D Mixing and Decay

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for the Belle Collaboration

XXX. PHYSICS IN COLLISION
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Outline

Charm as a probe of New Physics in

1. $D - \overline{D}$ mixing
2. CP violation
3. Rare decays

Mixing Phenomena

Mixing is a process

- in which particle changes to its anti-particle and vice versa
- possible only in flavored neutral particle–anti-particle systems

Mixing observed in all neutral meson systems:

Meson M	Flavors	Particle discovered	Mixing discovered	Implication
K^0	$\bar{s}d$	1950 (Caltech)	1956 (Columbia)	m_c
B_d^0	$\bar{b}d$	1983 (CESR)	1987 (Desy)	m_t
B_s^0	$\bar{b}s$	1992 (LEP)	2006 (Fermilab)	??
D^0	$c\bar{u}$	1976 (SLAC)	2007 (KEK, SLAC)	??

Mixing is not possible in π^0 system since $\pi^0 \equiv \overline{\pi}^0$;
t quark decays before it could form a hadron.

Uniqueness of Charm:

1. the only Up-type neutral meson allowing full range of probes for New Physics

Mixing Phenomenology - Time evolution

- Time evolution of $D^0 - \overline{D}^0$ system given by time-dependent Schrödinger Eq.

$$i\frac{\partial}{\partial t}\begin{pmatrix}|D^0\rangle \\ |\overline{D}^0\rangle\end{pmatrix} = [\mathbf{M} - \frac{i}{2}\mathbf{\Gamma}]\begin{pmatrix}|D^0\rangle \\ |\overline{D}^0\rangle\end{pmatrix}$$

- Eigenstates of $[\mathbf{M} - \frac{i}{2}\mathbf{\Gamma}]$ are mass eigenstates $D_{1,2}$ with $m_{1,2}$ and $\Gamma_{1,2}$

  $\hookrightarrow \neq$ flavor eigenstates D^0 and $\overline{D}^0$

$$|D_{1,2}\rangle = p|D^0\rangle \pm q|\overline{D}^0\rangle \qquad p^2 + q^2 = 1$$

- time evolution of flavor eigenstate

$$|D^0(t)\rangle = \left[|D^0\rangle cosh\left(\frac{ix+y}{2}t\right) + \frac{q}{p}|\bar{D}^0\rangle sinh\left(\frac{ix+y}{2}t\right)\right] \times e^{-\frac{1}{2}(1+\frac{im}{\Gamma})t}$$

  Mixing parameters:

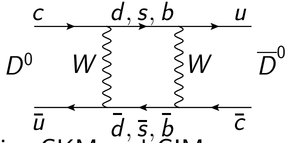
$$\mathbf{x} = \frac{\mathbf{m_1 - m_2}}{\mathbf{\Gamma}}, \quad \mathbf{y} = \frac{\mathbf{\Gamma_1 - \Gamma_2}}{\mathbf{2\Gamma}}, \quad \Gamma = \frac{1}{2}(\Gamma_1 + \Gamma_2)$$

Contributions to x and y

Standard Model

Burdman, Shipsey, Ann.Rev.Nucl.Part.Sci.53,431; Falk et al., PRD65, 054034; Bigi, Uraltsev, Nucl. Phys. B592, 92;

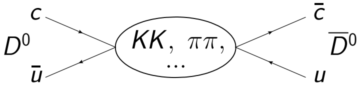
Short distance



Effective CKM and GIM suppression

$|x|, \; |y| \leq 10^{-3}$

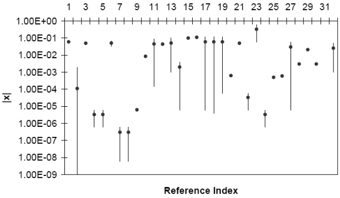
Long distance



Contribution from hadronic intermediate states

$x, \; y \sim$ up to 1%

New Physics predictions for |x|



A. Petrov, Int.J.Mod.Phys.A21, 5686;

- Large uncertainty in SM mixing rate
  $\hookrightarrow$ difficult to identify New Physics contributions (except if $x \gg y$)
- however, measurements of x and y still provide usefull constraints on many New Physics models

CP Violation in Charm

Q: If $D - \overline{D}$ mixing can't reveal New Physics, what can?
A: CP violation!

- Source of *CP* violation in the Standard Model
  $\hookrightarrow$single complex phase (η) in the quark mixing matrix

$$\mathbf{V}_{\rm CKM} = \begin{pmatrix} 1-\frac{1}{2}\lambda^2 & \lambda & A\lambda^3(\rho - i\eta + \frac{i}{2}\eta\lambda^2) \\ -\lambda & 1-\frac{1}{2}\lambda^2 - \mathbf{i}\eta\mathbf{A}^2\lambda^4 & A\lambda^2(1+i\eta\lambda^2) \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix}$$

- Charmed meson processes
  $\hookrightarrow$ *CP* violation in Standard Model is CKM suppressed: $\sim \mathcal{O}(10^{-3})$
    $\hookrightarrow$ Possible only in Singly Cabbibo supressed decays (tree + penguin amplitudes)
  $\hookrightarrow$ *CP* violation in New Physics models: up to 1%
    Grossman, Kagan, Nir, PRD75, 036008; Bigi, hep-ph/0104008
  $\hookrightarrow$ Current experimental sensitivity: few 0.1%

Observation of *large* $\mathcal{O}(1\%)$ *CPV* in charm decays would be a sign for New Physics!

CP Violation Phenomenology

- Classification of CP-violating effects:

$$\hookrightarrow \boxed{\mathbf{A^f_{CP} = \frac{\Gamma(D\to f)-\Gamma(\overline{D}\to\bar{f})}{\Gamma(D\to f)+\Gamma(\overline{D}\to\bar{f})} \approx a^f_d + a^f_m + a^f_i}}$$

1. $\mathbf{a^f_d}$: CP violation in decay

   $\hookrightarrow |\mathcal{A}_f| \neq |\overline{\mathcal{A}}_{\bar{f}}|$ $\qquad \mathcal{A}_f = \langle f|D\rangle, \quad \overline{\mathcal{A}}_{\bar{f}} = \langle \bar{f}|\overline{D}\rangle$

2. $\mathbf{a^f_m}$: CP violation in mixing

   $\hookrightarrow |q/p| \neq 1$ $\qquad |D_{1,2}\rangle = p|D^0\rangle \pm q|\overline{D}^0\rangle$

3. $\mathbf{a^f_i}$: CP violation in interference of decays with and without mixing ($f = \bar{f}$)

   $\hookrightarrow \phi \neq 0$ or π $\qquad \phi = arg(\frac{q}{p}\frac{\bar{A}_f}{A_f})$

Experimental observables

Time-integrated measurements:

$$A^f_{CP} = \frac{N(D\to f)-N(\overline{D}\to\bar{f})}{N(D\to f)+N(\overline{D}\to\bar{f})}$$

Time-dependent measurements:

$$A_\Gamma = \frac{\tau(D\to f_{CP})-\tau(\overline{D}\to f_{CP})}{\tau(D\to f_{CP})+\tau(\overline{D}\to f_{CP})} = -(a_m + a_i)$$

Available Charm Samples

Diverse exp. conditions!

B-factories:

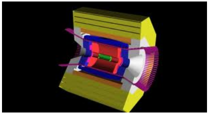
- continuum production @ $\Upsilon(4S)$: $\sigma(c\bar{c}) \approx 1.3$ nb
- Belle: $\sim 1.3 \cdot 10^9$ $c\bar{c}$ pairs
- Babar: $\sim 0.7 \cdot 10^9$ $c\bar{c}$ pairs

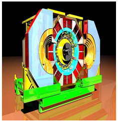
Tevatron:

- $p\bar{p}$ @ ~ 2 TeV
- CDF: $\sim 70 \cdot 10^9$ D^0's

Charm factories:

- $\psi(3770) \to D^0\overline{D^0},\ D^+D^-$
- CLEO: $\sim 2.8 \cdot 10^6$ $D^0\overline{D}^0$ pairs
- BESIII: $\sim 3.4 \cdot 10^6$ $D^0\overline{D}^0$ pairs





LHC:

- pp @ 7 TeV
- LHCb: *has only started*

Decay time distribution sensitive to mixing parameters x and y and depends on the final state:

$$\frac{dN(D^0 \to f)}{dt} \propto \left| \langle f | D^0 \rangle + \frac{q}{p} \left(\frac{ix+y}{2} \langle f | \overline{D}^0 \rangle \right) \right|^2$$

Final state	Belle	BaBar	CDF	Cleo	E791	Focus
$K^+\pi^-$	√	★	★	√	√	√
KK, $\pi\pi$	★	★		√	√	√
$K_S^0\pi\pi$	√	√		√		
K_S^0KK	√	√				
$K^+\pi^-\pi^0$		★				
$K^+\pi^-\pi^-\pi^+$		√				
$K^+\ell^-\nu_\ell$	√	√		√	√	
quantum corr. in $\psi(3770) \to D^0\overline{D}^0$				√		

√ – measurement performed; ★ – evidence for mixing

Full list of all $D^0 - \overline{D}^0$ mixing measurements is available at:
http://www.slac.stanford.edu/xorg/hfag/charm/index.html

Mixing and CPV in decays to CP eigenstates $(KK, \pi\pi)$

- Measurement of lifetime difference between $D^0 \to K^-\pi^+$ (CP-mixed) and $D^0 \to K^+K^-,\ \pi^+\pi^-$ (CP-even) decays (tagged and untagged samples)

  $\hookrightarrow \Gamma(D^0 \to K^-\pi^+) \quad \propto \quad e^{-t/\tau_{D^0}}$ $\qquad y_{CP} = \frac{\tau_{K\pi}}{\tau_{KK,\pi\pi}} - 1$

  $\hookrightarrow \Gamma(D^0 \to K^+K^-,\ \pi^+\pi^-) \quad \propto \quad e^{-(1+y_{CP})t/\tau_{D^0}}$ $\qquad A_\Gamma = \frac{\tau(\overline{D}^0 \to f_{CP}) - \tau(D^0 \to f_{CP})}{\tau(\overline{D}^0 \to f_{CP}) + \tau(D^0 \to f_{CP})}$

- In case of no CP violation: $y_{CP} = y$ and $A_\Gamma = 0$

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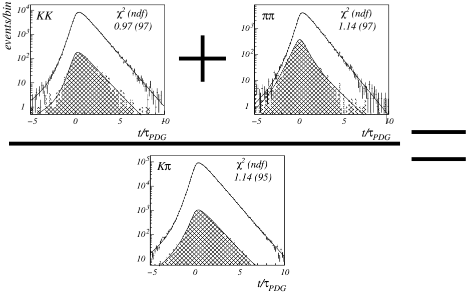
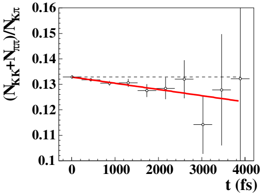
- In case of no CP violation: $y_{CP} = y$ and $A_\Gamma = 0$

Belle [PRL98, 211803 (2007)]



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

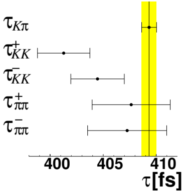
First evidence for mixing!



$A_\Gamma = (0.01 \pm 0.30 \pm 0.15)\%$

BaBar performed measurements of y_{CP} using:

1. Tagged Sample: require D^0 to originate in $D^{*+} \rightarrow D^0\pi^+$ decay

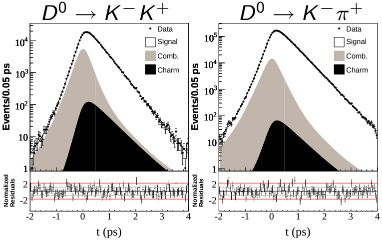


PRD78, 011105 (2008)

$$y_{CP} = (1.24 \pm 0.39 \pm 0.13)\%$$
$$\Delta Y = -(0.26 \pm 0.36 \pm 0.08)\%$$

$$\Delta Y = (1 + y_{CP})A_\Gamma$$

2. Untagged Sample: take all D^0 candidates (except from the tagged sample)



PRD80, 071103 (2009)

$$y_{CP} = (1.12 \pm 0.26 \pm 0.22)\%$$

Combined: tagged + untagged

$$y_{CP} = (1.16 \pm 0.22 \pm 0.18)\%$$

4.1σ significance!

Time dependent Dalitz analyses

- Many quasi 2-body intermediate states, e.g. in $D^0 \to K_S^0 \pi^+ \pi^-$ decays:
  $\hookrightarrow$ CF: $D^0 \to K^{*-}\pi^+$
  $\hookrightarrow$ DCS: $D^0 \to K^{*+}\pi^-$
  $\hookrightarrow$ CP: $D^0 \to \rho^0 K_S^0$

$$D^0 : \; \mathcal{A}(m_-^2, m_+^2) = \sum_r a_r e^{i\phi_r} \mathcal{A}_r(m_-^2, m_+^2) + a_{nr} e^{i\phi_{nr}}$$

$$\overline{D}^0 : \; \bar{\mathcal{A}}(m_-^2, m_+^2) = \sum_r \bar{a}_r e^{i\bar{\phi}_r} \bar{\mathcal{A}}_r(m_-^2, m_+^2) + a_{nr} e^{i\phi_{nr}}$$

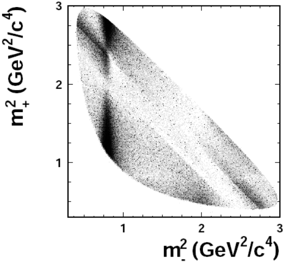
If $f = \overline{f} \Rightarrow$ *relative phases determined (unlike* $D^0 \to K^+\pi^-(\pi^0)$*)*

- Time dependent decay rate ($\mathcal{A}_{1,2} = \frac{1}{2}(\mathcal{A} \pm \bar{\mathcal{A}})$)

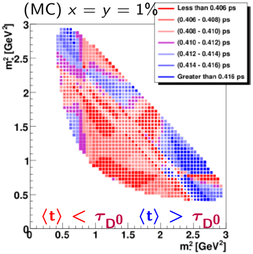
$$\Gamma(m_-^2, m_+^2, t) = e^{-\Gamma t}(|\mathcal{A}_1|^2 e^{-y\Gamma t} + |\mathcal{A}_2|^2 e^{y\Gamma t} + 2\mathcal{R}[\mathcal{A}_1\mathcal{A}_2^*]\cos(x\Gamma t) + 2\mathcal{I}[\mathcal{A}_1\mathcal{A}_2^*]\sin(x\Gamma t))$$

Simultaneous determination of x and y!

Dalitz plot for $D^0 \to K_S^0 \pi^+ \pi^-$



⟨t⟩ across Dalitz plot

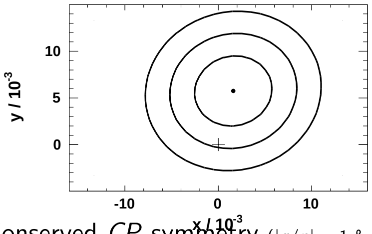


Mixing and CPV $D^0 \to K^0_S\pi^+\pi^-$, $D^0 \to K^0_S K^+K^-$ decays

BaBar [PRL105,081803]

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

68%, 95% and 99.9% confidence level contours



Conserved CP symmetry ($|q/p| = 1$ & $\phi = 0$)

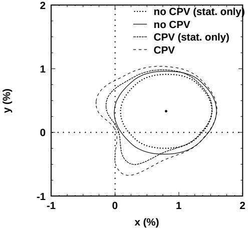
$$\mathbf{x = (0.16 \pm 0.23 \pm 0.14)\%}$$
$$\mathbf{y = (0.57 \pm 0.20 \pm 0.15)\%}$$

Measurements are consistent and together provide the most accurate determination of x and y!

Belle [PRL99,131803]

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

95% confidence level contours



Conserved CP symmetry ($|q/p| = 1$ & $\phi = 0$)

$$\mathbf{x = (0.80 \pm 0.29^{+0.13}_{-0.16})\%}$$
$$\mathbf{y = (0.33 \pm 0.24^{+0.10}_{-0.14})\%}$$

CPV allowed ($|q/p|$ & ϕ free parameters of the fit)

$$\mathbf{|q/p| = 0.86 \pm 0.30 \pm 0.09}$$
$$\mathbf{\phi = -0.24 \pm 0.30 \pm 0.09}$$

Consistent with no CPV!

Mixing and CPV in WS hadronic decays ($D^0 \to K^+\pi^-$)

- Right sign (RS) charge combination

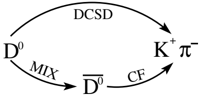
  $D^{*+} \to D^0(K^-\pi^+)\pi^+$

  $\Gamma_{RS} \propto e^{-t/\tau_{D^0}}$

- Wrong sign (WS) charge combination

  $D^{*+} \to D^0(K^+\pi^-)\pi^+$

  $\hookrightarrow$ DCS or mixing



$$\Gamma_{WS} \propto [R_D + y'\sqrt{R_D}(\Gamma t) + \frac{x'^2+y'^2}{4}(\Gamma t)^2]e^{-\Gamma t}$$

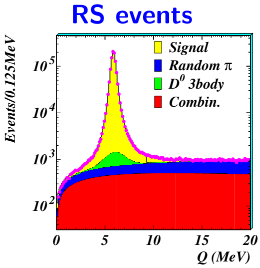
● DCS ● interference ● mixing

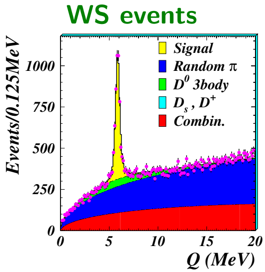
$\hookrightarrow$ R_D: DCS/CF rate

$\hookrightarrow$ $\mathbf{x' = x\cos\delta + y\sin\delta}$

$\hookrightarrow$ $\mathbf{y' = y\cos\delta - x\sin\delta}$

$\hookrightarrow$ δ strong phase between DCS and CF



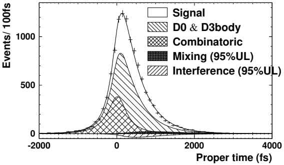


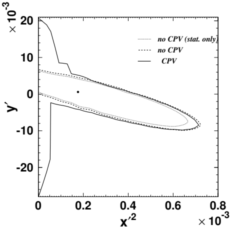
$Q = M_{K\pi\pi} - M_{K\pi} - m_\pi$

Mixing and CPV in WS hadronic decays $D^0 \to K^+\pi^-$

Belle [400 fb^{-1}]

PRL96, 151801 (2006).

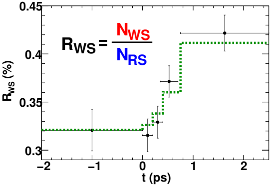


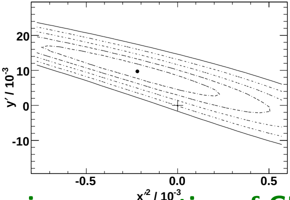


BaBar [384 fb^{-1}]

PRL98, 211802 (2007).

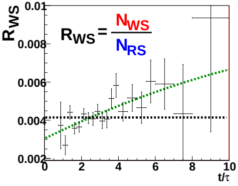
First Evidence!

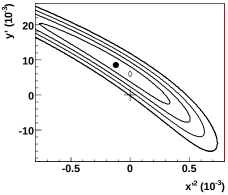




CDF [1.5 fb^{-1}]

PRL100, 121802 (2008).





Results assuming conservation of CP symmetry

Experiment	$R_D (10^{-3})$	$y' (10^{-3})$	$x'^2 (10^{-3})$	Signif.
CDF	3.04 ± 0.55	8.5 ± 7.6	-0.12 ± 0.35	3.8
BaBar	3.03 ± 0.19	9.7 ± 5.4	-0.22 ± 0.37	3.9
Belle	3.64 ± 0.17	$0.6^{+4.0}_{-3.9}$	$0.18^{+0.21}_{-0.23}$	2.0

PRL103, 211801

Analysis similar to the WS $D^0 \to K^+\pi^-$ analysis, however the strong phase δ varies across the Dalitz plot.

● DCS ● interference ● mixing

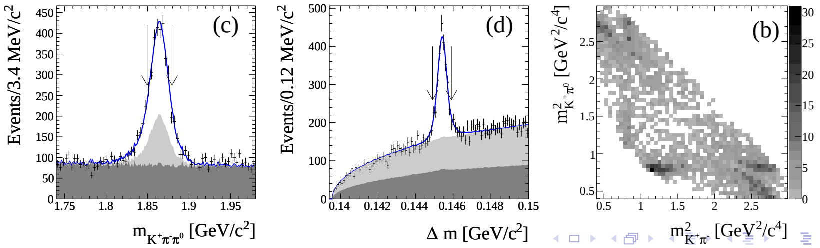
$$\frac{dN_{\bar f}(s_0,s_+,t)}{ds_0\,ds_+\,dt} = e^{-\Gamma t}\left\{|A_{\bar f}|^2 + |A_{\bar f}||\bar A_{\bar f}|\left[y''\cos\delta_{\bar f} - x''\sin\delta_{\bar f}\right](\Gamma t) + \frac{x''^2+y''^2}{4}|\bar A_{\bar f}|^2(\Gamma t)^2\right\}$$

$$s_0 = m^2_{K^+\pi^-}\,;\; s_0 = m^2_{K^+\pi^0}$$

- Mixing parameters

$\hookrightarrow$

$$\mathbf{x'' = x\cos\delta_{K\pi\pi^0} + y\sin\delta_{K\pi\pi^0}} \quad \text{and} \quad \mathbf{y'' = y\cos\delta_{K\pi\pi^0} - x\sin\delta_{K\pi\pi^0}}$$



Mixing in WS $D^0 \to K^+\pi^-\pi^0$ decays (BaBar)

Assuming no CPV

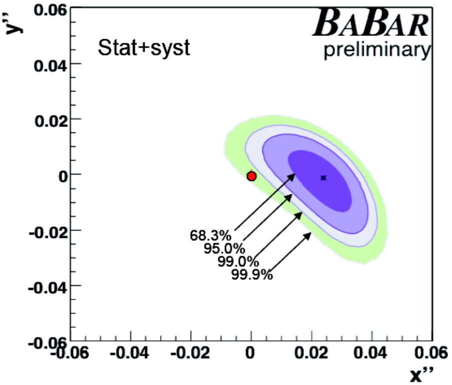
$$\begin{aligned} x'' &= (2.61^{+0.57}_{-0.68} \pm 0.39)\% \\ y'' &= -(0.05^{+0.55}_{-0.64} \pm 0.34)\% \\ R_M &= (2.9 \pm 1.6) \times 10^{-4} \end{aligned}$$

Allowing CPV

$$\begin{aligned} x''^{+} &= (2.53^{+0.54}_{-0.63} \pm 0.39)\% \\ y''^{+} &= -(0.05^{+0.63}_{-0.67} \pm 0.50)\% \end{aligned}$$

$$\begin{aligned} x''^{-} &= (3.55^{+0.73}_{-0.83} \pm 0.65)\% \\ y''^{-} &= -(0.54^{+0.40}_{-1.16} \pm 0.41)\% \end{aligned}$$

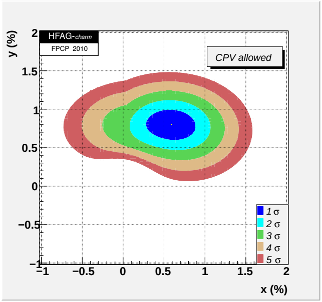
Results consistent with no CPV.

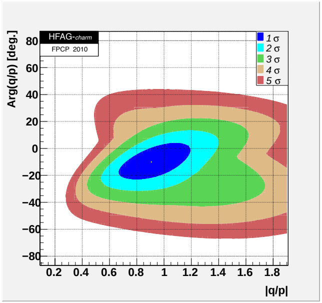


No mixing is excluded at 99% confidence level.

World average of mixing parameters

Heavy Flavor Averaging Group (HFAG) perfromes an average of 8 underlying physics parameters from currently 30 observables. [www.slac.stanford.edu/xorg/hfag/]





$$\mathbf{x} = (0.59 \pm 0.20)\%$$
$$\mathbf{y} = (0.80 \pm 0.13)\%$$

$$|q/p| = 0.91^{+0.19}_{-0.16}$$
$$\phi(^\circ) = -10.0^{+9.3}_{-8.7}$$

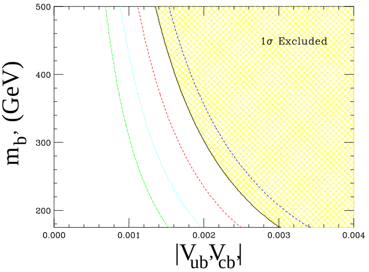
No mixing point $(x, y) = (0, 0)$ is excluded at 10.2σ, while no *CP* violation point $(|q/p|, \phi) = (1, 0)$ is consistent within 1σ.

Impact – Constraints on new physics models from mixing

E. Golowich *et al.*, PRD76,095009

- Constraints on new physics models from $D^0 - \overline{D}^0$ complementary to those obtained in B and K sector
  $\hookrightarrow$ FCNC transitions with *down-like* quarks in charm sector (unique feature)
- 21 NP models considered $\rightarrow$ 17 with useful constraints

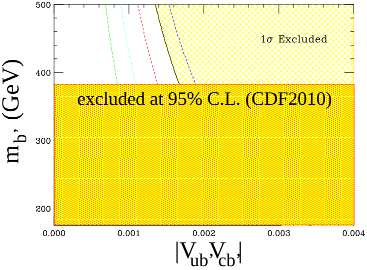
Example: quark b' from 4^{th} generation



E. Golowich *et al.*, PRD76,095009

- Constraints on new physics models from $D^0 - \overline{D}^0$ complementary to those obtained in B and K sector
  $\hookrightarrow$ FCNC transitions with *down-like* quarks in charm sector (unique feature)
- 21 NP models considered $\rightarrow$ 17 with useful constraints

Example: quark b' from 4^{th} generation



$|V_{ub'} V_{cb'}| < 0.002$

order of magnitude stronger constraint as from CKM unitarity

Providing complementary and improved constraints!

Time-integrated searches of *CP* Violation

- Searches for direct *CP* violation performed in total over 30 D^0, D^+ and D_s^+ decay modes in past 15 years
  - $\hookrightarrow$ Belle, BaBar, Cleo, CDF, FOCUS, E796, E687
- No evidence for *CP* violation found so far
  - $\hookrightarrow$ Sensitivity is in some cases reaching 0.2%
- Measurements statistical limited
  - $\hookrightarrow$ All measurements can be significantly improved!

$D^0 \to$	A_{CP} [%]	$D^+ \to$	A_{CP} [%]	$D_s^+ \to$	A_{CP} [%]
K^+K^-	-0.16 ± 0.23	$K_S^0\pi^+$	-0.72 ± 0.26	$K_S^0K^+$	-0.28 ± 0.41
$\pi^+\pi^-$	$+0.22 \pm 0.37$	$K_S^0K^+$	-0.09 ± 0.63	$K_S^0\pi^+$	$+6.5 \pm 2.5$
$\pi^+\pi^-\pi^0$	-0.23 ± 0.42	$K^+K^-\pi^+$	$+0.39 \pm 0.61$	$K^+K^-\pi^+$	$+0.3 \pm 1.4$
$K^-\pi^+\pi^0$	$+0.16 \pm 0.89$	$K^-\pi^+\pi^+$	-0.5 ± 1.0	$\pi^+\pi^-\pi^+$	$+2.0 \pm 4.7$
$K_S^0\pi^0$	$+0.10 \pm 1.3$	$K^-\pi^+\pi^+$	-0.5 ± 1.0	$K^+\pi^-\pi^+$	$+11.2 \pm 7.1$
$K^+K^-\pi^0$	$+1.00 \pm 1.7$	$K_S^0\pi^+\pi^0$	$+0.3 \pm 0.9$	$\pi^+\eta$	-8.2 ± 5.3
$\pi^0\pi^0$	$+0.10 \pm 4.8$	$\pi^+\pi^-\pi^+$	-1.7 ± 4.2	$\pi^+\eta'$	-5.5 ± 3.9
$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$

Full list of all *CPV* measurements is available at:
http://www.slac.stanford.edu/xorg/hfag/charm/index.html

Time-integrated searches of *CP* Violation

Key is to distinguish possible *CPV* asymmetry from detector effects and production asymmetry in reconstructed asymmetry

$$A^{\rm reco} = \frac{N_D^{\rm reco} - N_{\bar{D}}^{\rm reco}}{N_D^{\rm reco} + N_{\bar{D}}^{\rm reco}}$$

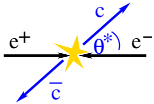
$$N_D^{\rm reco} = N_D^{\rm prod} \cdot \mathcal{B}(D \to f) \cdot \varepsilon_f \implies \text{if } A_i \ll 1 \implies \boxed{\mathbf{A^{reco} = A_{FB}^{D} + A_{CP}^{f} + A_{\epsilon}^{f}}}$$

A_{CP}
CP asymmetry

independent of any kinematic variable

A_{FB}
Production asymmetry

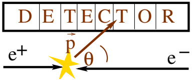
due to γ/Z interference in $e^+e^- \to c\bar{c}$ (only at e^+e^- coll.)



(anti-symmetric in $cos\theta_D^*$)

A_{ϵ}^{f}
Reconstruction asymmetry

$h^{\pm}$ reconstruction efficiency asymmetry

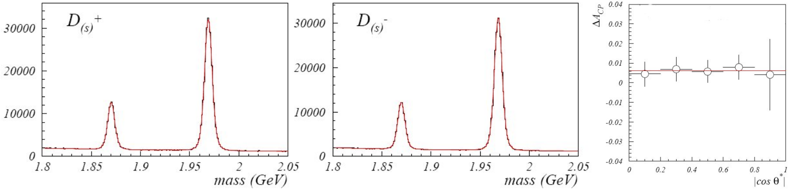


$(p^{\rm lab},\ cos\theta^{\rm lab})$

In order to control systematics $\mathbf{A_i}$'s are estimated on real data sample!

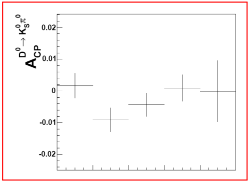
ΔA_{CP} between $D^+ \to \phi\pi^+$ and $D_s^+ \to \phi\pi^+$ and A_{CP} in $D^0 \to K_S^0 P^0$ (Belle preliminary)

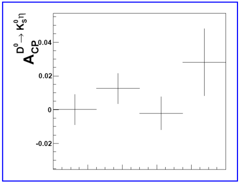
- ΔA_{CP} between $D^+ \to \phi\pi^+$ and $D_s^+ \to \phi\pi^+$

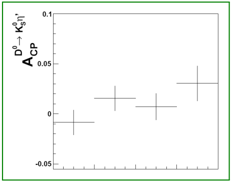


$$\Delta A_{CP} = (+0.62 \pm 0.30 \pm 0.15)\%$$

- A_{CP} in $D^0 \to K_S^0\pi^0$, $D^0 \to K_S^0\eta(\star)$ and $D^0 \to K_S^0\eta'(\star)$ $\star$ – first measurement







$A_{CP} = (-0.28 \pm 0.19 \pm 0.10)\%$ $(+0.54 \pm 0.51 \pm 0.13)\%$ $(+0.90 \pm 0.67 \pm 0.15)\%$

Search for *CP* Violation with *T*-odd correlations

Assuming *CPT* invariance: *T* violation $\Rightarrow$ *CP* violation

- Possible only in $\geq$ 4-body decay
  $\hookrightarrow D^0 \rightarrow K^- K^+ \pi^- \pi^+$
- *T*-odd quantity:

$$C_T \equiv \langle \vec{p}_{K^+} \cdot (\vec{p}_{\pi^+} \times \vec{p}_{\pi^-}) \rangle$$

- *T* violating asymmetry $\mathcal{A}_T$

$$D^0: \quad A_T = \frac{\Gamma(\ \ C_T>0)-\Gamma(\ \ C_T<0)}{\Gamma(\ \ C_T>0)+\Gamma(\ \ C_T<0)}$$

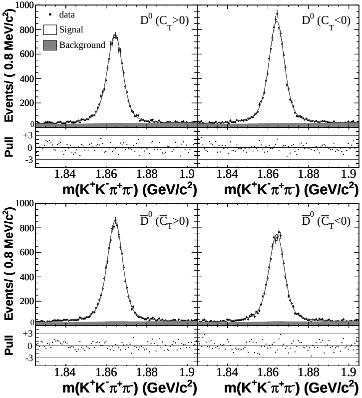
$$\overline{D}^0: \quad \overline{A}_T = \frac{\Gamma(-\overline{C}_T>0)-\Gamma(-\overline{C}_T<0)}{\Gamma(-\overline{C}_T>0)+\Gamma(-\overline{C}_T<0)}$$

$$\boxed{\mathcal{A}_T = \frac{1}{2}\left(A_T - \overline{A}_T\right)}$$

Bigi, hep-ph/0107102 (2001)

Bensalem et al., PRD66, 094004 (2002)

BaBar PRD81, 111103 (2010)



$$A_T = (-68.5 \pm 7.3 \pm 4.5) \times 10^{-3}$$

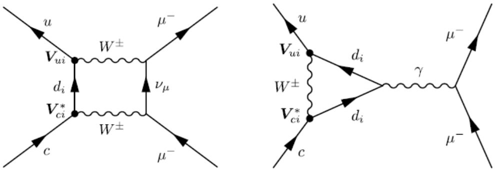
$$\overline{A}_T = (-70.5 \pm 7.3 \pm 3.9) \times 10^{-3}$$

$$\boxed{\mathcal{A}_T = (1.0 \pm 5.1 \pm 4.4) \times 10^{-3}}$$

A_T can be different from zero due to final state interactions, but $\mathcal{A}_T \neq 0$ represents *CP* violation.

Charm rare decays: $D^0 \to \ell^+\ell^-$ (Motivation)

- Standard Model:



$\hookrightarrow$ Flavor Changing Neutral Current decays ($D^0 \to \ell^+\ell^-$) are highly suppressed

$\hookrightarrow$ with long distance contributions $\mathcal{B} \sim 10^{-13}$

$\hookrightarrow$ Lepton Flavor Violating decays ($D^0 \to e^\pm\mu^\mp$) are forbidden

- New Physics:

$\hookrightarrow$ Flavor Changing Neutral Current transitions may be enhanced by many orders of magnitude

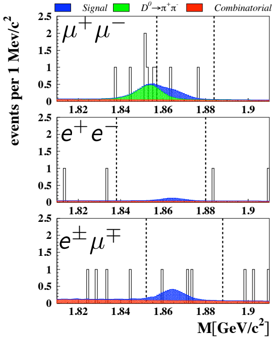
$\hookrightarrow$ R-parity violating SUSY: $\mathcal{B}(\mu^+\mu^-)$ up to 10^{-8}

$\hookrightarrow$ Leptoquarks: $\mathcal{B}(\mu^+\mu^-) \sim 8 \cdot 10^{-8}$

Golowich et. al., PRD79 114030 (2009); Dorsner et. al. PLB682 67 (2009)

Search for $D^0 \to \ell^+\ell^-$ at Belle and CDF

Belle [PRD81 091102 (2010)]



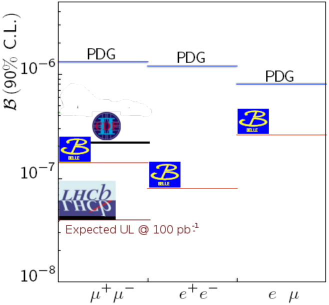
Channel	$N_{\ell\ell}$	$N_{\rm bkg}$	90% C.L. UL
Belle e^+e^-	0	1.7±0.2	7.9×10^{-8}
Belle $e^\pm\mu^\mp$	3	2.6±0.2	2.6×10^{-7}
Belle $\mu^+\mu^-$	2	3.1±0.1	1.4×10^{-7}
CDF $\mu^+\mu^-$	4	9±2	2.1×10^{-7}

CDF [arXiv:1008.5077]

$\hookrightarrow$ used less than 10% of available sample

$D^0 \to \pi^+\pi^-$ used as normalization channel:

$$\mathcal{B}(D^0 \to \ell^+\ell^-) = \frac{N_{\ell\ell}}{N_{\pi\pi}}\frac{\varepsilon_{\pi\pi}}{\varepsilon_{\ell\ell}}\mathcal{B}(D^0 \to \pi^+\pi^-)$$



UL in $D^0 \to \ell^+\ell^-$ disfavors leptoquark contribution as explanation of f_{D_s} anomaly.

Conclusions

- Collective evidence for $D^0 - \overline{D}^0$ mixing are compelling
  - No single measurement exceeds 5σ
  - The no-mixing point is excluded at around 10σ
  - The WA of x and y seem consistent with SM expectations
  - Providing strong constraints for some New Physics models
- No evidence of CP violation (at the level of 0.3%)
- Still room for improvements using existing data sets
  - exploiting the entire data sets and covering all the sensitive measurements (Belle, BaBar, CDF)
- Is the best yet to come?

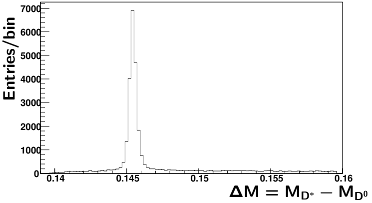
Backup slides

Common steps in $D^0 - \overline{D}^0$ mixing and CPV measurements

1. Tag the flavor of the produced neutral D meson
2. Measure proper decay time

Flavor tagging

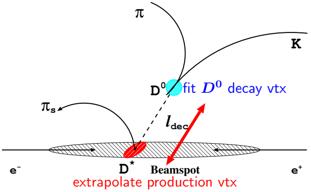
- require $\mathbf{D^{*+} \to D^0\pi^+}$
  - $\hookrightarrow$ flavor tagging with π's charge
  - $\hookrightarrow$ background suppression with $\Delta M = M_{D^*} - M_{D^0}$



eliminate D^0s from $b \to c$ with $p_{\rm CMS}^{D^*} > 2.5$ GeV$/c^2$ (B-fact.) or use impact parameter (hadron col.)

Proper decay time

- Vertexing with beam point constraint



$$t = \frac{l_{dec}}{c\beta\gamma}\ , \quad \beta\gamma = \frac{p_{D^0}}{M_{D^0}}$$

σ_t uncertainty of the measurement typically between $1/6\tau_{D^0}$ and $1/2\tau_{D^0}$

Mixing probability

- probability to observe an initial M^0 as M^0 or $\overline{M}^0$ after time t

$$\mathcal{P}_{\mathrm{non-mix}}(t) = |\langle M^0(t)|M^0\rangle|^2 = \frac{1}{2}e^{-\Gamma t}\left[cosh(y\Gamma t) + cos(x\Gamma t)\right]$$

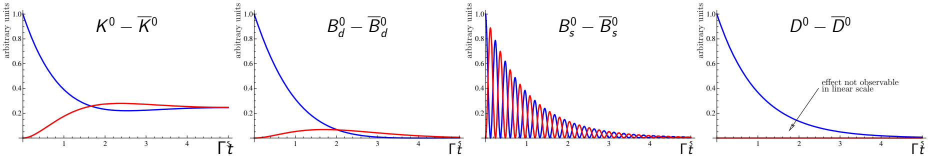
$$\mathcal{P}_{\mathrm{mix}}(t) = |\langle M^0(t)|\overline{M}^0\rangle|^2 = \frac{1}{2}e^{-\Gamma t}\left[cosh(y\Gamma t) - cos(x\Gamma t)\right]$$

- time integrated mixing rate

$$R_M = \frac{\int_0^\infty \mathcal{P}_{\mathrm{mix}}(t)dt}{\int_0^\infty \mathcal{P}_{\mathrm{non-mix}}(t)dt} = \frac{x^2+y^2}{2+x^2-y^2}$$

M^0	x	y	R_M
K^0	0.946	0.997	0.994
B_d^0	0.776	< 0.01	0.23
B_s^0	26.1	0.15	0.997
D^0	0.01	0.01	**10^{-4}**

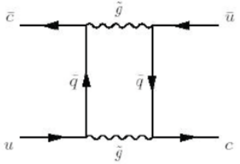
1 out of 10^4 D^0 mesons oscillates before it decays



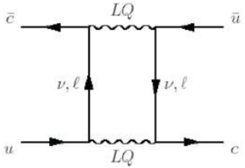
Large sample of D^0 mesons needed to observe $D^0 - \overline{D}^0$ mixing

New Physics in Charm Mixing

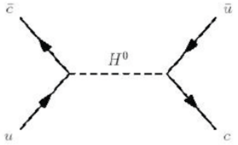
SUSY



Leptoquarks



Extended Higgs

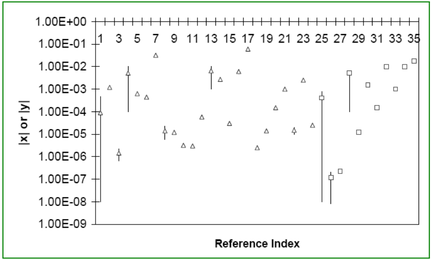


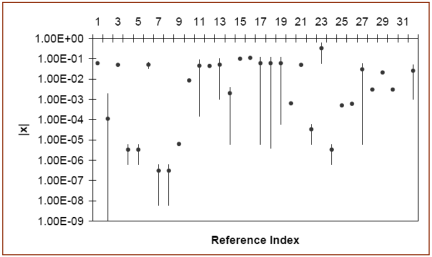
- Possible New Physics contributions can increase x, while y is mostly unaffected

  $\hookrightarrow$ $|x| \gg |y|$ would be a hint of New Physics

Compilation of predictions for x and y

Compilation of SM predictions for $|x|$ ($\triangle$) and $|y|$ ($\square$)
and New Physics predictions for $|x|$ ($\bullet$)

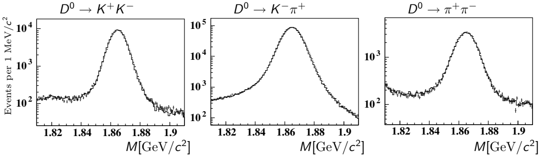




A. Petrov, Int.J.Mod.Phys.A21, 5686;

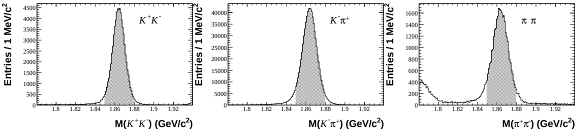
Mixing and CPV in $D^0 \to K^+K^-$, $\pi^+\pi^-$ decays

- Belle tagged analysis (540 fb^{-1}): PRL98, 211803 (2007)



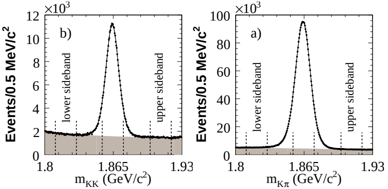
$D^0 \to$	Sig. yield	Purity
$K^-\pi^+$	1.22M	99%
K^+K^-	111k	98%
$\pi^+\pi^-$	49k	92%

- BaBar tagged analysis (384 fb^{-1}): PRD78, 011105 (2008)



$D^0 \to$	Sig. yield	Purity
$K^-\pi^+$	731k	99.9%
K^+K^-	70k	99.6%
$\pi^+\pi^-$	31k	98%

- BaBar untagged analysis (384 fb^{-1}): arXiv:0908.0761

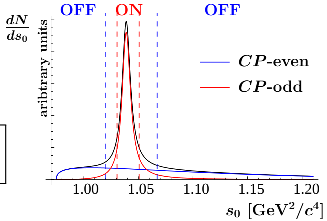


$D^0 \to$	Sig. yield	Purity
$K^-\pi^+$	2.71M	94.2%
K^+K^-	264k	80.9%

4× the size of the tagged sample and independent arXiv:0905.4185 (PRD accepted) [673 fb^{-1}]

Measurement of lifetime difference between CP-even and CP-odd eigenstates

- $\sqrt{s_0} = m_{K^+K^-}$ dependent CP mixture
  - $\hookrightarrow$ ON region: mainly CP-odd ($\phi(1020)K^0_S$)
  - $\hookrightarrow$ OFF region: mainly CP-even ($a_0(980)^0 K^0_S$)



$$\frac{d^2N(s_0,t)}{ds_0\,dt} \propto a_1(s_0)e^{-(1+y_{CP})t/\tau_{D^0}} + a_2(s_0)e^{-(1-y_{CP})t/\tau_{D^0}}$$

$a_{1,2}(s_0) = \int |\mathcal{A}_{1,2}(s_0,s_+)|^2 ds_+; \sqrt{s_+} = m_{K^0_S K^+}; \mathcal{A}_{1,2} = \frac{1}{2}(\mathcal{A} \pm \overline{\mathcal{A}})$

- Effective lifetimes in ON and OFF regions

$\hookrightarrow$ $$\tau_{\rm ON,OFF} = [1 + (1-2f_{\rm ON,OFF})y_{CP}]\tau_{D^0} \quad \Rightarrow \quad y_{CP} = \frac{1}{f_{\rm ON} - f_{\rm OFF}}\left(\frac{\tau_{\rm OFF}-\tau_{\rm ON}}{\tau_{\rm OFF}+\tau_{\rm ON}}\right)$$

$\hookrightarrow$ $f_{\rm ON}, f_{\rm OFF}$ are CP-even fractions in ON and OFF regions, determined using 8-resonant Dalitz model (REF!!!)

$$y_{CP} = +(0.11 \pm 0.61(\text{stat.}) \pm 0.52(\text{syst.}))\%$$

Mixing parameters in $D^0 \to K_S^0 K^+ K^-$ and $D^0 \to K_S^0 \pi^+ \pi^-$

TABLE I: Results from the mixing fits. The first uncertainty is statistical, the second systematic and the third systematic from the amplitude model. For the nominal fit, the corresponding correlation coefficients between x and y are 3.5%, 16.0% and −2.7%, respectively.

Fit type	$x/10^{-3}$	$y/10^{-3}$
Nominal	$1.6 \pm 2.3 \pm 1.2 \pm 0.8$	$5.7 \pm 2.0 \pm 1.3 \pm 0.7$
$K_S^0 \pi^+ \pi^-$	2.6 ± 2.4	6.0 ± 2.1
$K_S^0 K^+ K^-$	-13.6 ± 9.2	4.4 ± 5.7
D^0	0.0 ± 3.3	5.5 ± 2.8
$\overline{D}^0$	3.3 ± 3.3	5.9 ± 2.8

Mixing in semileptonic decays $D^0 \to K^{(*)-}\ell^+\nu_\ell$

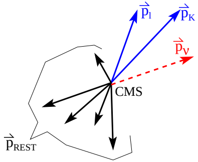
U. Bitenc *et al.* [Belle Collaboration], PRD77, 112003 (2008). [$\mathcal{L}$ =492 fb^{-1}]

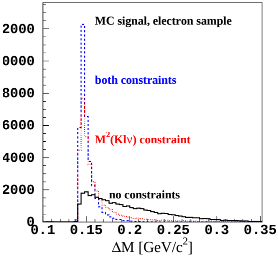
- Wrong sign (WS) charge combination accessible only via mixing

	Flavor at production		Flavor at decay	
without mixing	$D^{*+} \to D^0\pi^+$		$D^0 \to K^-\ell^+\nu_\ell$	**RS**
with mixing	$D^{*+} \to D^0\pi^+$	$D^0 - \overline{D}^0$	$\overline{D}^0 \to K^+\ell^-\nu_\ell$	**WS**

Neutrino reconstruction:

- $P_\nu = P_{\rm cms} - P_{K\ell} - P_{\rm rest}$
- $M^2_{K\ell\nu} = m^2_{D^0}$ & $(P^*_\nu)^2 = 0$



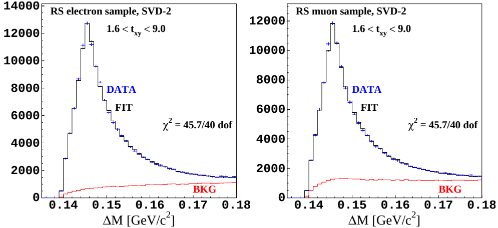


Time integrated mixing rate:

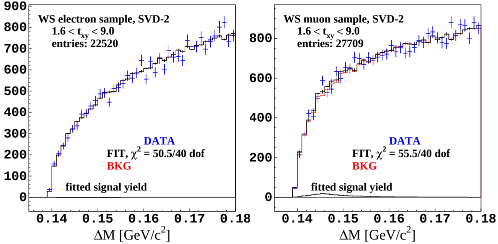
$$R_M \simeq \frac{x^2+y^2}{2} = \frac{N_{\rm WS}}{N_{\rm RS}}$$

Mixing in semileptonic decays $D^0 \to K^{(*)-}\ell^+\nu_\ell$

RS events

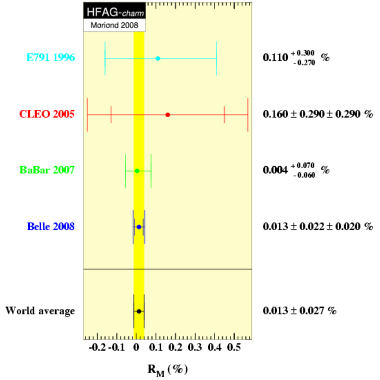


WS events



No WS charge combinations observed.

$$R_M = (1.3 \pm 2.2 \pm 2.0) \times 10^{-4}$$
$$R_M < 6.1 \times 10^{-4} \text{@ 90\% C.L.}$$



http://www.slac.stanford.edu/xorg/hfag/

Future Prospects

TABLE V: Expected precision (σ) on the measured quantities using methods described in the text for Super$B$ with an integrated luminosity of 75 ab^{-1} at Super$B$ at 10 GeV, 300 fb^{-1} ($\sim$ two months) running at charm threshold with Super$B$, and LHCb with 10 fb^{-1}[13].

Mode	Observable	$\Upsilon(4S)$ (75 ab^{-1})	$\psi(3770)$ (300 fb^{-1})	LHCb (10 fb^{-1})
$D^0 \to K^+\pi^-$	x'^2	3×10^{-5}		6×10^{-5}
	y'	7×10^{-4}		9×10^{-4}
$D^0 \to K^+K^-$	y_{CP}	5×10^{-4}		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		$(1-2) \times 10^{-3}$	
	$\cos\delta$		$(0.01-0.02)$	

arXiv:0810.1312

FutureProspects

Table 5.23: Expected number of reconstructed $D^{*+} \to D^0\pi^+$, $D^0 \to K^-\pi^+$ decays at different facilities (projected using [292], [293], [294], [295]). †For charm factory the expected yield of $\Psi(3770) \to D^0\bar{D}^0$, $D^0 \to K^-\pi^+$, $\bar{D}^0 \to K^+\pi^-$ is quoted.

Facility	num. of $D^{*+} \to D^0\pi^+$, $D^0 \to K^-\pi^+$	int. luminosity [fb^{-1}]	Comment
existing B factories	2.5×10^6	1000	final data set
Super-KEKB	14×10^6	5000	purity $\sim 99\%$
Charm factory†	4×10^4	20	both D^0's reconstructed; $D^0\bar{D}^0$ in coherent state
Tevatron	0.5×10^6	0.35	
LHCb	15×10^6	2	

http://belle2.kek.jp/physics.html

FutureProspects

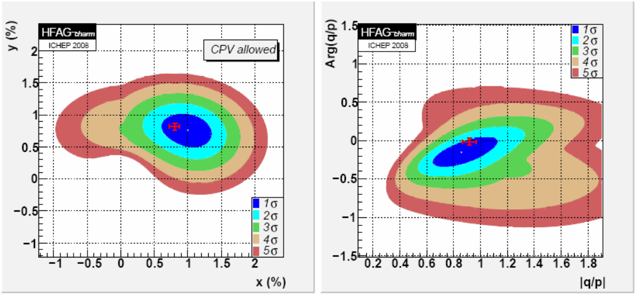


Figure 5.67: Left: The probability contours for the current world average values of the mixing parameters x and y [338]. The error bars denote the expected accuracy on the parameters with 50 ab^{-1} following from the extrapolation of results using K^+K^-, $\pi^+\pi^-$, $K^+\pi^-$ and $K_S\pi^+\pi^-$ final states. Right: The probability contours for the current world average values of the CPV parameters $|q/p|$ and ϕ [338]. The error bars denote the expected accuracy with the same assumptions as above.

http://belle2.kek.jp/physics.html

World average

$$R_M = \frac{1}{2}(x^2 + y^2)$$

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

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

$$\begin{pmatrix} x'' \\ y'' \end{pmatrix}_{K^+\pi^-\pi^0} = \begin{pmatrix} \cos\delta_{K\pi\pi} & \sin\delta_{K\pi\pi} \\ -\sin\delta_{K\pi\pi} & \cos\delta_{K\pi\pi} \end{pmatrix} \begin{pmatrix} x \\ y \end{pmatrix}$$

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

$$A_M = \frac{|q/p|^2 - |p/q|^2}{|q/p|^2 + |p/q|^2}$$

$$x'^{\pm} = \left(\frac{1 \pm A_M}{1 \mp A_M}\right)^{1/4} (x' \cos\phi \pm y' \sin\phi)$$

$$y'^{\pm} = \left(\frac{1 \pm A_M}{1 \mp A_M}\right)^{1/4} (y' \cos\phi \mp x' \sin\phi)$$

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

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

HFAG: arXiv:0808.1297 or
http://www.slac.stanford.edu/xorg/hfag/

χ^2 fit of 8 underlying parameters using all measured quantaties (30 observables) including correlations between them

Parameter	Value
x	$(0.59 \pm 20)\%$
y	$(0.80 \pm 0.13)\%$
δ	$(27.8^{+11.2}_{-13.2})^\circ$
$\delta_{K\pi\pi}$	$(23.2^{+22.3}_{-23.3})^\circ$
R_D	$(0.3319 \pm 0.0081)\%$
A_D	$(-2.0 \pm 2.4)\%$
$\|q/p\|$	$0.91^{+0.19}_{-0.16}$
ϕ	$(-10.0^{+9.3}_{-8.7})^\circ$

$(x, y) = (0, 0)$ excluded at 10.2σ

No CPV within 1σ

CPV backup

Number of reconstructed decays:

$$N^{reco} = N^{prod}_{D^{*+}} \cdot \mathcal{B}(D^{*+} \to D^0\pi^+) \cdot \mathcal{B}(D^0 \to h^+h^-) \cdot \epsilon_{hh} \cdot \epsilon_\pi$$

- Contributions to asymmetry in N^{reco}:
  - production (A_{FB})
  - branching fractions (A_{CP})
  - efficiencies (A_ϵ)
- If asymmetries are small ($A_{FB}, A_{CP}, A_\epsilon \ll 1$) it is easy to see, that the asymmetry in N^{reco} is:

$$A^{reco} = A^{D^{*+}}_{FB} + A^{D^0\pi}_{CP} + A^{hh}_{CP} + A^{hh}_\epsilon + A^\pi_\epsilon$$

- Some are zero: $A^{D^0\pi}_{CP} = 0$ (strong decay), $A^{hh}_\epsilon = 0$ (same final state)

CPV backup

- Production asymmetry (A_{FB}) is due to interference in $e^+e^- \rightarrow c\bar{c}$ (mediated by virtual γ or Z^0)
  - anti-symmetric function of $\cos\theta^*$ (follows from CP conservation)

$$A_{FB}(\cos\theta^*) = -A_{FB}(-\cos\theta^*)$$

- Measured asymmetry:

$$A^{reco} = A_{FB}^{D^{*+}}(\cos\theta^*) + A_{CP}^{hh} + A_{\epsilon}^{\pi}(\theta, p)$$

- Asymmetry in π_{slow} efficiency $A_{\epsilon}^{\pi}(\theta, p)$ can be measured in $D^0 \rightarrow K^-\pi^+$ by using tagged and untagged decays
- Corrected asymmetry

$$A_{corr}^{reco} = A^{reco} - A_{\epsilon}^{\pi}(\theta, p)$$

$$A_{corr}^{reco}(\cos\theta^*) = A_{FB}^{D^{*+}}(\cos\theta^*) + A_{CP}^{KK}$$

CPV backup

Number of reconstructed tagged and untagged $D^0 \to K^- \pi^+$ decays:

$$N^{\mathrm{untag}} = N^{\mathrm{prod}}_{D^0} \cdot \mathcal{B}(D^0 \to K^- \pi^+) \cdot \epsilon_{K\pi}$$
$$N^{\mathrm{tag}} = N^{\mathrm{prod}}_{D^{*+}} \cdot \mathcal{B}(D^{*+} \to D^0 \pi^+_S) \cdot \mathcal{B}(D^0 \to K^- \pi^+) \cdot \epsilon_{K\pi} \cdot \epsilon_\pi$$

Measured asymmetry:

$$A^{\mathrm{untag}} = A^{D^0}_{FB} + A^{K\pi}_{CP} + A^{K\pi}_{\epsilon}$$
$$A^{\mathrm{tag}} = A^{D^0}_{FB} + A^{K\pi}_{CP} + A^{K\pi}_{\epsilon} + A^{\pi}_{\epsilon}$$

Assuming $A^{D^0}_{FB} = A^{D^{*+}}_{FB}$:

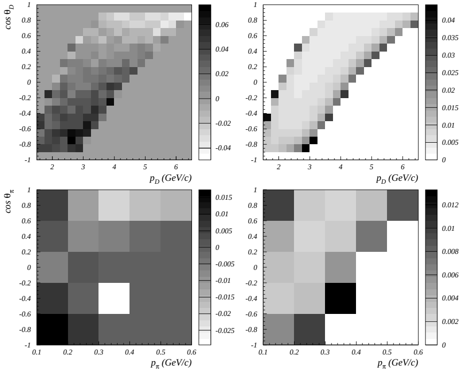
$$A^{\pi}_{\epsilon} = A^{\mathrm{tag}} - A^{\mathrm{untag}}$$

$A^{K\pi}_{\epsilon}$ and A^{π}_{ϵ} are functions of corresponding phase spaces.

CPV in $D^0 \to K^-K^+, \pi^-\pi^+$ decays backup (time-integrated)

Determination of soft pion π_s asymmetry:

- using tagged and untagged $D^0 \to K^-\pi^+$ decays



$\Longrightarrow$ asymmetry map of the untagged $K\pi$ sample (left) with uncertainty (right)

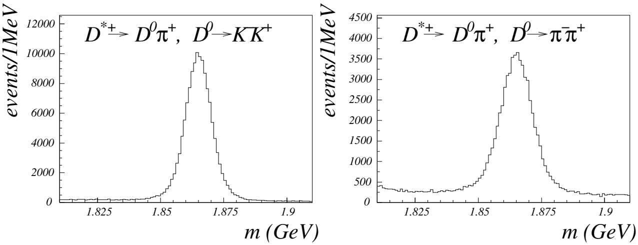
$\hookrightarrow$ weight D^0 candidates in the π_s tagged $K\pi$ sample

$\Longrightarrow$ asymmetry map of the slow pion efficiency (left) with uncertainty (right)

$\hookrightarrow$ weight D^0 yields to correct for tagging asymmetry

Averaging over the phase space the correction due to the π_S efficiency is found to be $(0.76 \pm 0.09\%)$.

CPV in $D^0 \rightarrow K^-K^+, \pi^-\pi^+$ decays backup (time-integrated)



The signal counting was performed by the mass-sideband subtraction.

Systematics:

Signal counting

	KK	$\pi\pi$
Signal shape diff.	0.02%	0.04%
Sideband position	0.01%	0.03%
Random π_{slow} bkg.	0.03%	0.03%
Total	0.04%	0.06%

π_S eff. correction

	KK	$\pi\pi$
Statistics of $K\pi$	0.09%	0.09%
Binning	0.03%	0.02%
Min. num. events/bin	0.04%	0.03%
Total	0.10%	0.10%

A_{CP} extraction

	KK	$\pi\pi$
Binning	0.03%	0.03%
SVD1/2	0.03%	0.00%
Total	0.04%	0.03%

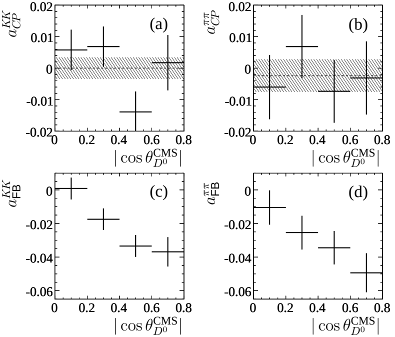
Time integrated CPV in $D^0 \to K^+K^-, \pi^+\pi^-$ decays

$$A^{\rm reco}_{\rm corr}(cos\theta^*) = \frac{N(D^0) - N(\bar{D}^0)}{N(D^0) + N(\bar{D}^0)}$$

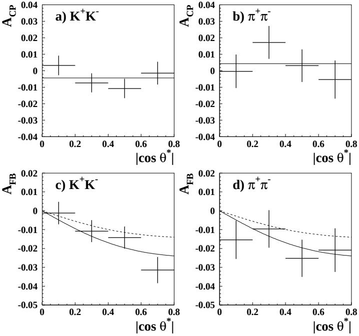
$$= A_{FB}^{D^{*+}} + A_{CP}^{hh}$$

- $A_{CP} = \frac{A^{\rm reco}_{\rm corr}(cos\theta^*) + A^{\rm reco}_{\rm corr}(-cos\theta^*)}{2}$
- $A_{FB} = \frac{A^{\rm reco}_{\rm corr}(cos\theta^*) - A^{\rm reco}_{\rm corr}(-cos\theta^*)}{2}$

BaBar



Belle



PRL100, 061803

PLB670, 190

$A_{CP}^{KK} = (\ \ 0.00 \pm 0.34(\mathrm{stat}) \pm 0.13(\mathrm{syst}))\%$

$A_{CP}^{\pi\pi} = (-0.24 \pm 0.52(\mathrm{stat}) \pm 0.22(\mathrm{syst}))\%$

$A_{CP}^{KK} = (-0.41 \pm 0.30(\mathrm{stat}) \pm 0.11(\mathrm{syst}))\%$

$A_{CP}^{\pi\pi} = (+0.41 \pm 0.52(\mathrm{stat}) \pm 0.12(\mathrm{syst}))\%$

CPV in $D^+_{(s)} \to PP$ decays

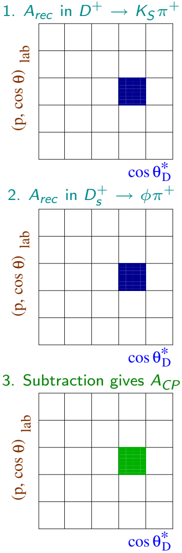
What is so special about $D^+_{(s)} \to K_S h^+$ decays?

- $D^+ \to K_S\pi^+$ appears to be a CF mode, however the same final state can be reached through a DCS amplitude
  $\hookrightarrow D^+ \to \overline{K}^0\pi^+ / K^0\pi^+ \to K_S\pi^+$
  ⋆ two interfering amplitudes generate asymmetry $\sim \mathcal{O}(10^{-4})$
- The CP impurity in the K_S wave function induces larger asymmetry
  ⋆ $A_{CP}(D^+ \to K_S\pi^+) \simeq \frac{|q_K|^2-|p_K|^2}{|q_K|^2+|p_K|^2} \simeq -(0.332 \pm 0.006)\%$

$D^+_{(s)} \to K_S \pi^+$ channels

Use $D_s^+ \to \phi\pi^+$ decays to correct for:

- production asymmetry A_{FB}
- reconstruction asymmetry $A_\epsilon^{\pi^+}$
- no asymmetry due to $\phi \to K^+K^-$ reconstruction



Method

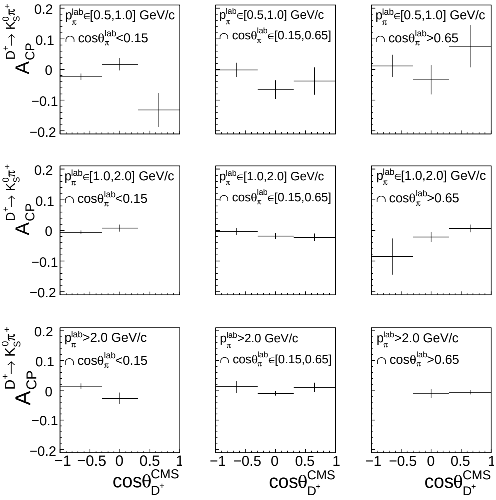
In each $(p_\pi^{\rm lab},\ cos\theta_\pi^{\rm lab}, cos\theta_D^*)$ bin

1. Measure $A_{rec}^{D^+_{(s)} \to K_S\pi^+} = A_{FB}^{D_{(s)}} + A_\epsilon^{\pi^+} + A_{CP}^{D_{(s)} \to K_s^0\pi^+}$
2. Measure $A_{rec}^{D_s^+ \to \phi\pi^+} = A_{FB}^{D_s} + A_\epsilon^{\pi^+}$
3. Subtract measured asymmetries

$$A_{CP}^{D^+ \to K_S\pi^+} = A_{rec}^{D^+ \to K_S\pi^+} - A_{rec}^{D_s^+ \to \phi\pi^+}$$

$D^+_{(s)} \to K_S\pi^+$ channels

Measured $A_{CP}^{D^+\to K_S\pi^+}$ in bins of ($p_\pi^{\rm lab}$, $cos\theta_\pi^{\rm lab}$, $cos\theta_{D^+_{(s)}}^{\rm CMS}$)



$$A_{CP}^{D^+\to K_S\pi^+} = -(0.71 \pm 0.26)\%$$
$$A_{CP}^{D_s^+\to K_S\pi^+} = \quad (5.45 \pm 2.50)\%$$

$D^+_{(s)} \to K_S K^+$ channels

Use $D_s^+ \to \phi\pi^+$ and $D^0 \to K^-\pi^+$ decays to correct for:

- production asymmetry A_{FB}
- reconstruction asymmetry $A_\epsilon^{K^+}$

Method

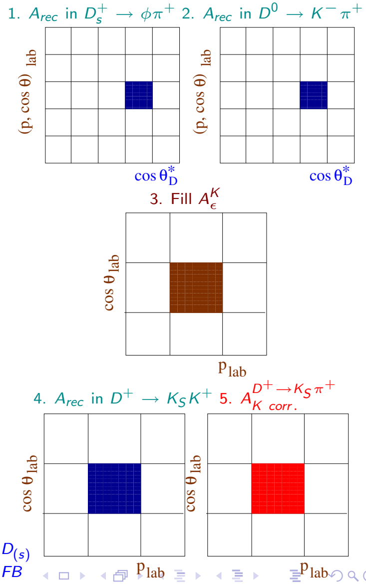
In each $(p_\pi^{\rm lab},\ cos\theta_\pi^{\rm lab}, cos\theta_D^*)$ bin

1. Measure $A_{rec}^{D_s^+ \to \phi\pi^+} = A_{FB}^{D_s} + A_\epsilon^\pi$
2. Measure $A_{rec}^{D^0 \to K^-\pi^+} = A_{FB}^{D^0} + A_\epsilon^\pi + A_\epsilon^K$

In each $(p_K^{\rm lab},\ cos\theta_K^{\rm lab})$ bin

1. Obtain $A_\epsilon^K = A_{rec}^{D^0 \to K^-\pi^+} - A_{rec}^{D_s \to \phi\pi^+}$
2. Measure $A_{rec}^{D^+_{(s)} \to K_S K^+} = A_{FB}^{D_{(s)}} + A_\epsilon^{K^+} + A_{CP}^{D_{(s)} \to K_s^0 K^+}$
3. Obtain

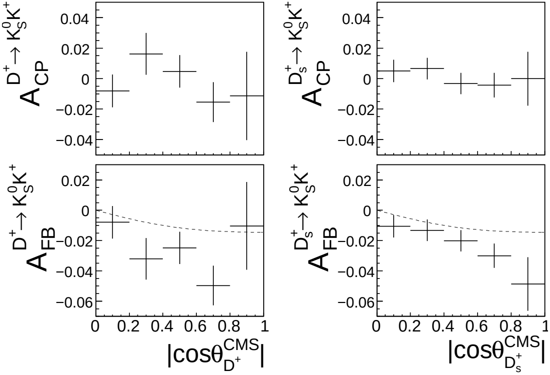
$$A_{K\ corr.}^{D^+ \to K_S\pi^+} = A_{rec}^{D^+ \to K_S\pi^+} - A_{\pi\ corr.}^{D^0 \to K^-\pi^+} = A_{CP}^{D^+ \to K_S\pi^+} + A_{FB}^{D_{(s)}}$$



Using (anti-)symmetric properties of A_{CP} (A_{FB}) in $cos\theta_D^{\mathrm{CMS}}$

$$A_{CP}^D = \frac{1}{2}\left[A^D_{K\ corr}(cos\theta_D^{\mathrm{CMS}}) + A^D_{K\ corr}(-cos\theta_D^{\mathrm{CMS}})\right]$$

$$A_{FB}^D = \frac{1}{2}\left[A^D_{\pi\ corr}(cos\theta_D^{\mathrm{CMS}}) - A^D_{\pi\ corr}(-cos\theta_D^{\mathrm{CMS}})\right]$$



$$A_{CP}^{D^+\to K_S K^+} = -(0.16 \pm 0.58)\%$$
$$A_{CP}^{D_s^+\to K_S K^+} = (0.12 \pm 0.36)\%$$

Systematics

Source		$D^+ \to K_S\pi^+$	$D_s^+ \to K_S\pi^+$	$D^+ \to K_S K^+$	$D_s^+ \to K_S K^+$
$A_{\rm rec}^{D_s^+\to\phi\pi^+}$	$D_s^+ \to \phi\pi^+$ statistics	0.18	0.18	-	-
	$A_{\rm rec}^{D_s^+\to\phi\pi^+}$ binning	0.03	0.03	-	-
	$M(K^+K^-)$ window	0.03	0.03	-	-
$A_\epsilon^{K^-}$	$D_s^+ \to \phi\pi^+$ statistics	-	-	0.18	0.18
	$A_{\rm rec}^{D_s^+\to\phi\pi^+}$ binning	-	-	0.03	0.03
	$M(K^+K^-)$ window	-	-	0.03	0.03
	$D^0 \to K^-\pi^+$ statistics	-	-	0.06	0.06
	$A_\epsilon^{K^-}$ binning	-	-	0.04	0.04
	Possible $A_{CP}^{D^0\to K^-\pi^+}$	-	-	0.01	0.01
$\cos\theta_{D_{(s)}^+}^{\rm CMS}$ binning		-	-	0.06	0.06
Fitting		0.04	0.27	0.12	0.05
$K^0/\bar{K}^0$-material effects		0.06	0.06	0.06	0.06
Total		0.20	0.33	0.25	0.22

Table of systematic uncertainty in A_{CP} (%).

CPV in $D^+_{(s)} \to K_S h^+$ decays: Results

A_{CP} in	Belle (%)	Cleo (%)	HFAG WA (%)	A_{CP}^{SM} (%)
$D^+ \to K_S\pi^+$	$-0.71\pm0.19\pm0.20$	$-1.3\pm0.7\pm0.3$	-0.72 ± 0.26	$-0.332^{\dagger}$
$D_s^+ \to K_S\pi^+$	$+5.45\pm2.50\pm0.33$	$+16.3\pm7.3\pm0.3$	$+6.5\pm2.5$	$+0.332$
$D^+ \to K_S K^+$	$-0.16\pm0.58\pm0.25$	$-0.2\pm1.5\pm0.9$	-0.09 ± 0.63	-0.332
$D_s^+ \to K_S K^+$	$+0.12\pm0.36\pm0.22$	$+4.7\pm1.8\pm0.9$	$+0.28\pm0.41$	$-0.332^{\dagger}$

† Interference of CF and DCS amplitudes is neglected.

- Major source of systematics is due to $h^{\pm}$ reconstruction asymmetry correction (limited sample sizes of $D_s^+ \to \phi\pi^+$ and $D^0 \to K^-\pi^+$)
  - Scales with luminosity!