Short update from Valencia: Charm Physics

SuperB Meeting
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Proceedings
of
Super$B$ Workshop VI

New Physics
at the
Super Flavor Factory

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Charm Physics

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Charm physics: Mixing and CPV

Prologue: New Physics Scenarios & Uniqueness of Charm

I. Bigi

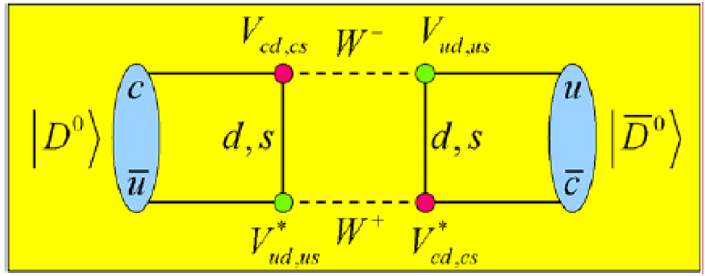
- New Physics in general induces FCNC
  - their couplings could be substantially stronger for Up-type than for Down-type quarks

(actually happens in some models which `brush the dirt of FCNC in the down-type sector under rug of the up-type sector)

- SM `background' much smaller for FCNC of *Up*-type quarks
  - ➥ cleaner -- albeit smaller -- signal!

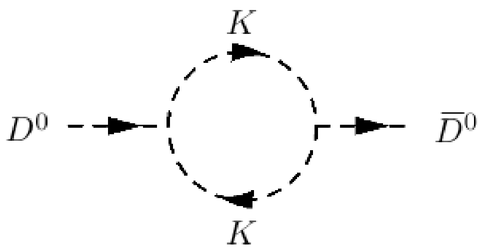
D^0-$\overline{D}^0$ mixing, CPV, and the SM

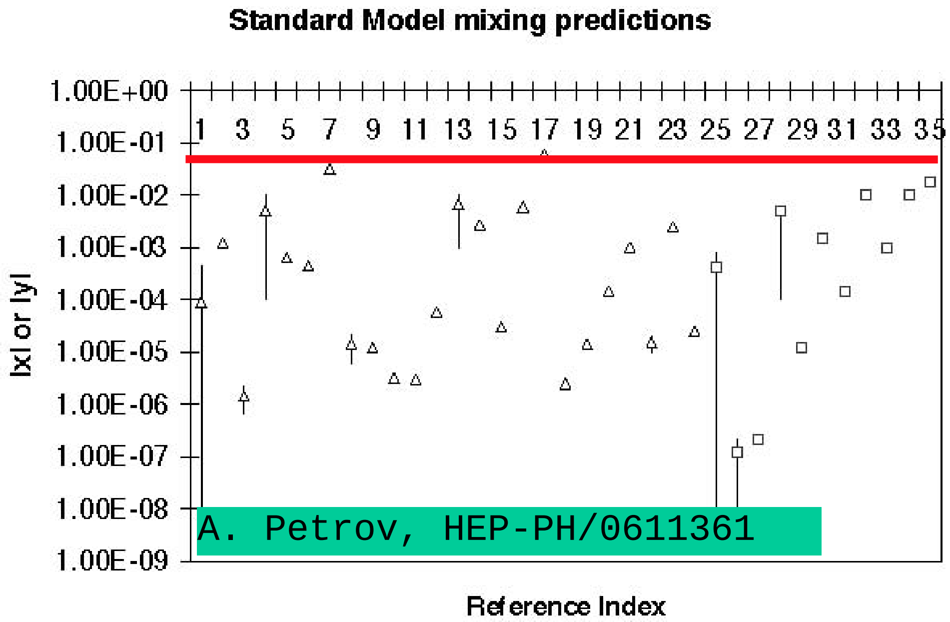
- Short-distance contributions from mixing box diagrams in the Standard Model are expected to be small :
  - *b* quark is CKM-suppressed
  - *s* and *d* quarks are GIM suppressed
  - mainly contributes to the mass difference $x \approx O(10^{-5})$ or less



$$x = \frac{m_2 - m_1}{\Gamma} \qquad y = \frac{\Gamma_2 - \Gamma_1}{2\Gamma} \qquad \Gamma = \frac{\Gamma_2 + \Gamma_1}{2}$$

- Long-distance contributions dominate but hard to estimate precisely
  - expect $|y| \leq 0.01$
  - $|x| \sim 0.1 - 1|y|$





- CP violation in mixing expected in SM at 10^{-5} [10^{-4}] level in Cabibbo-allowed and single [doubly]-suppressed modes

D^0-$\bar{D}^0$ mixing

$\mathcal{R}$, time-dependent decay rate

Wrong sign hadronic: $D^0 \to K^+\pi^-$

$$\mathcal{R} = e^{-\Gamma t}\left\{r_D + \sqrt{r_D}y't + \frac{x'^2+y'^2}{4}t^2\right\}$$

$$\begin{pmatrix} x' \\ y' \end{pmatrix} = \begin{pmatrix} \cos\delta & \sin\delta \\ -\sin\delta & \cos\delta \end{pmatrix}\begin{pmatrix} x \\ y \end{pmatrix}$$

Wrong sign semileptonic: $D^0 \to K^+ l^- \nu$

$$\mathcal{R} = e^{-\Gamma t}\{1 + R_M t^2\}, \qquad R_M \equiv \frac{x^2+y^2}{2}$$

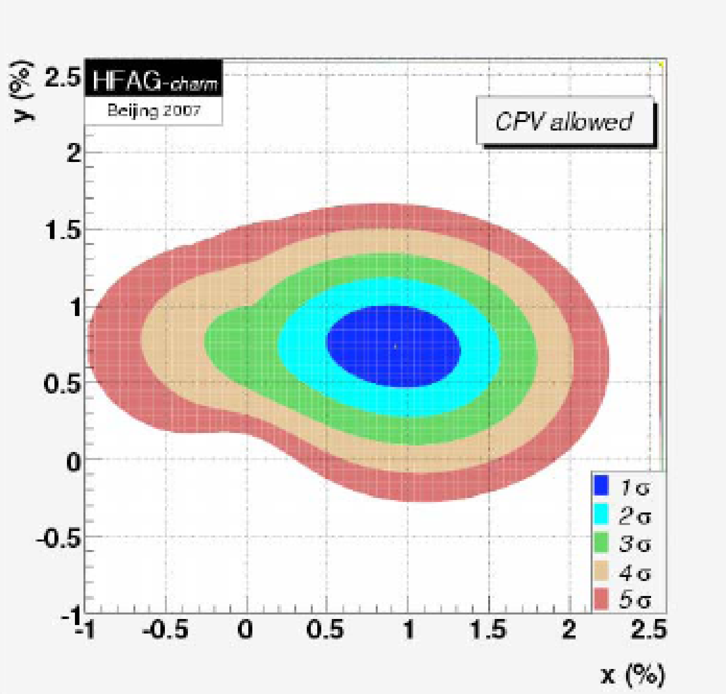
$$R_M = (0.004^{+0.07}_{-0.06})\%$$

CP eigenstates: $D^0 \to h^+h^-$

$$\mathcal{R} \simeq e^{-\Gamma(1+y_{CP})t}$$

$$y_{CP} = y\cos\phi \simeq \frac{\tau_{K^-\pi^+}}{\tau_{h^+h^-}} - 1$$

$$y_{CP} = (1.31 \pm 0.32 \pm 0.25)\%$$



Dalitz technique $D^0 \to K_S h^+ h^-$

$$\mathcal{R} = e^{-\Gamma(1+y)t}|A_1|^2 + e^{-\Gamma(1-y)t}|A_2|^2 + 2e^{-\Gamma t}(\cos(\Gamma x t)\Re(A_1 A_2^*) + \sin(\Gamma x t)\Im(A_1 A_2^*))$$

Dalitz technique is the only able to measure directly x,y, with sign and w/o rotations

Basic measurement of the strong phase@Ψ(3770)

$e^+e^- \to \psi(3770) \to D^0\bar{D}^0 \to f_1 f_2$ $CP(f_1 f_2)=CP(f_1)CP(f_2)(-1)^{l=1}=CP+$

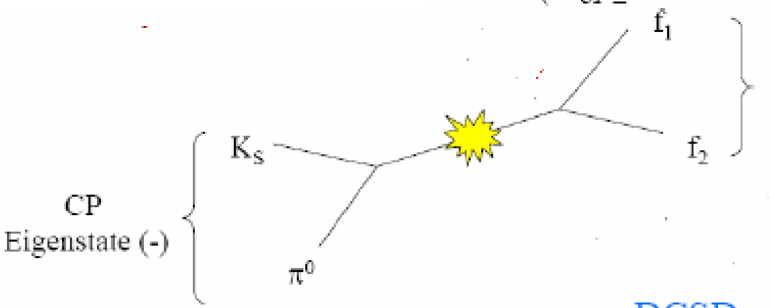
$J^{PC}=1^{--}$ Two final states of opposite CP

· If CP violation in charm is neglected: mass eigenstates = CP eigenstates

$$|D_{CP\pm}\rangle = \frac{1}{\sqrt{2}}\left[|D^0\rangle \pm |\bar{D}^0\rangle\right]$$

$$\sqrt{2}\,A(D_{CP\pm} \to K^-\pi^+) = A(D^0 \to K^-\pi^+) \pm A(\overline{D^0} \to K^-\pi^+)$$

CF   DCSD



Flavor mode

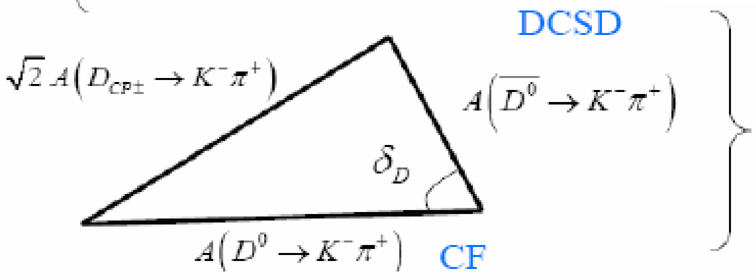
$$D_{CP(+)} \to f_1 f_2$$

CP eigenstate tag X flavor mode

$K^+K^- \leftarrow D_{CP} \leftarrow \psi(3770) \to D_{CP} \to K^-\pi^+\ (-1)^l$

+   -

= CP+



$$\cos\delta_D = \frac{Br(D_{CP+} \to K^-\pi^+) - Br(D_{CP-} \to K^-\pi^+)}{2\sqrt{r_D}\,Br(D^0 \to K^-\pi^+)}$$

as r_D is well measured $r_D = (3.76 \pm 0.09)\times 10^{-3}$

FNAL Seminar May 18 2007   Ian Shipsey

Mixing and CPV

- Mixing at 1% level does not prove the presence of New Physics
  - Ambiguous probe for New Physics (long distance QCD effects…)
- However, greatly widens the stage on which CP violation can appear as a manifestation of New Physics

- At SuperB precision measurements of mixing should be considered as a tool for searches for CPV and as validation of SuperB physics
- CPV, either in decay or in mixing or interference, is the way to Search for New Physics

New Physics via charm CPV

I. Bigi

Finding $\not{CP}$ somewhere in $\Delta C \neq 0$ is a seminal discovery -- yet not a program, `merely' its first step!

Program (exp)

Study $\not{CP}$ & $\not{T}$ in

- $\Delta C = 1$ vs. $\Delta C = 2$; i.e., direct vs. indirect $\not{CP}$ via t dependance
- CF vs. CS vs. DCS
- partial rates vs. Final State Distributions (FSD)
- down to 10^{-3} - 10^{-4} levels

using runs at ~ 10 GeV & ~ 4 GeV

Only achievable with a 10^{36} machine !

Program (th)

- Develop phenomenology for $\not{CP}$ & $\not{T}$ in FSD
- Derive reliable SM predictions
- Analyze NP scenarios -- in particular Little Higgs Models

Indirect CPV (in mixing)

- Observable sensitive to |q/p| (ΔC=2)

$$A_{sl} = \frac{N^{++} - N^{--}}{N^{++} + N^{--}} = \frac{|q|^4 - |p|^4}{|q|^4 + |p|^4} \qquad R_M = \frac{1}{2}(x^2 + y^2)$$

$$D^0 \to l^- \nu X$$

$$N^{++} = \bar{D}^0 \to l^+ \nu K^-, \quad N^{--} = D^0 \to l^- \bar{\nu} K^+ \quad D^0 = -, \bar{D}^0 = +, \quad l^\pm = \pm$$

$$D^0 \to K^+ \pi^-$$

  - At threshold –ψ''(3770)-, time dependent asymmetry can reveal a new source of WS leptons (violation of SM selection rules)
  - Use sum of several exclusive channels
    - Coherence forbids DCSD

$D^0 \to K^-\pi^+, K^-\pi^+\pi^0, K^-\pi^+\pi^0, K^-\pi^+\pi^+\pi^-, K^-e^+\nu, K^{*-}e^+\nu, K^-\mu^+\nu, K^{*-}\mu^+\nu, K^+K^-, \pi^+\pi^-$
$(\Sigma\ (\varepsilon \times \mathcal{B}) \sim 22.7\%)$

- Measurement can be performed
  - At threshold with D double-tagging
    - Clean environment (closed kinematics), smaller systematics
    - Sensitivities: **δA ~ 2.5%/month** (Only sl $D^0 \to K^-\ell^+\nu$ **δA ~ 9.5%/month**)

      → 4 months of running @ threshold (0.6 ab) → **δA ~ 1%**
  - At Υ(4S) with D* tagging
    - More background, possible to tag the other c quark
    - Sensitivities: **δA ~ 2.7%/year**

      → 5 years of running (75 ab) → **δA ~ 1%**

CPV in interference of mixing and decay

$D^0 \to CP$

- Observable sensitivity to $\phi = \arg\left(\frac{q}{p}\frac{\overline{A}_f}{A_f}\right)$ (interference between ΔC=1 and ΔC=2)

- Lifetime measurements in CP eigenstates: time distribution is exponential only approximately. Good approximation since mixing and CPV are small

$$y_{CP} = \frac{\tau_{K\pi}}{\langle \tau_{hh} \rangle} - 1 \quad , \quad \Delta Y = \frac{\tau_{K\pi}}{\langle \tau_{hh} \rangle} A_\tau$$

$$2y_{CP} = \left(\left|\frac{q}{p}\right| + \left|\frac{p}{q}\right|\right)(\pm y)\cos(\phi) - \left(\left|\frac{q}{p}\right| - \left|\frac{p}{q}\right|\right)(\pm x)\sin(\phi)$$

$$2A_\Gamma = \left(\left|\frac{q}{p}\right| - \left|\frac{p}{q}\right|\right)(\pm y)\cos(\phi) - \left(\left|\frac{q}{p}\right| + \left|\frac{p}{q}\right|\right)(\pm x)\sin(\phi)$$

$$A_\Gamma = \frac{\tau\left(\overline{D}^0 \to CP\right) - \tau\left(D^0 \to CP\right)}{\tau\left(\overline{D}^0 \to CP\right) + \tau\left(D^0 \to CP\right)}$$

  – May require full time-dependent analysis with SuperB statistics

- Sensitivities with 75/ab:

$$\sigma(\cos\phi) \approx \sigma(y_{CP})/y \approx 3\times10^{-4}/y$$
$$\sigma(\sin\phi) \approx \sigma(\Delta Y)/x \approx 3\times10^{-4}/x$$

Direct CP

- Estimates from BaBar analysis to 75/ab from 2-body decays
  - $D^0 \to K^+\pi^-$ in time dependent analysis

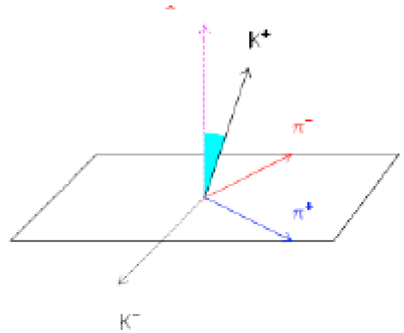
$$D^0 \to K^+\pi^- \qquad A_D = \frac{R(D^0 \to K^+\pi^-) - R(\bar{D}^0 \to K^-\pi^+)}{R(D^0 \to K^+\pi^-) + R(\bar{D}^0 \to K^-\pi^+)} \qquad \sigma(A_D) \sim 0.4\%$$

  - $D^0 \to K^+K^-, \pi^+\pi^-$ in time independent analysis
    (in this case, direct CPV effect mixed with indirect)

$$D^0 \to CP \qquad A_{CP} = \frac{R(D^0 \to K^+K^-) - R(\bar{D}^0 \to K^-K^+)}{R(D^0 \to K^+K^-) + R(\bar{D}^0 \to K^-K^+)} \qquad \sigma(A_{CP}) \sim 0.03\%$$

- Dalitz plot analysis, time integrated (e.g. Kshh)
  - Strong phase variation over resonances of the Dalitz plot can improve the sensitivity to the asymmetry
    - Asymmetry on regions of phase spaces can have different signs which could averaged out when integrating over the DP
  - Comparison of time-integrated CP conjugate DPs (model indep.) vs model dep.
  - From $D^0 \to \pi^+\pi^-\pi^0$, expect sensitivity at 3×10^{-4} at SuperB
- T odd correlations in Cabibbo Suppressed decays $D^0 \to K^+K^-\pi^+\pi^-$

T-odd corrrelations



- Consider the Cabibbo Suppressed D^0 decay:

$$D^0 \longrightarrow K^+K^-\pi^+\pi^-$$

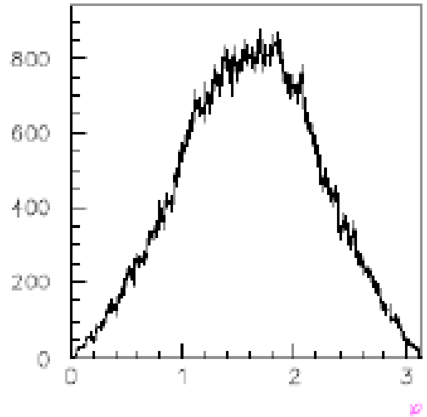
- Compute the angle ϕ between the K^+K^- and $\pi^+\pi^-$ decay planes for $D^0 \rightarrow K^+K^-\pi^+\pi^-$. Then one has:

$$\frac{d\Gamma}{d\phi}(D^0 \rightarrow K^+K^-\pi^+\pi^-) = \Gamma_1 cos^2\phi + \Gamma_2 sin^2\phi + \Gamma_3 cos\phi sin\phi$$

$$\frac{d\Gamma}{d\phi}(\overline{D^0} \rightarrow K^+K^-\pi^+\pi^-) = \bar{\Gamma}_1 cos^2\phi + \bar{\Gamma}_2 sin^2\phi + \bar{\Gamma}_3 cos\phi sin\phi$$

$$\Gamma_3 \neq \bar{\Gamma}_3 \rightarrow CP \quad violation$$

- Distribution of ϕ using BaBar data.



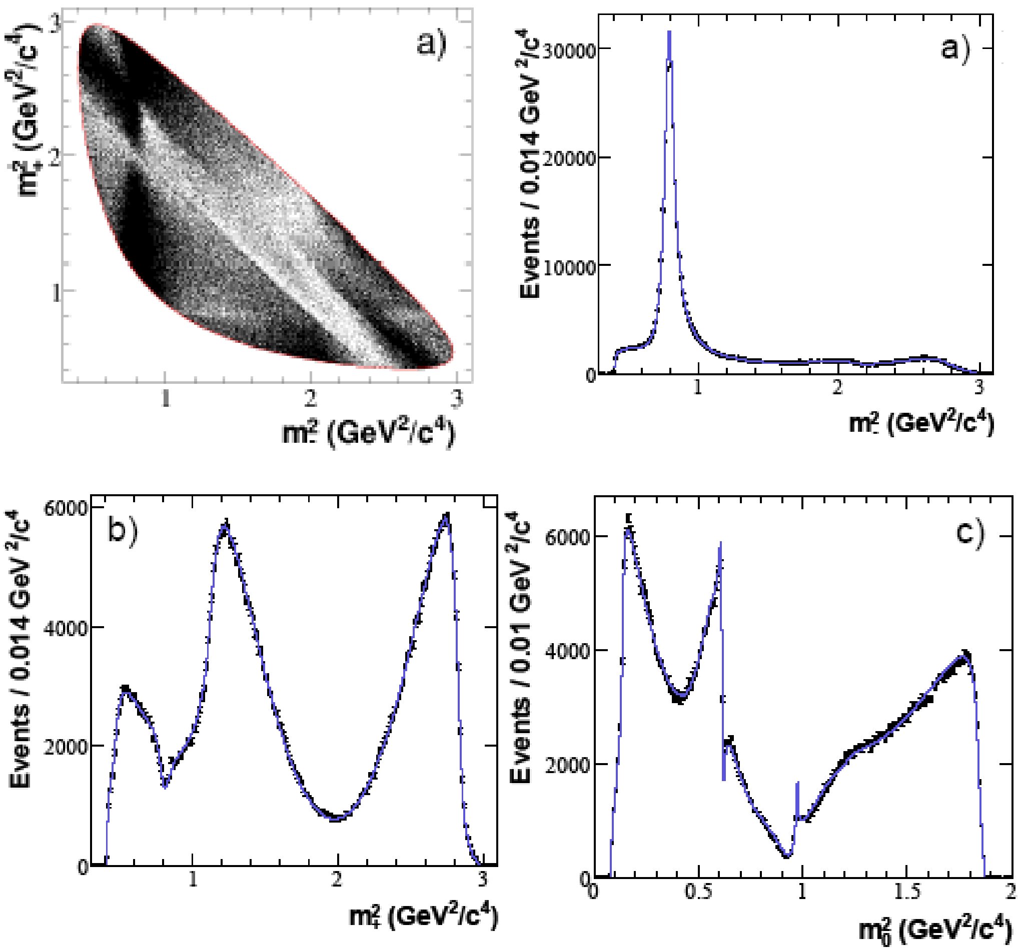
Sensitivity to T violation ~ 0.04% with 75 ab^{-1}

3-body decays and running energies

- Time-dependent Dalitz plot analyses are the golden modes for mixing, CPV in interference from mixing and decay, and perhaps too direct CP
  - Requires to keep under control Dalitz model systematics
    - Improved models with larger statistics
    - Full PWA analyses
    - Make use of $\psi(3770)$ data
  - Very hard to estimate w/o performing analysis, but extremely promising
- Running at $\psi(3770)$ is important
  - Quantum coherence provides unique oportunity to directly measure and/or validate from other (mostly model dependent) measurements D-$\overline{\text{D}}$ strong phase
    - (x',y') → (x,y) $$\begin{pmatrix} x' \\ y' \end{pmatrix} = \begin{pmatrix} \cos\delta & \sin\delta \\ -\sin\delta & \cos\delta \end{pmatrix} \begin{pmatrix} x \\ y \end{pmatrix}$$
    - Dalitz model systematics in 3-body (e.g. $K_S\pi\pi$) analyses
  - Time-dependent measurements possible, but poor time resolution ($\sigma_t \sim \tau$) and poor statistical reach (cross-section 3×wrt 10GeV but luminosity 10×smaller)
  - 0.6/ab (~4 months) would give ~1% (very clean) CPV in mixing

3-body decays and running energies (con't)

arXiv:0804.2089 [hep-ex] submitted to Phys. Rev. D

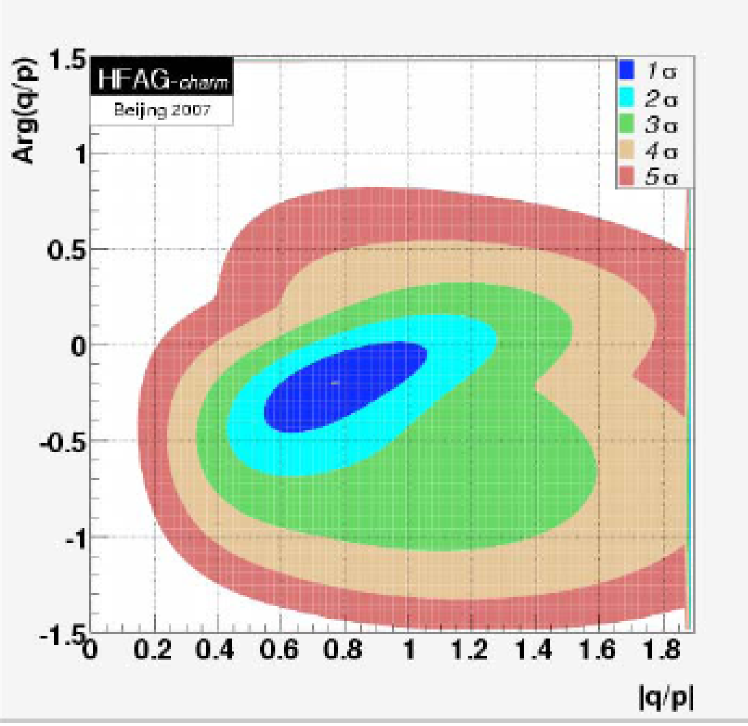


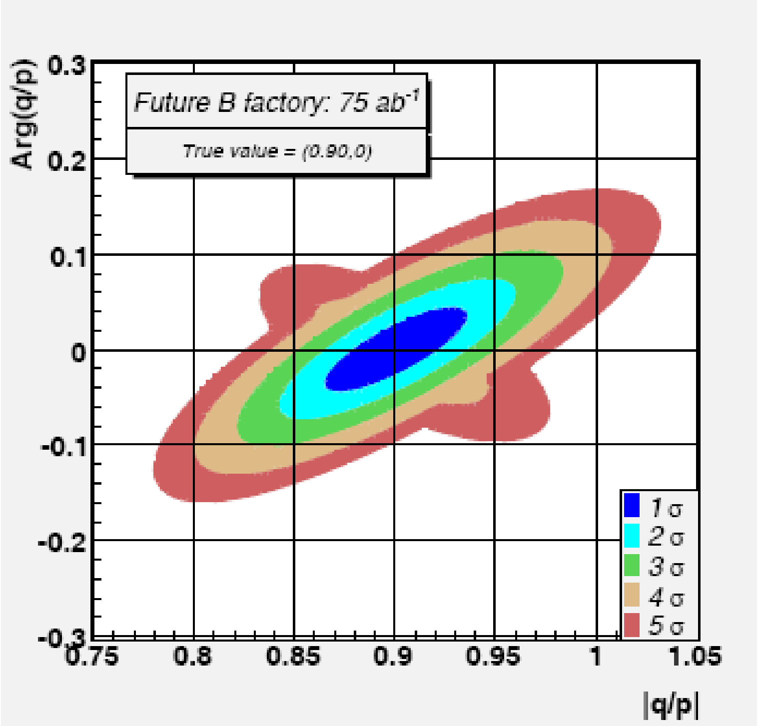
Component	$\Re\{a_r e^{i\phi_r}\}$	$\Im\{a_r e^{i\phi_r}\}$	Fraction (%)
$K^*(892)^-$	-1.314 ± 0.010	1.141 ± 0.009	55.7 ± 2.8
$K_0^*(1430)^-$	-7.3 ± 0.4	3.7 ± 1.2	10.2 ± 1.5
$K_2^*(1430)^-$	-1.054 ± 0.019	0.936 ± 0.025	2.2 ± 1.6
$K^*(1680)^-$	-1.45 ± 0.10	-0.16 ± 0.10	0.7 ± 1.9
$K^*(892)^+$	0.116 ± 0.004	-0.107 ± 0.003	0.46 ± 0.23
$K_0^*(1430)^+$	-0.26 ± 0.05	0.19 ± 0.07	< 0.05
$K_2^*(1430)^+$	0.008 ± 0.017	0.091 ± 0.016	< 0.12
$\rho(770)^0$	1	0	21.0 ± 1.6
$\omega(782)$	-0.031 ± 0.001	0.042 ± 0.001	0.9 ± 1.0
$f_2(1270)$	-0.559 ± 0.026	0.232 ± 0.023	0.6 ± 0.7
β_1	1.82 ± 0.25	-9.1 ± 0.4	
β_2	-10.18 ± 0.19	-3.9 ± 0.5	
β_3	-23.7 ± 2.0	5.0 ± 1.6	
β_4	-0.1 ± 0.4	9.16 ± 0.24	
f_{11}^{prod}	2.19 ± 0.15	7.6 ± 0.3	
$f_{12}^{\prime prod}$	1.9 ± 0.3	-0.6 ± 0.3	
$f_{13}^{\prime prod}$	4.3 ± 0.3	2.8 ± 0.3	
$f_{14}^{\prime prod}$	3.22 ± 0.18	0.27 ± 0.14	
s_0^{prod}	-0.07 ± 0.03		
$\pi\pi$ S-wave			11.9 ± 2.6
M (GeV/c^2)	1.463 ± 0.002		
Γ (GeV/c^2)	0.233 ± 0.005		
F	0.80 ± 0.09		
ϕ_F	2.33 ± 0.13		
R	1		
ϕ_R	-5.31 ± 0.04		
a	1.07 ± 0.11		
r	-1.8 ± 0.3		

ππ S-wave

Kπ S-wave

CPV: today → SuperB





Fit	Parameter	HFAG Average	95% C.L. Interval
CPV	$x(\%)$	$0.97^{+0.27}_{-0.29}$	(0.39:1.48)
	$y(\%)$	$0.78^{+0.18}_{-0.19}$	(0.41:1.13)
	$R_D(\%)$	0.335 ± 0.009	(0.316:0.353)
	$\delta_{K\pi}(^\circ)$	$21.9^{+11.5}_{-12.5}$	(-6.3:44.6)
	$\delta_{K\pi\pi^0}(^\circ)$	$32.4^{+25.1}_{-25.8}$	(-20.3:82.7)
	$A_D(\%)$	-2.2 ± 2.5	(-7.10:2.67)
	$\|q/p\|$	$0.86^{+0.18}_{-0.15}$	(0.59:1.23)
	$\phi(^\circ)$	$-9.6^{+8.3}_{-9.5}$	(-30.3:6.5)

Mode	Observable	$\Upsilon(4S)$ (75 ab^{-1})	$\psi(3770)$ (300 fb^{-1})
$D^0 \to K^+\pi^-$	x'^2	3×10^{-5}	
	y'	7×10^{-4}	
$D^0 \to K^+K^-$	y_{CP}	5×10^{-4}	
$D^0 \to K^0_S\pi^+\pi^-$	x	4.9×10^{-4}	
	y	3.5×10^{-4}	
	$\|q/p\|$	3×10^{-2}	
	ϕ	2°	
$\psi(3770) \to D^0\overline{D}^0$	x^2		$(1-2) \times 10^{-5}$
	y		$(1-2) \times 10^{-3}$
	$\cos\delta$		$(0.01-0.02)$

Summary

– A 10^{36} machine (i.e. SuperB) is “the” unique facility within the reach for New Physics from CPV in charm
– Mixing measurements will significantly improve results from previous experiments, but should be seen as a physics calibration/validation of the experiment
– Running at Υ(4S) + ~4 month at ψ’’(3770) offers complete framework to provide comprehensive picture of mixing and CPV measurements. ψ’’(3770) running would provide:
  - One order of magnitude more data than BESIII
  - Access to 1% sensitivity on CPV in mixing
  - Unique tool for several other key measurements (e.g. 3-body decays, measurement of strong phase for wrong sign $K^+\pi^-$ decays)

Assumptions made

- SuperB will accumulate 75/ab on the Υ(4S)
  - Beam energies 7 GeV e^- on 4 GeV e^+
  - 5 years operation @ $L_{peak} \sim 10^{36}/cm^2/s$
  - Data taking starts ~2015 ⇒ 75/ab by ~2020
- SuperB can operate at different energies
  - L_{peak} scales with s
    - $L_{peak} \sim 10^{35}/cm^2/s$ @ ψ''(3770)
- SuperB will be able to work with 80% polarized electron beam
- LHC operation will be successful
  - LHCb will accumulate 10/fb before SuperB starts
  - ATLAS & CMS will have plenty of data

  (no assumption whether or not NP is discovered at LHC
- SuperKEKB will start at ~2012 and will accumulate 10/fb @ Υ(4S)
- BESIII will have accumulate 15/fb at $D\bar{D}$ threshold (100×smaller peak luminosity)