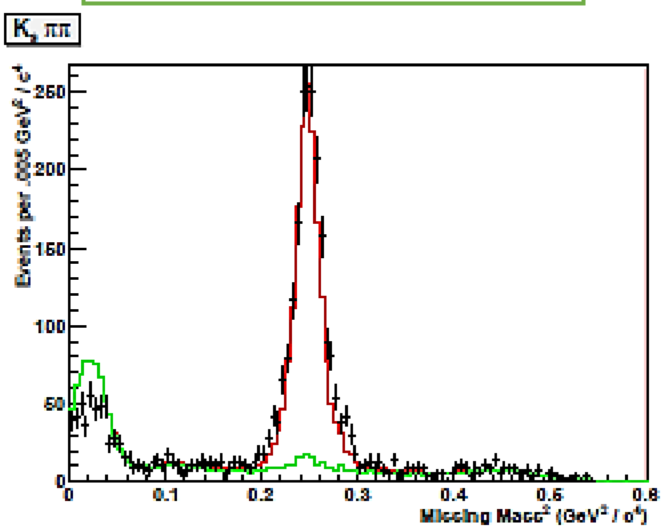
Double Tagging reconstructs both D’s

Reconstructing both D’s significantly removes background ,

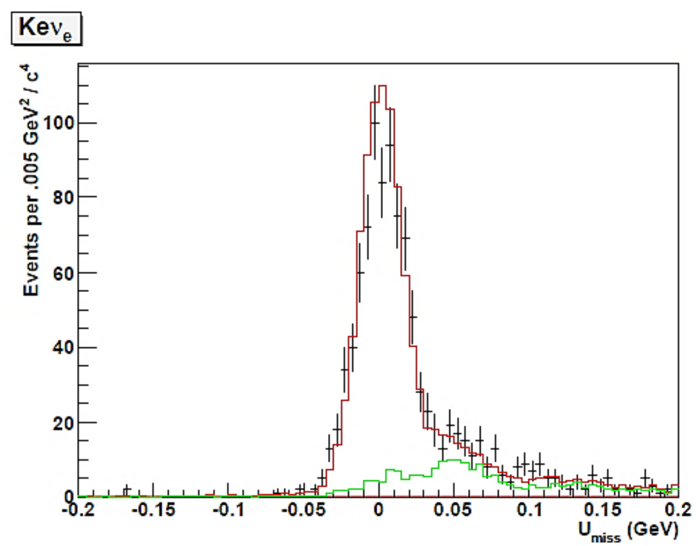
however it is at the cost of statistics.

Ability to reconstruct particles that don’t decay in our detector (K_L^0, υ)

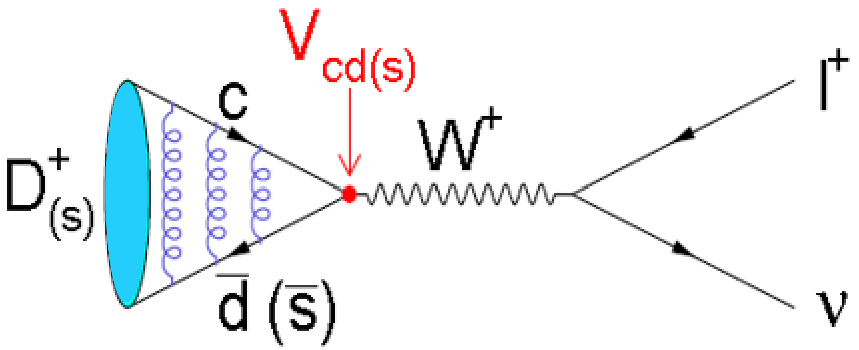
$$M_{miss}^2 \equiv E_{miss}^2 - |\vec{p}_{miss}|^2$$



$$U_{miss} \equiv E_{miss} - |\vec{p}_{miss}|$$



Leptonic decays



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

Allows us to explore precision measurements of :

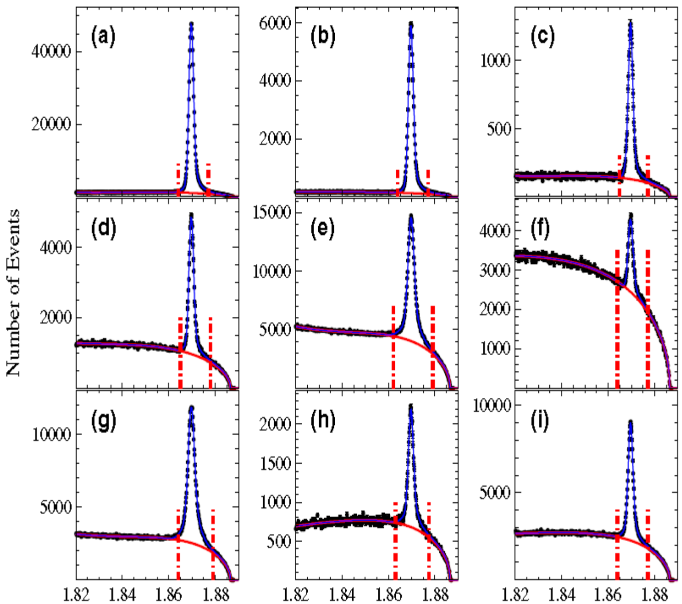
- Decay constants $f_{D^+_{(s)}}$ using input from $|V_{cd(s)}|^{\mathrm{CKMfitter}}$
- CKM matrix elements $|V_{cd(s)}|$ using input from $f^{LQCD}{}_{D^+_{(s)}}$

Measurement of $\mathcal{B}(D^+ \to \mu^+ \upsilon_\mu)$, f_{D^+} and $|V_{cd}|$

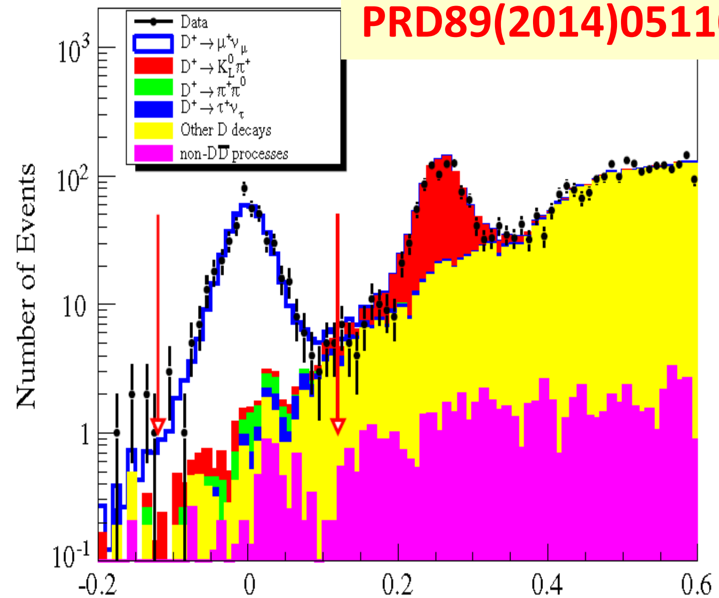
$e^+e^- \to \psi(3770) \to D^+D^-$

2.92 fb^{-1} data@ 3.773 GeV

PRD89(2014)051104R



$$M_{BC}[\mathrm{GeV/c^2}] = \sqrt{E_{beam}^2 - |\vec{P}_{D\ Rec}|^2}$$



$$M_{miss}^2[\mathrm{GeV^2/c^4}] = E_{miss}{}^2 - |\vec{p}_{miss}|^2$$

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

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

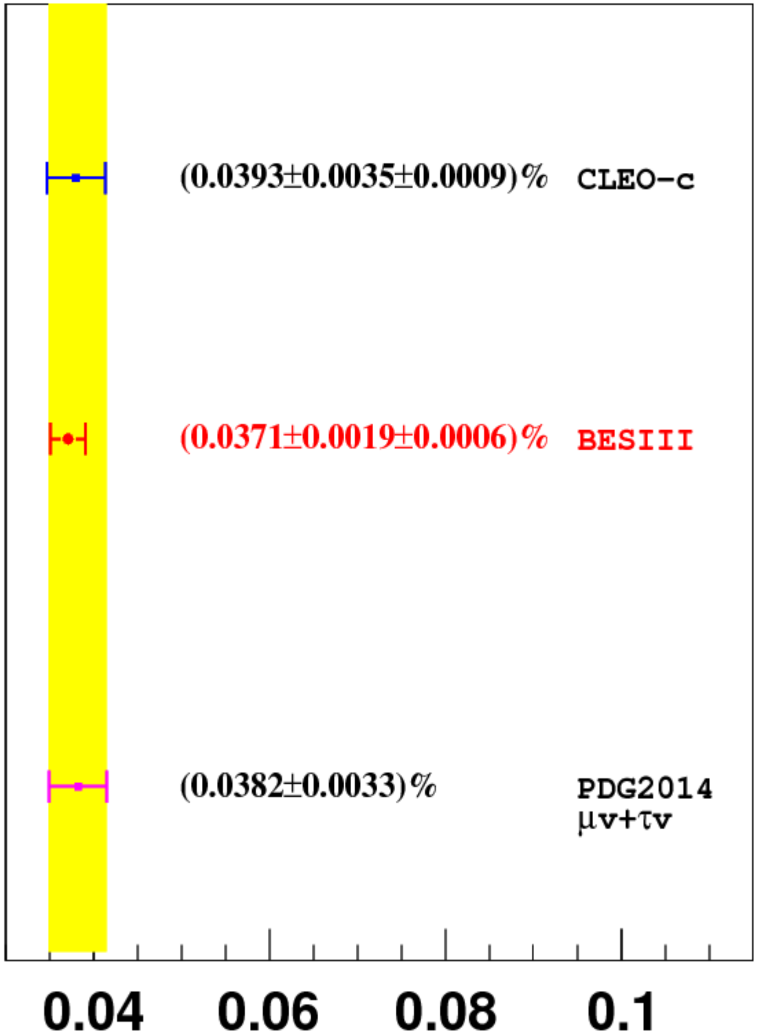
Input t_{D+}, m_{D+}, $m_{\mu+}$ on PDG and $|V_{cd}|$=0.22520 ±0.00065 from CKM-Fitter

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

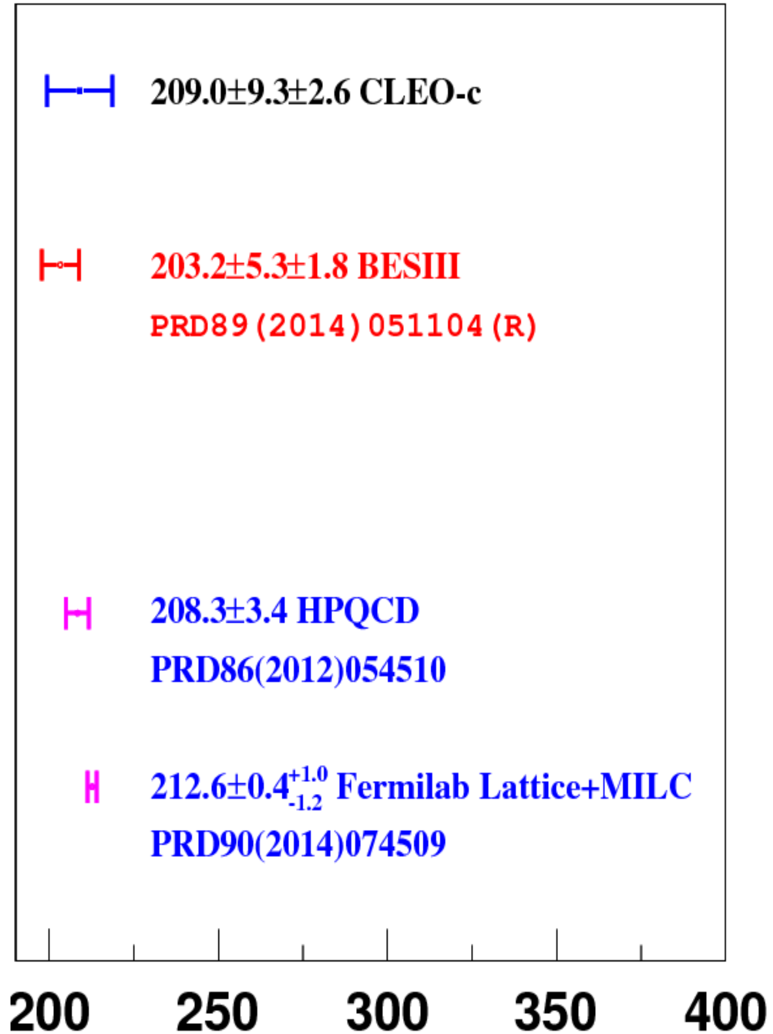
Input t_{D+}, m_{D+}, $m_{\mu+}$ on PDG and LQCD calculated f_{D+}=207±4 MeV[PRL100(2008)062002]

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

Comparison of $\mathcal{B}(D^+ \to \mu^+ \upsilon_\mu)$ and f_{D^+}

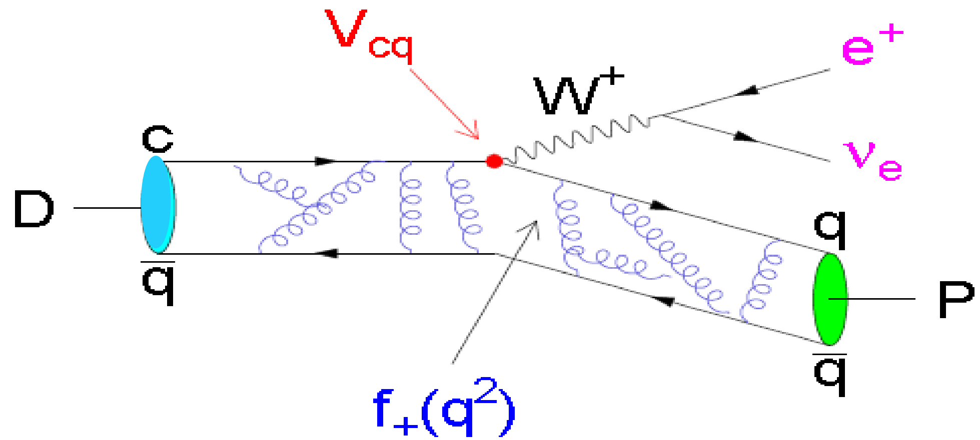


$\mathcal{B}(D^+ \to \mu^+ \upsilon_\mu)$



f_{D^+} [MeV]

Semi-leptonic decays: $D^0 \to K(\pi)^- e^+ \nu_e$



Differential Rates: $\frac{d\Gamma(D \to K(\pi)e\nu)}{dq^2} = \frac{G_F^2 \left|V_{cs(d)}\right|^2}{24\pi^3} p^3 |f_+(q^2)|^2$

Allows us to explore precision measurements of :

- Form factors $f_+^{D\to K(\pi)^-}(q^2)$ using input from $|V_{cs(d)}|^{\text{CKMfitter}}$
  - **Single pole form**

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

  - **Modified pole model**

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

  - **ISGW2 model**

    $$f_+(q^2) = f_+(q_{max}^2)\left(1 + \frac{r_{ISGW2}^2}{12}(q_{max}^2 - q^2)\right)^{-2}$$

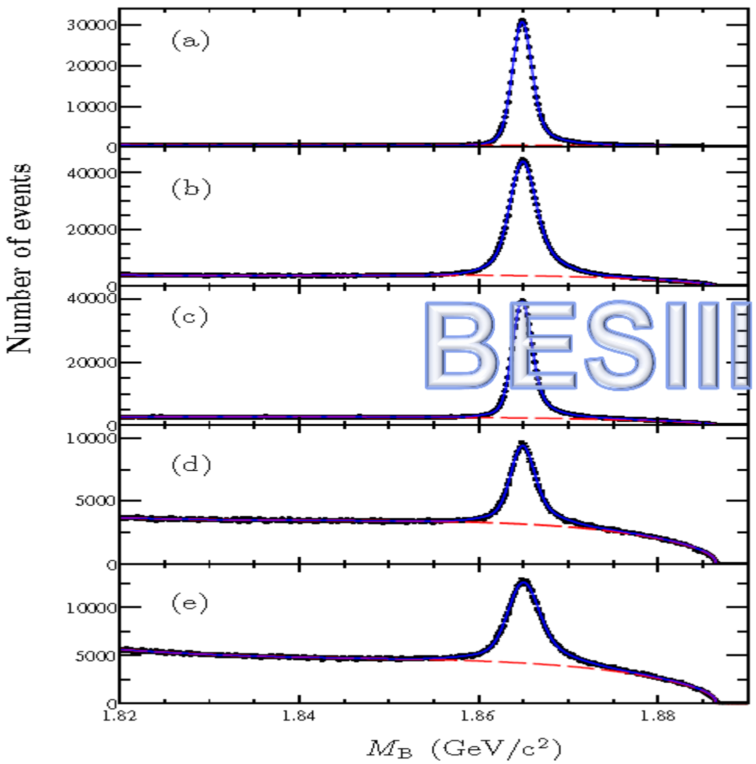
  - **Series expansion model**

    $$f_+(t) = \frac{1}{P(t)\Phi(t, t_0)} a_0(t_0)\left(1 + \sum_{k=1}^{\infty} r_k(t_0)[z(t, t_0)]^k\right)$$

- CKM matrix elements $|V_{cs(d)}|$ using input from $f^{LQCD}{}_{D^0}$

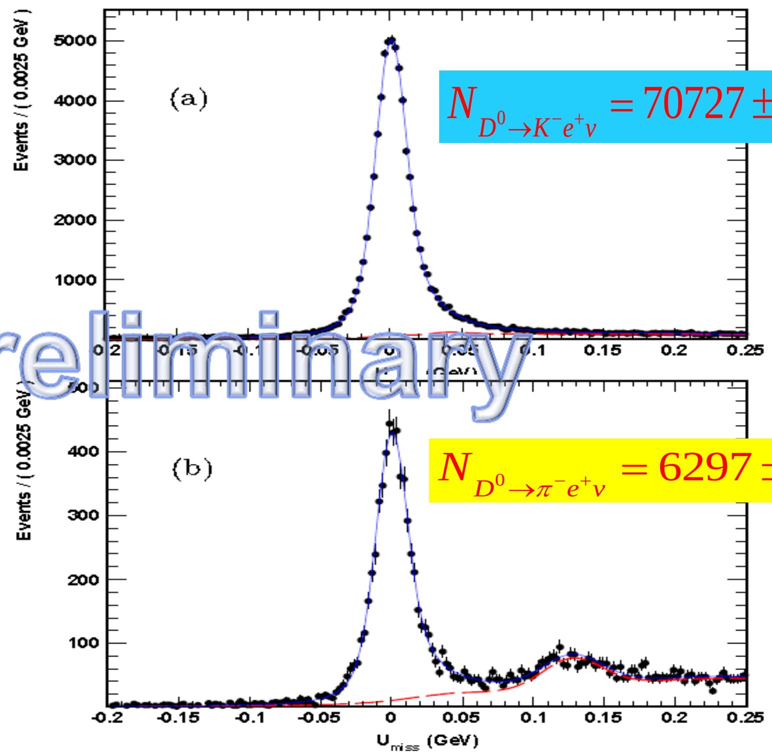
Measurement of $\mathcal{B}(D^0 \to K(\pi)^- e^+ \upsilon_e)$

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



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

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



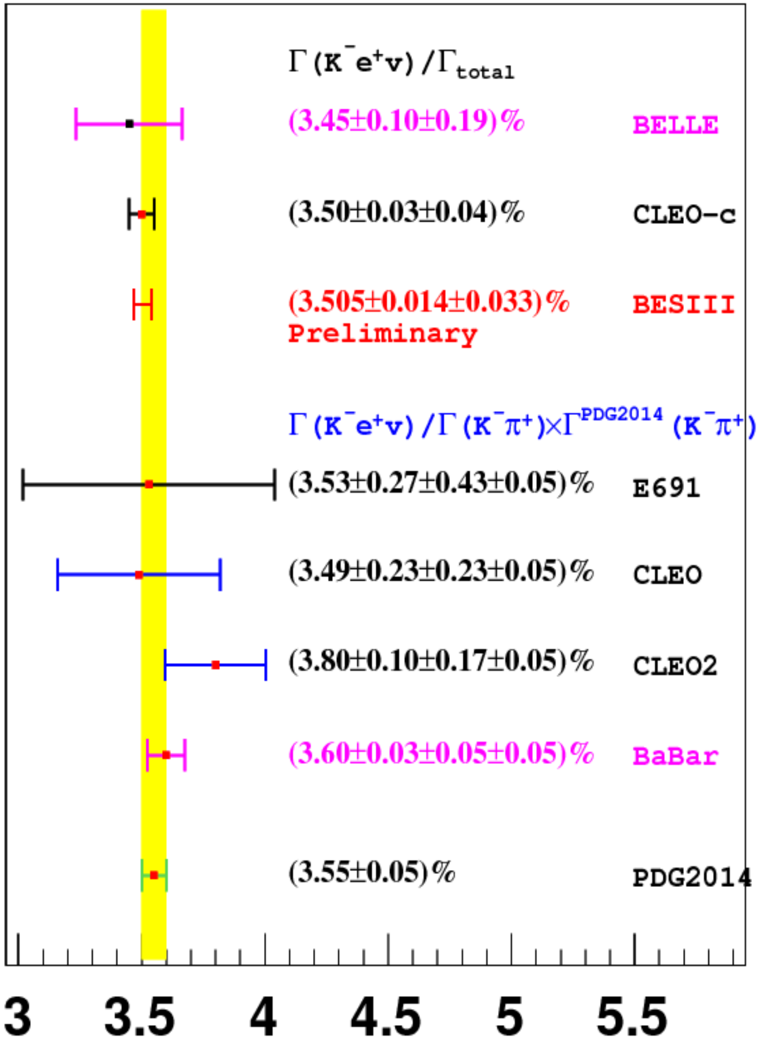
$N_{D^0 \to K^- e^+ \nu} = 70727 \pm 278$

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

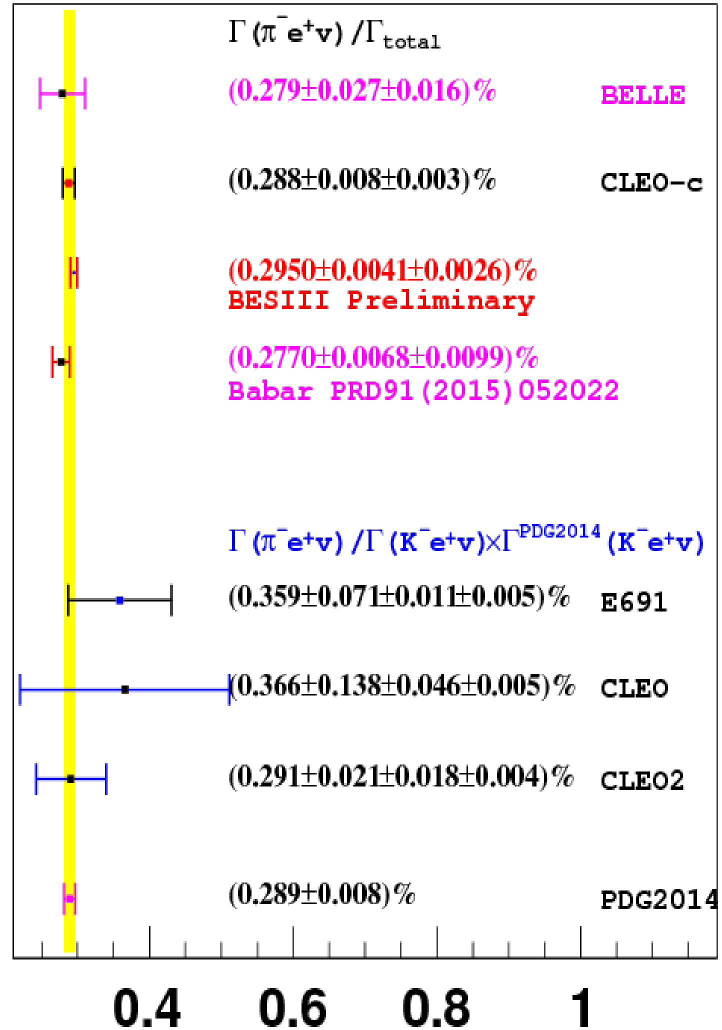
$B_{D^0 \to K^- e^+ \nu} = (3.505 \pm 0.014 \pm 0.033)\%$

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

Comparison of $\mathcal{B}(D^0 \to K(\pi)^- e^+ \nu_e)$

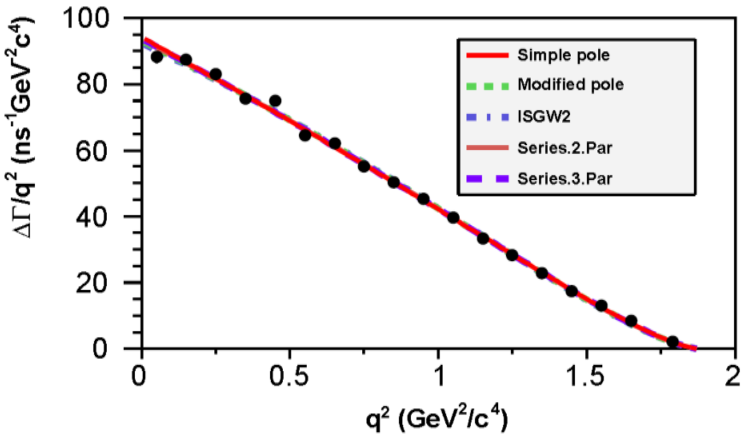


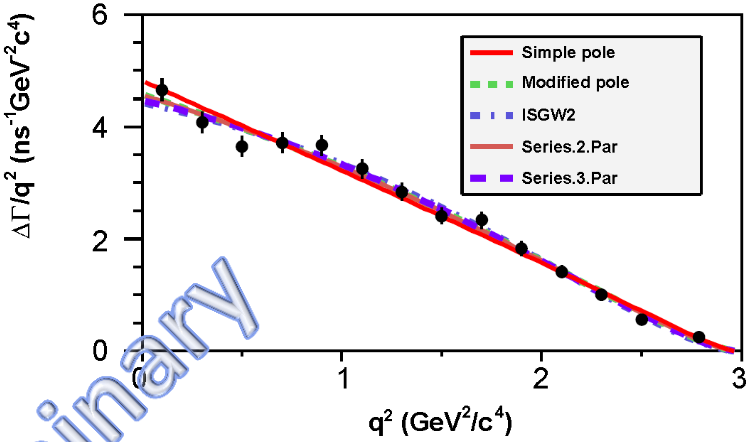
$\mathcal{B}(D^0 \to K^- e^+ \nu_e)$



$\mathcal{B}(D^0 \to \pi^- e^+ \nu_e)$

Extracted Parameters of Form Factors





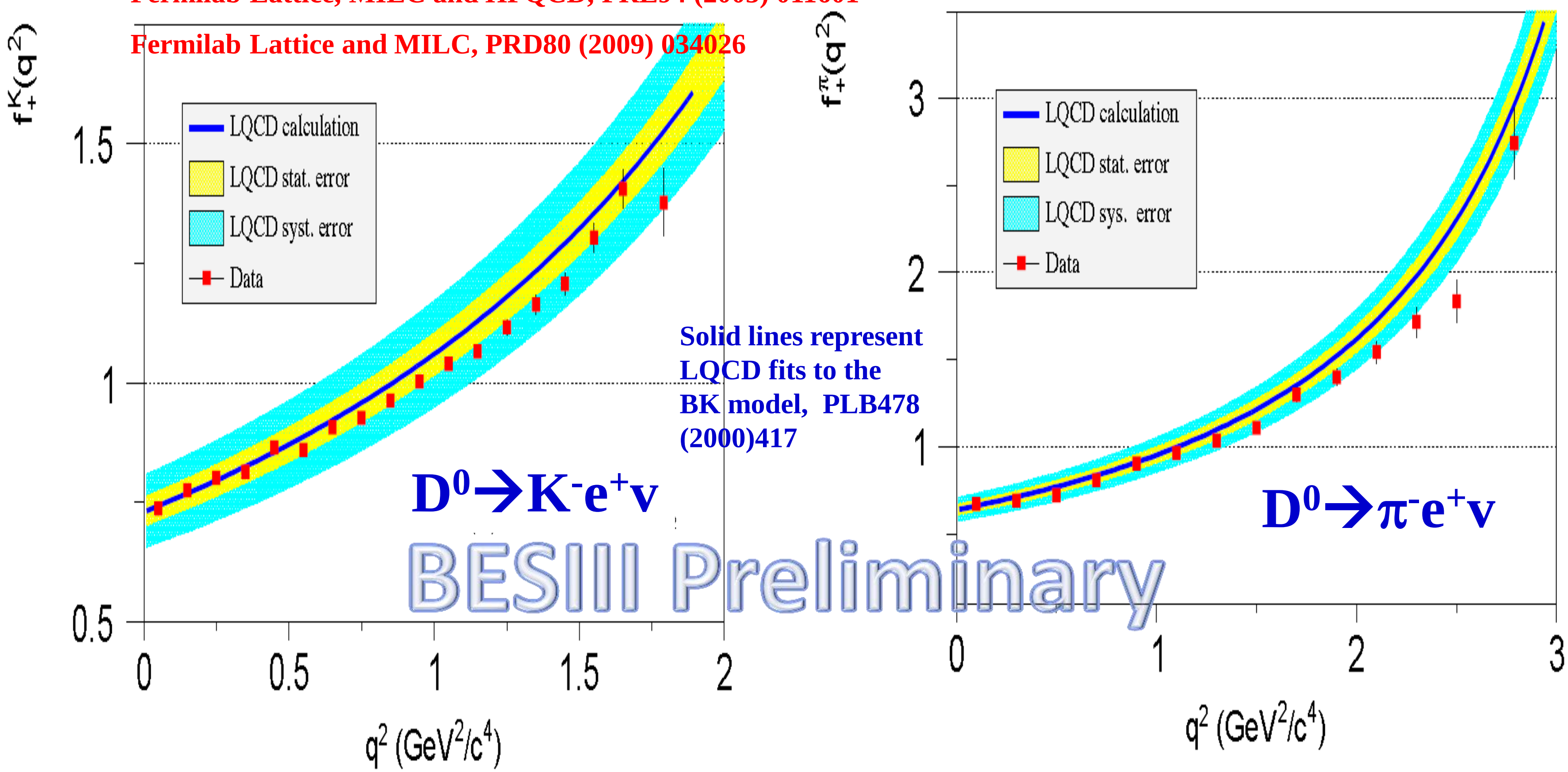
		$D^0 \rightarrow K^- e^+ \nu$		$D^0 \rightarrow \pi^- e^+ \nu$
Simple Pole	$f_K^+(0)\|V_{cs}\|$	0.7209±0.0022±0.0033	$f_\pi^+(0)\|V_{cd}\|$	0.1475±0.0014±0.0005
	M_{pole}	1.9207±0.0103±0.0069	M_{pole}	1.9114±0.0118±0.0038
Mod. Pole	$f_K^+(0)\|V_{cs}\|$	0.7163±0.0024±0.0034	$f_\pi^+(0)\|V_{cd}\|$	0.1437±0.0017±0.0008
	α	0.3088±0.0195±0.0129	α	0.2794±0.0345±0.0113
ISGW2	$f_K^+(0)\|V_{cs}\|$	0.7139±0.0023±0.0034	$f_\pi^+(0)\|V_{cd}\|$	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	$f_K^+(0)\|V_{cs}\|$	0.7172±0.0025±0.0035	$f_\pi^+(0)\|V_{cd}\|$	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	$f_K^+(0)\|V_{cs}\|$	0.7196±0.0035±0.0041	$f_\pi^+(0)\|V_{cd}\|$	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

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

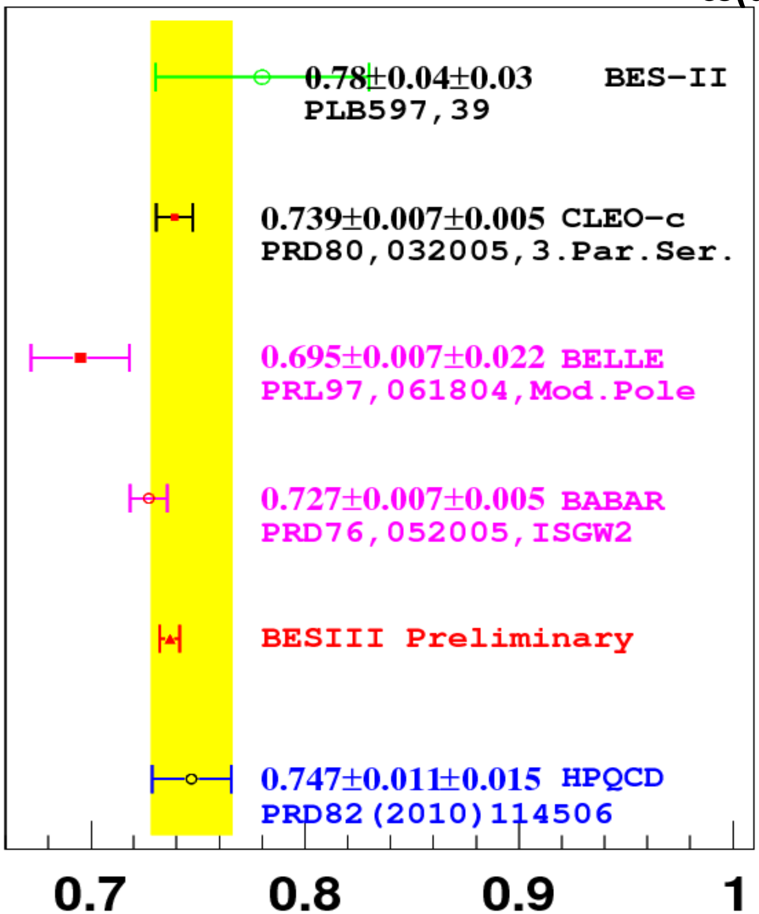
Fermilab Lattice and MILC, PRD80 (2009) 034026



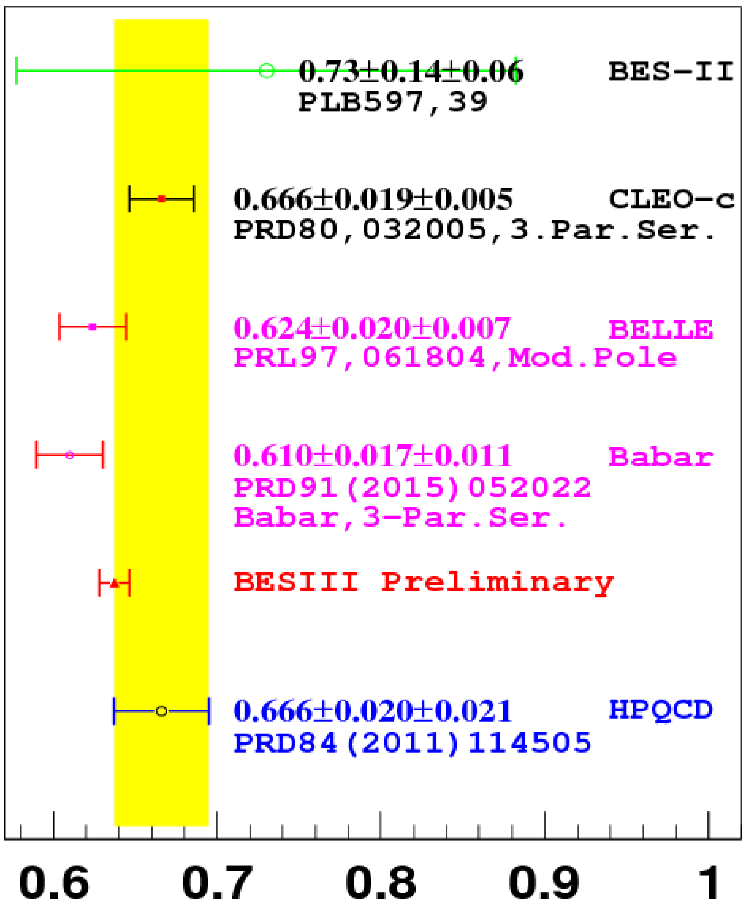
Solid lines represent LQCD fits to the BK model, PLB478 (2000)417

Improved Form Factor at q=0

Input |$V_{cs(d)}$| from CKM-Fitter



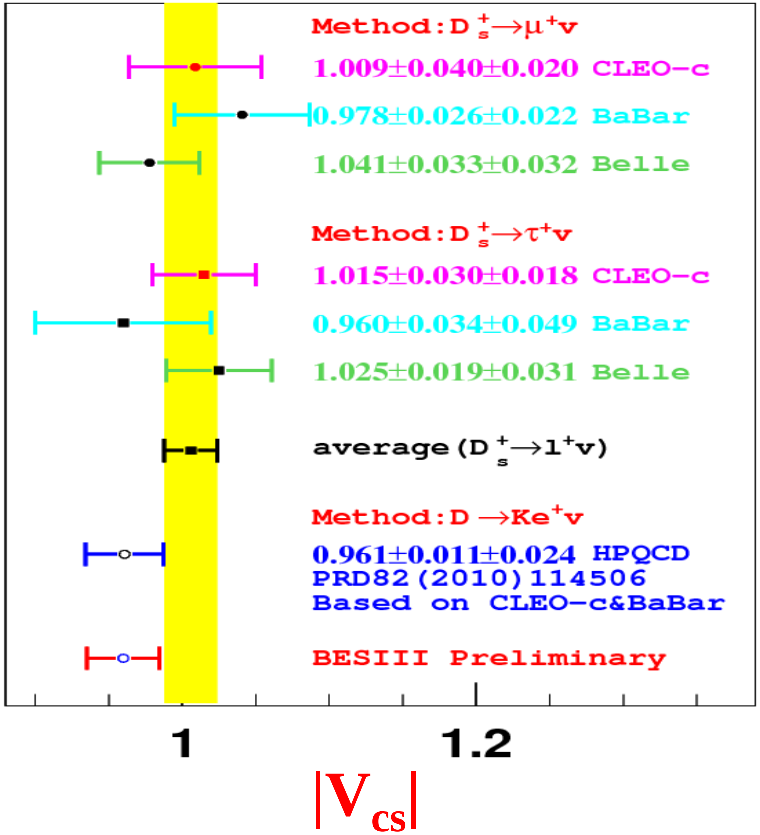
$f_+^K(0)$

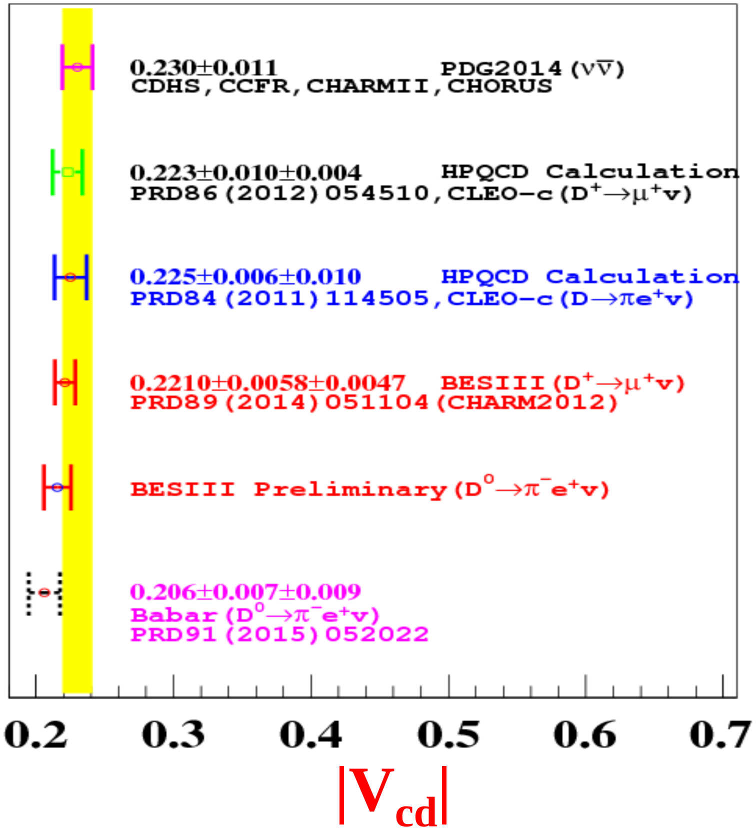


$f_+^\pi(0)$

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 → $|V_{cs(d)}|$





Definition of Y_{CP} in $D^0\overline{D^0}$ oscillation

Oscillations in $D^0\overline{D^0}$ system are characterized by two mixing parameters

$$x = \Delta m/\Gamma$$
$$y = \Delta\Gamma/2\Gamma$$

Where Δm and $\Delta\Gamma$ are the mass and width differences between the two mass eigenstates

$$|D_{1,2}\rangle = p|D^0\rangle \pm q|\overline{D^0}\rangle$$
$$\phi = \arg(\,p/q)$$

The D meson's CP eigenstates can be written as

$$|D_{CP\pm}\rangle = \frac{|D^0\rangle \pm |\overline{D^0}\rangle}{\sqrt{2}}$$

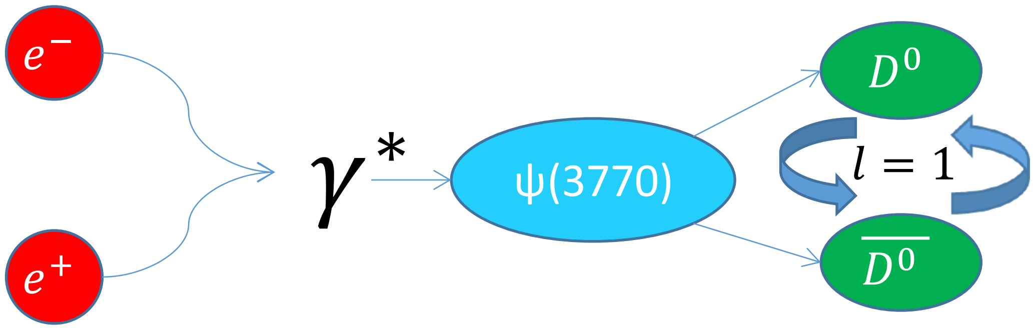
Allowing for small indirect CPV, the y parameter of the CP eigenstates becomes

$$y_{cp} = \frac{1}{2}\left[y\cos\phi\left(\left|\frac{q}{p}\right| + \left|\frac{p}{q}\right|\right) - x\sin\phi\left(\left|\frac{q}{p}\right| - \left|\frac{p}{q}\right|\right)\right]$$

In absence of CPV :

- $y_{cp} = y$
- $\left|\frac{q}{p}\right| = 1$
- $\phi = 0$

Using Semi-leptonic decays to measure Y_{CP}



If D^0 in CP eigenstate, $\overline{D^0}$ must be in opposite CP eigenstate

Total decay width of CP eigenstates:

$$\Gamma_{CP\pm} = \Gamma(1 \mp y_{CP})$$

Semi-leptonic $(D \rightarrow l)$ decay width is only sensitive to flavor content

Therefore, Semi-leptonic decay from a CP eigenstate

$$\mathcal{B}_{D_{CP\pm} \rightarrow l} \approx \mathcal{B}_{D \rightarrow l}(1 \mp y_{CP})$$

$$\therefore\ y_{CP} \approx \frac{1}{4}\left(\frac{\mathcal{B}_{D_{CP-} \rightarrow l}}{\mathcal{B}_{D_{CP+} \rightarrow l}} - \frac{\mathcal{B}_{D_{CP+} \rightarrow l}}{\mathcal{B}_{D_{CP-} \rightarrow l}}\right)$$

This can be obtained through Single and double tag yields and efficiencies

$$\mathcal{B}_{D_{CP\mp} \rightarrow l} = \frac{N_{CP\pm;l}}{N_{CP\pm}} \cdot \frac{\varepsilon_{CP\pm}}{\varepsilon_{CP\pm;l}}$$

Y_{CP} Results

$$\mathcal{B}_{D_{CP\mp}\to l} = \frac{N_{CP\pm;l}}{N_{CP\pm}} \cdot \frac{\varepsilon_{CP\pm}}{\varepsilon_{CP\pm;l}}$$

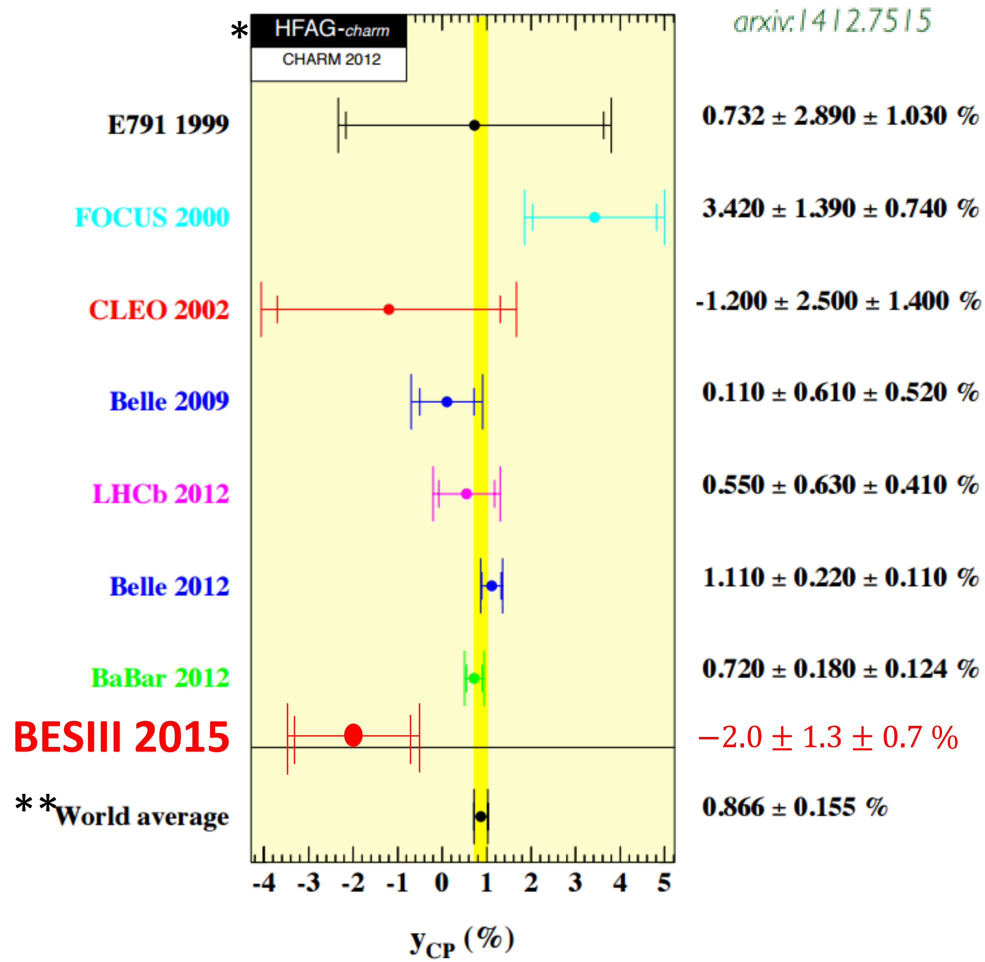
Branching ratios of $Ke\nu$ and $K\mu\nu$ are combined to get $\mathcal{B}_{D_{CP\mp}\to l}$

Results are combined from different CP modes into a global fit using standard weighted least-square method.

Result:

$y_{cp} = (-2.0 \pm 1.3_{(\mathrm{stat})} \pm 0.7_{(\mathrm{sys})})\%$

Phys.Lett.B 744(2015) 339-346

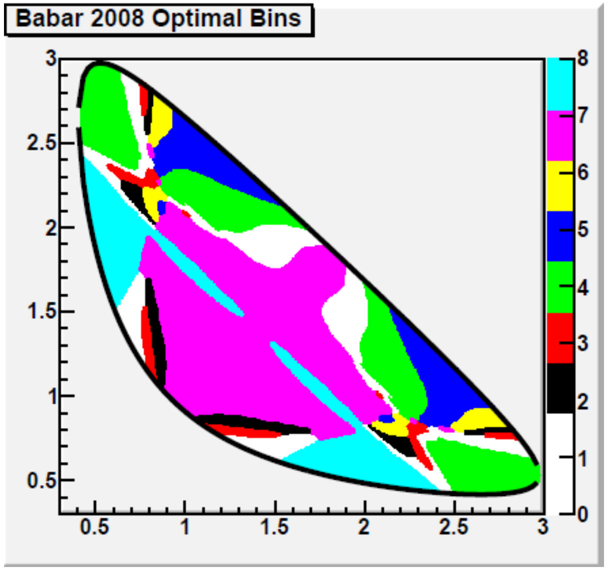


*Edited to compare with BESIII result

**BESIII not included in world average

$D^0 \to K_S^0\pi^+\pi^-$ Strong-Phase Parameters

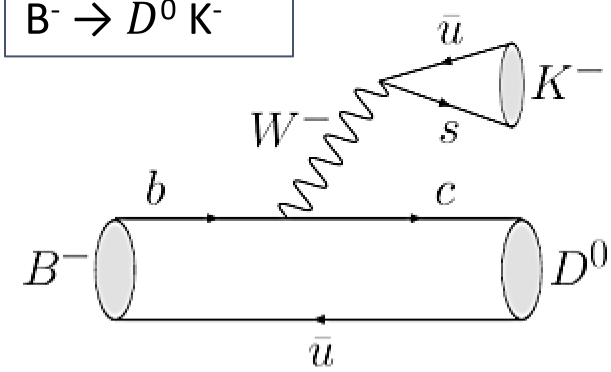
Measuring the Dalitz binned strong-phase difference between D^0 and $\overline{D^0} \to K_S^0\pi^+\pi^-$



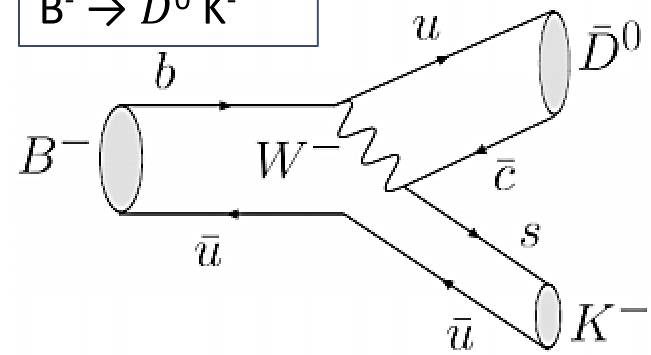
This measurement is important for reducing the systematic/model uncertainty of the measurement of the CKM UT angle γ done at the B factories using the GGSZ method.

CKM UT angle γ measurement

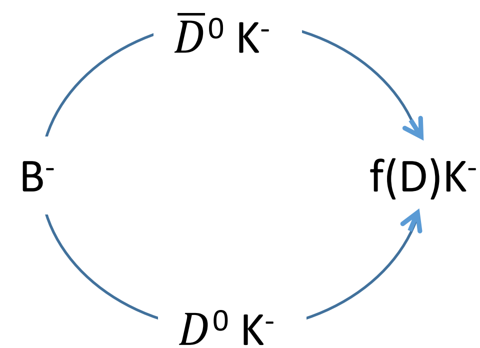
$B^- \rightarrow D^0 K^-$



$B^- \rightarrow \overline{D}^0 K^-$



$$\frac{\langle B^- \longrightarrow \overline{D}^0 K^- \rangle}{\langle B^- \longrightarrow D^0 K^- \rangle} = r_B e^{i(\delta_B - \gamma)}$$



Determine γ through the measurement of the interference between b →c and b →u transitions when D^0 and $\overline{D}^0$ both decay to the same final state f(D).

GGSZ method of measuring γ

Binned decay rate:

$$\Gamma(B^{\pm} \to D(K_s\pi^+\pi^-)K^{\pm})_i = T_i + r_B{}^2 T_{-i} + 2r_B\sqrt{T_iT_{-i}}\cos(\delta_B \pm \gamma - \Delta\delta_D)$$
$$= T_i + r_B{}^2 T_{-i} + 2r_B\sqrt{T_iT_{-i}}\{c_i\cos(\delta_B \pm \gamma) + s_i\sin(\delta_B \pm \gamma)\}$$

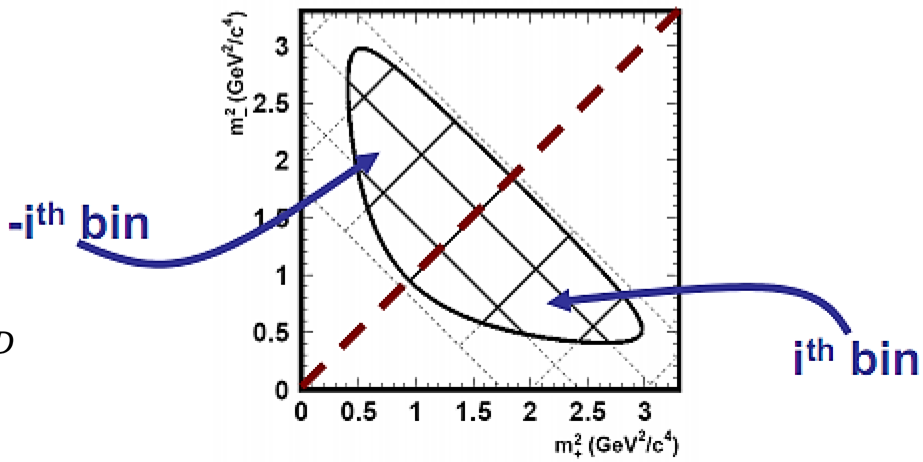
Distribution sensitive to variables:

T_i : Bin yield measured in flavor decays

r_B : color suppression factor ~ 0.1

δ_B : strong phase of B decay

c_i, s_i : weighted average of $\cos(\Delta\delta_D)$ and $\sin(\Delta\delta_D)$ respectively where $\Delta\delta_D$ is the difference between phase of D^0 and $\overline{D}^0$

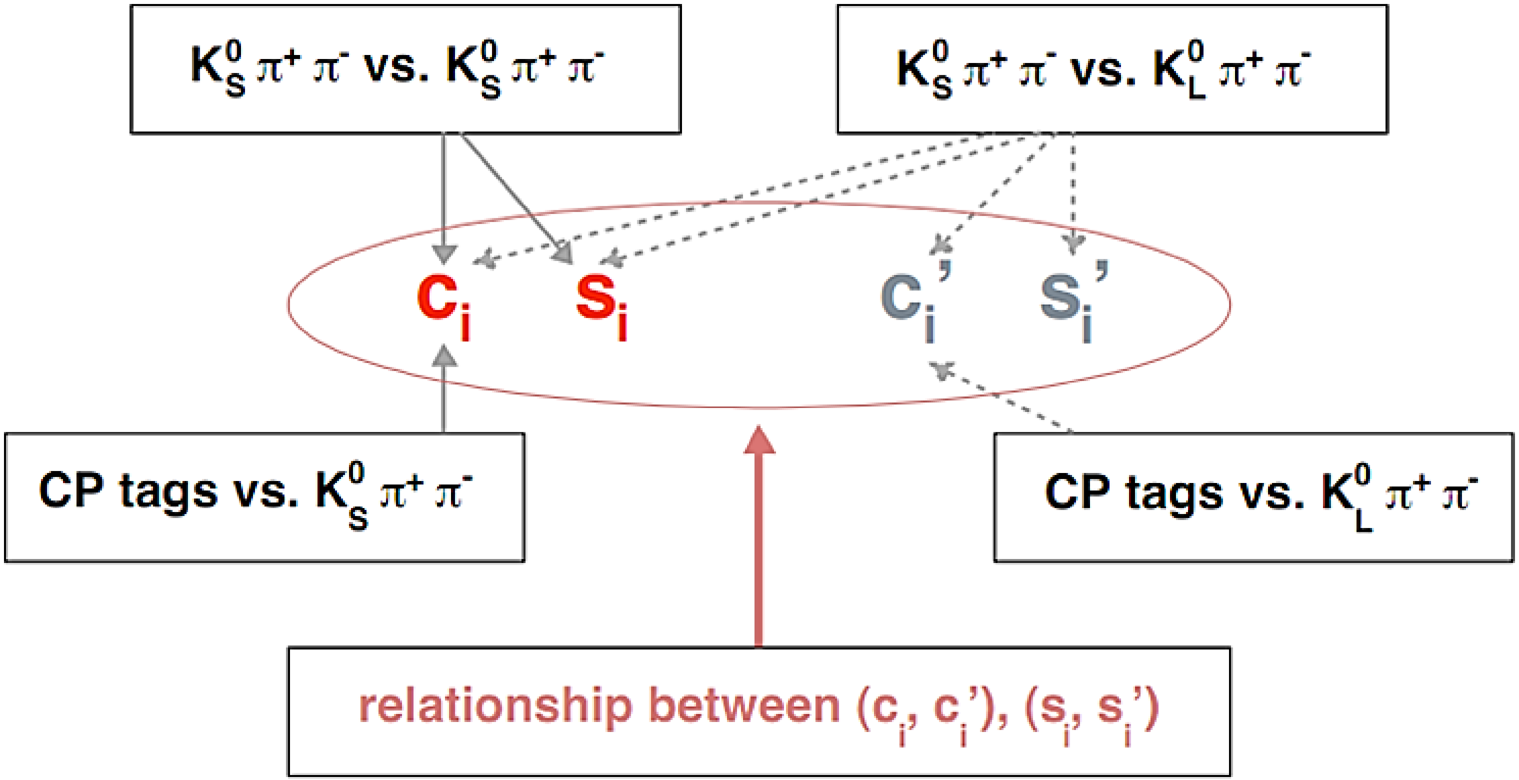


Mirrored binning over x=y makes it so $c_i = c_{-i}$ and $s_i = -s_{-i}$

T_i , r_B, δ_B are measured at B-Factories

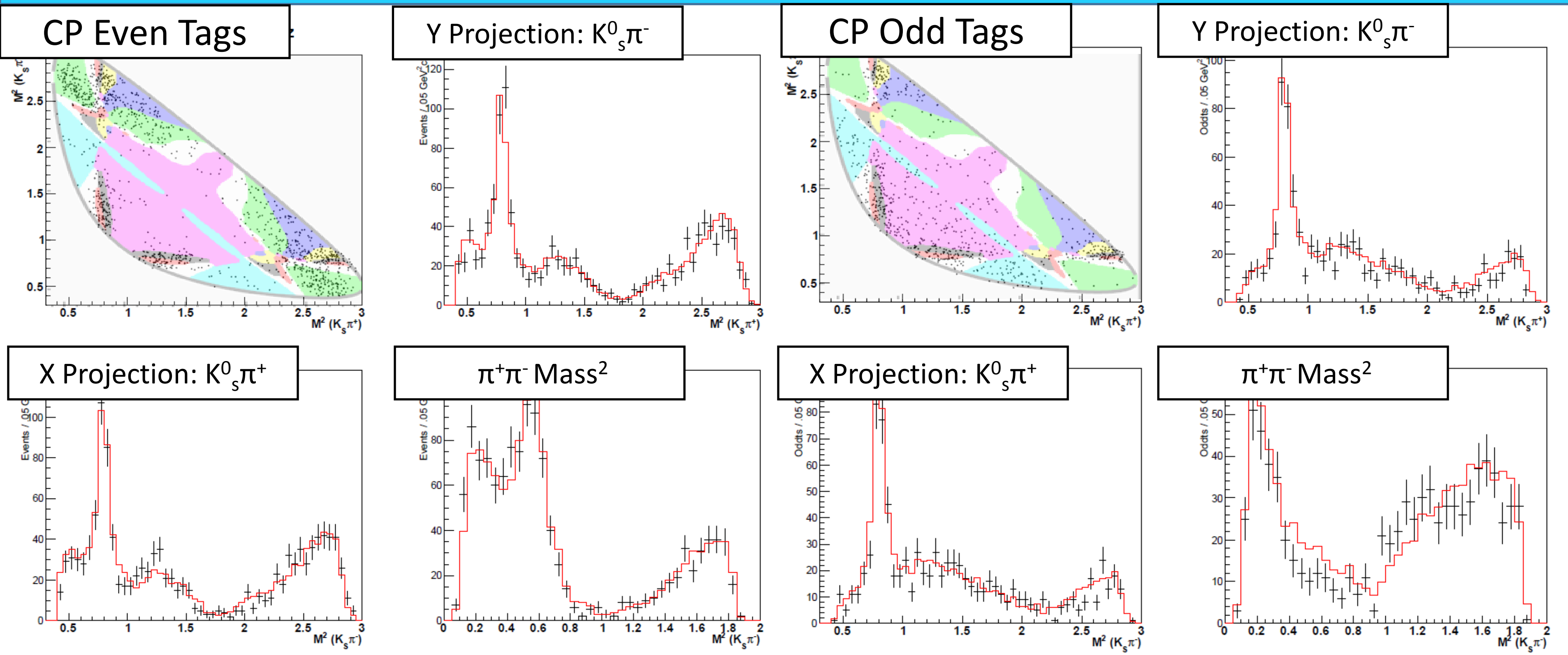
c_i and s_i can be found through $K_s\pi^+\pi^-$ Analysis

Calculation of strong phase parameters



It can be shown that the strong phase parameters can be determined through yields and efficiencies of ST and DT modes.

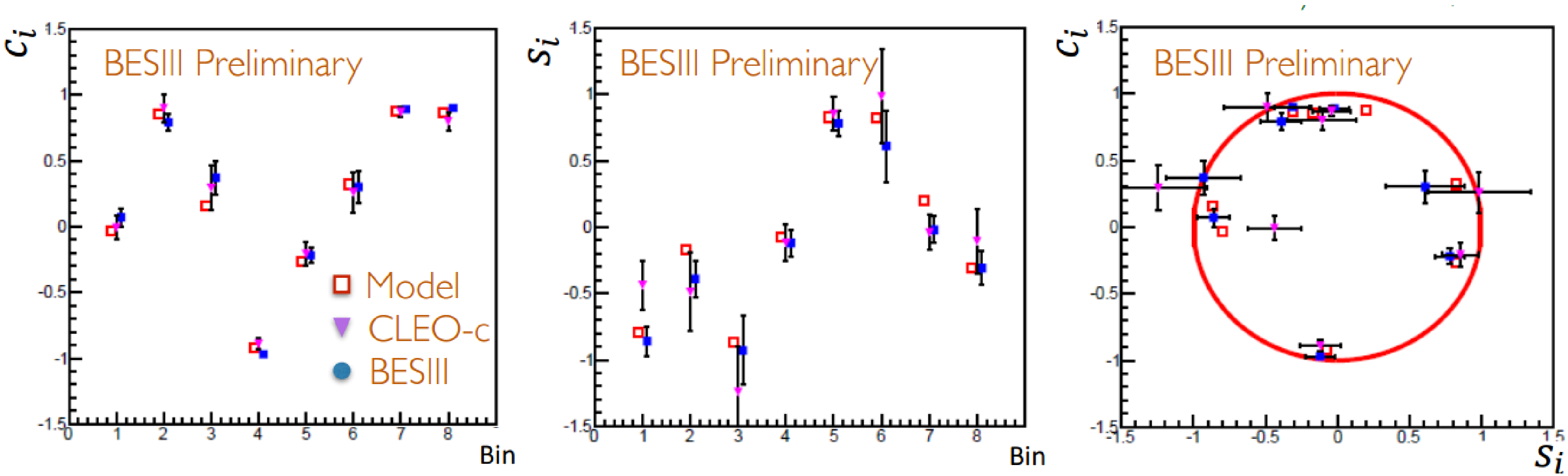
$K_S^0\pi^+\pi^-$ vs CP tags



BESIII
Preliminary

Type	Tag List
Pseudo-Flavored	$K^-\pi^+$, $K^-\pi^+\pi^0$, $K^-\pi^+\pi^+\pi^-$
S^+	K^+K^-, $\pi^+\pi^-$, $K_S\pi^0\pi^0$, $K_L\pi^0$
S^-	$K_S\pi^0$, $K_S\eta(\to\gamma\gamma)$, $K_S\eta(\to\pi^+\pi^-\pi^0)$, $K_S\omega$, $K_S\eta'$

Strong-phase parameters results



BESIII Preliminary

Bins	c_i BES-III	c_i CLEO-c	s_i BES-III	s_i CLEO-c
1	0.066 ± 0.066	-0.009 ± 0.088	-0.843 ± 0.119	-0.438 ± 0.184
2	0.796 ± 0.061	0.900 ± 0.106	-0.357 ± 0.148	-0.490 ± 0.295
3	0.361 ± 0.125	0.292 ± 0.168	-0.962 ± 0.258	-1.243 ± 0.341
4	-0.985 ± 0.017	-0.890 ± 0.041	-0.090 ± 0.093	-0.119 ± 0.141
5	-0.278 ± 0.056	-0.208 ± 0.085	0.778 ± 0.092	0.853 ± 0.123
6	0.267 ± 0.119	0.258 ± 0.155	0.635 ± 0.293	0.984 ± 0.357
7	0.902 ± 0.017	0.869 ± 0.034	-0.018 ± 0.103	-0.041 ± 0.132
8	0.888 ± 0.036	0.798 ± 0.070	-0.301 ± 0.140	-0.107 ± 0.240

CLEO-c result: Phys. Rev. D 82, 112006

- Reduction in the c_i s_i contribution to the uncertainty in γ of ~40%
- Improved statistics from B factories could place uncertainty from the c_i s_i contribution at ~1%

More Upcoming Analysis

Leptonic:

- $D_s^+ \rightarrow l^+\nu$ analysis

Semi-leptonic:

- $D^+ \rightarrow K_L e^+\nu$
- $D^+ \rightarrow (\omega, \phi)e^+\nu$
- $D^+ \rightarrow K^-\pi^+e^+\nu$

Hadronic:

- Dalitz analysis KsKK
- $D_S^+ \rightarrow \eta' X$ and $D_S^+ \rightarrow \eta'\rho^+$
- $\sigma(e^+e^+ \rightarrow D\bar{D})$ at E_{cm} = 3.773 GeV
- $\sigma(e^+e^+ \rightarrow D\bar{D})$ Line shape near E_{cm} = 3.773 GeV

Summary

Through the leptonic decay of $D^+ \rightarrow \mu^+ \upsilon_\mu$ and the semi-leptonic decay $D^0 \rightarrow K(\pi)^- e^+ \upsilon_e$, we have obtained improved measurements of decay constant f_{D^+} and form factors $f_+^{D \to K(\pi)}(q^2)$, which are important to test and calibrate LQCD calculations accurately.

Leptonic and semi-leptonic decays improved measurements of CKM matrix elements, which are important for unitarity test of the CKM matrix.

Measurement of y_{CP}, the mixing parameter in $D^0\overline{D^0}$ oscillation, is a competitive measurement which takes advantage of the quantum correlation of the ψ(3770) dataset.

Measurement of parameters of the strong-phase difference between D^0 and $\overline{D^0} \rightarrow K_S^0 \pi^+ \pi^-$, which are important for reducing systematics in CKM UT angle γ measurements.

Many more BESIII analysis are on their way and we look forward to sharing our results.

$K_S^0\pi^+\pi^-$ Calculation of c_i, s_i

For CP tag vs $K_S^0\pi^+\pi^-$, we are able to find c_i

$$M_i^{\pm} = \frac{S_{\pm}}{2S_f}\left(K_i \pm 2c_i\sqrt{K_i K_{-i}} + K_{-i}\right)$$

$M_i^+(M_i^-)$ yields in each bin of Dalitz plot for CP even(odd) modes.
$S_+(S_-)$ number of single tags for CP even(odd) modes.
S_f number of single tags for flavor modes.
$K_i(K_{-i})$, yields in each bin of Dalitz plot in flavor modes.

From the Double Dalitz modes, we are able to find c_i, s_i

$$M_{i,j} = \frac{N_{D,\bar{D}}}{2S_f^2}\left(K_i K_{-j} + K_{-i}K_j - 2\sqrt{K_i K_{-j} K_{-i} K_j}\left(c_i c_j + s_i s_j\right)\right)$$

$M_{i,j}$ yields in bin i of first Dalitz plot and bin j of second Dalitz plot.
S_f number of single tags for flavor modes.
$N_{D,\bar{D}}$ total number of $D^0\overline{D}^0$ events.
$K_i(K_{-i})$, yields in each bin of Dalitz plot in flavor modes.

$K_L^0\pi^+\pi^-$ Calculation of c_i, c'_i, s_i, s'_i

For CP tag vs $K_L^0\pi^+\pi^-$, we are able to find c'_i

' indicates numbers from $K_L\pi^+\pi^-$ decays

$$M'^{\pm}_i = \frac{S_\pm}{2S_f}\left(K'_i \mp 2c'_i\sqrt{K'_i K'_{-i}} + K'_{-i}\right)$$

$M'^{+}_i(M'^{-}_i)$ yields in each bin of Dalitz plot for CP even(odd) modes.
$S_+(S_-)$ number of single tags for CP even(odd) modes.
S_f number of single tags for flavor modes.
$K'_i(K'_{\bar{i}})$, yields in each bin of Dalitz plot in flavor modes.

From the Double Dalitz modes, we are able to find c_i, c'_i, s_i, s'_i

$$M'_{i,j} = \frac{N_{D,\bar{D}}}{2S_f^2}\left(K_i K'_{-j} + K_{-i}K'_j + 2\sqrt{K_i K'_{-j} K_{-i} K'_j}\left(c_i c'_j + s_i s'_j\right)\right)$$

i[th] bin for $K_S^0\pi^+\pi^-$
j[th] bin for $K_L^0\pi^+\pi^-$

$M_{i,j}$ yields in bin i of $K_S^0\pi^+\pi^-$ Dalitz plot and bin j of $K_L^0\pi^+\pi^-$ Dalitz plot.
S_f number of single tags for flavor modes.
$N_{D,\bar{D}}$ total number of $D^0\overline{D}^0$ events.
$K_i(K_{-i})$, yields in each bin of $K_S^0\pi^+\pi^-$ Dalitz plot in flavor modes.
$K'_j(K'_{-j})$, yields in each bin of $K_L^0\pi^+\pi^-$ Dalitz plot in flavor modes.