Charm Decays and CKM Matrix Measurements at BESIII

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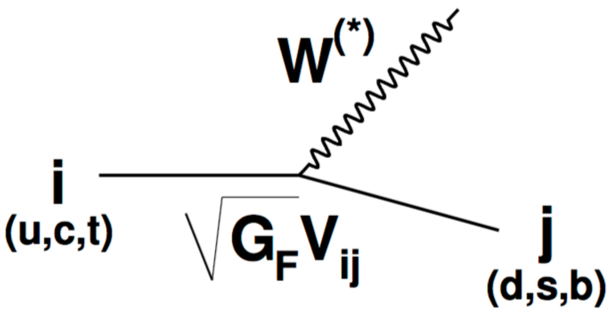
CKM matrix and D decays

Quark mass eigenstates are not their weak eigenstates: Quark-mixing described by unitary CKM matrix in the Standard Model (SM). The CKM matrix elements are fundamental parameters of the SM.



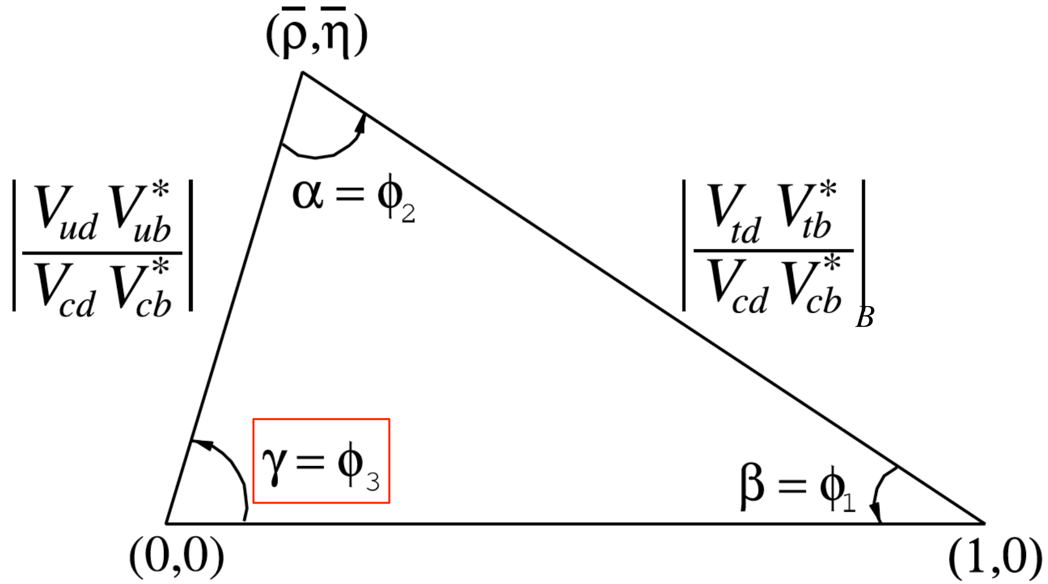
weak eigenstates — V_{CKM} — mass eigenstates

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

The magnitude of V_{cd} and V_{cs} can be extracted from semileptonic and leptonic D and D_s decays, using theoretical knowledge of the form factors.

Unitarity Triangle

The unitarity of the CKM matrix can be represented by a triangle in a complex plane.



$$\beta = \phi_1 = \arg\left(-\frac{V_{cd}V_{cb}^*}{V_{td}V_{tb}^*}\right)$$

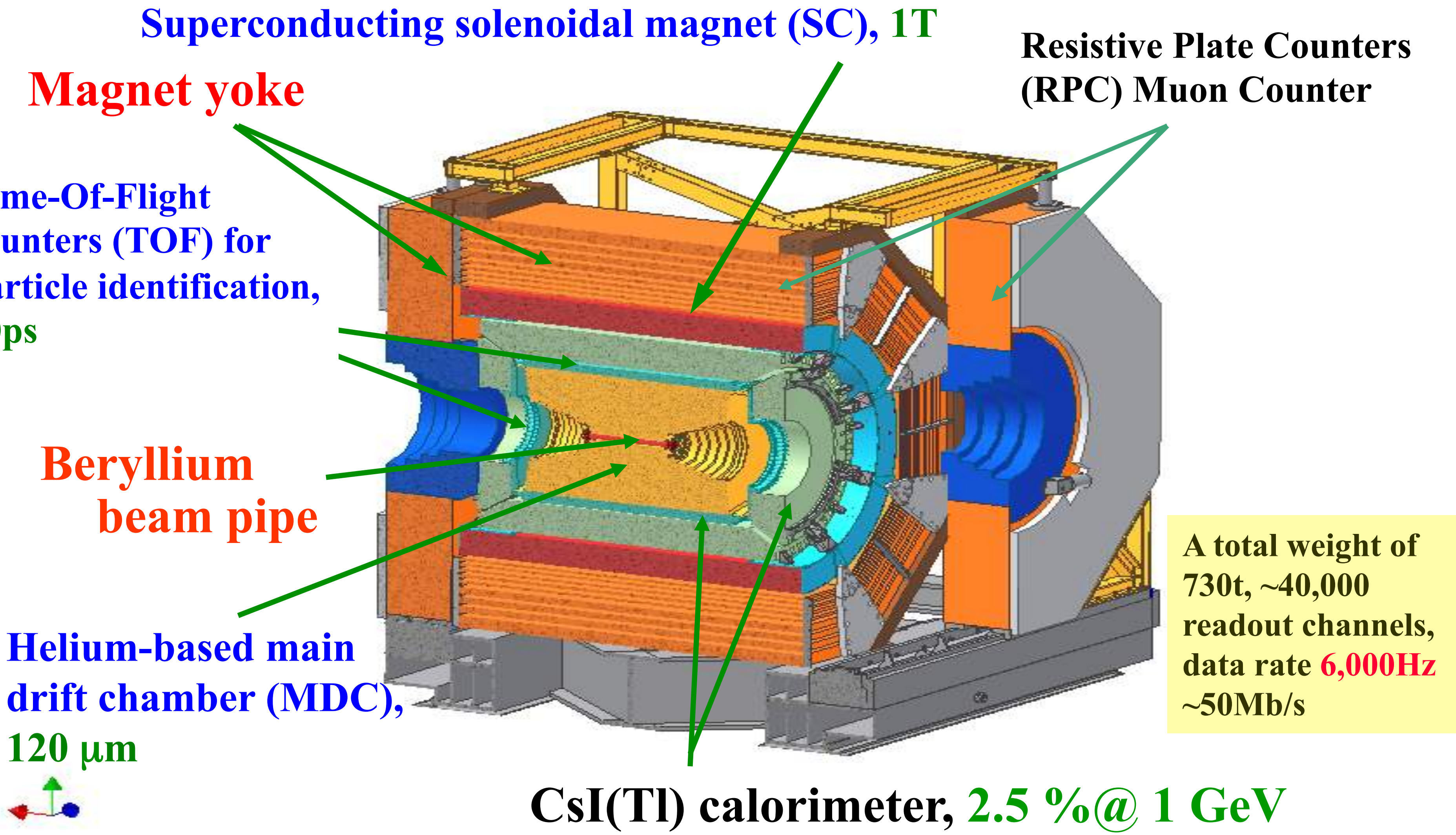
$$\alpha = \phi_2 = \arg\left(-\frac{V_{td}V_{tb}^*}{V_{ud}V_{ub}^*}\right)$$

$$\gamma = \phi_3 = \arg\left(-\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}\right)$$

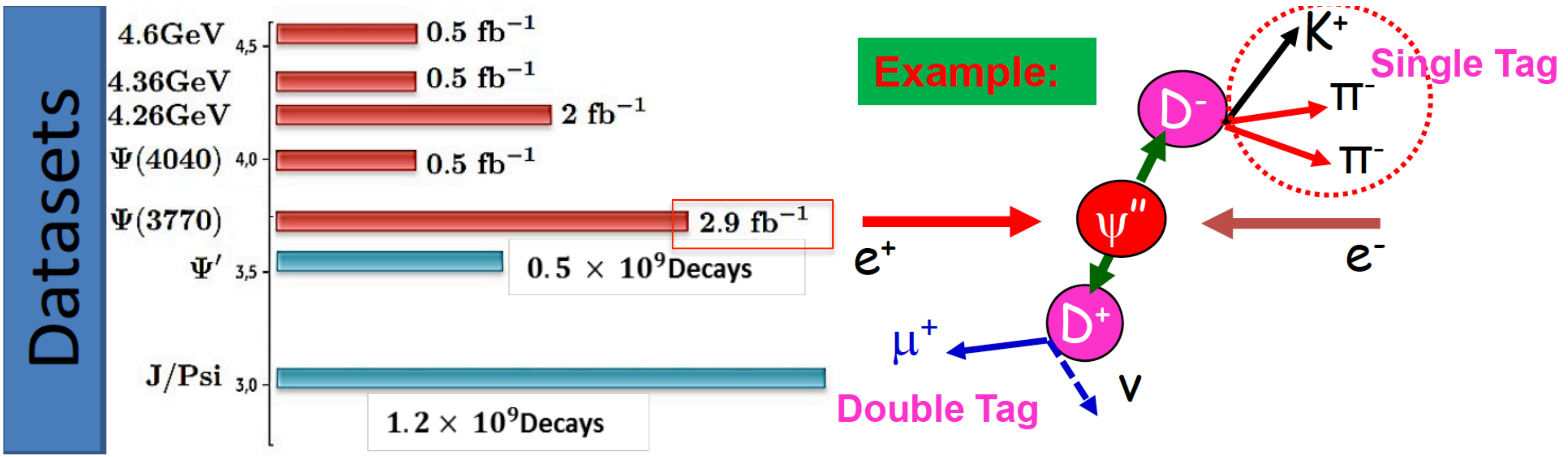
γ/ϕ_3 in the unitarity triangle can be directly measured through the interference of $B^- \to D^0(\bar{D}^0)K^- \to$ same final states, in which strong phase difference between D^0 and $\bar{D}^0$ can be determined from D decays

Beijing Electron Positron Collider II (BEPCII)

The BESIII Detector



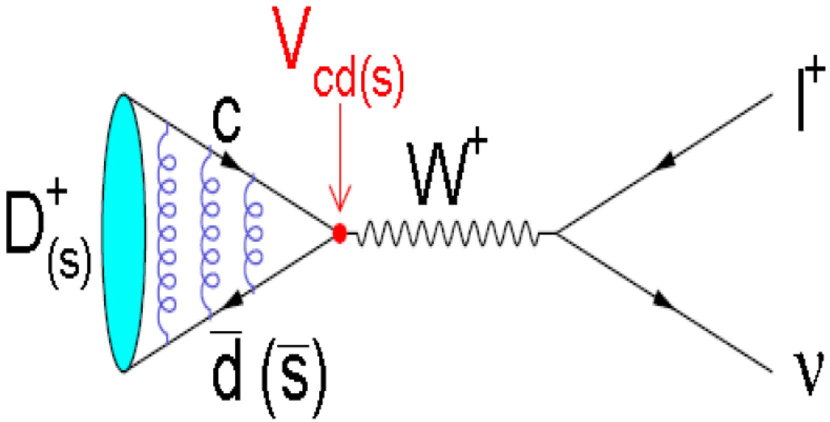
Samples of Charm decays

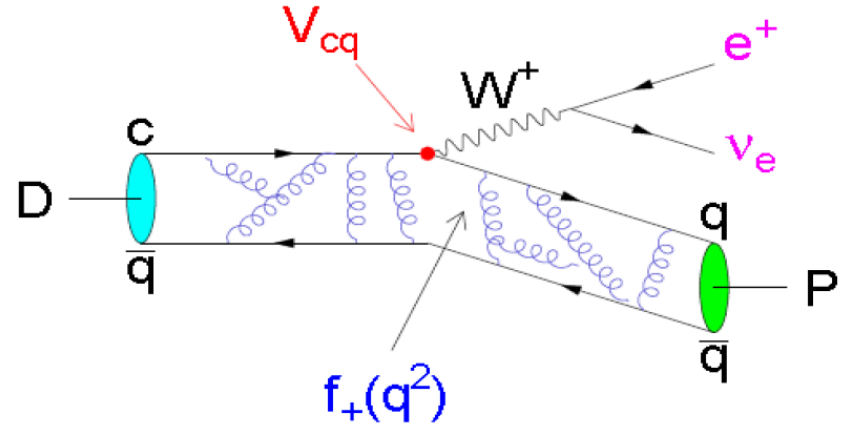


Generate *ψ*" and *D* pairs at rest. Beam energy can be used to constrain kinematics of *D* decay final states, providing clean singlely/doublely tagged *D* samples to study (semi-)leptonic decays and hadron decays.

D leptonic and semileptonic decays

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





$$\Gamma(D^+_{(s)} \to \ell^+ \nu_\ell) = \frac{G_F^2 f^2_{D^+_{(s)}}}{8\pi} |V_{cd(s)}|^2 m_\ell^2 m_{D^+_{(s)}} \left(1 - \frac{m_\ell^2}{m^2_{D^+_{(s)}}}\right)^2 \qquad \frac{d\Gamma}{dq^2} = X \frac{G_F^2 |V_{cd(s)}|^2}{24\pi^3} p^3 |f_+(q^2)|^2$$

- In CKM measurements, the uncertainty is dominated by the uncertainty from $f_{B(S)}$ and $f_+^{B\to\pi}(q^2)$ of *B* meson calculated in LQCD.
- Precision measurement of (semi-)leptonic *D* decay rate can be used to validate $f_{D(S)+}$ and $f_+^{D\to K(\pi)}(q^2)$ calculated in LQCD, and then improve LQCD calculation of $f_{B(S)}$ and $f_+^{B\to\pi}(q^2)$ for B meson.
- Recent improved LQCD calculation on $f_{D(S)+}$(0.5%) and $f_+^{D\to K(\pi)}(q^2)$ (1.7%, 4.4%) provide good chance to constrain the CKM matrix element $|V_{cs(d)}|$, test the unitarity of CKM and search for NP.

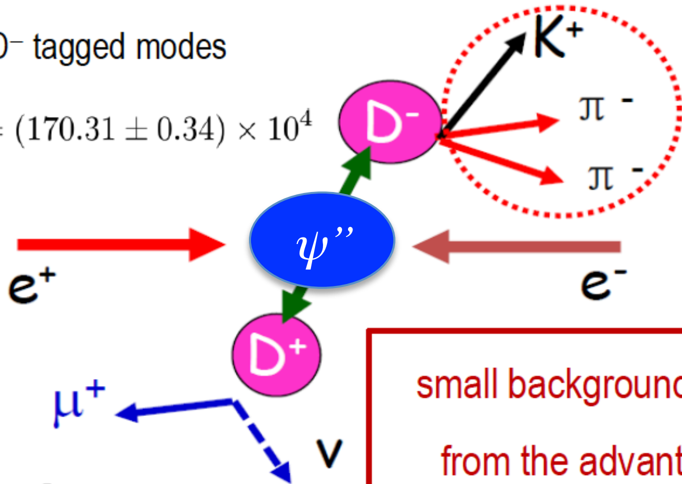
Measurement of $B[D^+ \to \mu^+\nu]$, f_{D+} and $|V_{cd}|$

$e^+e^- \to \psi'' \to D^+D^-$ (2.9fb^{-1})

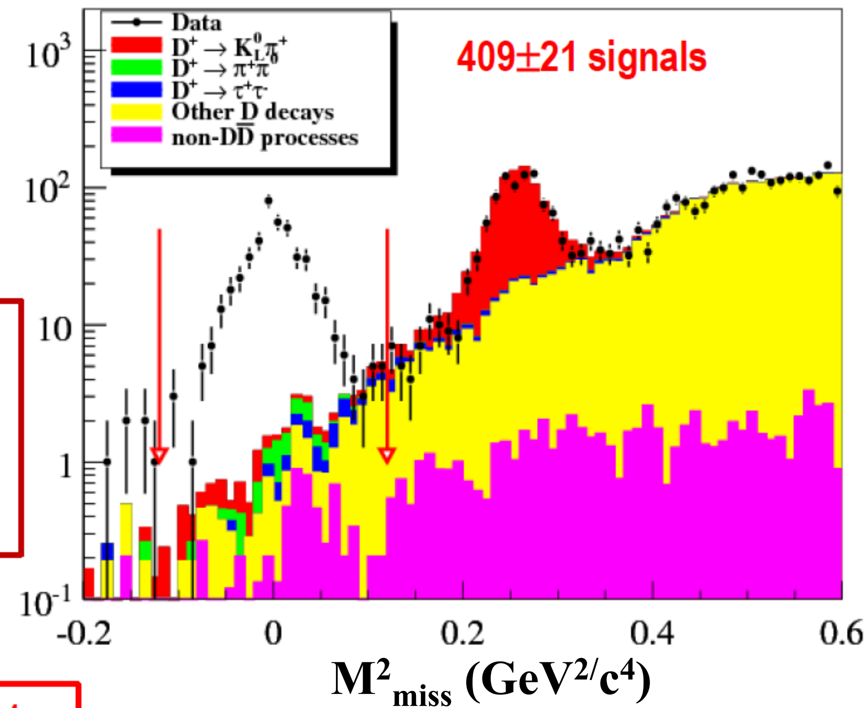
PRD 89, 051104 (2014)

9 D^- tagged modes

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



small background benefit from the advantage of threshold production



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

$|V_{cd}|$ of CKM-Fitter — Others from PDG — f_{D+} of LQCD

Most precise measurement, but statistical uncertainty dominant

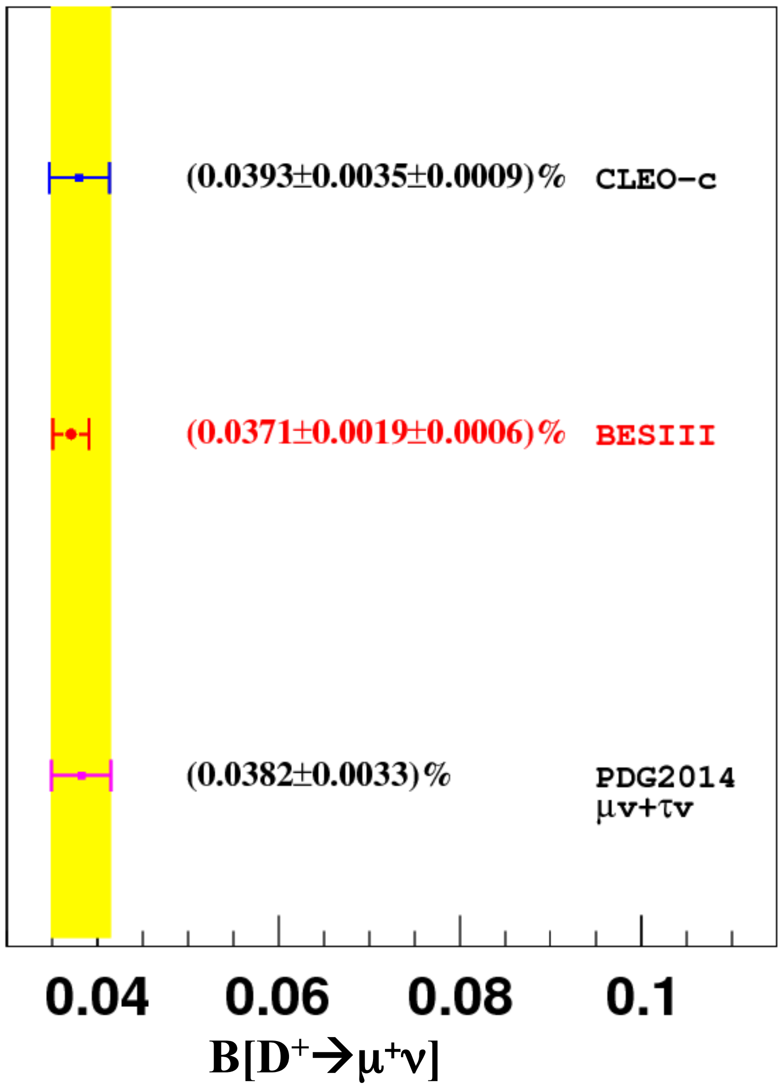
$f_{D+} = (203.2 \pm 5.3 \pm 1.8)$ MeV

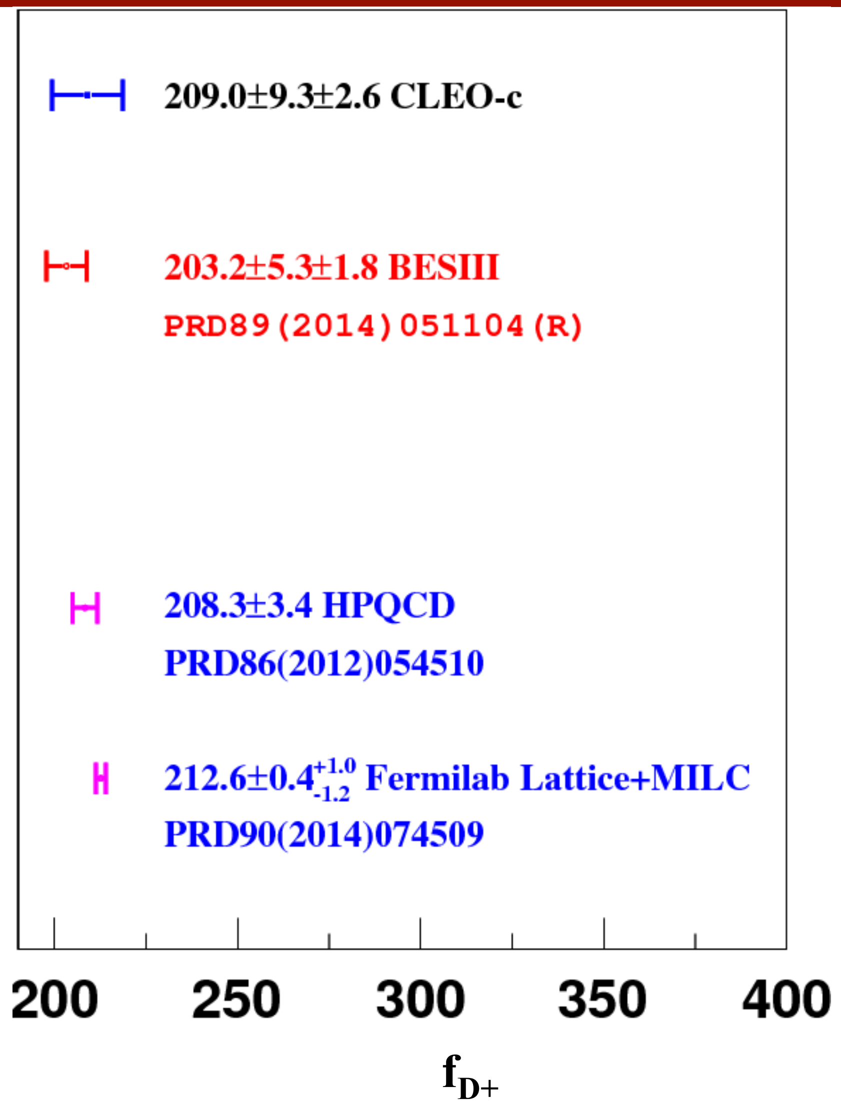
$|V_{cd}| = 0.2210 \pm 0.0058 \pm 0.0047$

208.3±3.4 HPQCD PRD86(2012)054510

$212.6 \pm 0.4^{+1.0}_{-1.2}$ Fermilab Lattice+MILC PRD90(2014)074509

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

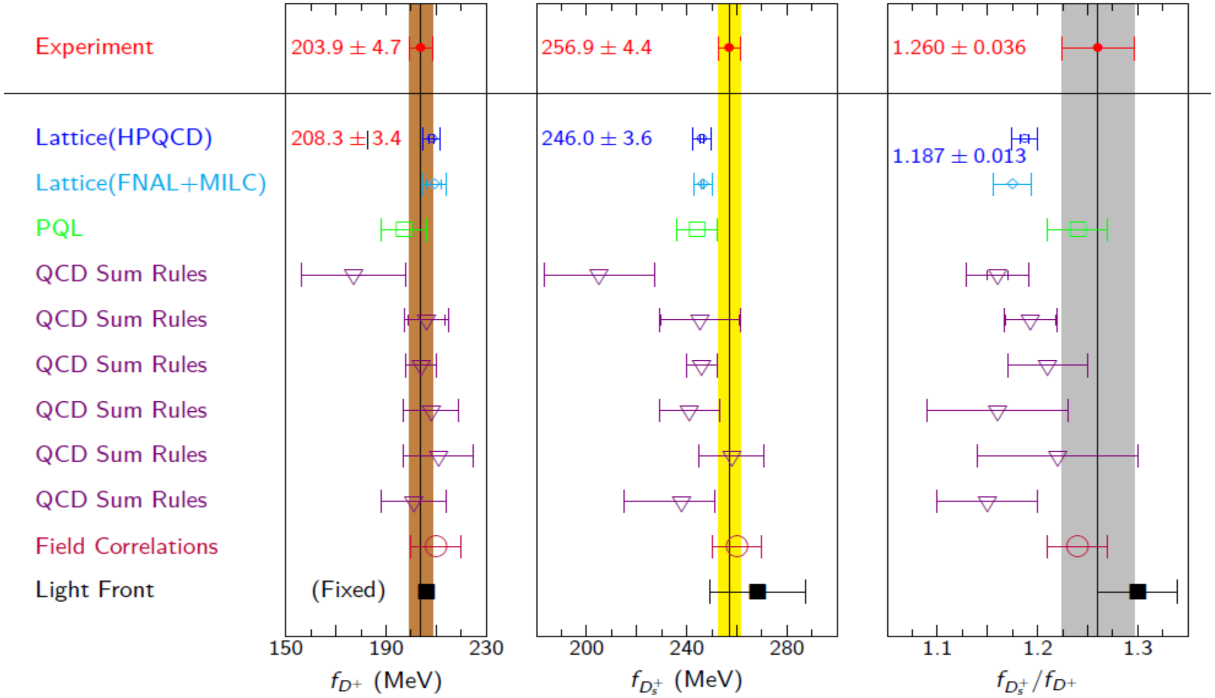




- BESIII achieves the best experimental precision
- Some tension between experiment results and LQCD calculations

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

The plots taken from Gang's talk at CMK2014



	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

- Precision of the LQCD calculation of f_{D+}, f_{DS+}, $f_{D+}:f_{DS+}$ reach ~0.5%
- The experiments have worse precision
- The experimental measured and the LQCD calculation different by ~2σ for $f_{D+}:f_{DS+}$
- Need to improve experimental measurements with larger data samples

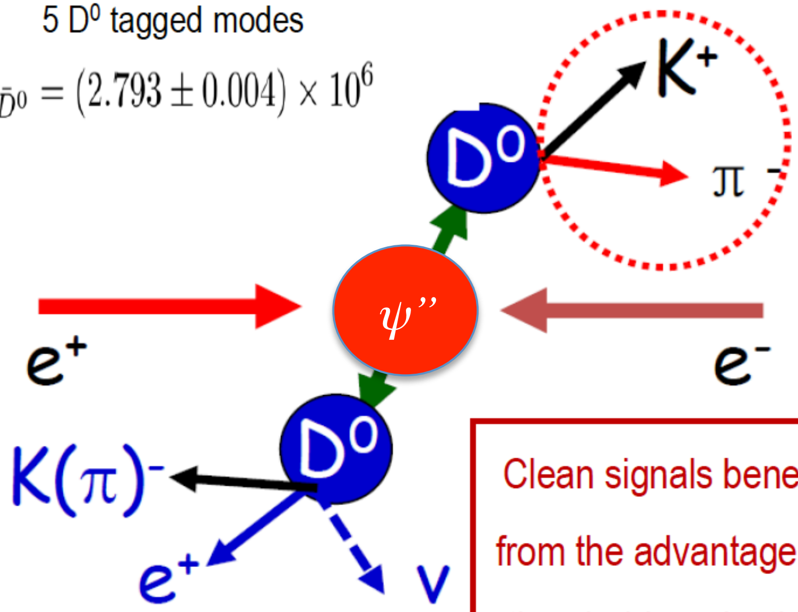
Measurement of B[D^+→K(π)eν]

$$e^+e^- \to \psi'' \to D^0\bar{D}^0$$

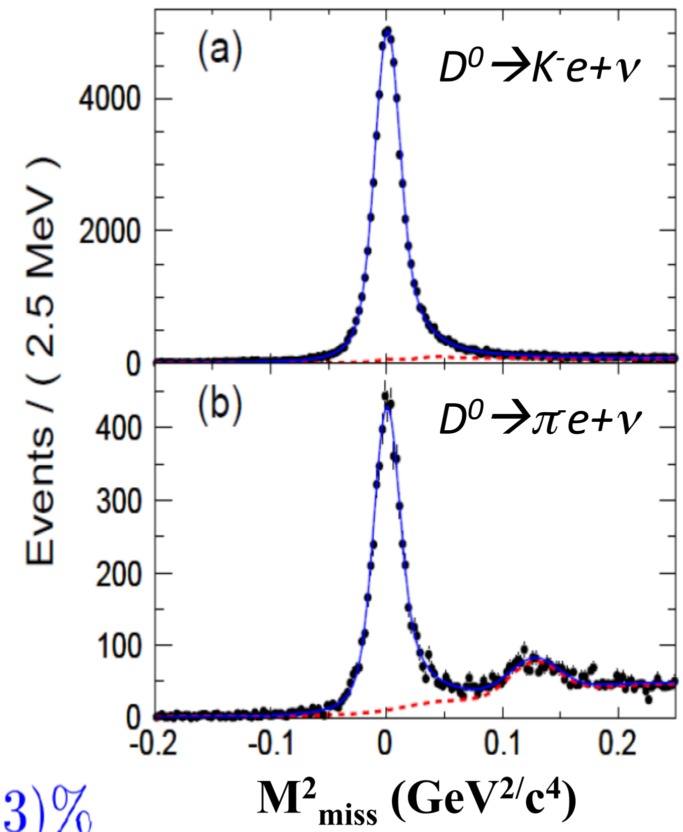
PRD 92, 072012 (2015)

5 D^0 tagged modes

$$N_{\bar{D}^0} = (2.793 \pm 0.004) \times 10^6$$



Clean signals benefit from the advantage of threshold production

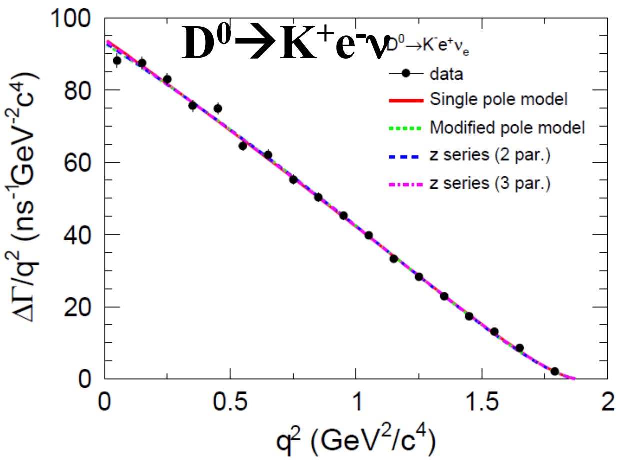


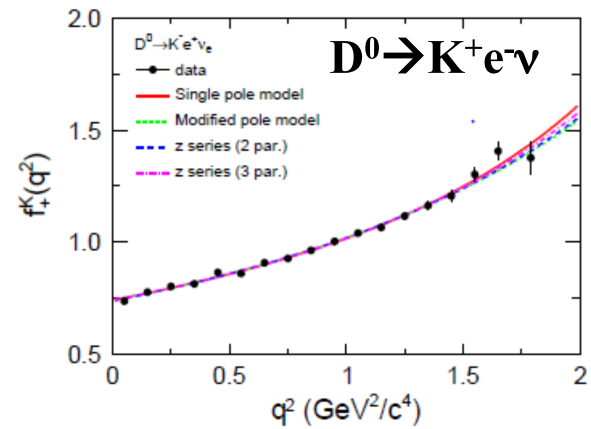
$$B(D^0 \to K^- e^+ \nu_e) = (3.505 \pm 0.014 \pm 0.033)\%$$

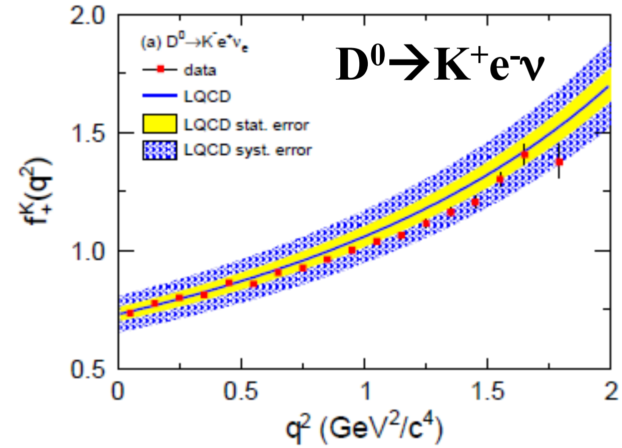
$$B(D^0 \to \pi^- e^+ \nu_e) = (0.295 \pm 0.004 \pm 0.003)\%$$

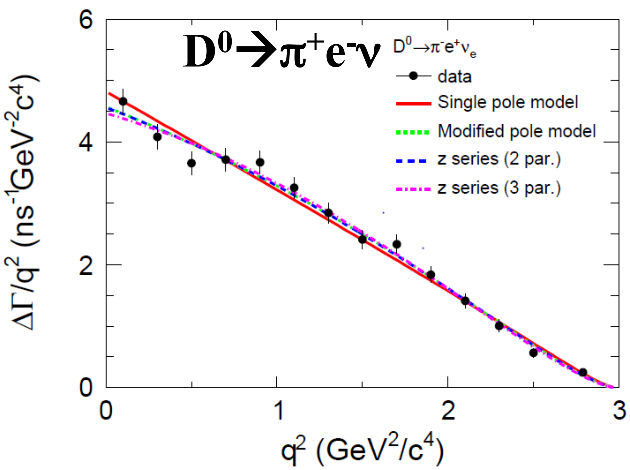
Most precise measurements

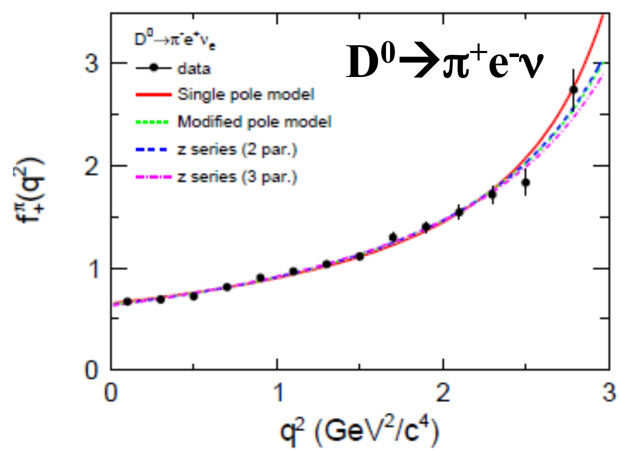
Measurement of $f_+^{K(\pi)}(q^2)$

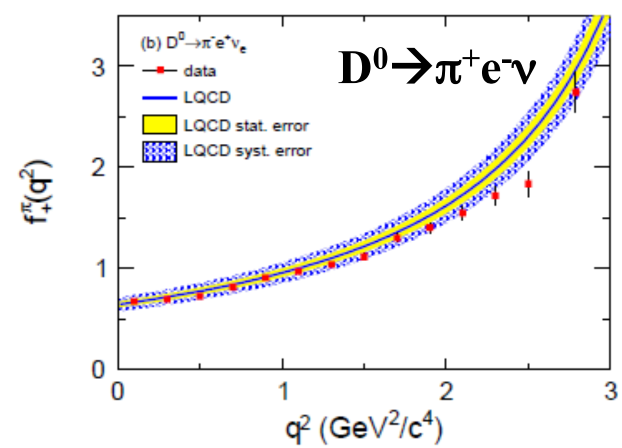










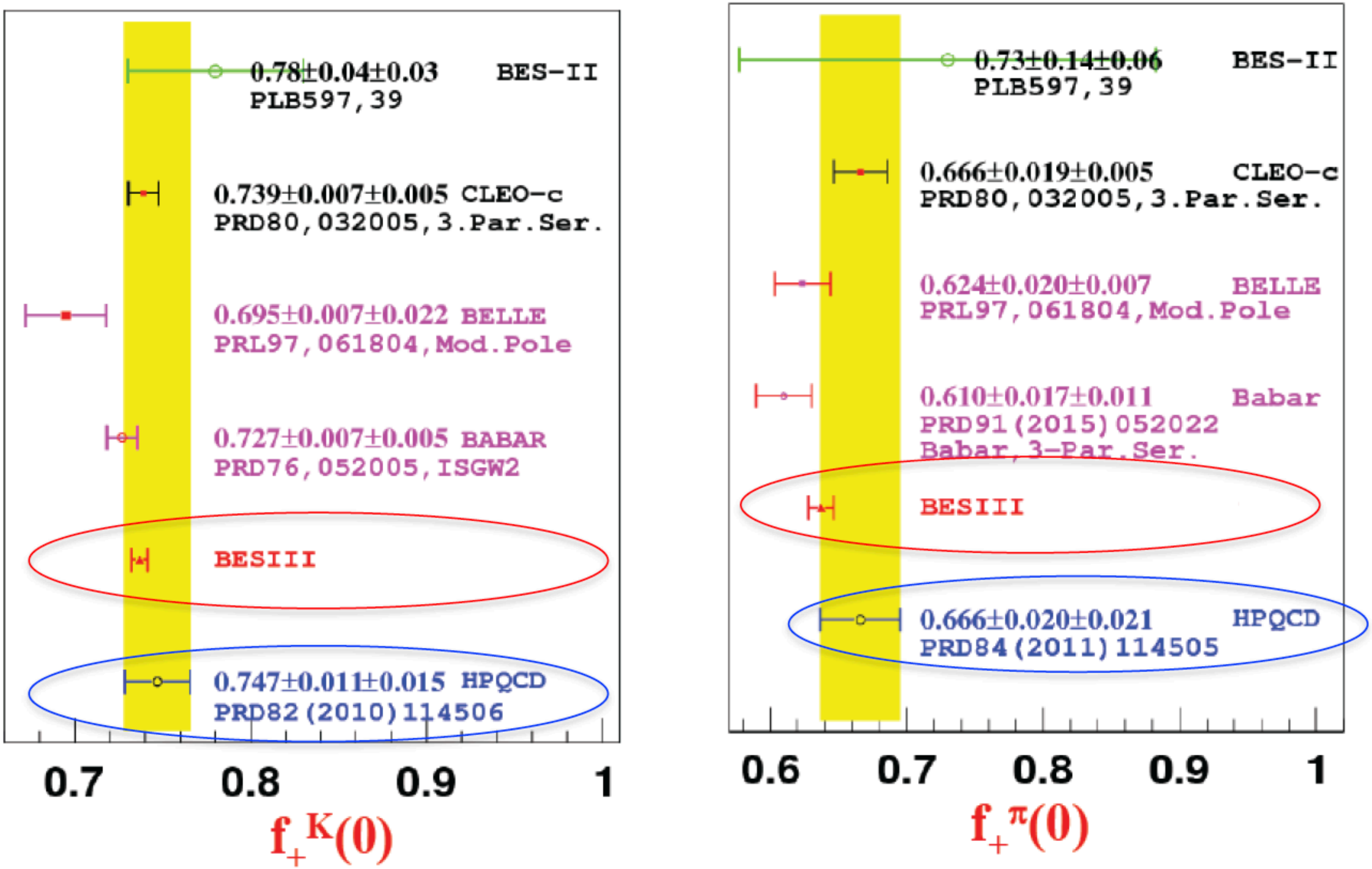


Fit yields vs. q^2 with different FF parameterization

Projection on FF with $|V_{cd(s)}|$ from CKMfiter

Comparisons of measured FF with LQCD predictions

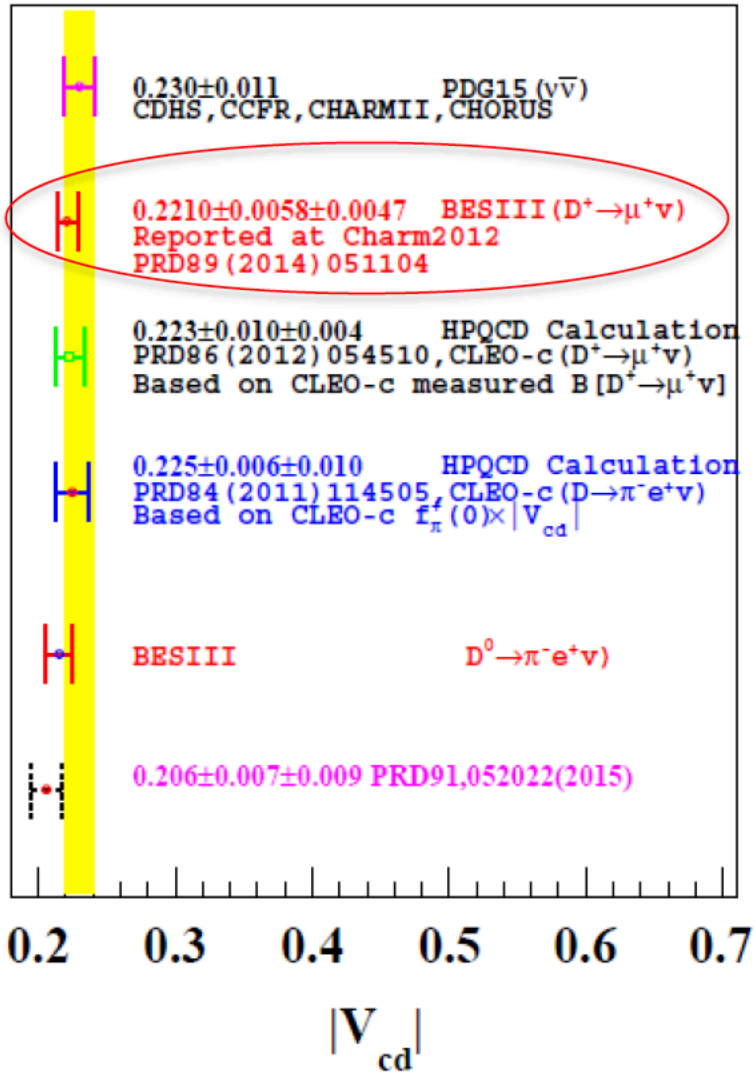
Comparisons of FF

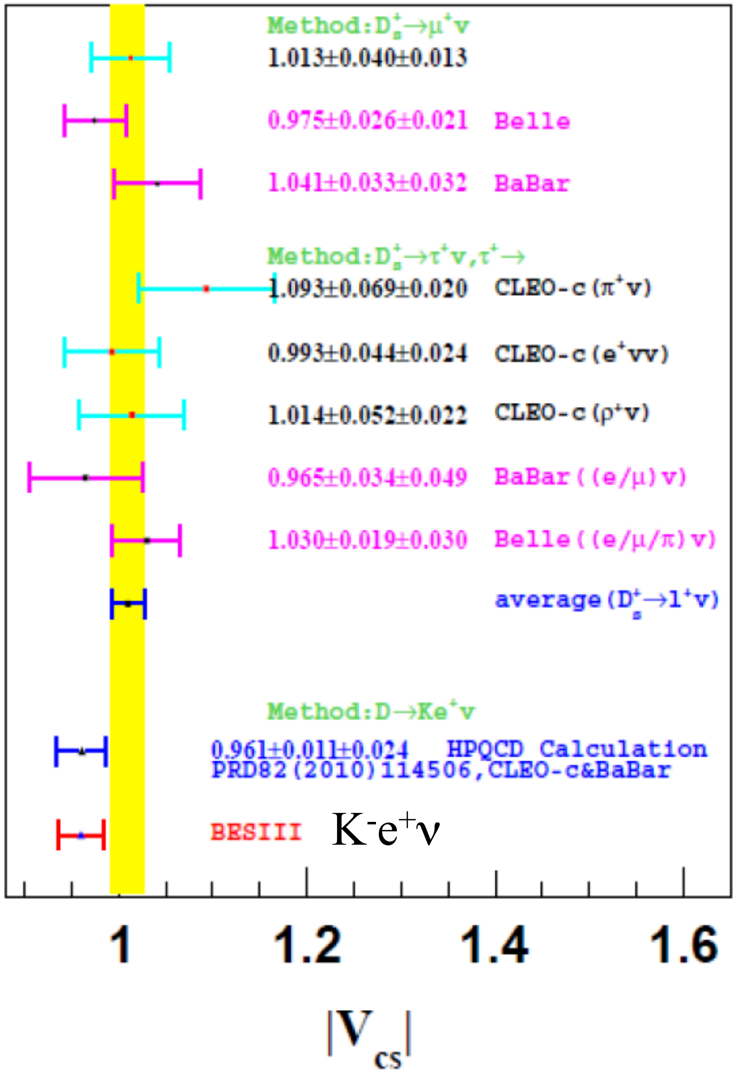


BESIII experiment achieved most precise measurement

The experimental accuracy is better than that of theoretical predictions

Extraction of $|V_{cd}|$ and $|V_{cs}|$





Fits to $d\Gamma[D^+ \rightarrow K^0(\pi^0)e^+v]$

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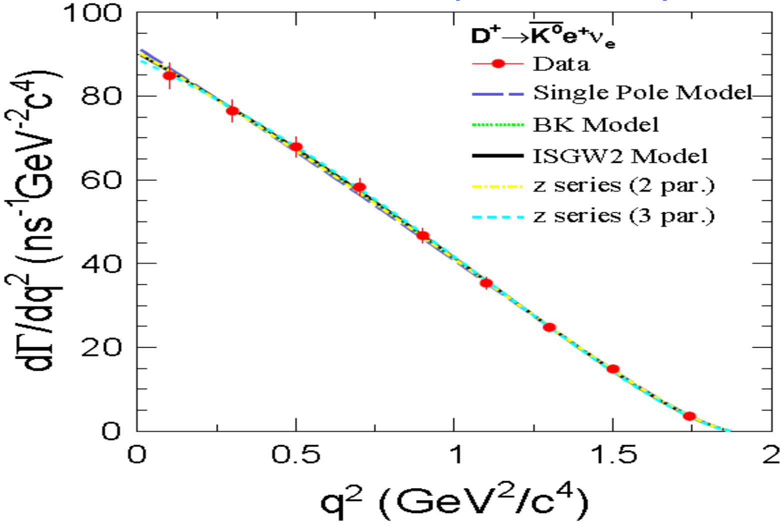
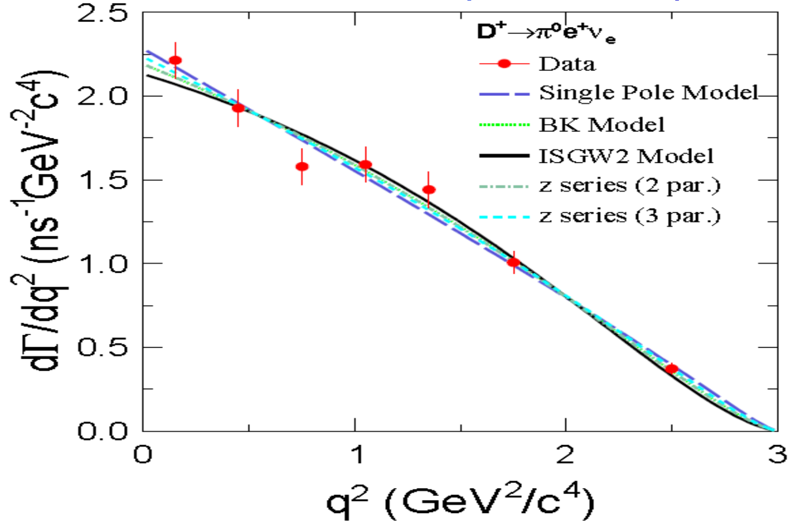
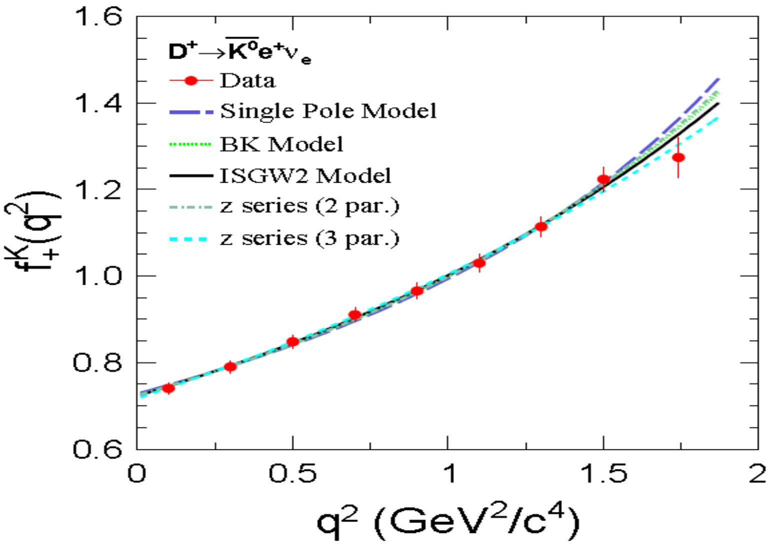
Fits to $\Delta\Gamma(D^+ \rightarrow \bar{K}^0 e^+ v)$



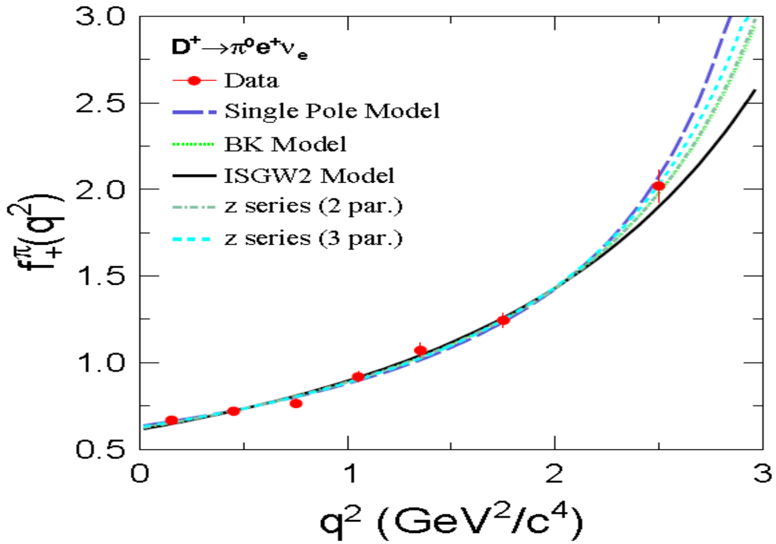
Fits to $\Delta\Gamma(D^+ \rightarrow \pi^0 e^+ v)$



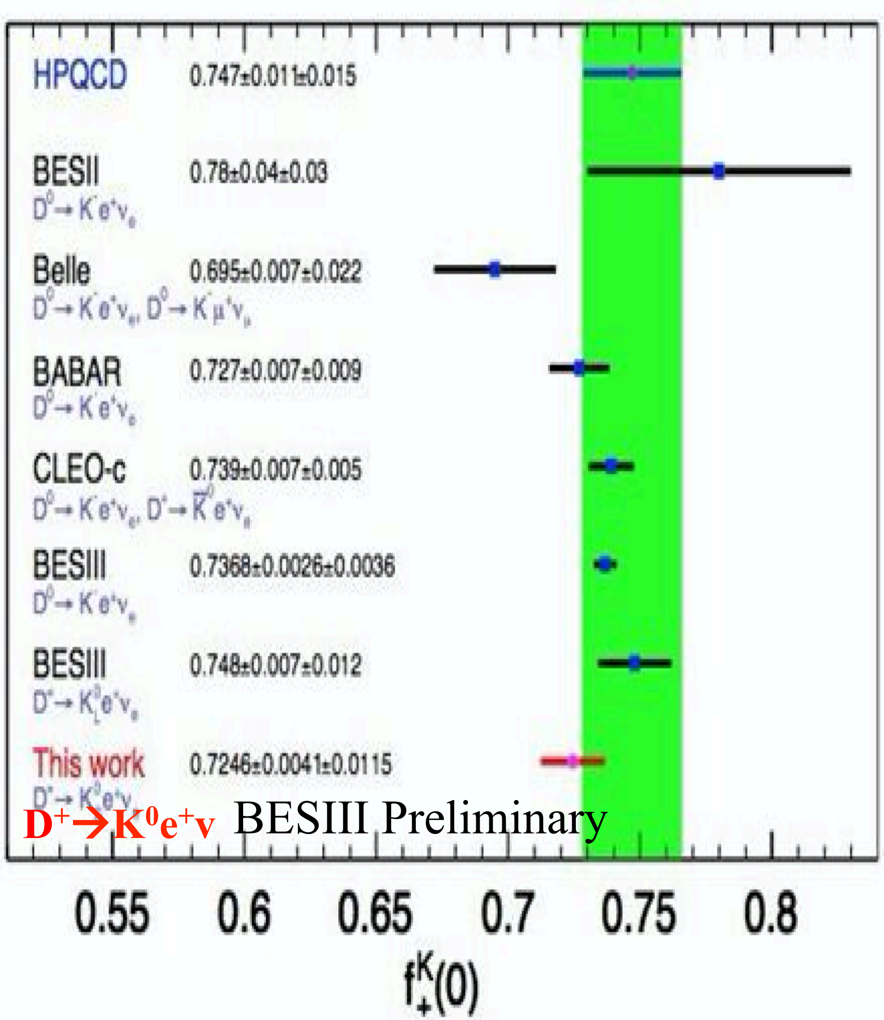
Projections to $f_+^K(q^2)$

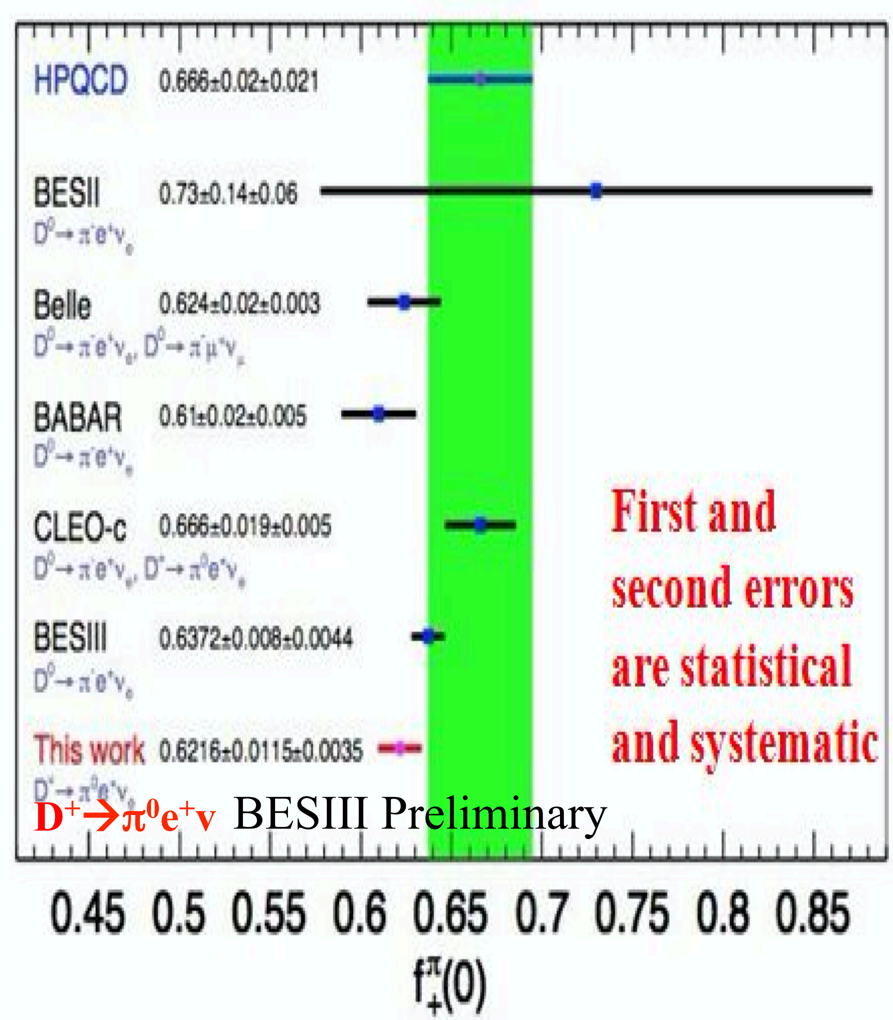


Projections to $f_+^\pi(q^2)$



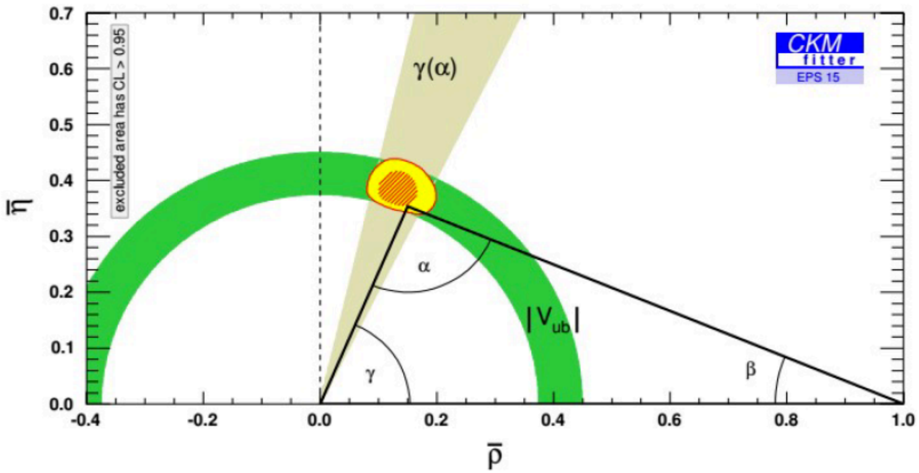
Comparisons of $f_+^{K(\pi)}(0)$



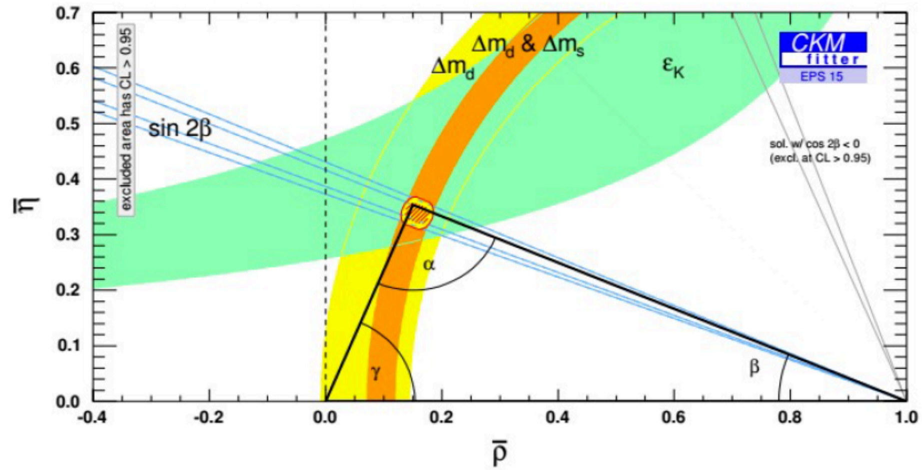


Current Status of the Measurement of the CKM Unitarity

Tree Measurements



Loop Measurements



Differences would imply new physics

$$\phi_1/\beta = \left(21.85^{+0.68}_{-0.67}\right)^\circ$$

$$\phi_2/\alpha = \left(87.6^{+3.5}_{-3.3}\right)^\circ$$

$$\phi_3/\gamma = \left(73.2^{+6.3}_{-7.0}\right)^\circ$$

2015 CKMfitter (Direct Measurements)

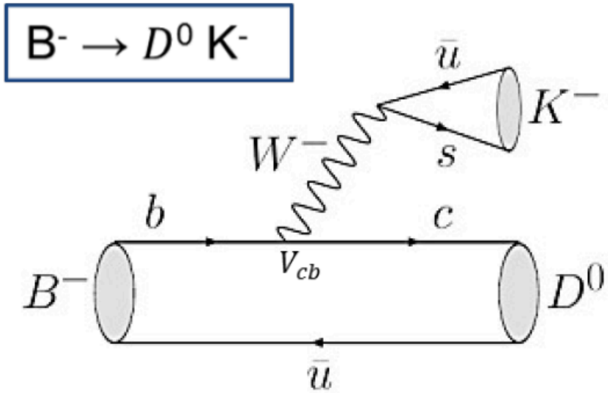
$$\phi_1/\beta = \left(22.62^{+0.44}_{-0.42}\right)^\circ$$

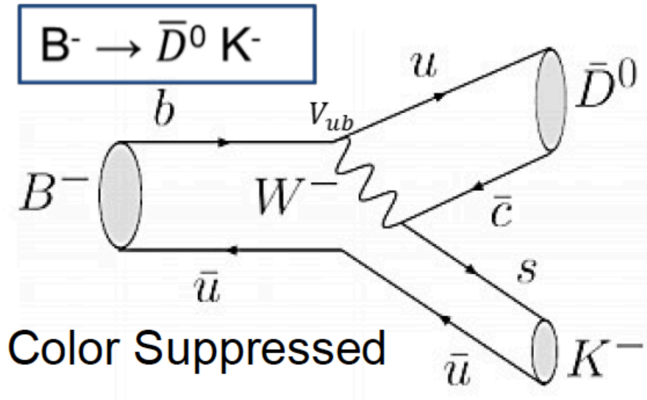
$$\phi_2/\alpha = \left(90.4^{+2.0}_{-1.0}\right)^\circ$$

$$\phi_3/\gamma = \left(67.01^{+0.88}_{-1.99}\right)^\circ$$

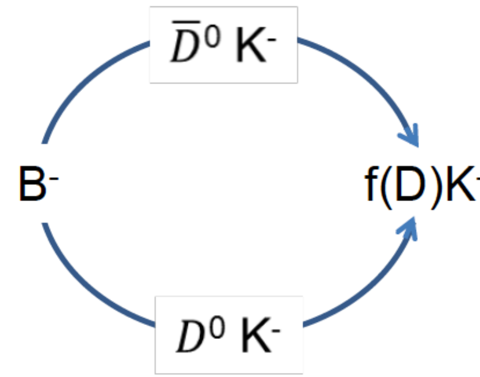
2015 CKMfitter (Global Fits)

Directly Measuring γ/ϕ_3 Through $B^-\rightarrow D^0(\overline{D}^0)K^-$





$$\frac{\langle B^- \rightarrow \overline{D^0} K^- \rangle}{\langle B^- \rightarrow D^0 K^- \rangle} = r_B e^{i(\delta_B - \phi_3)}$$



Determine ϕ_3 through the measurement of the interference between b →c and b →u transitions when D^0 and $\bar{D}^0$ both decay to the same final state f(D).

Total Decay Rate

$$\Gamma(B^- \rightarrow f(D^0)K^-) = A_B^2 A_f^2 (r_D^2 + r_B^2 + 2 r_D r_B \cos(\delta_B + \delta_D - \phi_3))$$

Status of Direct Measurement of γ/ϕ_3

Example of ϕ_3 measurements from GGSZ method

Belle Model-Dependent Dalitz [Phys. Rev. D 81, 112002 (2010)]

$$78.4^{+10.8}_{-11.6}(stat) \pm 3.6(syst) \pm 8.9(Model)$$

Belle Model-Independent Dalitz [Phys. Rev. D 85, 112014 (2012)]

$$77.3^{+15.1}_{-14.9}(stat) \pm 4.2(syst) \pm 4.3(c_i/s_i)$$

Strong phase from: CLEO-c, PRD 82 112006 (2010)

Currently statistically limited, but soon systematically limited

Combine methods measurement

$$\phi_3 = \begin{cases} \left(69^{+17}_{-16}\right)^\circ \; BABAR(2013) \\ \left(68^{+15}_{-14}\right)^\circ \; Belle(2013) \\ \left(70.9^{+7.1}_{-8.5}\right)^o \; LHCb\,(2016) \end{cases}$$

γ/ϕ_3 Fit Through GGSZ Method

Due to both amplitude and having only charged tracks, $K_s\pi^+\pi^-$ is the preferred final state for this method.

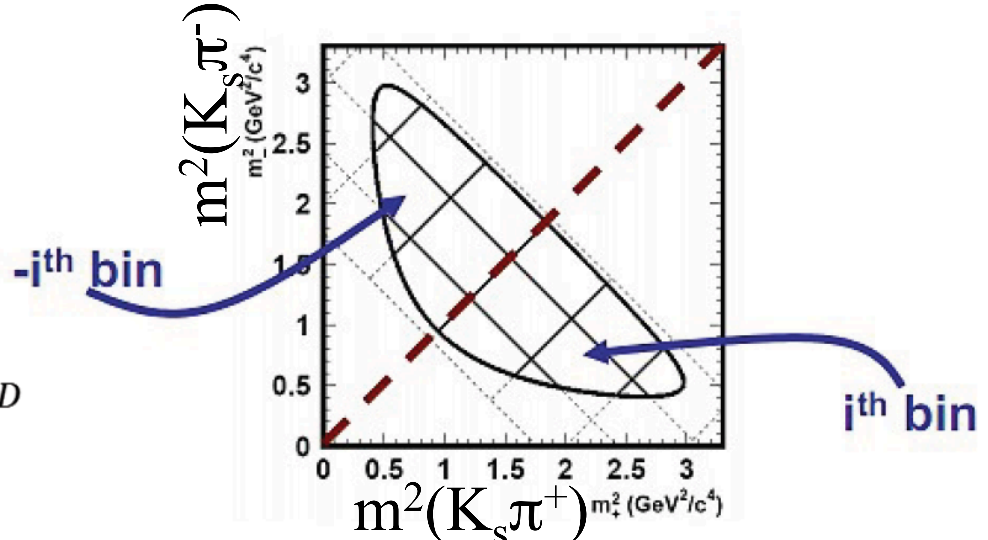
Distribution sensitive to variables:

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

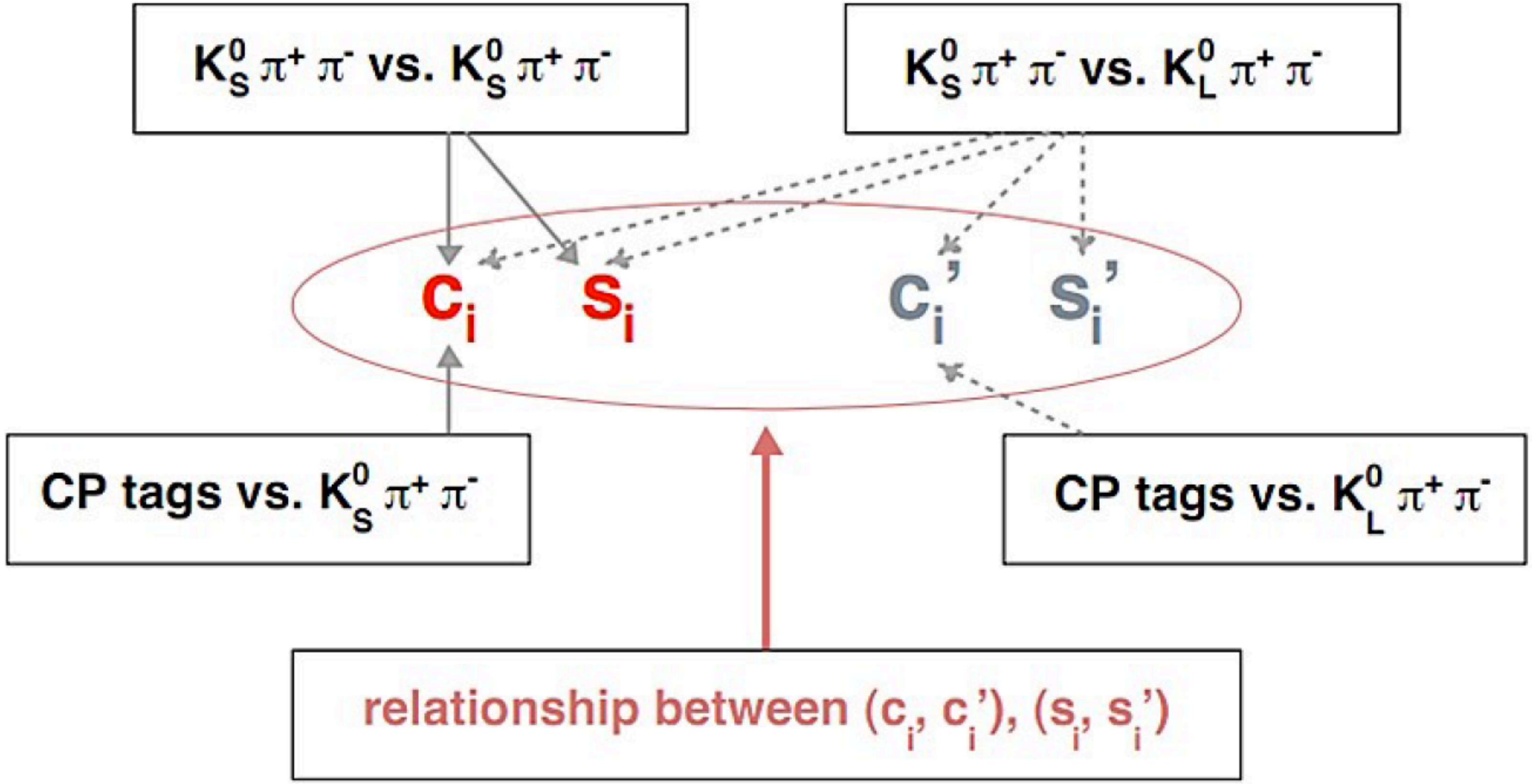
c_i and s_i can be found through $K_s\pi^+\pi^-$ Analysis at BESIII

Binned decay rate:

$$\Gamma(B^\pm \to D(K_s\pi^+\pi^-)K^\pm)_i = T_i + r_B^2 T_{-i} + 2r_B\sqrt{T_i T_{-i}}\cos(\delta_B \pm \phi_3 - \Delta\delta_D)$$

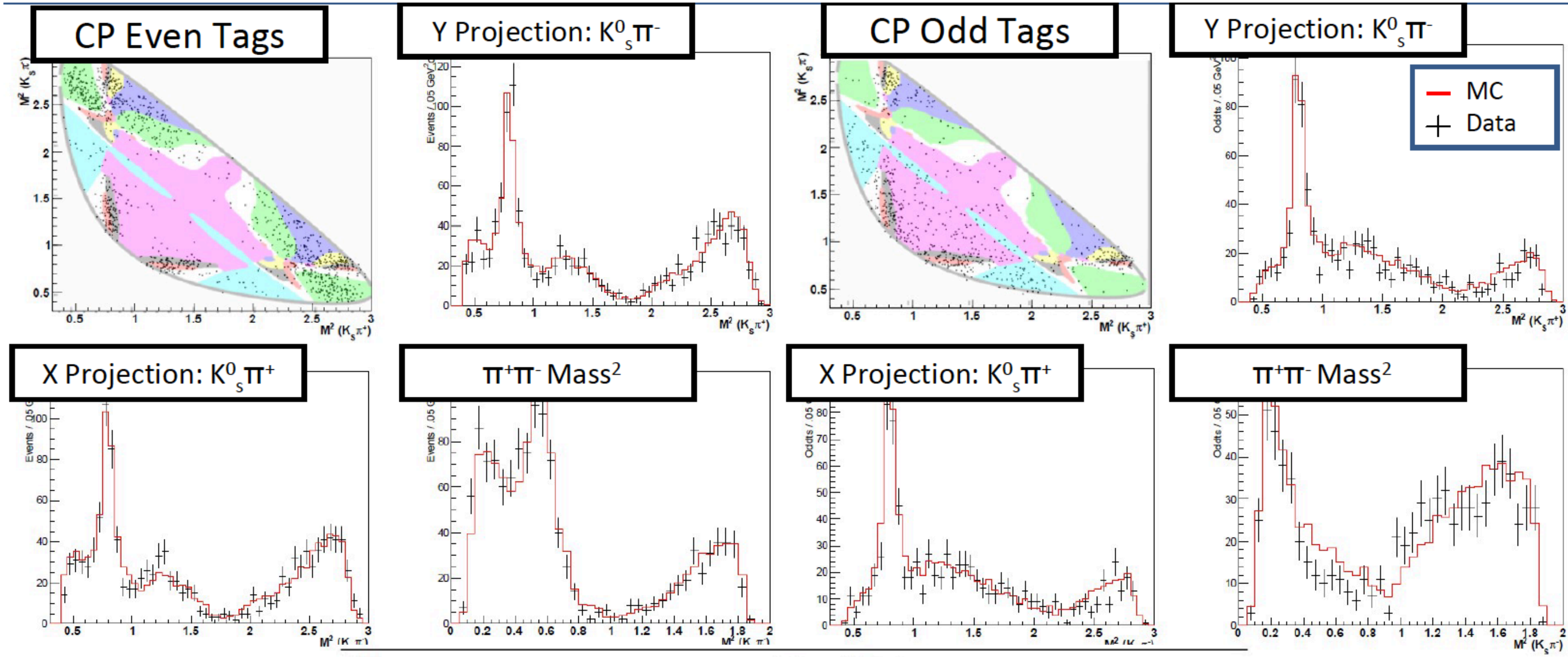
$$= T_i + r_B^2 T_{-i} + 2r_B\sqrt{T_i T_{-i}}\{c_i\cos(\delta_B \pm \phi_3) + s_i\sin(\delta_B \pm \phi_3)\}$$

Constraining c_i and s_i



Only c_i, s_i from $K_s\pi^+\pi^-$ is used to calculate ϕ_3.
However adding in $D^0 \rightarrow K_L\pi^+\pi^-$ we can calculate c'_i, s'_i and use how they relate to c_i, s_i to further constrain our results in a Global fit.

$K_s^0\pi^+\pi^-$ Dalitz Plots vs. CP Modes



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

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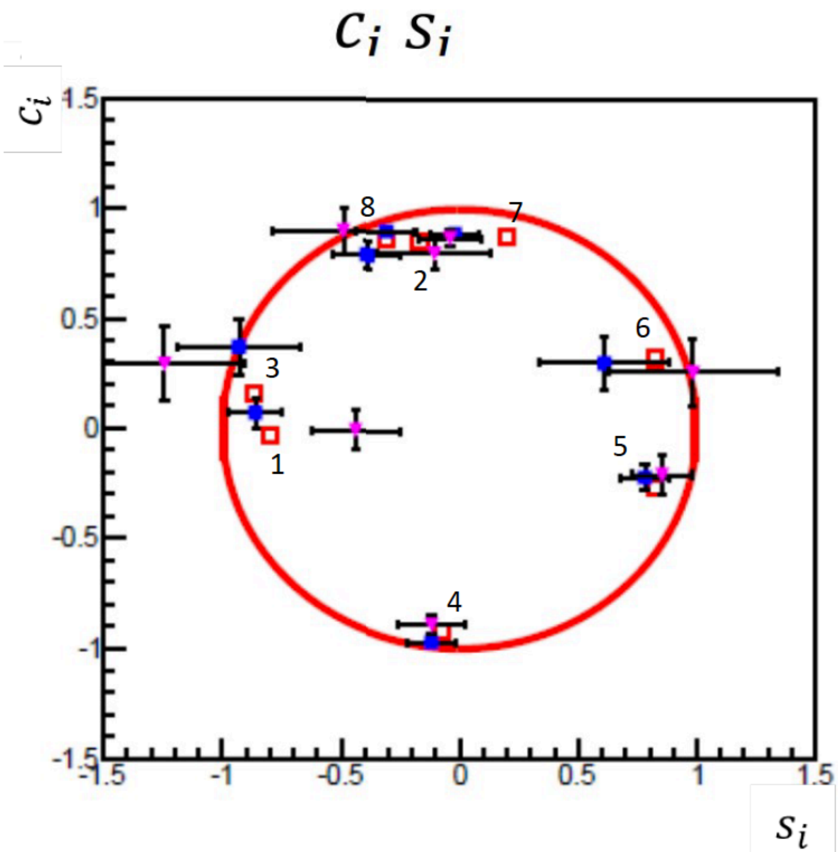
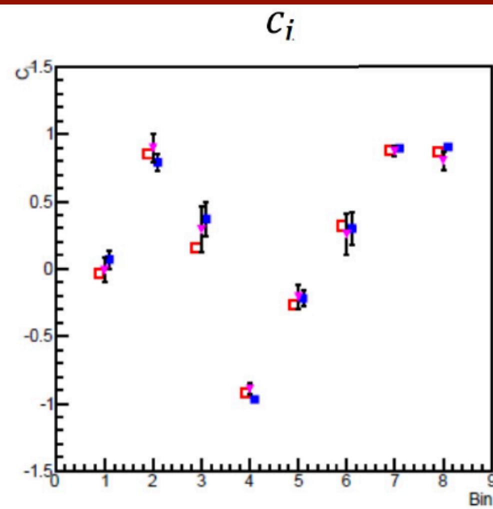
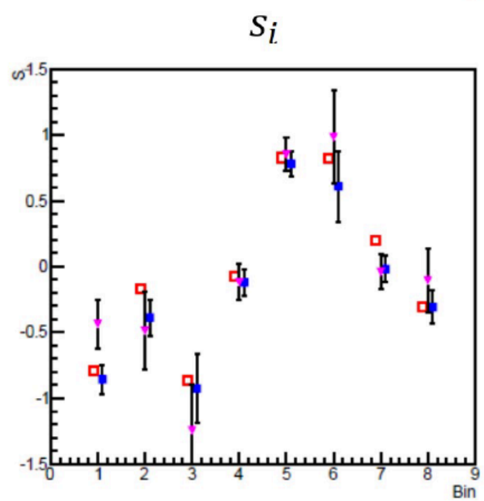
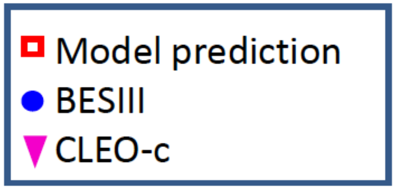
- Data is using the full 2.9 fb^{-1} $\psi(3770)$ dataset
- Results presented here will be using Optimal Binning scheme.

Comparison to Model/Previous Measurement









Comparison	χ^2/DOF	Probability
CLEO-c	9.57/16	88%
Model	26.9/16	4.3%

Estimate from Toy MC suggests BESIII achieves 55% of CLEO-c [PRD, 82 112006 (2010)] uncertainty

BESIII Preliminary

Belle Model-Independent Dalitz [Phys. Rev. D 85, 112014 (2012)]

$$\gamma/\phi_3 = 77.3^{+15.1}_{-14.9}(stat) \pm 4.2(syst) \pm 4.3(c_i/s_i)$$

Reduce to 2.2

Summary

- With 2.93 fb^{-1} data taken at 3.773 GeV BESIII has measured
  - Precise *D* decay constant and form factors in (semi-)leptonic *D* decays
  - Accurate CKM element $|V_{cs(d)}|$, and *D* strong phase parameters for γ/ϕ_3 determination
- 3 fb^{-1} data at 4.18 GeV is being taken in 2016, will perform CKM measurements with D_s decays.

Backup

Equation for $K_s^0\pi^+\pi^-$ Dalitz Plots vs. CP Modes

For the CP tag modes, one can show that the total bin yields are related to c_i by

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

$M_i^+(M_i^-)$ 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.

Single Tag modes

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^-	$K_S\pi^0$, $K_S\eta(\to\gamma\gamma)$, $K_S\eta(\to\pi^+\pi^-\pi^0)$, $K_S\omega$, $K_S\eta'$

Equation for $K_s^0\pi^+\pi^-$ vs. $K_s^0\pi^+\pi^-$

Using $D^0 \to K_s\pi^+\pi^-$ vs $\overline{D}^0 \to K_s\pi^+\pi^-$ we can calculate both c_i and s_i:

$$M_{i,j} = \frac{N_{D,\overline{D}}}{2S_f^2}\left(K_iK_{-j} + K_{-i}K_j - 2\sqrt{K_iK_{-j}K_{-i}K_j}\left(c_ic_j + s_is_j\right)\right)$$

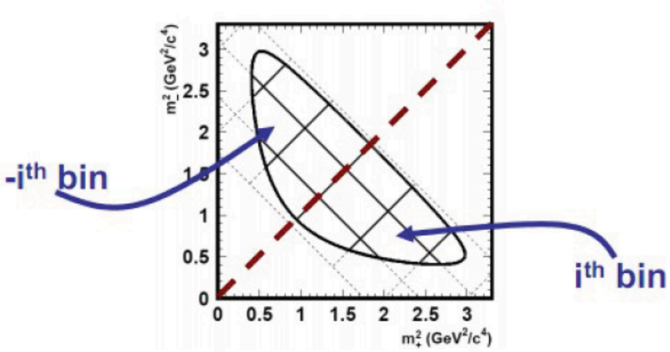
$M_{i,j}$ yields in bin i of first Dalitz plot and bin j of second Dalitz plot.
S_f number of single tags for flavor modes.
$N_{D,\overline{D}}$ total number of $D^0\overline{D}^0$ events.
$K_i(K_{-i})$, yields in each bin of Dalitz plot in flavor modes.

Mirroring the bins over the x=y line in the Dalitz plot, we note the following points:

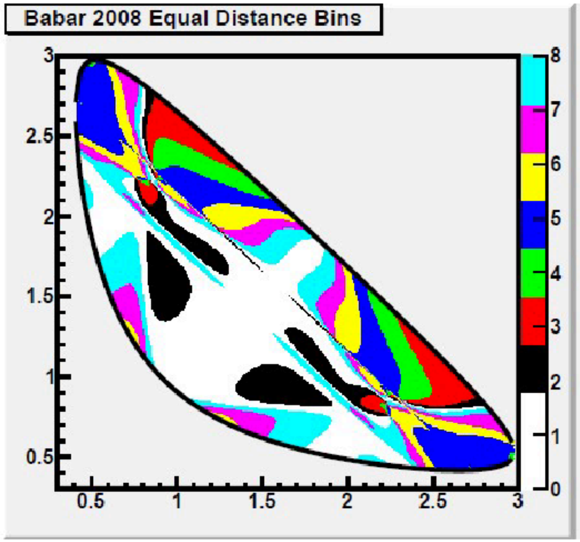
- $M_{i,j} = M_{-i,-j}$
- $M_{i,-j} = M_{-i,j}$
- $M_{i,j} \neq M_{-i,j}$

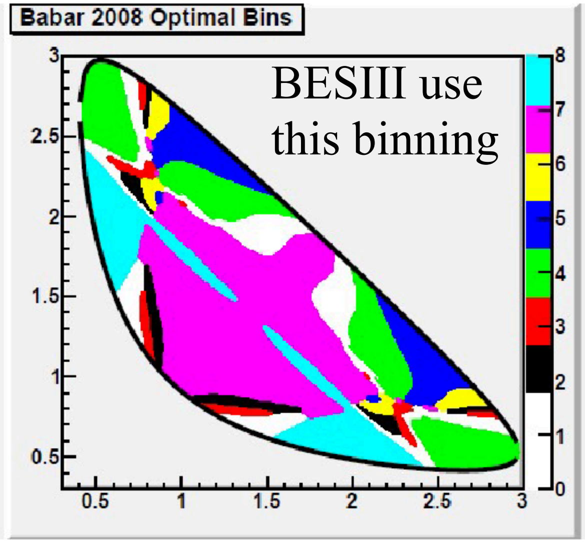
Symmetric Matrix because the order which tag is i or j

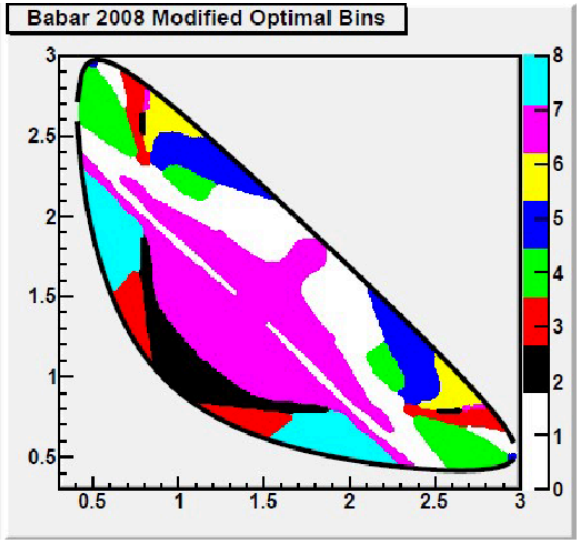
- $M_{i,j} = M_{j,i}$



Binning of Dalitz Plot







Result of splitting the Dalitz phase space into 8 equally spaced phase bins based on the BaBar 2008 Model.

Starting with the equally spaced bins, bins are adjusted to optimize the sensitivity to ϕ_3. A secondary adjustment smooths binned areas smaller than detector resolution.

Similar to the "optimal binning" except the expected background is taken into account before optimizing for ϕ_3 sensitivity.

Source: CLEO Collaboration, Physical Review D, vol 82., pp. 112006 - 112035

Likelihood of the Fit for c_i and s_i

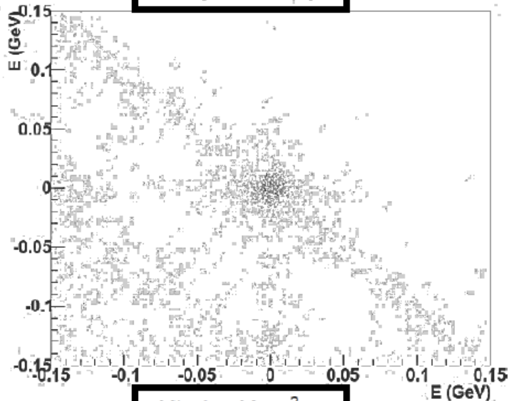
The total fit maximizes the likelihood of

$$
\begin{aligned}
-2\log\mathcal{L} = & -2\sum_i \log P(M_i^{\pm}, < M_i^{\pm} >)_{(CP, K_S^0\pi^+\pi^-)} \\
& -2\sum_i \log P(M_i'^{\pm}, < M_i'^{\pm} >)_{(CP, K_L^0\pi^+\pi^-)} \\
& -2\sum_{i,j} \log P(M_{i,j}^{\pm}, < M_{i,j}^{\pm} >)_{(K_S^0\pi^+\pi^-, K_S^0\pi^+\pi^-)} \\
& -2\sum_{i,j} \log P(M_{i,j}'^{\pm}, < M_{i,}'^{\pm} >)_{(K_S^0\pi^+\pi^-, K_L^0\pi^+\pi^-)} \\
& \cdot \quad \cdot \quad \cdot \quad \cdot
\end{aligned}
$$

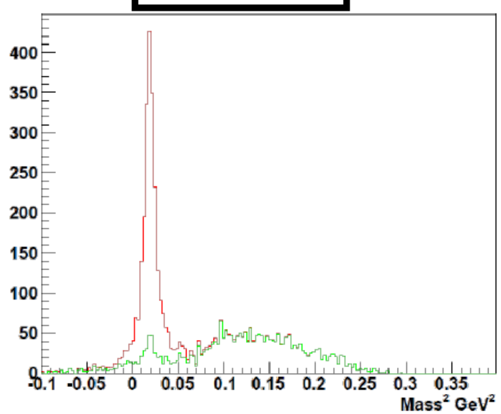
P is Poisson probability of finding M events with the expected number <M>

$K_s^0\pi^+\pi^-$ vs. $K_s^0\pi^+\pi^-$

ΔE $K_S\pi^+\pi^-$ vs. $K_S\pi^+\pi^-$

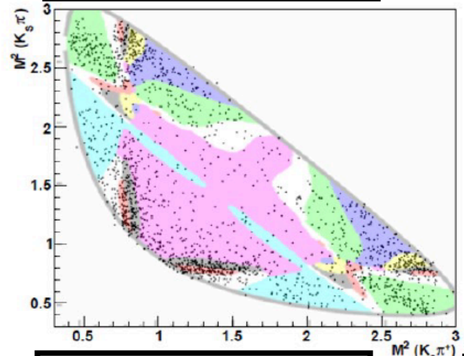


Missing Mass^2 π

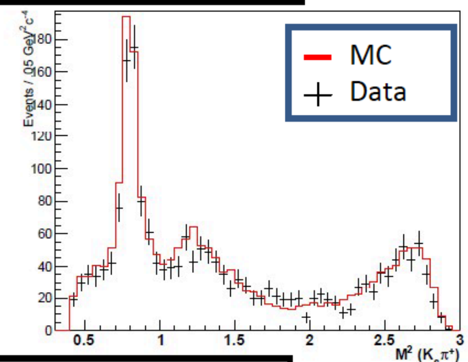


BESIII
Preliminary

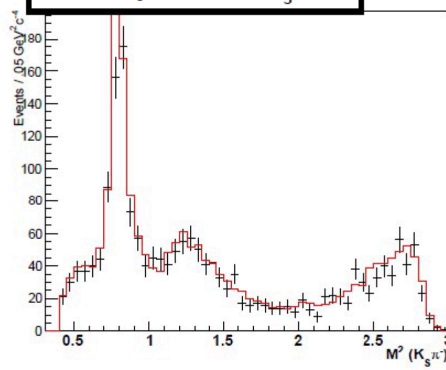
$K^0_s\pi^+\pi^-$ Tags



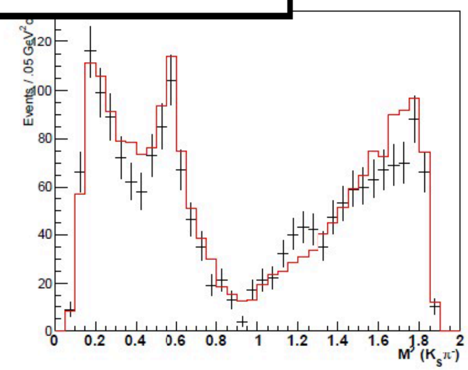
Y Projection: $K^0_s\pi^-$



X Projection: $K^0_s\pi^+$

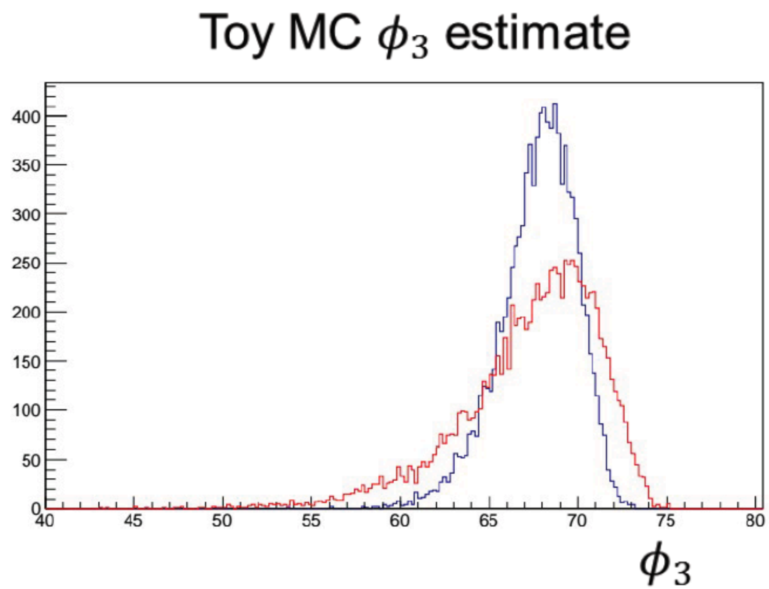


$\pi^+\pi^-$ Mass^2



- This is the most statistically limited part of the analysis.
- Further increase statistics by reconstructing a missing π.

Impact on γ/ϕ_3



BESIII :	RMS 2.165
CLEO-c :	RMS 3.927

Toy MC estimates the effects on ϕ_3 by letting c_i, s_i vary by a Gaussian of their given uncertainty.

Width of variation due to BESIII uncertainty is 55% the previous measurement.

We are still statistically limited with 3 fb^{-1}.
Future measurements with 10 fb^{-1} and 20 fb^{-1} reduce the uncertainty to 33% and 27% the CLEO-c measurement, respectively.