Sharpening the Physics case for Charm at SuperB

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Charm AWG report

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From Bigi's talk

Prologue: New Physics Scenarios & Uniqueness of Charm

- 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!

Physics case for charm: search for New Physics

- The real certainty in charm physics is that ~~CP~~, either in decay or in mixing or in interference, is the way to search for New Physics.
- At SuperB precision measurements of mixing should be considered as a tool for searches for ~~CP~~.

Mixing and ~~CP~~ toolkit

Mass eigenstates
≠
flavor eigenstates:

$$\left|D^0_{1,2}\right\rangle = p\left|D^0\right\rangle \pm q\left|\overline{D^0}\right\rangle$$

$$\left(\frac{q}{p}\right)^2 = \frac{M^*_{12} - \frac{i}{2}\Gamma^*_{12}}{M_{12} - \frac{i}{2}\Gamma_{12}}$$

$$A_f = \left\langle f\right|H\left|D^0\right\rangle \qquad \bar{A}_f = \left\langle f\right|H\left|\bar{D}^0\right\rangle \qquad \frac{\bar{A}_{\bar{f}}}{A_f} \neq 1$$

~~CP~~ in decay

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

$$r_m = \left|\frac{q}{p}\right| \qquad \varphi_f = \arg\left(\frac{q}{p}\frac{\bar{A}_f}{A_f}\right)$$

$r_m \neq 1$ ~~CP~~ in mixing

$\varphi_f \neq 0$ ~~CP~~ in interference of mixing and decay

New Physics via ~~CP~~

(2.1) The Program

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

Program (exp)

Study ~~CP~~ & ~~T~~ in

- $\Delta C = 1$ vs. $\Delta C = 2$; i.e., direct vs. indirect ~~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

Program (th)

- Develop phenomenology for ~~CP~~ & ~~T~~ in FSD
- Derive reliable SM predictions
- Analyze NP scenarios -- in particular Little Higgs Models

Mixing and ~~CP~~ violation observables

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

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

$D^0 \to CP$

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

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

$$x_{K^0\pi\pi} = x$$
$$y_{K^0\pi\pi} = y$$

$$|q/p|_{K^0\pi\pi} = |q/p|$$
$$\mathrm{Arg}\,(q/p)_{K^0\pi\pi} = \phi$$

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

$$x'^{\pm} = \left(\frac{1 \pm A_M}{1 \mp A_M}\right)^{1/4} (x' \cos\phi \pm y' \sin\phi) \qquad A_M = \frac{|q/p|^2 - |p/q|^2}{|q/p|^2 + |p/q|^2}$$

$$y'^{\pm} = \left(\frac{1 \pm A_M}{1 \mp A_M}\right)^{1/4} (y' \cos\phi \mp x' \sin\phi) \qquad \begin{pmatrix} x' \\ y' \end{pmatrix} = \begin{pmatrix} \cos\delta & \sin\delta \\ -\sin\delta & \cos\delta \end{pmatrix} \begin{pmatrix} x \\ y \end{pmatrix}$$

$$\frac{1}{2}\left[R(D^0 \to K^+\pi^-) + \overline{R}(\overline{D}^0 \to K^-\pi^+)\right] = R_D$$

$$\frac{R(D^0 \to K^+\pi^-) - \overline{R}(\overline{D}^0 \to K^-\pi^+)}{R(D^0 \to K^+\pi^-) + \overline{R}(\overline{D}^0 \to K^-\pi^+)} = A_D$$

Output from this workshop

Ikaros first homework

(1.5) First Task for WG: how to measure best x_D, y_D

Must measure x_D, y_D accurately

- serves as validation of Super-B charm analyses
- " " " " time dependent CP studies
- a breakthrough in theoret. technologies might occur

Questions for the WG

- How well can one do ?
- Running on the Υ(4S) vs. near charm threshold ?
- near charm threshold:
  - Can do time dependent measurements?
  - EPR correlations?
- time dependent Dalitz plots

Comparison with different running experiments

- ***SuperKEK***: besides lumi difference ~10x smaller, there is no possibility to run at threshold. Expected larger background, possible impact on systematics.
- ***LHCb***: statistics not a problem. Systematics not evaluated in sensitivity studies, possibly limiting precise measurements. Decays with neutrals, neutrinos and Ks very challenging. Coherent production not possible.
- ***BESIII***: Coherent production. 100x smaller lumi.

Not possible time-dependent measurements.

- ***CLEO-c***: same considerations for BESIII. 26x smaller data sample wrt BESIII.

SuperB will offer the opportunity of:

- Improving precision on almost all measurements.
- Wider range of possible measurements.

Question 1: sensitivity to charm mixing

Estimates from CDR. Systematic uncertainties assumed to be kept under control. More comments later.

Mode	Observable	B Factories (2 ab^{-1})	Super$B$ (75 ab^{-1})
$D^0 \to K^+K^-$	y_{CP}	2–3×10^{-3}	5×10^{-4}
$D^0 \to K^+\pi^-$	y'_D	2–3×10^{-3}	7×10^{-4}
	x'^2_D	1–2×10^{-4}	3×10^{-5}
$D^0 \to K^0_S\pi^+\pi^-$	y_D	2–3×10^{-3}	5×10^{-4}
	x_D	2–3×10^{-3}	5×10^{-4}
Average	y_D	1–2×10^{-3}	3×10^{-4}
	x_D	2–3×10^{-3}	5×10^{-4}

Comparison with other experiments

Exp. sensitivities	$y_{CP}(10^{-3})$	y' (10^{-3})	x'^2 (10^{-4})	$\cos\delta$
B-factories (2ab^{-1})	2-3	2-3	1-2	-
SuperB (75 ab^{-1})	0.4-0.5	0.7	0.3	-
CLEO-c (750 pb^{-1})	10	-	2-3	0.1-0.2
BESIII (20fb^{-1})	4	-	0.5-1	0.05
SuperB - 4 GeV (0.3 ab^{-1} or 2 month)	1-2	?	0.5-1	0.01-0.02
LHCb 10fb^{-1}	0.5 (stat only)	0.9 (stat only)	0.64 (stat only)	-

Question 2: running at $\Upsilon(4S)$ *vs* $D\overline{D}$ threshold

- Charm events at threshold are very clean: pure $D\overline{D}$, no additional fragmentation
- High signal/bkg ratio: optimal for decays with neutrinos.
- Quantum Coherence: new and alternative CP violation measurement wrt to $\Upsilon(4S)$. Unique opportunity to measure D-$\overline{D}$ relative phase.
- Increased statistics is not an advantage running at threshold: cross-section 3x wrt 10GeV but luminosity 10x smaller.
- SuperB lumi at 4 GeV = 10^{35} $cm^{-2}s^{-1}$ to be compared with 10^{33} $cm^{-2}s^{-1}$ of BESIII. Possibility to improve BESIII results by sizeable amount in few months running.
- Time-dependent measurements at 4 GeV only possible at SuperB, to be assessed.

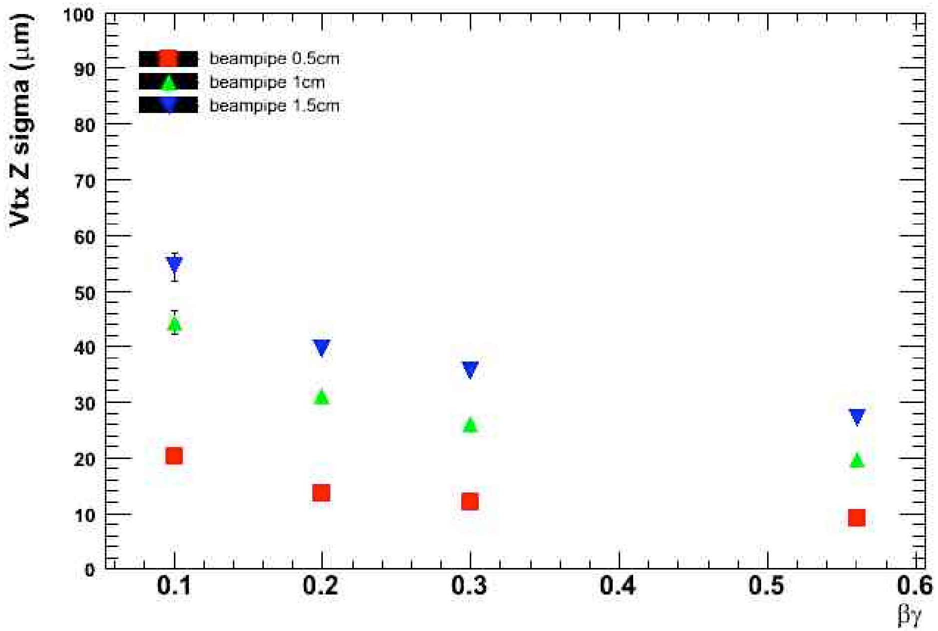
A 4.0 GeV detector: important peculiarities

- BaBar-Belle detector are similar to CLEO-c detector.
- CLEO-c use CLEOIII detector operated at Υ4S with some differences due to reduced particle momentum range:
  - **Multiple scattering** reduces vertexing capability.
  - **Low pT tracks** have **lower reco efficiency** since they reach only the inner layers of the DCH .
  - Low pT tracks **loops in the DCH** complicating pattern recognition.

CLEO-c $\beta\gamma$=0 replaced Vertex detector with Micro Vertex Chamber.
Reduced B magnetic field 1.5T$\rightarrow$1.0T
Ameliorate the tracking efficiency with loss of vertex capability and reduction of invariant mass resolution.

Question 3: time dependent measurements at threshold

- Vertex resolution affected by increase of multiple scattering. D->Kπ decay mode as an example:



Average flight distance similar to vertex resolution → $\sigma_t \sim \tau$.

Error on lifetime $\approx \sqrt{\frac{\tau^2 + \sigma_t^{\,2}}{N}} = \sqrt{2}\,\frac{\tau}{\sqrt{N}}$ (wrt perfect resolution)

Question 4: EPR correlations

- Clean a_{SL} measurement. SL ($D^0 \to l^- \nu K^+$ vs $\overline{D}^0 \to l^- \nu K^+$) and also Hadronic ($D^0 \to K^+\pi^-$ vs $\overline{D}^0 \to K^+\pi^-$). In later case only possible if mixing induced (no DCSD).
- Using CP tagged events it is a unique possibility to measure relative D-$\overline{D}$ strong phase.
- In 3-body decays (e.g. Kshh) allows to keep under control dalitz model systematics. To be assessed.
- Time-dependent measurement at threshold:
  - Time-dependent measurements can distinguish between different types of CP violation.
  - Interest besides statistics to be assessed.

Question 5: time dependent Dalitz plot

- Only method in literature sensitive to x, y directly. Sign of x is accessible.
- Golden channel if Dalitz model uncertainty is kept under control. Data at threshold, where evaluation of D-$\overline{D}$ relative phase is possible, are key ingredient.
- Need to understand if a Dalitz model independent measurement is feasible (as in the case of γ analysis) using data at threshold. Work started on this item.

Charm Physics Benchmarks

(2.5) Benchmarks

☞ Allowed New Physics scenarios could produce $\not{CP}$ close to present experim. bounds, but hardly higher!

- time dependant CP asymmetries in
  - $D^0 \to K^+K^-, \pi^+\pi^-, K_S\rho^0, K_S\phi$ down to $\mathcal{O}(10^{-4})$
  - $D^0 \to K^+\pi^-$ down to $\mathcal{O}(10^{-3})$

  LHCb: $\geq 10^6$ $D^* \to D\pi \to [KK]_D\pi$ per 2 fb^{-1}

  $\sim$ 58K $D^* \to D\pi \to [K^+\pi^-]_D\pi$
- direct $\not{CP}$ in partial widths of
  - $D^\pm \to K_{S[L]}\pi^\pm$ down to $\mathcal{O}(10^{-3})$
  - in a host of 1xCS channels down to $\mathcal{O}(10^{-3})$
  - in 2xCS channels down to $\mathcal{O}(10^{-2})$
- direct $\not{CP}$ in the final state distributions:

  Dalitz plots, T-odd correlations etc. down to $\mathcal{O}(10^{-3})$

Sensitivity to ~~CP~~ in mixing

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

- $$A_{sl} = \frac{N^{++} - N^{--}}{N^{++} + N^{--}} = \frac{|q|^4 - |p|^4}{|q|^4 + |p|^4}$$
  $$N^{++} = \bar{D}^0 \to l^+ \nu K^-, \quad N^{--} = D^0 \to l^- \bar{\nu} K^+ \qquad D^0 = -, \bar{D}^0 = +, \;\; l^{\pm} = \pm$$

At threshold, time dependent asymmetry can reveal a new source of WS leptons (violation of SM selection rules).

Measurement can be performed:

- at threshold with D double-tagging. Clean environment, smaller systematics.

- at Υ(4S) with D* tagging.

Sensitivity @ $\psi''(3770)$: (150/fb per month)

$$A_{CP} = \frac{N_{++} - N_{--}}{N_{++} + N_{--}}$$

Advantage: closed kinematics

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

$N_{mixed\ \&\ tagged} = \_N_{\psi''}\,(x^2+y^2)/2\,\Sigma\,(\varepsilon\times\mathcal{B})^2 \sim 1600$ evts/month $\to$ **$\delta A \sim 2.5\%$/month**

(Only sl $D^0 \to K^-\ell^+\nu$ **$\delta A \sim 9.5\%$/month**)

$\to$ 4 months of running @ threshold (0.6 ab) $\to$ **$\delta A \sim 1\%$**

Sensitivity @ $\Upsilon(4S)$

Advantage: tagged soft π^* from D^*

Search for wrong sign leptons in sl decays $D^0 \to K^- \ell^+ \nu$

$N_{ws\ sl} = 2N_{cc} P_{c\to D^*}\ \varepsilon_{\pi^*}\ \mathcal{B}(D^* \to D^0\pi^+)\ \varepsilon_{Kl}\ \mathcal{B}(D^0 \to K^- \ell^+ \nu)\ (x^2+y^2)/2 \sim 1350$ evts/year$\to$

$\delta A \sim 2.7\%$/year

$\to$ 5 years of running (75 ab) $\to$ **$\delta A \sim 1\%$**

But more bkg

Possible to tag the other c

Sensitivity to ~~CP~~ in interference between mixing and decay

Observable sensitive to $\phi = \arg\left(\frac{q}{p}\frac{\bar{A}_f}{A_f}\right)$ (ΔC=1 and ΔC=2):

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

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

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

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

- Sensitivities with 75 ab^{-1}: $\sigma(\cos\Phi) \sim 0.04\%/y$, $\sigma(\sin\Phi) \sim 0.03\%/x$

Sensitivity to ~~CP~~ in decay

Estimates from BaBar analysis to 75 ab^{-1}:

- $D^0 \to K^+\pi^-$ in time dependent analysis

$$A_D = \frac{R\left(D^0 \to K^+\pi^-\right) - R\left(\bar{D}^0 \to K^-\pi^+\right)}{R\left(D^0 \to K^+\pi^-\right) + R\left(\bar{D}^0 \to K^-\pi^+\right)}$$

$\sigma(A_D) \sim 0.4\%$

- $D^0 \to K^+ K^+, \pi^- \pi^+$ in time independent analysis

$$A_{CP} = \frac{R\left(D^0 \to K^+K^-\right) - R\left(\bar{D}^0 \to K^-K^+\right)}{R\left(D^0 \to K^+K^-\right) + R\left(\bar{D}^0 \to K^-K^+\right)}$$

$\sigma(A_{CP}) \sim 0.03\%$

- Dalitz plot analysis, time integrated (e.g. Kshh)

Strong phase variation over resonances of the Dalitz plot can improve the sensitivity to the asymmetry and help reducing systematic uncertainties.

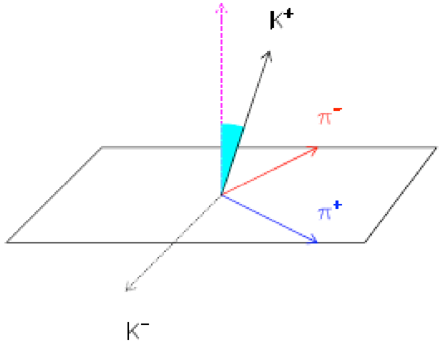
Search for T-odd correlations.

- Consider the Cabibbo Suppressed D^0 decay:

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

- T-odd correlations can be formed using the momenta of the particles:

$$C_T = p_{K^+} \cdot (p_{\pi^+} \times p_{\pi^-})$$



- Under time reversal T, we have $C_T \to -C_T$.
- $C_T \neq 0$ does not necessarily established T violation.
- Consider also:

$$\overline{D^0} \to K^+ K^- \pi^+ \pi^-$$

where we can compute:

$$\overline{C_T} = p_{K^-} \cdot (p_{\pi^-} \times p_{\pi^+})$$

- Finding:

$$C_T \neq -\overline{C_T}$$

establishes CP violation.

A different approach (I. Bigi).

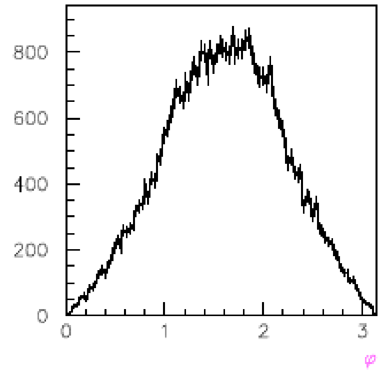
- Compute the angle ϕ between the K^+K^- and $\pi^+\pi^-$ decay planes for $D^0 \to K^+K^-\pi^+\pi^-$. Then one has:

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

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

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

- Distribution of ϕ using BaBar data.



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

- Not necessarily the above expression gives a good fit.

Plans for the report

CP violation is the charm physics case for SuperB:

- Refine estimates of sensitivities for CP violation.
- Evaluation of time-dependent measurements at threshold.
- Assess impact of threshold data on dalitz model uncertainty.
- Feasibility of dalitz model independent analysis for mixing and CP violation.