Recent Results and Trends in Charm Physics

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Prologue

> *" An important goal in charm physics is not just*
> *to observe CP Violation in D decays*
> *but also to understand its origin”*
>
> -- *Ikaros Bigi*

Tools available:

Hadron:	LHCb
Charm threshold:	BES3 (~10 fb^{-1}), INFN (5 ab^{-1}?)
At Y(4S):	Belle2 (~50 ab^{-1})

We are off to a good start:

BaBar and Belle, evidence for D^0-$\overline{D}^0$ mixing confirmed by CDF ?
LHCb, observation of D^0-$\overline{D}^0$ mixing at 9.1σ level

LHCb, evidence for 3.5σ direct CPV in $D^0 \rightarrow h^+h^-$

CPV in mixing – not yet, but …?

Outline

- D^0 Mixing and evidence for it - .
  - Analysis methods, new results
- Projection to the new generation of experiments
  - Use of threshold data
- Prospects for searches for *CPV* in mixing
  - Time-Dependent CP asymmetry
- Time-integrated and direct CPV

Why Charm is Interesting

- Charm was “invented” (GIM mechanism) to account for small FCNC interactions in nature.
- In this scenario, for the charm sector,
  - *CP* violation (*CPV*) is also expected to be small, mostly because weak phases are small ($\mathrm{Arg}\{V_{cd}\} \sim \lambda^4$);
  - Mixing is greatly suppressed;
  - Many charm particle decays are also small.
  - Brings with it the prospect of studying the role of the up-type quarks.
- With SM “backgrounds” so small, charm is a good place to look for new physics (*NP*).
- Some of this was discussed almost 40 years ago !

  A. Pais and S.B. Treiman, Phys. Rev. **D12**, 2744 (1975).

CKM Matrix - Wolfenstein Expansion

- So

$$V_{CKM} = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{13}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix}$$

- The terms have a numerical hierarchy that suggests an expansion in powers of the Cabibbo angle $\lambda = V_{us}$:

$$V_{CKM} \approx \begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^3 \\ A\lambda^3(1-\rho - i\eta) & A\lambda^3 & 1 \end{pmatrix} + \mathcal{O}(\lambda^4)$$

where A, ρ and η are parameters of order one.

Expansion of CKM to O(λ^5)

- Wolfenstein expansion preserves unitarity below λ^4.
- Preserving unitarity to all orders is possible (Buras, Lautenbacher and Ostermaier, 1994) with parameters:

$$\begin{aligned} s_{12} &= \lambda \\ s_{23} &= A\lambda^2 \\ s_{13}e^{-i\delta} &= A\lambda^3(\rho - i\eta) \end{aligned}$$

- At order λ^5, this leads to

$$\begin{pmatrix} 1-\lambda^2/2-\lambda^4/8 & \lambda & A\lambda^3\boxed{(\bar{\rho}-i\bar{\eta})}(1+\lambda^2/2) \\ -\lambda+A^2\lambda^5\boxed{[1-2(\bar{\rho}+i\bar{\eta})]/2} & 1-\lambda^2/2-\lambda^4(1+4A^2)/8 & A\lambda^2 \\ A\lambda^3\boxed{[1-\bar{\rho}-i\bar{\eta}]} & -A\lambda^2+A\lambda^4\boxed{[1-2(\bar{\rho}+i\bar{\eta})]/2} & 1-A^2\lambda^4/2 \end{pmatrix} + \mathcal{O}(\lambda^6).$$

Phase of V_{ub}
is STILL $-\gamma$

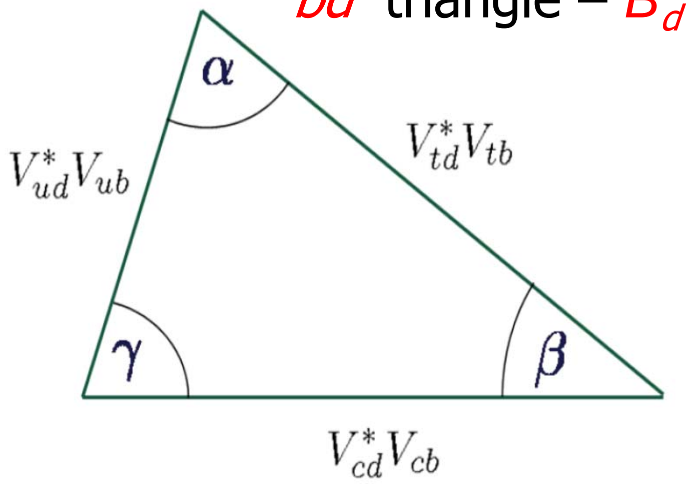
Phase of V_{td}
is STILL $-\beta$

Phase "β_c"
of order λ^4

V_{ts} acquires a
phase of order λ^2

Weak phases in B_d and *D* decays

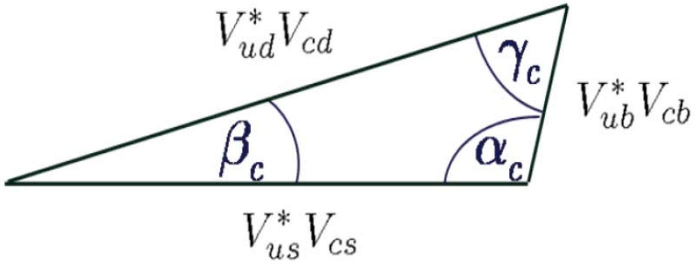
bd triangle – B_d decays, phases are large.



$$\begin{aligned}\alpha &= \left[V_{td}V_{tb}^*/V_{ud}V_{ub}^*\right] = (89.4 \pm 4.3)^\circ \\ \beta &= \left[V_{cd}V_{cb}^*/V_{cd}V_{cb}^*\right] = (22.1 \pm 0.6)^\circ \\ \gamma &= \left[V_{ud}V_{ub}^*/V_{cd}V_{cb}^*\right] = (68.4 \pm 3.7)^\circ\end{aligned}$$

Tree phases β_c are tiny
BUT *b*-penguin phase
$\gamma_c = \gamma$ is large.

cu triangle – *D* decays



$$\begin{aligned}\alpha_c &= \left[V_{ub}^*V_{cb}/V_{us}^*V_{cs}\right] = (111.5 \pm 4.2)^\circ \\ \beta_c &= \left[V_{ud}^*V_{cd}/V_{us}^*V_{cs}\right] = (0.0350 \pm 0.0001)^\circ \\ \gamma_c &= \left[V_{ub}^*V_{cb}/V_{ud}^*V_{cd}\right] = (68.4 \pm 0.1)^\circ\end{aligned}$$

Bevan, Inguglia, BM: Phys.Rev. D83 (2011) 051101

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D^0 Mixing

- Flavour oscillations in the neutral *D* system arise from the propagation of two mass eigenstates D_1 and D_2 that comprise the flavour states

$$i\frac{\partial}{\partial t}\begin{pmatrix} |D^0> \\ |\bar{D}^0> \end{pmatrix} = \left(\mathcal{M} - \frac{i}{2}\mathcal{G}\right)\begin{pmatrix} |D^0> \\ |\bar{D}^0> \end{pmatrix}$$

$$\begin{aligned} |D_1> &= p|D^0> + q|\bar{D}^0> \\ |D_2> &= p|D^0> - q|\bar{D}^0> \end{aligned} \qquad \begin{aligned} |D_1(t)> &= |D_1>\, e^{-i(\Gamma_1/2 + i m_1)t} \\ |D_2(t)> &= |D_2>\, e^{-i(\Gamma_2/2 + i m_2)t} \end{aligned}$$

Eigenvalues are
$m_{1,2} + i\Gamma_{1,2}/2$

with means:
$M = (m_1 + m_2)/2$
$\Gamma = (\Gamma_1 + \Gamma_2)/2$

- It is usual to define four mixing parameters:

$$x_D = \frac{m_2 - m_1}{\Gamma} \;;\; y_D = \frac{\Gamma_2 - \Gamma_1}{2\Gamma} \;;\; \left|\frac{q}{p}\right| \;;\; \phi_M = \mathrm{Arg}\left\{\frac{q}{p}\right\}$$

CPV signalled by
$p \neq q$

- Decays and oscillations of neutral *D* mesons compete.

Define decay amplitudes:

$$\begin{aligned} &\mathcal{A}_f(D^0 \to f) \\ &\bar{\mathcal{A}}_f(\bar{D}^0 \to f) \end{aligned}$$

Time-dependence involves the quantity

$$\lambda_f = \frac{q\bar{\mathcal{A}}_f}{p\mathcal{A}_f} \propto e^{i(\phi_M - 2\phi_f + \delta_f)}$$

Mixing

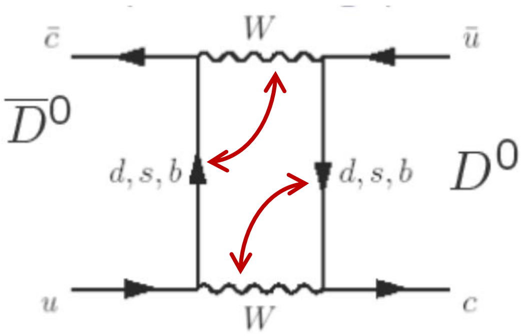
Weak decay

Strong decay

D^0 Mixing is hard to compute in SM

- Off-diagonal mass matrix – two leading terms:

$\Delta C=2$ (short-range)
(contributes mostly to x)



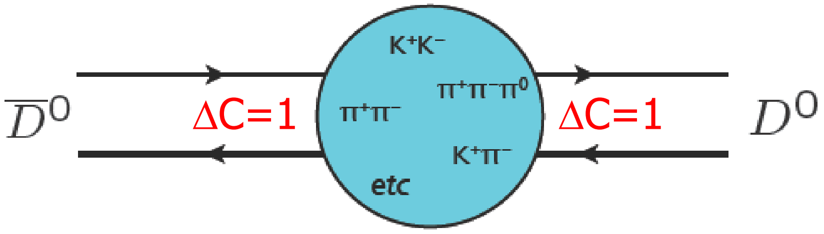
Down-type quarks in loop:

b : CKM-suppressed ($|V_{ub}V_{cb}|^2$)
d, s : GIM-suppressed

$$x \propto (m_s^2 - m_d^2)/m_c^2 \sim 10^{-5}$$

(almost 2 orders of magnitude less than current sensitivity)

Hadronic intermediate states (long-range)



Difficult to compute (need to know all the magnitudes and phases, …)

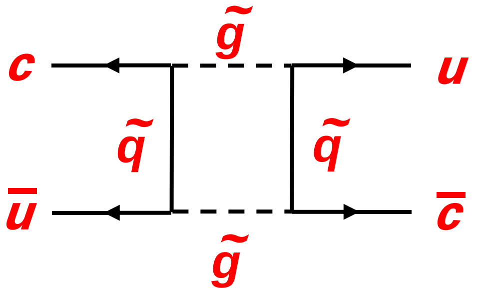
Most computations predict x and y in the range 10^{-3}–10^{-2} and $|x|<|y|$

Recent predictions: $|x| \leq 1\%$, $|y| \leq 1\%$

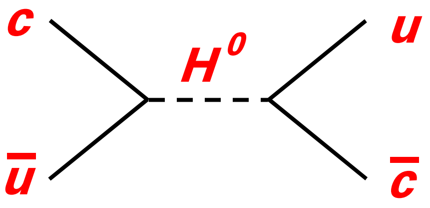
(consistent with current observation)

New Physics and Mixing

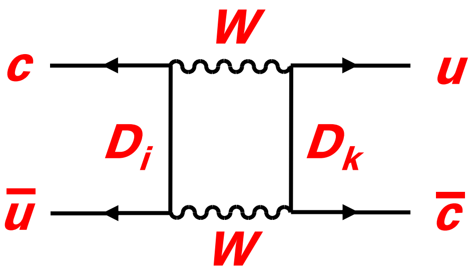
- Several extensions to the SM have been considered that can increase the value of x include:



Supersymmetry



FCNC



Heavy, weak iso-singlet quarks

[A survey: **Phys. Rev. D76, 095009 (2007), arXiv:0705.3650**]

- Generally agreed that signals for new physics would be:
  - EITHER $|x|>>|y|$
  - OR Any evidence for *CPV* in mixing

Three types of *CPV*

1. In the mixing ("indirect *CPV*")

$$\frac{q}{p} = r_M e^{i\phi_M} \neq 1 \qquad \left(r_M \equiv \left|\frac{q}{p}\right|\right).$$

2. In interference between mixing and decay ("indirect *CPV*" – a.k.a. "mixing-induced *CPV*")

$$\lambda_f = \frac{q}{p}\frac{\bar{\mathcal{A}}_f}{\mathcal{A}_f} \neq 1$$

3. In the decay ("direct *CPV*")

$$\left|\bar{\mathcal{A}}_f\right| \neq \left|\mathcal{A}_{\bar{f}}\right|$$

In the last two, *CP* asymmetry can depend on decay mode

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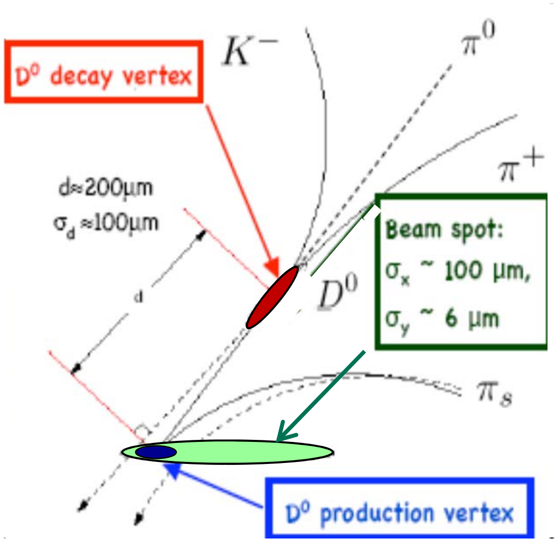
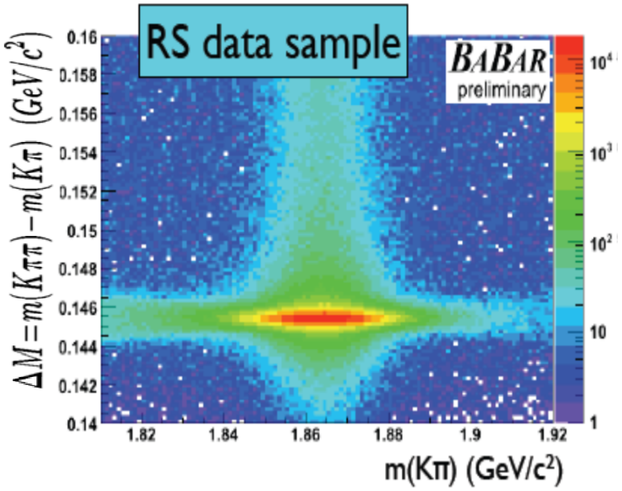
Mixing Measurements at B Factories

- Vertex resolution allows measurement of time-dependence of D^0 decays, but is a challenge.
- Distortion from B decays easily removed by cutting out low momentum D^0's
- Excellent particle ID (Dirc/Aerogel and dE/dx) allows good K/π separation





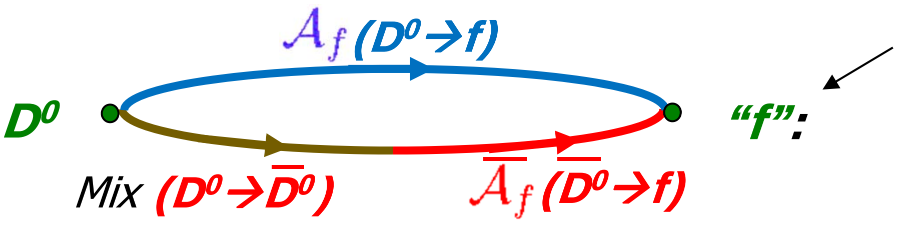
- D^0's from $D^{*+} \rightarrow D^0\pi^+$ decays:
  - Tag flavor of D^0 by the sign of the "slow pion" in D^* decays
  - Allow clean rejection of backgrounds
- **BUT untagged events can be used too !**

Mixing measurements at *LHCb*

- Decay time resolution - little issue (D^0 momenta ~50 times larger than at *B* factories) but short lifetime events cut out.
- Trigger includes *D* (&/or *B)* displaced vertex and "slow pion" (π_s).
  - Displaced μ from B –> $\mu\nu D$ (or D^*) can form vertex
  - Prompt $D^{*+} \rightarrow D\pi^+_s$
- Trigger and offline decay length cuts very effective at reducing background.
- Two RICH's allow clean K/π separation

Mixing Measurements

- Exploit interference between direct decays $D^0 \to f$ and decays through mixing:



Accessible to D^0 or $\overline{D}^0$
Point in Dalitz Plot (DP), etc

$$\boxed{\lambda_f = \frac{q}{p}\frac{\bar{\mathcal{A}}_f}{\mathcal{A}_f} \equiv \frac{1}{\bar{\lambda}_f}}$$

- Time-dependence to 2nd order in x and y.

$$\underbrace{\frac{e^{\Gamma t}}{|\overline{\mathcal{A}}_f|^2}\frac{dN}{dt}}_{\text{Direct decay}} \propto 1 + \underbrace{\bar{\lambda}_f (y_D \cos\delta - x_D \sin\delta)\Gamma t}_{\text{Interference}} + \underbrace{|\bar{\lambda}_f|^2 \frac{x_D^2 + y_D^2}{4}(\Gamma t)^2}_{\text{Decay through Mixing}}$$

$$\delta = \delta_f(s_1, s_2) + \delta_0 \pm \phi_M$$

$\delta_f(s_1,s_2)$: Depends on DP decay model

δ_0: Generally unknown

$\pm\phi_M$: CPV in Mixing — "+" for D^0, "-" for $\overline{D}^0$

Mixing Measurements

- Experimentally, tag D^0 flavour at birth with sign of π_s from $D^{*\pm}$ decay or of μ from B at LHCb and record decay time t.
- Mixing established from the non-exponential decay.
- Interference term, linear in x, y and t/τ, allows best measurement of mixing parameters.
- Decays to “wrong sign” (WS) final states clearly have the greatest sensitivity since all three terms then of same order.
- Phase δ is generally unkown, so we only measure x' and y' :

$$x' = x\cos\delta + y\sin\delta \quad \text{and} \quad y' = y\cos\delta - x\sin\delta$$

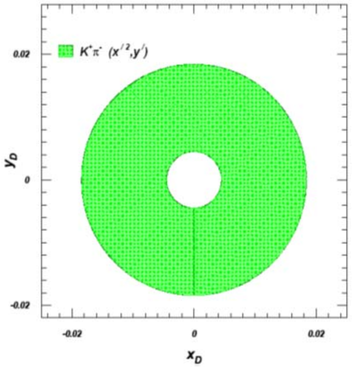
“Wrong sign” (WS) decays $D^0 \rightarrow K^+\pi^-$

- Measure ratio:

$$\frac{N_{K^+\pi^-}}{N_{K^-\pi^+}} = 1 + \lambda_f \boxed{(y\cos\delta - x\sin\delta)}\Gamma t + |\lambda_f|^2 \frac{x^2+y^2}{4}(\Gamma t)^2$$

y'

  - Single point in phase space determines x'^2 and y' .
  - As δ unknown, these define annular region around $x=y=0$.



"Wrong sign" (WS) decays $D^0 \rightarrow K^+\pi^-\pi^0$

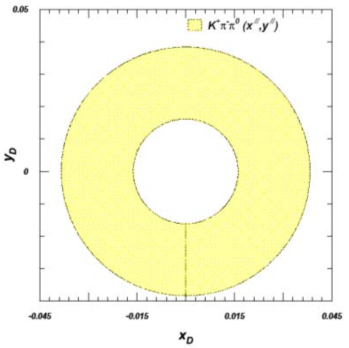
- Fit time-dependent Dalitz plot:

$$|\mathcal{A}_f(s_1,s_2,t)|^2 = 1 + \lambda_f(y\cos\delta - x\sin\delta)\Gamma t + |\lambda_f|^2\frac{x^2+y^2}{4}(\Gamma t)^2$$

Dalitz plot coordinates

  - With model for δ, we determine *x'* and *y'* (both linear)

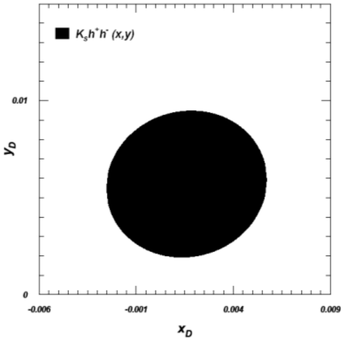
    where $$\delta = \arg\left\{\frac{q}{p}\frac{\overline{\mathcal{A}}(s_1,s_2)}{\mathcal{A}(s_1,s_2)}\right\} + \delta_0$$



Again, since δ_o is unknown, these define annular region around origin at $x = y = 0$.

Decays $D^0 \rightarrow K_S\pi^+\pi^-$ or $K_SK^+K^-$

- Again fit time-dependent Dalitz plot:
  - Channels consist of CF, DCS and CP eigenstates
  - Presence of CP eigenstates, e.g. $D^0 \to K_s^0\rho$, set over all relative phase of D^0 and D^0 ie $\delta_o=0$.
  - So these CP self-conjugate channels define x and y directly and define an (error) elliptical area.



$$\delta = \arg\left\{\frac{q}{p}\frac{\overline{\mathcal{A}}(s_1,s_2)}{\mathcal{A}(s_1,s_2)}\right\} + \delta_0$$

BUT – CF modes form a huge “background”.

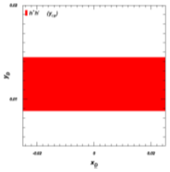
Decays to *CP* eigenstates, e.g. *K*$^+$*K*$^-$, $\pi^+\pi^-$

- In the absence of *CPV*, *D*$_1$ is *CP*-even and *D*$_2$ is *CP*-odd
  - Measurement of lifetimes τ for *D*^{0} decays to *CP*-even and *CP*-odd final states lead to a measurement for *y* in absence of *CPV*.

Mixed CP. Assume τ is mean of CP -even and CP -odd

$$y_{CP} \approx y = \frac{\tau(D^0 \to K^-\pi^+)}{\tau(D^0 \to h^+h^-)} - 1$$

K $^+$K $^-$ or $\pi^+\pi^-$
CP -even



Defines horiz. band

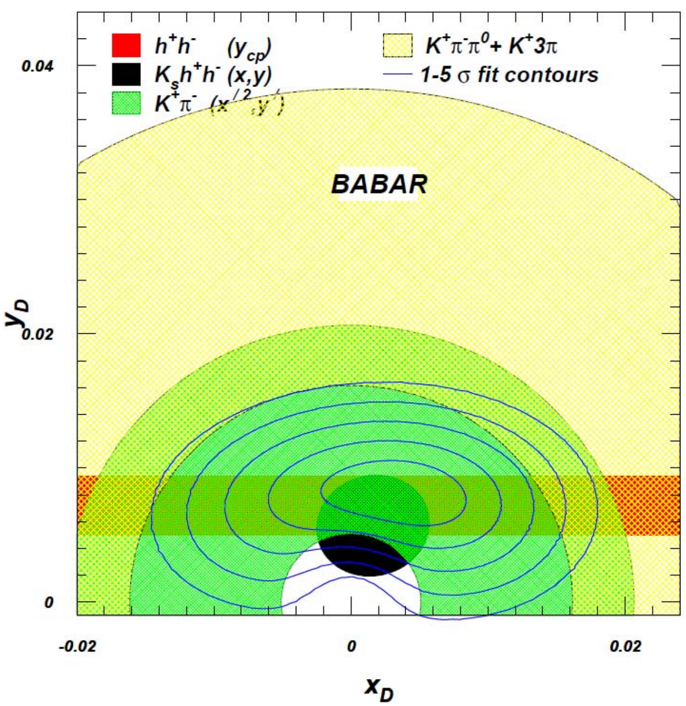
- Allowing for *CPV*, measure the *D*^{0} and $\bar{D}^0$ asymmetry

$|q/p|^2-1$

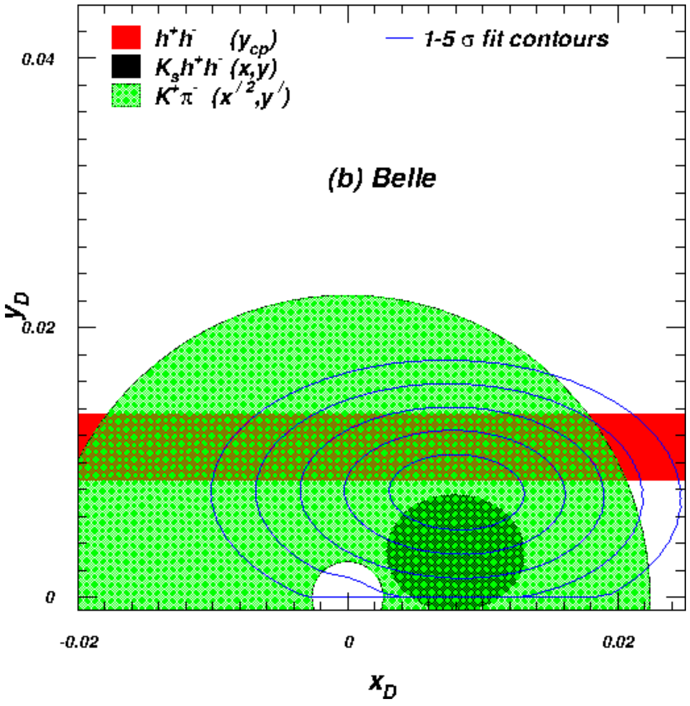
$$A_\Gamma = \frac{\tau(\bar{D}^0 \to h^+h^-) - \tau(D^0 \to h^+h^-)}{\tau(\bar{D}^0 \to h^+h^-) + \tau(D^0 \to h^+h^-)} = \frac{1}{2}A_M y \cos\phi_M - x \sin\phi_M$$

PRD 69,114021 (Falk, Grossman, Ligeti, Nir & Petrov)

D^0 Mixing at B Factories

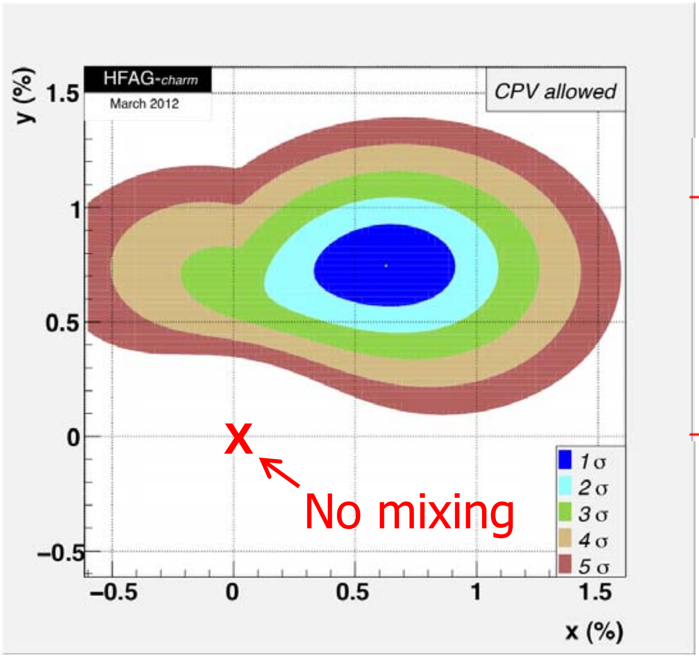


$$\sigma_x = 3.2 \times 10^{-3}$$
$$\sigma_y = 1.7 \times 10^{-3}$$



$$\sigma_x = 3.3 \times 10^{-3}$$
$$\sigma_y = 1.9 \times 10^{-3}$$

HFAG combination of all available observables

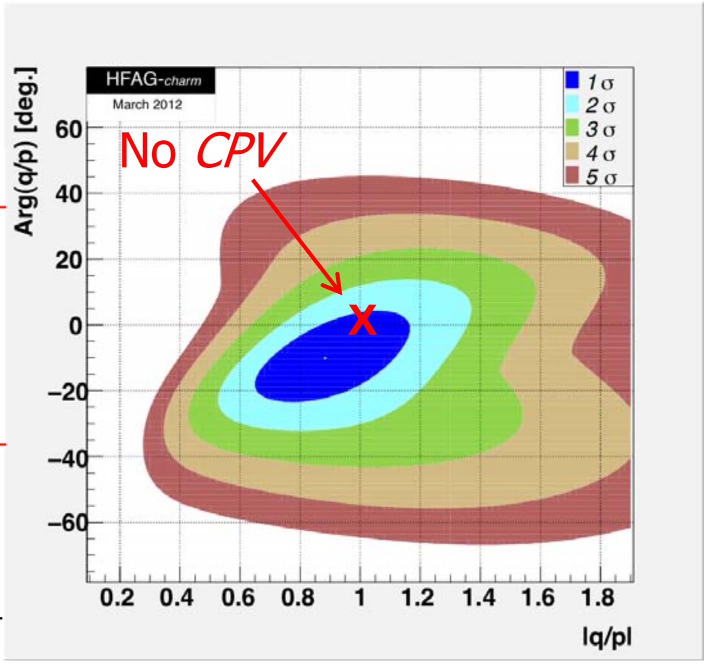


Four main parameters

Parameter	Value
$x(\%)$	$0.63^{+0.19}_{-0.20}$
$y(\%)$	0.75 ± 0.12
$\lvert q/p\rvert$	$0.88^{+0.18}_{-0.16}$
ϕ_M	$-10.1^{+9.5}_{-8.9}$

Uncertainties in x and $y \sim 20\text{x}10^{-4}$

We hope for ~$1\text{x}10^{-4}$

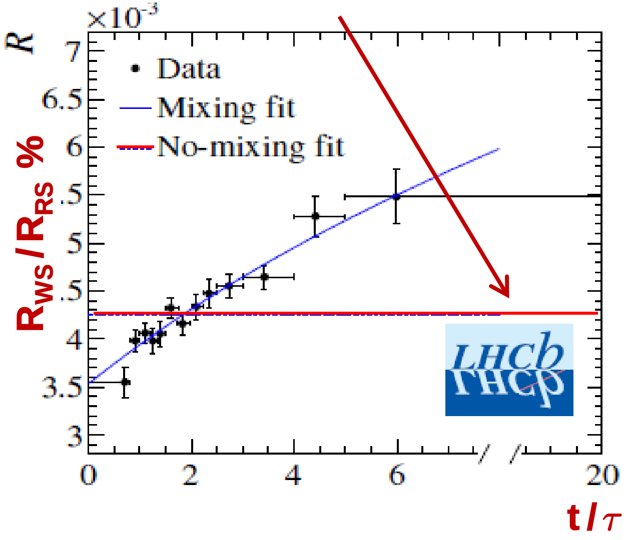


- No evidence yet for *CPV* in mixing.
- Evidence for mixing strong but, until recently, no single observation > 5σ
  - But LHCb has now changed this !

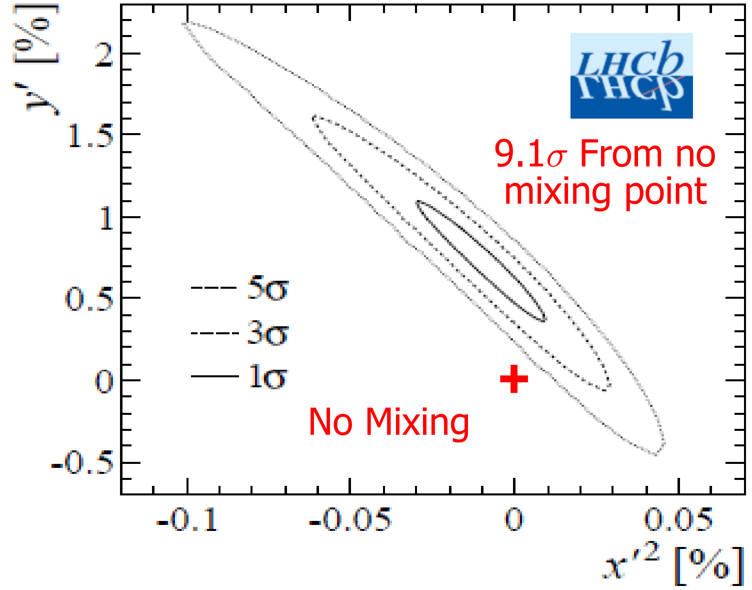
New Result from LHCb: Observation of Mixing in "Wrong Sign" (WS) $D^0 \rightarrow K^+\pi^-$ decays

arXiv:1211.1230v1 [hep-ex] Nov 2012 – 1 fb^{-1}

Preliminary



Mixing signal clear in time-dependence of R_{WS}/R_{RS} ratio



9.1σ From no mixing point

No Mixing

Likelihood contours (expanded to account for systematic uncertainty).

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Projections for LHCb and Belle2

- Sensitivity to x or to y depends on decay mode, so projections depend on the admixture of channels we expect to use.
- The LHCb model, based on its current samples, differs in a relatively low efficiency in $K^+\pi^-\pi^0$ or $K_s h^+ h^-$ modes. However, the efficiency for the latter is increasing.
- LHCb will probably use $K^+\pi^-\pi^+\pi^-$ instead of $K^+\pi^-\pi^0$. and Belle2 will probably use it in addition to $K^+\pi^-\pi^0$.
- The impact is also considered of the following
  - Charm threshold machines (a new Super D???)
  - Time-dependent *CP* asymmetry measurements (a la sin2β).

LHCb Projection through 2012 (3 fb^{-1})

Starting point: LHCb arXiv:1208.3355

Sample	Observable	Sensitivity (1.0 fb^{-1})
Tagged KK	y_{CP}	6×10^{-4}
Tagged $\pi\pi$	y_{CP}	11×10^{-4}
Tagged KK	A_Γ	6×10^{-4}
Tagged $\pi\pi$	A_Γ	11×10^{-4}
Tagged WS/RS $K\pi$	$x_D'^2$	7×10^{-5}
Tagged WS/RS $K\pi$	y_D'	13×10^{-4}
Tagged $K_S^0\pi\pi$	x_D	4×10^{-3}
Tagged $K_S^0\pi\pi$	y_D	3×10^{-3}
Tagged $K_S^0\pi\pi$	$\|q/p\|$	0.4
Tagged $K_S^0\pi\pi$	ϕ	25°

→

2012 Yield	Actual (incl. syst.)
$\times 4$	3.3×10^{-4}
$\times 4$	6.4×10^{-4}
$\times 4$	3.5×10^{-4}
$\times 4$	6.4×10^{-4}
$\times 4$	4.1×10^{-5}
$\times 4$	7.6×10^{-4}
$\times 8$	1.7×10^{-3}
$\times 8$	1.2×10^{-3}
$\times 8$	0.16
$\times 8$	10°

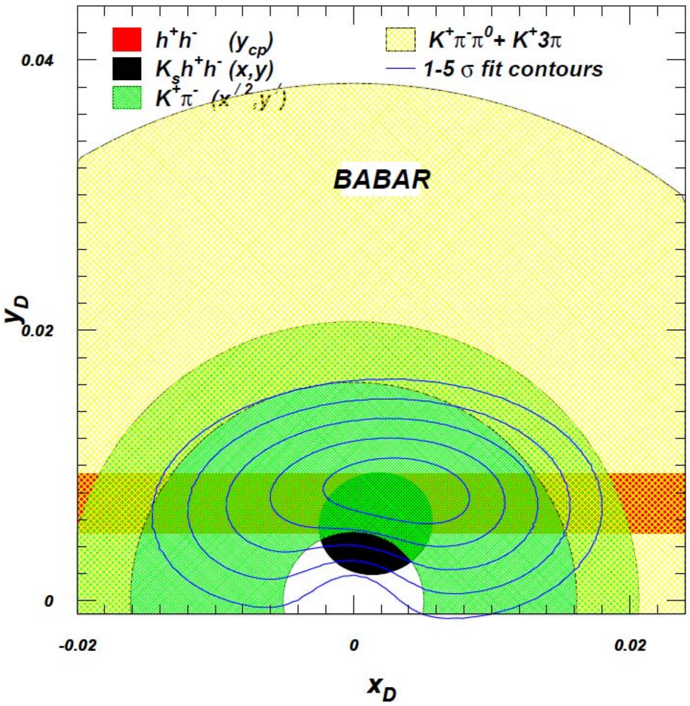
Actual:
(incl. syst)

13×10^{-5}
24×10^{-4}

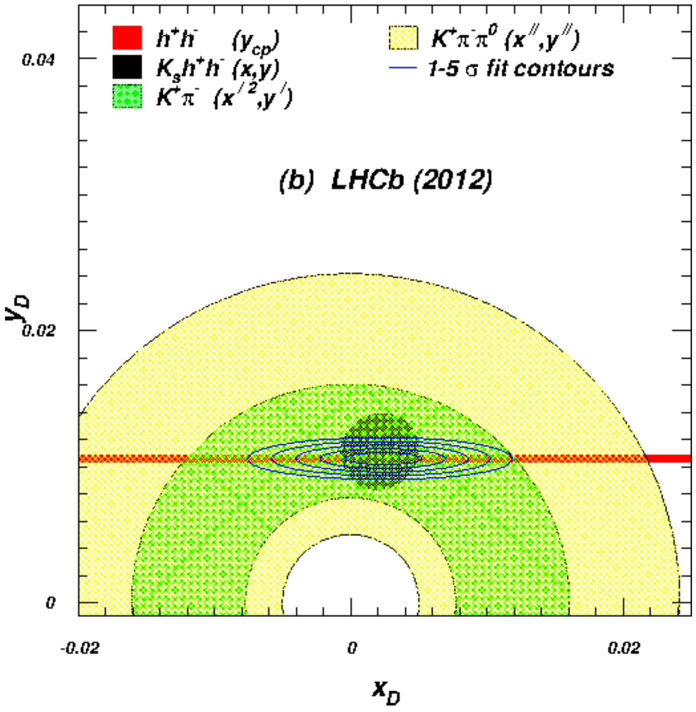
arXiv:1211.1230v1 [hep-ex]
Nov 2012 – ~0.4 fb^{-1}

Assume:
- Syst. contrib. same as in $K\pi$ WS mode
- All uncertainties scale as sqrt # of events.

LHCb Projection through 2012 (3 fb^{-1})

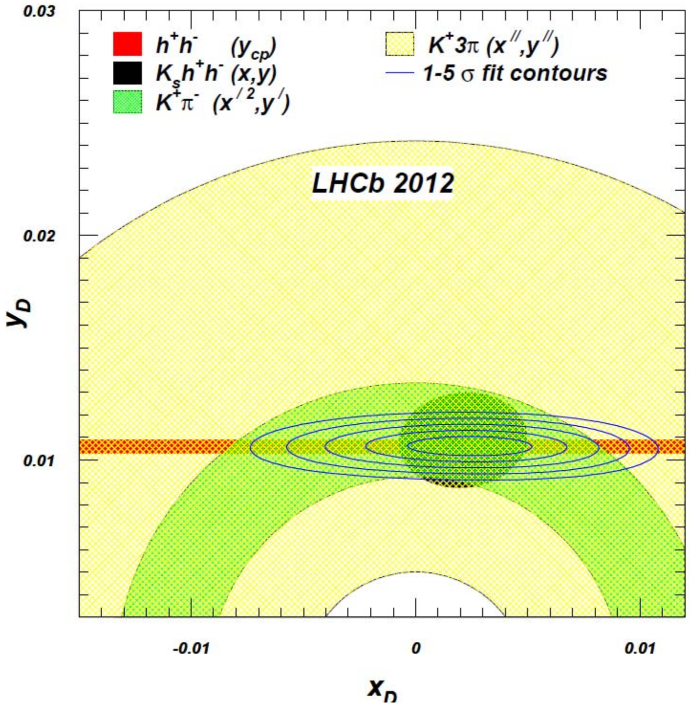


$$\sigma_x = 3.3 \times 10^{-3}$$
$$\sigma_y = 1.7 \times 10^{-3}$$

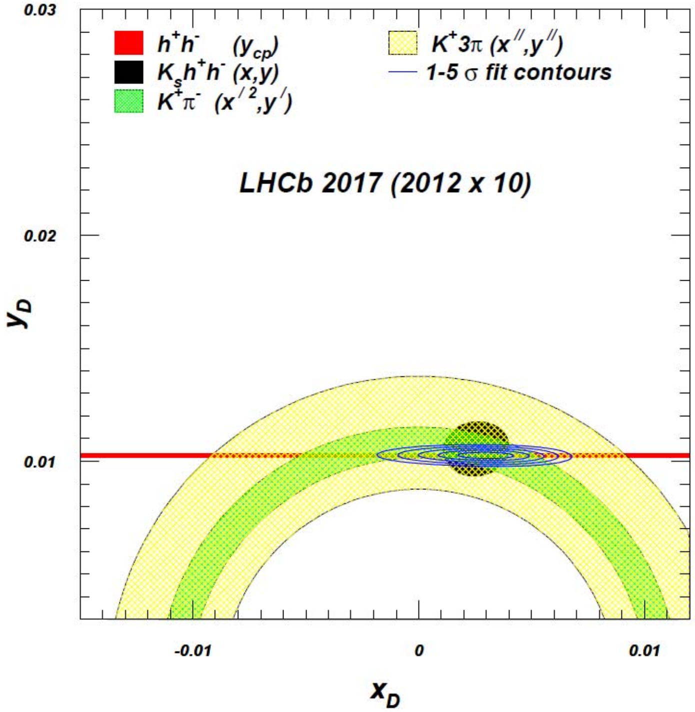


$$\sigma_x = 1.8 \times 10^{-3}$$
$$\sigma_y = 0.3 \times 10^{-3}$$

Project to 2017

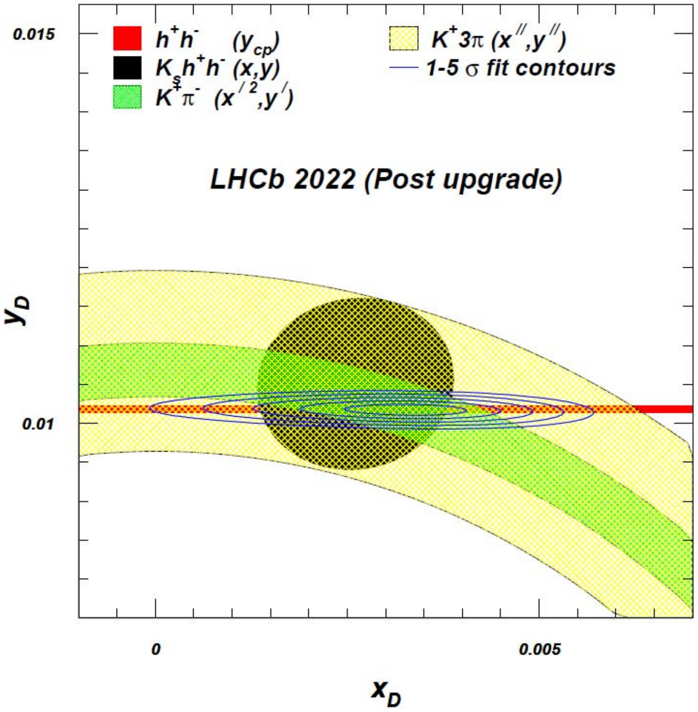


$$\sigma_x = 18 \times 10^{-4}$$
$$\sigma_y = 3 \times 10^{-4}$$

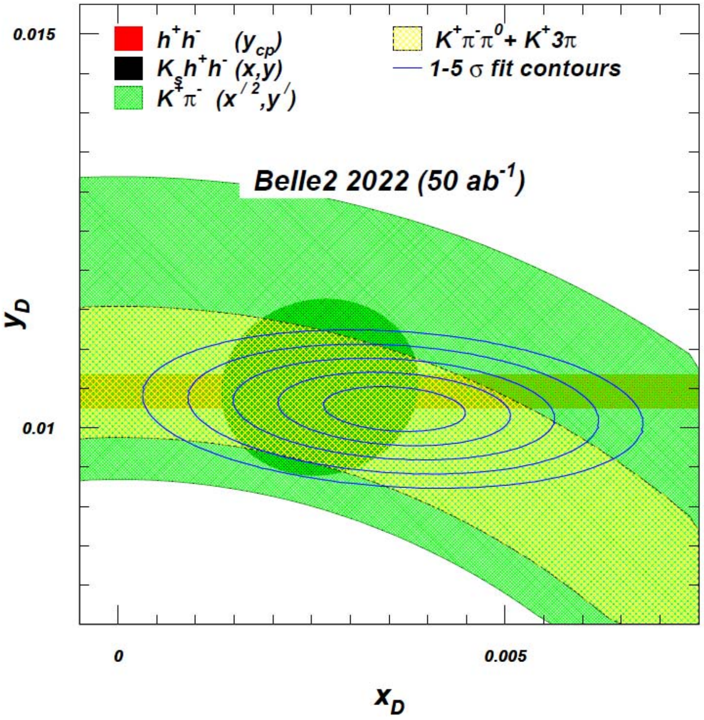


$$\sigma_x = 8.1 \times 10^{-4}$$
$$\sigma_y = 0.9 \times 10^{-4}$$

Projection to 2022 (Belle2 ends?)



$$\sigma_x = 5.3 \times 10^{-4}$$
$$\sigma_y = 0.5 \times 10^{-4}$$



$$\sigma_x = 6.0 \times 10^{-4}$$
$$\sigma_y = 1.9 \times 10^{-4}$$

Outline

- D^0 Mixing and evidence for it.
  - Analysis methods, recent results
- Projection to the new generation of experiments
  - Use of threshold data
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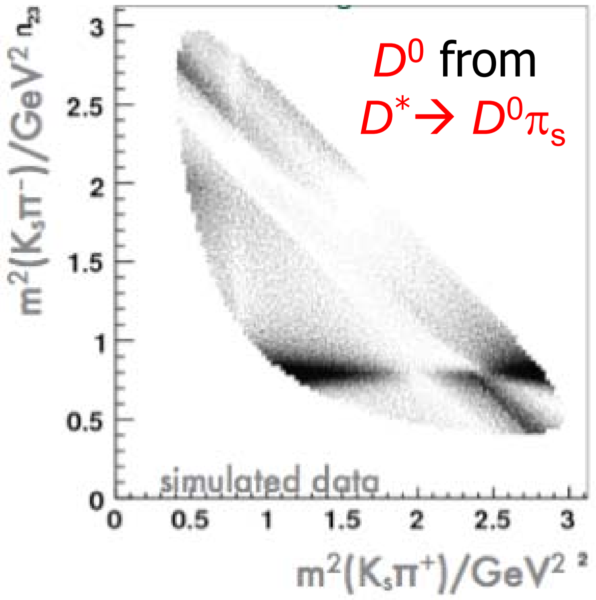
Irreducible Model Uncertainty (IMU)

- The problem – it is not easy to find a model $\mathcal{A}(m^2_{K\pi^+}, m^2_{K\pi^-})$ for the $D^0 \to K^0_S\pi^+\pi^-$ Dalitz plot.
- This introduces an uncertainty in mixing parameters

BaBar: x = (0.16 ± 0.23 ± 0.12 ± 0.08)%
y = (0.57 ± 0.20 ± 0.13 ± 0.07)%

IMU (our goal ~ 0.01)



D^0 from $D^* \to D^0\pi_s$

Some see poles in $\mathcal{A}(m^2_{K\pi^+}, m^2_{K\pi^-})$

Others see it as just a complex number !

→ They need data from charm threshold.

Define bins, measure relative phase ϕ_i *in each from* $\psi(3770)$ *decays.*

Model independence from Charm threshold

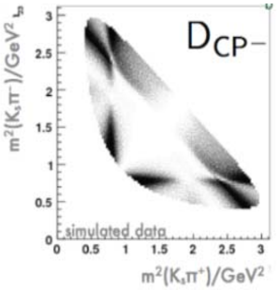
- Decay of $\psi(3770)$ prepares the $D^{(1)}D^{(2)}$ system in a state

$$A_\psi = [A_D^{(1)}\bar{A}_D^{(2)} + (-1)^L A_D^{(2)}\bar{A}_D^{(1)}]/\sqrt{2} \quad \text{where} \quad (L=1)$$

- 3 TAGS: used

CP

$$|D_i^0|^2+|\bar{D}_i^0|^2 \pm 2|D_i^0||\bar{D}_i^0|\,c_i$$

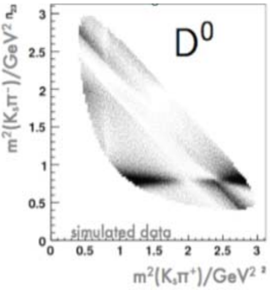


$\psi(3770)$

(CP=+1)
KK, etc.

Flavour

$$|D_i^0|^2$$

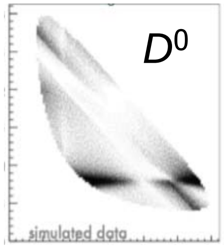


$\psi(3770)$

Semi-leptonic
$K^-l^+\nu_l$, etc.

"Double Dalitz" ?

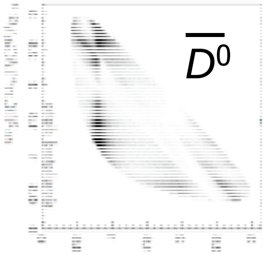
$$|D_i^0||\bar{D}_j^0|\times(c_ic_j+s_is_j)$$



Signal
e.g. $K_S\pi\pi$

$\psi(3770)$

(sig←→ tag)



TAG

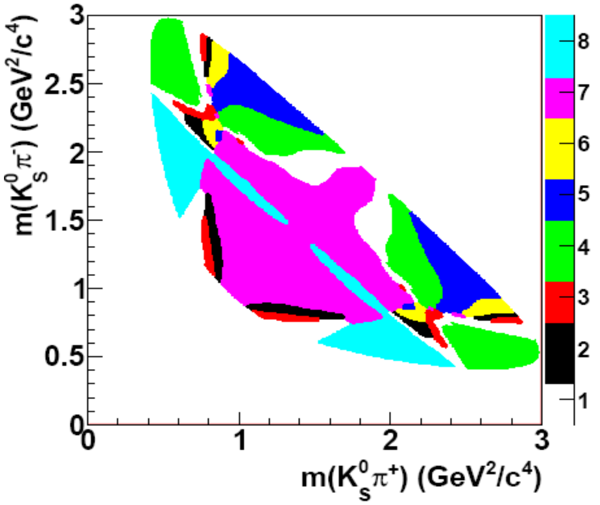
- Ignore mixing - solve for $c_i=\cos\phi_i$ & $s_i=\sin\phi_i$ for each bin

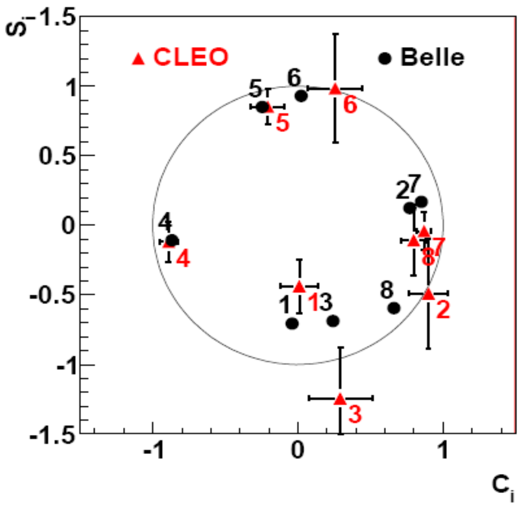
Application for CKM γ

Belle PRD85, 112014 (2012)

CLEOc PRD80, 032002 (2009),
PRD82, 112006 (2010)

- 16 bin test of CLEO c_i and s_i values vs. Belle isobar model.





χ^2/NDF=18.6/16

	Model-independent	Model-dependent
$\mathbf{CKM}\gamma$	$(77.3^{+15.1}_{-14.9} \pm 4.1 \boxed{\pm} 4.3)^0$	$(78.4^{+10.8}_{-11.6} \pm 3.6 \boxed{\pm} 8.9)^0$

From strong phase measurements ↗

Belle IMU for γ ↗

- c_i, s_i uncertainties should scale as ψ(3770) samples grow?

Effect of threshold data on mixing

- We assume that
  - The IMU uncertainties in mixing from CLEO phase measurements (c_i and s_i) will be in similar proportion to those for the Belle test.
  - That these should shrink as the square root of available threshold sample sizes[*].
- The projections are as illustrated …

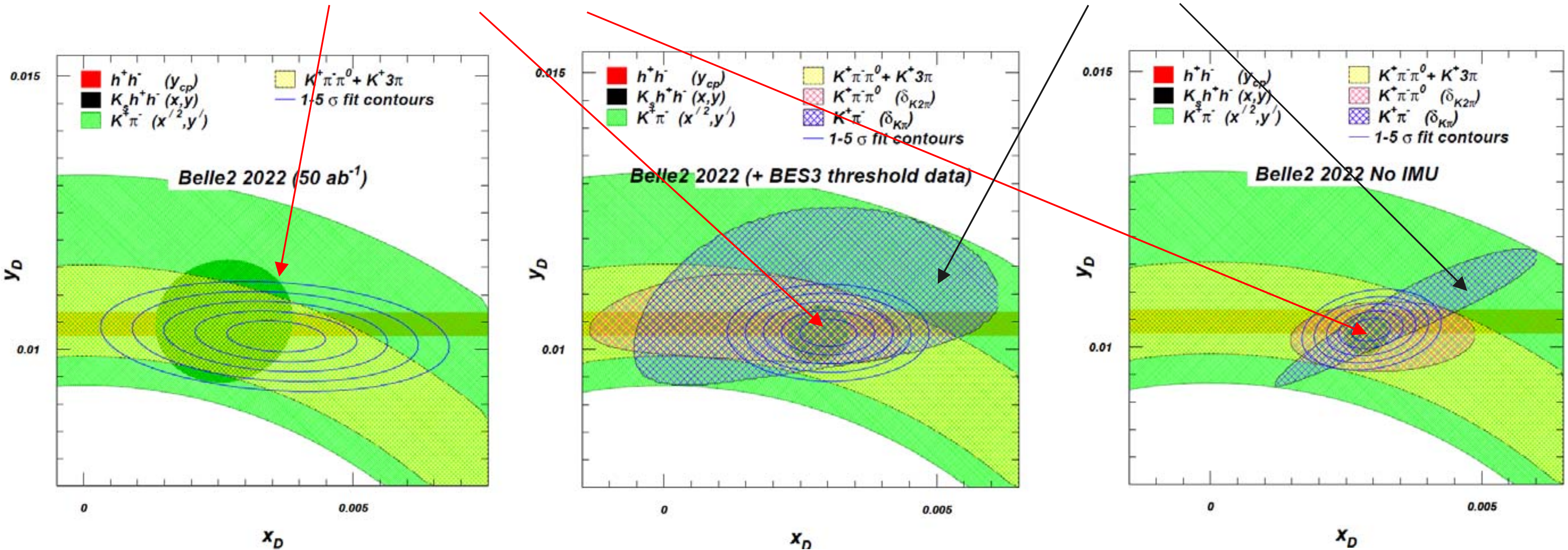
[*] This last assumption seems not to be so in simulations though this is puzzling. [JHEP 1210 (2012) 85]

Include strong phase measurements

- Two improvements in mixing precision come from threshold data:

  - Dalitz plot model uncertainty shrinks ●

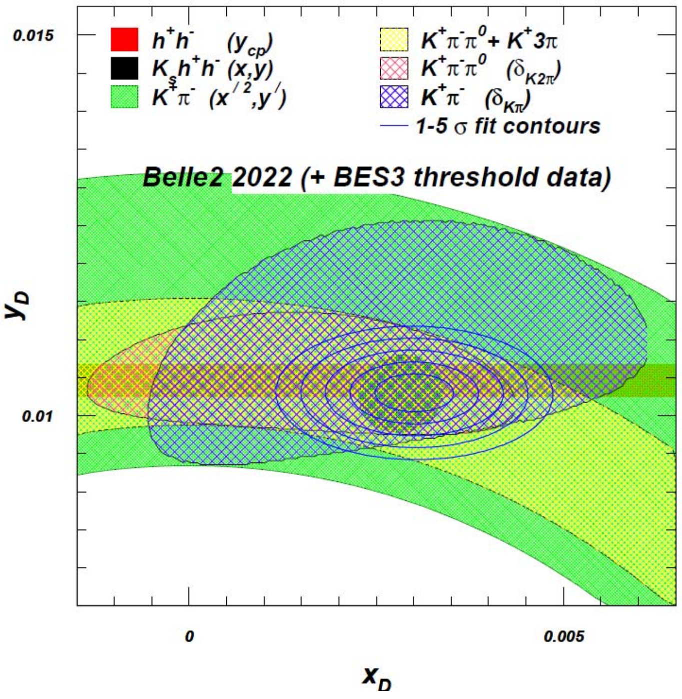
  - Precision of overall strong phase $\delta_{K\pi(\pi)}$ increases ●



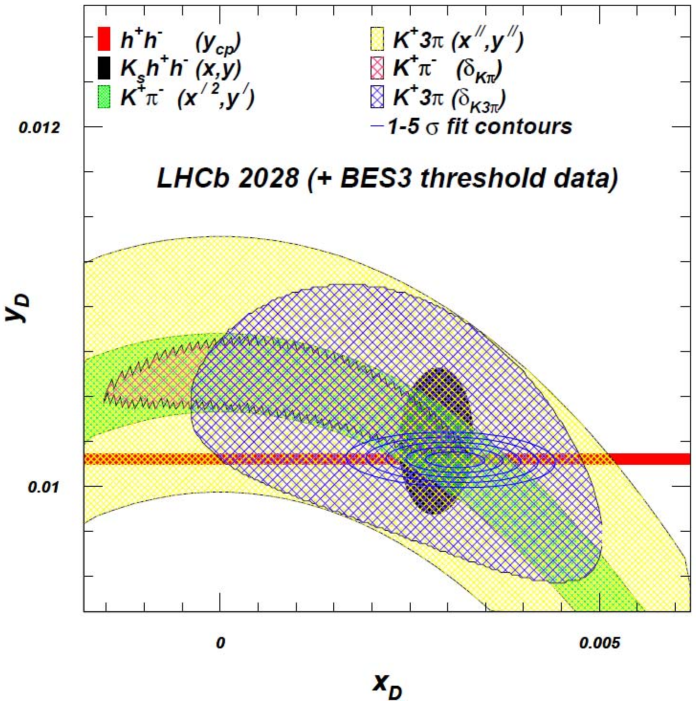
$$\boxed{\begin{array}{c}\sigma_x = 6.0\times10^{-4}\\ \sigma_y = 1.9\times10^{-4}\end{array}} \xrightarrow{\text{BES III}} \boxed{\begin{array}{c}\sigma_x = 3.5\times10^{-4}\\ \sigma_y = 1.6\times10^{-4}\end{array}} \xrightarrow{\text{SuperD}} \boxed{\begin{array}{c}\sigma_x = 2.4\times10^{-4}\\ \sigma_y = 1.4\times10^{-4}\end{array}}$$

Uncertainty in x_D improves more than that of y_D

End LHCb (2028 ?)



$$\sigma_x = 3.5 \times 10^{-4}$$
$$\sigma_y = 1.6 \times 10^{-4}$$



$$\sigma_x = 2.6 \times 10^{-4}$$
$$\sigma_y = 0.3 \times 10^{-4}$$

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Prospects for observing CPV in mixing

- The assumption of no *CPV* in mixing or decay in measurements should be abandoned as event samples grow. However, asymmetries in measurements of x and y (or x' and y') values for $\bar{D}^0$ and D^0 separately should continue to be useful:

$$\text{e.g.}\quad \frac{\mathrm{x}-\bar{\mathrm{x}}}{\mathrm{x}+\bar{\mathrm{x}}} = \frac{1-|q/p|^2}{1+|q/p|^2} = |p|^2-|q|^2 \quad \text{if} \quad \arg\{q/p\} = 0$$

  - Dependence on decay mode would indicate direct CPV.

- Weak mixing phase ϕ_M = Arg{q/p} can be measured in $K_s h^+ h^-$ time-dependent Dalitz plot analyses.

- ϕ_M also be measured from t-dependence of CP asymmetry

CPV Parameters $|q_D/p_D|$, ϕ_M=Arg{q/p}

- Several strategies:

Current World Averages (HFAG): →

D⁰- $\overline{\text{D}}$⁰ parameter asymmetries:
$a_z = (z_+ - z_-)/(z_+ + z_-) \sim |q|^2 - |p|^2$
where z is x, y, x′, y′, x″, y″, x'^2 →

Time-dependent amplitude analysis of Golden channels →

Time-dependent CP asymmetry →

	Decay mode	$\sigma(\vert q/p\vert)$ x 100	$\sigma(\phi_M)^0$
Global χ^2 Fit to all modes: **(HFAG - direct CPV allowed)**		**± 18**	**± 9**
Asymmetries a_z:			
x	<All modes>	±1.8	–
y	<All modes>	±1.1	–
y_{CP}	K^+K^-	±1.0	–
y'	$K^+\pi^-$	±1.3	–
x'^2	$K^+\pi^-$	±1.2	–
x''	$K^+\pi^-\pi^0$	±5.4	–
y''	$K^+\pi^-\pi^0$	±5.0	–
Model for $\mathcal{A}_f$	$K_sh^+h^-$	±8.4	±3.3
BES III DP model	$K_sh^+h^-$	±3.7	±1.9
No IMU	$K_sh^+h^-$	±2.7	±1.4
arg λ_{KK}	K^+K^-	–	±1.4
arg $\lambda_{\pi\pi}$	$\pi^+\pi^-$	–	±2.3

Improvement in precision by 2022 is tabulated.
Will allow distinction between decay modes to few %

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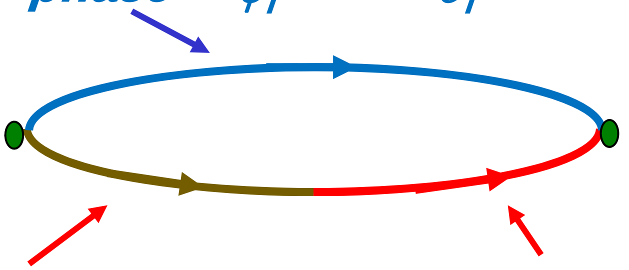
Another approach to measuring ϕ_M

Bevan, Inguglia, BM, Phys.Rev. D84 (2011) 114009

- Proceed as in $\sin 2\beta$ measurements for B_d decays.
- For decays to *CP* eigenstates, strong phase δ_f in λ_f is zero



phase $= \phi_f^{\text{weak}} + \delta_f^{\text{strong}}$

CP eigenstate or CP self-conjugate state

D^0

"f_{CP}":

phase $= \phi_M$

phase $= -\phi_f^{\text{weak}} + \delta_f^{\text{strong}}$

CKM phase

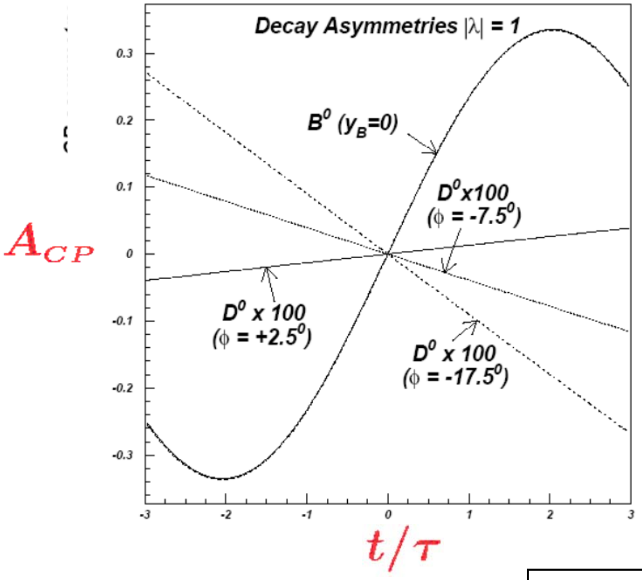
So weak phase $\boxed{\mathrm{Arg}\{\lambda_f\} = \phi_M - 2\phi_f^{\text{weak}}}$

- If K^+K^- mode is dominated by a tree diagram, $\mathrm{Arg}\{\lambda_f\} = \phi_M$

Time-Dependent CP Asymmetry (TDCP)

- Since D^0 and $\overline{D}^0$ oscillate at different rates, this leads to time-dependent CP asymmetry.

$$A_{CP} = \frac{\bar{\Gamma} - \Gamma}{\bar{\Gamma} + \Gamma} = -\eta_{CP} \frac{(1 - |\lambda_f|^2)\cos(x\Gamma t) - 2\Im(\lambda_f)\sin(x\Gamma t)}{(1 + |\lambda_f|^2)\cosh(y\Gamma t) + \Re(\lambda_f)\sinh(y\Gamma t)}$$

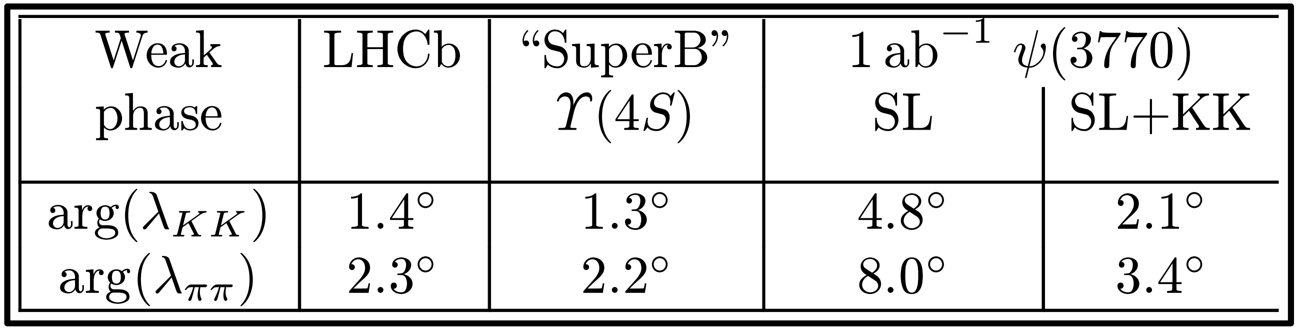


- The D^0 asymmetry is much smaller than that for B^0
- $|A_{CP}|$ is almost linear in t (for B^0 it is sinusoidal).
- Slope of line $\propto$ Arg $\{\lambda\}$
- $|A_{CP}|$ grows with t

Any asymmetry at t=0 is from direct CPV

Expected performance

- A toy MC study was used to estimate precision of measure of Arg{λ_f}.
  - Sets of events with expected yields generated in 3 scenarios with asymmetries as predicted for various values for Arg{λ_f}
  - Mis-tag rates similar to BaBar's, and perfect time resolution assumed
- Unbinned likelihood fits made to obtain Arg{λ_f} in each case.



Weak phase	LHCb	"SuperB" $\Upsilon(4S)$	$1\,\mathrm{ab}^{-1}$ $\psi(3770)$ SL	SL+KK
$\arg(\lambda_{KK})$	1.4°	1.3°	4.8°	2.1°
$\arg(\lambda_{\pi\pi})$	2.3°	2.2°	8.0°	3.4°

Arg{λ_f} = $\phi_M - 2\phi_f^{weak}$

Il Nuovo Cimento C, DOI: 10.1393/ncc/i2012-11374-6, pp. 389-398 (2012)

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CPV in D decays

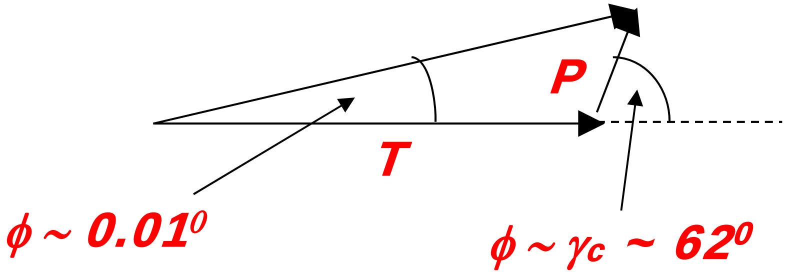
- Decays are classified by level of Cabibbo suppression - CF, DCS, SCS.
- CF and DCS decays dominated by tree diagrams but penguins can contribute to SCS. We therefore do NOT expect CPV in CF or DCS decays, but we do in SCS.

F. Bucella et al., Phys. Rev. D51, 3478 (1995)
S. Bianco et al., Riv. Nuovo Cim. 26N7, 1(2003)
S. Bianco, F.L. Fabbri, D. Benson, and I. Bigi, Riv., Nuovo Cim. 26N7, 1 (2003).

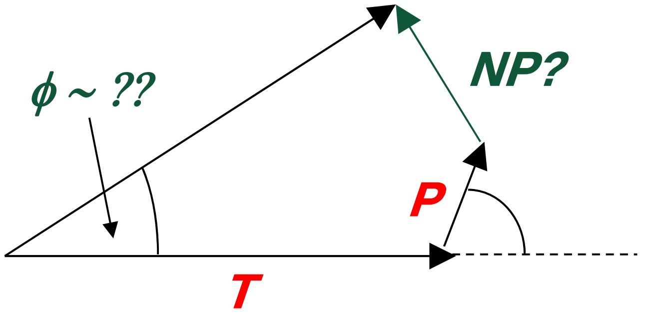
- In the SM, CPV is highly suppressed, but there can be NP in loops.

A.A. Petrov, Phys. Rev. D69, 111901 (2004)
Y. Grossman, A.L. Kagan, and Y. Nir, Phys. Rev. D75,036008 (2007)

SM: $$\frac{P}{T}=\frac{V_{cb}V_{ub}}{V_{cs}V_{us}}=r_{\mathrm{P}}\,e^{-i\,\gamma}\sim 10^{-3}\frac{\alpha_s}{\pi}e^{-i\;62^{\pm}}$$



NP:



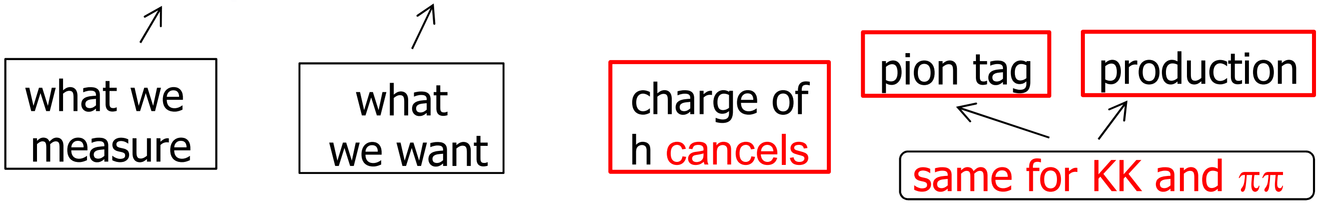
- Measurements of $A^{f}_{\mathbf{CP}}$ are now made with data-driven systematic uncertainties at level of a few x10^{-3}.
- Only one measurement has, so far, been reported as a relatively significant asymmetry arising from charm decay, though confirmation (or otherwise) is expected soon.
- With its large sample, LHCb is in the best position to make measurements, but it has to consider differences between pairs of modes in order to sufficiently control systematics.

Evidence for Direct *CPV* in *D*^{0} decay

PRL 108, 111602 (2012) – 0.62 fb^{-1}

- LHCb measured $\Delta A_{\rm CP} = A_{\rm CP}^{K^+K^-} - A_{\rm CP}^{\pi^+\pi^-}$ - a clever idea:
  - This cancels most of the production (and other) asymmetries:

$$A^{h^+h^-}_{\rm raw} = A_{\rm CP} + A_{\rm charge} + A_{\pi_s} + A_{\rm prod}$$



what we measure

what we want

charge of h cancels

pion tag

production

same for KK and ππ

  - U-spin conservation suggests that $A_{CP}^{\pi\pi} = -A_{CP}^{KK}$, doubling any asymmetry

Grossman, Kagan and Nir, PRD72, 036008 (2007)

  - Any asymmetry from time-dependent mixing effects cancels so $\Delta A_{\rm CP}$ measures ONLY direct CPV.

$$\boxed{\Delta A_{\rm CP} = (-0.82 \pm 0.21 \pm 0.11)\% \;\; !!}$$

Confirmation with 3 fb^{-1} ?

Confirmation ?

Year	Experiment	Results
2007	Belle	$A_\Gamma = 0.01 \pm 0.30 \pm 0.15$
2008	*BABAR*	$A_\Gamma = 0.26 \pm 0.36 \pm 0.08$
2011	LHCb	$A_\Gamma = 0.59 \pm 0.59 \pm 0.21$
2008	*BABAR*	$A_{\mathrm{CP}}^{\mathrm{KK}} = 0.00 \pm 0.34 \pm 0.13$ $A_{\mathrm{CP}}^{\pi\pi} = 0.24 \pm 0.52 \pm 0.22$
2008	Belle	$\Delta A_{\mathrm{CP}} = 0.87 \pm 0.41 \pm 0.06$
2011	LHCb	$\Delta A_{\mathrm{CP}} = 0.82 \pm 0.21 \pm 0.11$
2012	CDFPreliminary	$\Delta A_{\mathrm{CP}} = 0.62 \pm 0.21 \pm 0.10$

Seem to confirm the evidence from LHCb.

- These results are combined by HFAG to determine $\Delta a_{\mathrm{CP}}^{\mathrm{dir}}$, the difference between *KK* and $\pi\pi$ of direct *CPV*, and $a_{\mathrm{CP}}^{\mathrm{indir}}$, the indirect *CPV*.

"Wow – $A_{CP} \sim 1\%$ too!!"

More on Penguins

- The b-penguin is small (~λ^4), but has phase γ that is large.
- The d- and s-penguins combine to have phase γ

$$P_s + P_d \propto V_{cs}V^*_{us} + V_{cd}V^*_{ud} = -V_{db}V^*_{ub}$$

  but would cancel in the SM at order $(m_s^2-m_d^2)/m_d^2$.

- In reality, however, they are not true short-range penguins, and are magnified by long range effects.
- Modest U-spin breaking can lead to large contribution to CP asymmetry and also to understanding why the ratio

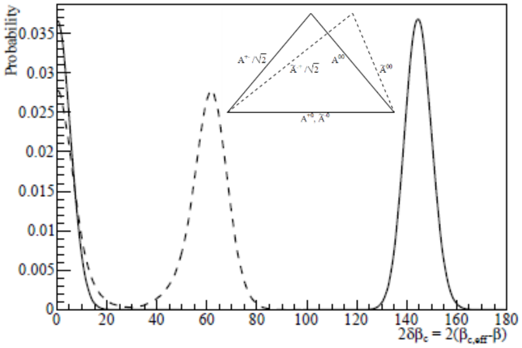
$$D^0 \to K^+K^- / D^0 \to \pi^+\pi^- \simeq 2.5$$

  is large - an old mystery in charm physics.

Brod, Grossman, Kagan and Zupan, JHEP 1210 (2012) 161

Possible ways forward (experimentally)?

- Methods used in B factories to estimate penguin contributions and their effect on the weak phases in heavy quark decays could be used.
- Bose statistics requires $I = 0$ or 2 in $\rho\rho$ or $\pi\pi$ final states so there are two reduced I-spin decay amplitudes A_1 ($\Delta I = ½$) and A_3 ($\Delta I = {}^3/_2$) . (For $\rho\pi$ there are five).
  - Use *t-dependent CP* asymmetry in h^+h^- to measure weak phase $\phi_M - 2\beta_{c,\mathrm{eff.}}$
  - Measure amplitudes and CP asymmetries for $D^0 \rightarrow h^0h^0$ and $D^+ \rightarrow h^+h^0$.
  - Can then extract *P/T* from the I-spin triangle (or pentagon for $\rho\pi$).



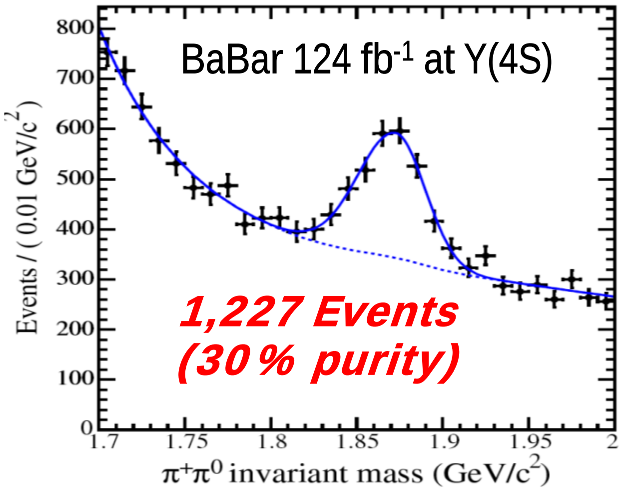
Toy MC study indicates the possibility to measure the shift $\delta\beta_c$ in β_c due to penguins can be measured, modulo theoretical uncertainties, with precision ~2.7^0 using BaBar and CLEOc $\pi\pi$ data available today.

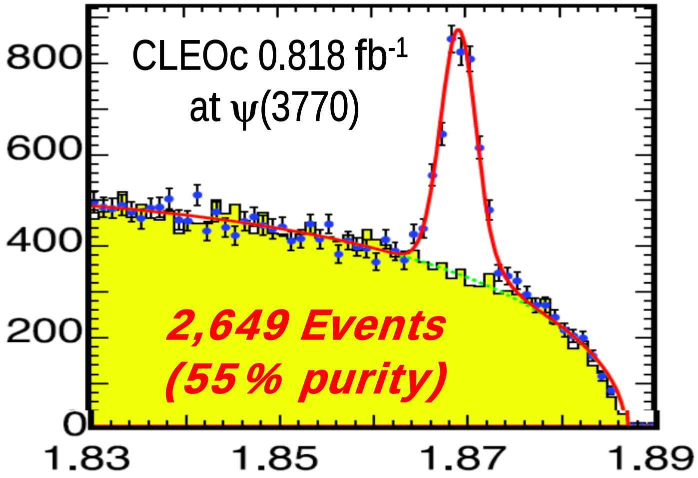
(A. Bevan and BM, in preparation).

$D^+ \rightarrow \pi^+\pi^0$ Asymmetry ?

- For $D^+ \rightarrow \pi^+\pi^0$ (OR $\rho^+\rho^0$) then ($\Delta I = {}^3/_2$) thus excluding any SM penguin contribution. *CP asymmetry in these decays would require NP !!*

- BaBar and CLEO measured this mode relative to $D^+ \rightarrow K^-\pi^+\pi^+$





$B_{\pi^+\pi^0} / B_{K^-\pi^+\pi^+} = (1.33 \pm 0.11 \pm 0.09) \times 10^{-2}$

$A^{CP} \sim (xxx \pm 6.2) \times 10^{-2}$

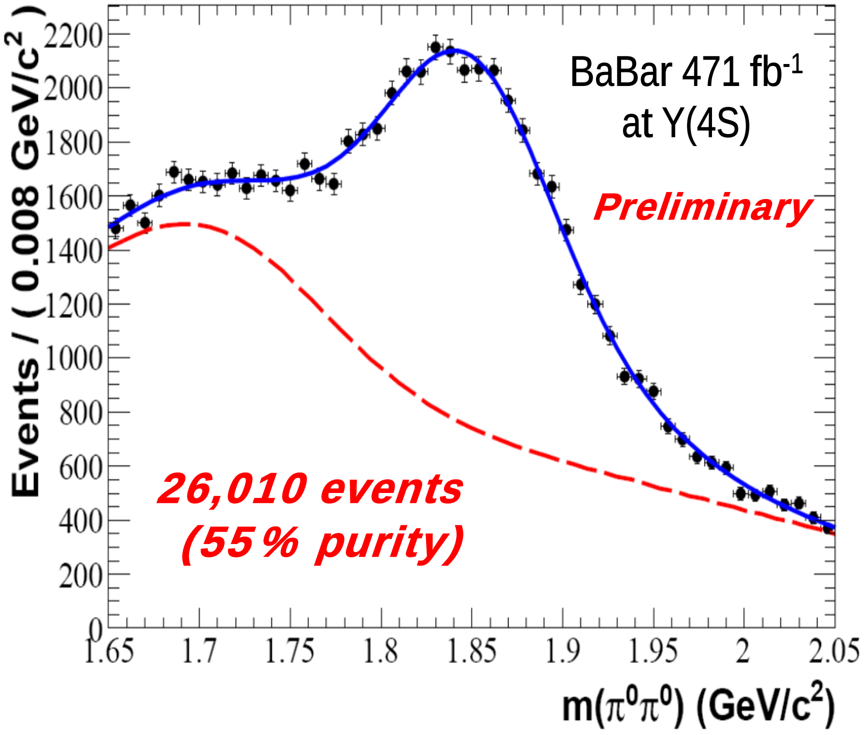
Phys.Rev. D74 (2006) 011107

$B_{\pi^+\pi^0} / B_{K^-\pi^+\pi^+} = (1.29 \pm 0.04 \pm 0.05) \times 10^{-2}$

$A^{CP} = (2.9 \pm 2.9 \pm 0.3) \times 10^{-2}$

Phys.Rev. D81 (2010) 052013

Prospects for Measuring other ππ Asymmetries



BaBar 471 fb^{-1} at Y(4S)

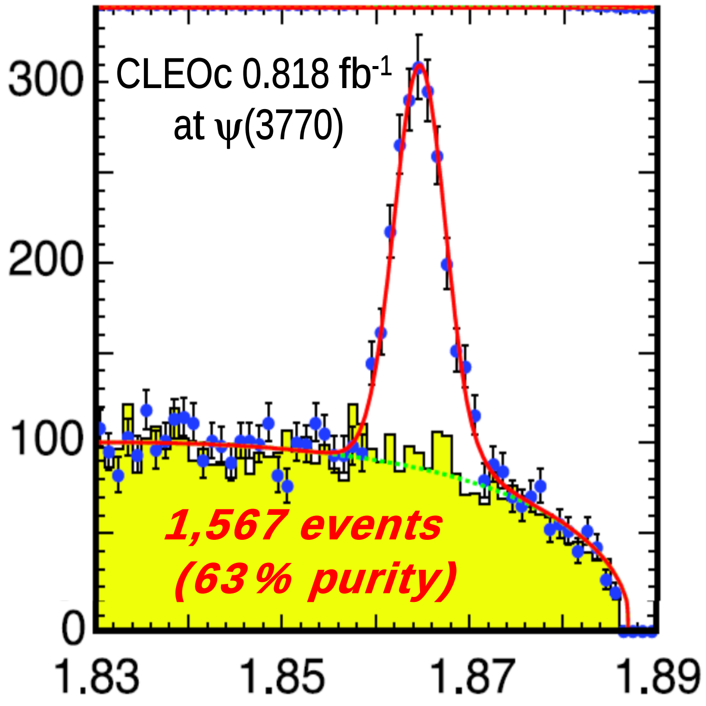
Preliminary

26,010 events (55% purity)

$B_{\pi^0\pi^0}/B_{K^0\pi^0} = (6.88 \pm 0.08 \pm 0.33)\times10^{-2}$

$A^{CP} \sim (xxx \pm 1.2)\ x10^{-2}$

Submitted to Phys.Rev. D



CLEOc 0.818 fb^{-1} at ψ(3770)

1,567 events (63% purity)

$B_{\pi^0\pi^0}/B_{K^\pm\pi^\mp} = (2.06 \pm 0.07 \pm 0.10)\times10^{-2}$

A^{CP} - *NOT possible*

Phys.Rev. D81 (2010) 052013

Projections for A^{CP} Measurements

- LHCb *CPV* measures $A^{CP}(KK)$-$A^{CP}(\pi\pi)$~0.8%
  - So each mode has A^{CP}~0.4% (assuming *U-spin symmetry*).
  - → Precision required to make GKZ tests is probably ~0.1%.
- For $D^0 \rightarrow \pi^0\pi^0$ BaBar measures BF, not A^{CP} which we estimate.
- For A^{CP} measurements, we observe that most systematic uncertainties cancel except for uncertainties in signal and background shapes.
  - We assume these should shrink with the data size

		At $\psi(3770)$ %			At $\Upsilon(4S)$ %	
$A^{CP}(\%)$	**LHCb** $5\,\mathrm{fb}^{-1}$	**CLEOc** $0.818\,\mathrm{fb}^{-1}$	**BES3** $10\,\mathrm{fb}^{-1}$	**SuperB** $1\,\mathrm{ab}^{-1}$	*BABAR* $481\,\mathrm{fb}^{-1}$	**SuperB** $75\,\mathrm{ab}^{-1}$
$\pi^+\pi^0$	—	±3.0	±1.0	±0.1	±6	±0.27
$\pi^+\pi^-$	?	—	—	—	±0.6	±0.04
$\pi^0\pi^0$	—	—	—	—	±1.2	±0.10
ΔA^{CP}	±0.07					±0.05

Direct and Indirect *CPV* in *D*^{0} decays

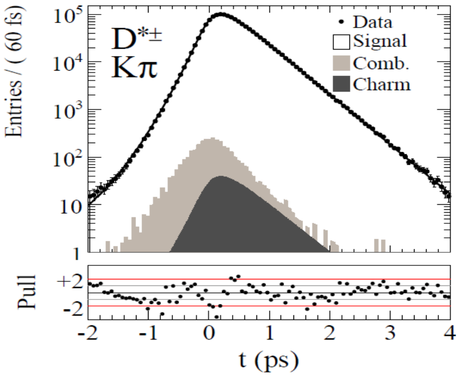
- Two physical observables we measure are

$$A_{CP}^{f} = \frac{\Gamma(D \to f) - \Gamma(\bar{D} \to \bar{f})}{\Gamma(D \to f) + \Gamma(\bar{D} \to \bar{f})} \quad \text{and} \quad A_{\Gamma} = \frac{\tau_D - \tau_{\bar{D}}}{\tau_D + \tau_{\bar{D}}}$$

Time-integrated CP asymmetry

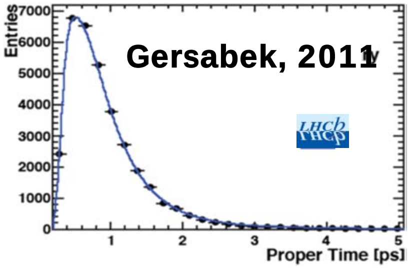
Mean decay time asymm.

- In presence of direct *CPV*, the first depends on decay mode *f*.
- Since *D*^{0} decays are not exponential, both observables depend on the (experiment-dependent) time-span for the observations.



LHCb has excellent resolution in decay time t, but rejects short times.

Babar have relatively poor t resolution but include events closer to t=0.



Gersabek, 2011

Direct and Indirect CPV

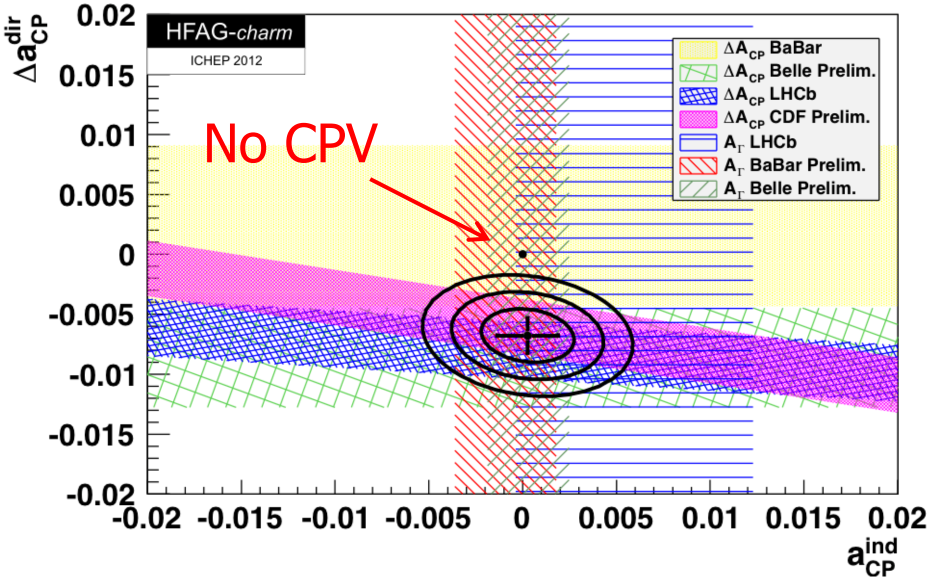
HFAG (Gersabek)

- The difference in time-integrated asymmetry

$$\Delta A_{\rm CP} = A_{\rm CP}^{KK} - A_{\rm CP}^{\pi\pi}$$

includes both direct and indirect components but the difference is mostly direct (with small time dependence due to finite integration time):

$$\Delta A_{\rm CP} = \Delta a_{\rm CP}^{\rm dir}\left(1 + y_{\rm CP}\frac{\overline{\langle t\rangle}}{\tau}\right) - \frac{\Delta\langle t\rangle}{\tau} a_{\rm CP}^{\rm ind}$$



A χ^2 fit leads to values:

$$\left.\begin{aligned} a_{\rm CP}^{\rm ind} &= 2.7 \pm 16.3 \\ \Delta a_{\rm CP}^{\rm dir} &= -67.8 \pm 14.7 \end{aligned}\right\} \times 10^{-4}$$

Central values are ~ 4σ from "no CPV" point (where CL= $2\text{x}10^{-5}$).

Summary

- Methods for measuring D mixing parameters are well developed, but usually build in the assumption that CPV is too small to include.
  - As data samples grow, this assumption will not be valid for much longer.
- Searches for time-integrated CPV asymmetries seem poised to soon become measurements of those asymmetries.
  - More reliable ways to recognize when NP is seen are required.
- Asymmetries in mixing have yet to be seen, but estimates for $|q/p|$ and $\arg\{q/p\}$ with precisions of about 2% and 1^0, respectively, are likely in the next few years.
- LHCb is working extremely well, and is clearly ready to lead way.
  - but there will still be room for e^+e^- machines to study the modes with π^0's and other neutrals.

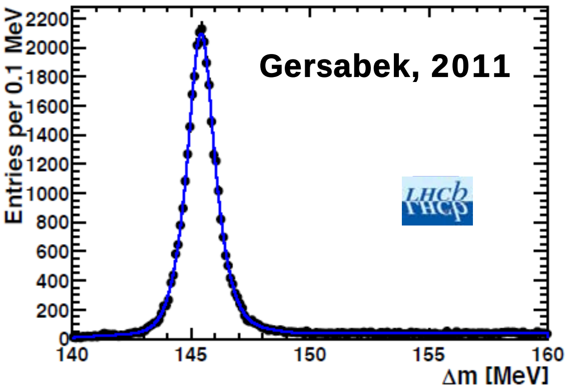
Epilogue

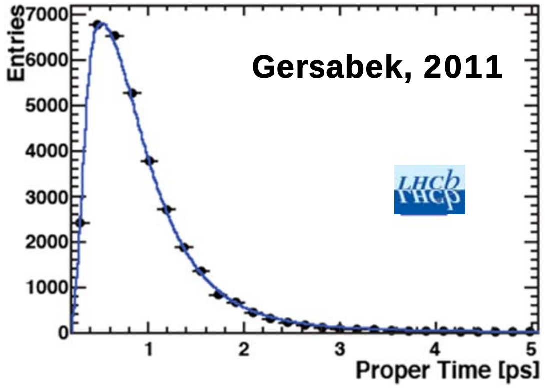
" An important goal in charm physics is not just
to observe CP Violation in D decays
but also to understand its origin”
-- Ikaros Bigi

" Thanks, Ikaros – we are still listening.”

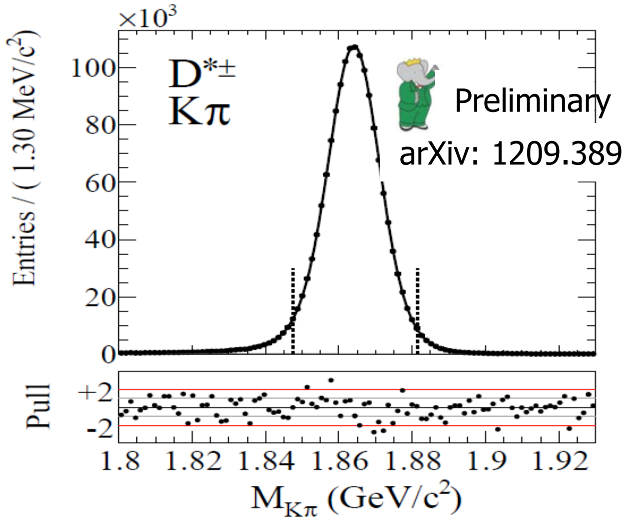
Backup Slides

Clean signals and lifetime measurements



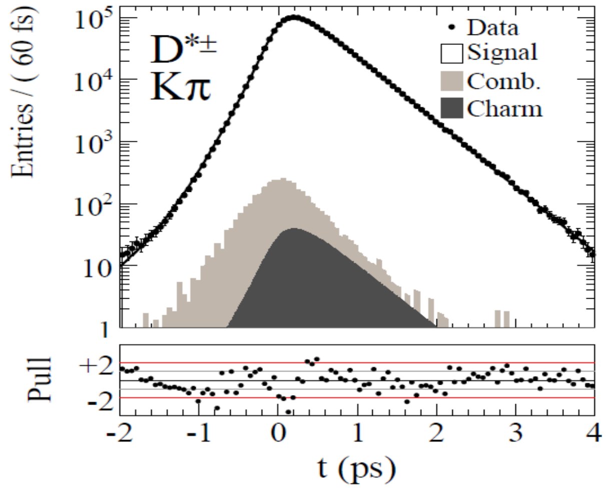


- LHCb measures only longer lifetimes due to decay length cuts.
- Also short decay times from B→D$^{(*)}\mu\nu$ triggers



Preliminary

arXiv: 1209.3896



- *B* factories measure more of lifetime range partly due to worse resolution.

Sensitivity comparison

	# Toy MC Events (BaBar data)	**Statistical uncertainty in *x* (scaled from BaBar data)**	**Statistical uncertainty in *y* (scaled from BaBar data)**
$K^+\pi^-\pi^0$	1,000 (~3,000)	2.1×10^{-3} (6.2×10^{-3})	1.5×10^{-3} (5.5×10^{-3})
$K_s\pi^-\pi^+$	500,000 (534,400)	1.9×10^{-3} (2.4×10^{-3})	1.6×10^{-3} (2.1×10^{-3})

- ❑ Pure signal Monte Carlo “toy MC” samples generated according to model for TD Dalitz Plot from BaBar data.
- ❑ $K^+\pi^-\pi^0$ channel 500 times sensitivity to x and y as $K_s\pi^-\pi^+$!
- ❑ BUT - experimental factors:
  - Larger Background and worse time resolution.

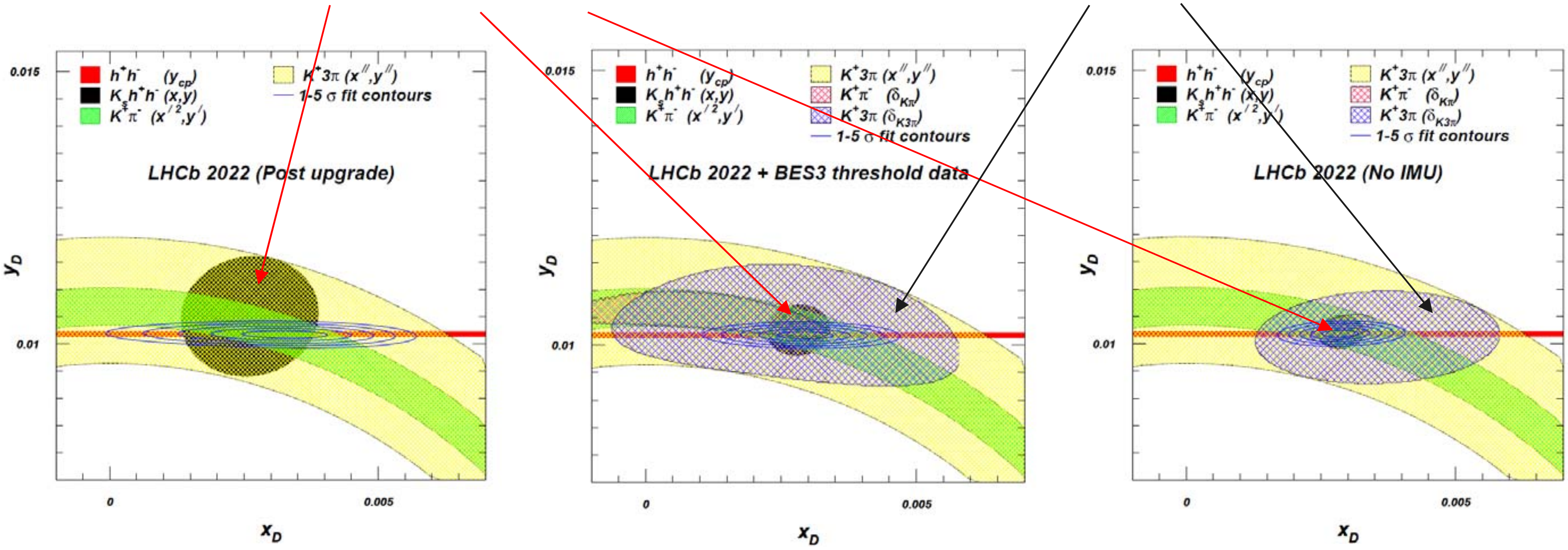
greatly compensate.

Value of strong phase measurements

- Two improvements in mixing precision come from threshold data:

- Dalitz plot model uncertainty shrinks

- Precision of overall strong phase $\delta_{K\pi(\pi)}$ increases



$$\sigma_x = 5.3 \times 10^{-4}$$
$$\sigma_y = 0.5 \times 10^{-4}$$

$\xrightarrow{\text{BES III}}$

$$\sigma_x = 3.4 \times 10^{-4}$$
$$\sigma_y = 0.5 \times 10^{-4}$$

$\xrightarrow{\text{SuperD}}$

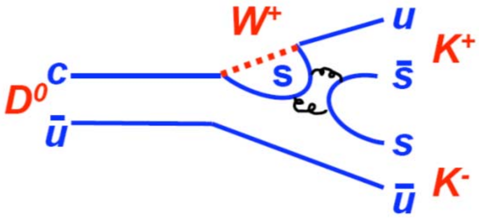
$$\sigma_x = 2.2 \times 10^{-4}$$
$$\sigma_y = 0.4 \times 10^{-4}$$

Uncertainty in x_D improves more than that of y_D

CPV in *D* Decays

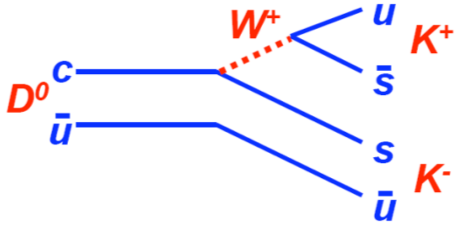
- In the charm sector *CPV* is expected to be small in the SM. If measured to be above the 0.1% level, it would signal NP.
- Singly Cabbibbo-suppressed SCS decays allow penguins → can lead to CPV

F. Bucella et al., Phys. Rev. D51, 3478 (1995)
S. Bianco et al., Riv. Nuovo Cim. 26N7, 1(2003)
S. Bianco, F.L. Fabbri, D. Benson, and I. Bigi, Riv., Nuovo Cim. 26N7, 1 (2003).



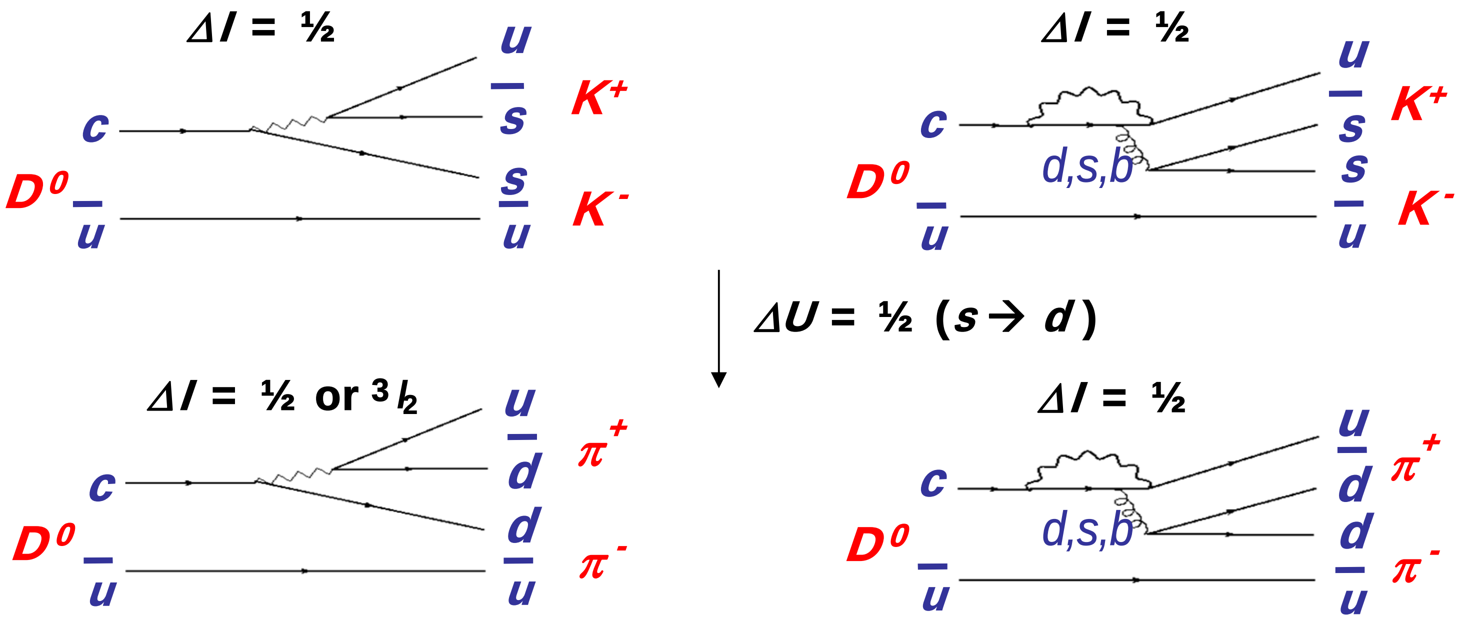
- Also, NP can be involved in the loops.

A.A. Petrov, Phys. Rev. D69, 111901 (2004)
Y. Grossman, A.L. Kagan, and Y. Nir, Phys. Rev. D75,036008 (2007)



I-spin and U-spin

- There are differences in $I-$ and $U-$spin in each amplitude



- The relation between K^+K^- and $\pi^+\pi^-$ modes is a change $\Delta U = ½$ ($s \to d$) that, if $SU(3)_{\text{flav.}}$ is not broken, results in a change in sign of the *CP* asymmetries.

On the LHCb ΔA_{CP} result *(cited 86 times)*

- It is hard for the SM to account for ΔA_{CP} of ~1%, but maybe not impossible? Some suggestions from theorists:
  - The problem might just be long-range in nature, perhaps dynamical enhancement of penguins ("penguin contraction"?)
  - Evidence that U-spin is not conserved ($K^+\pi^-$, $K^-\pi^+$, $\pi\pi$, KK) ratios.

    Anyway, or some reason, penguin amplitudes are enhanced !
  - *CPV* symmetries from a $\Delta I = {}^3\!/_2$ decay amplitude would be a clear signal for NP. (Not easy to look for though!)
  - While recognizing that I–spin breaking has similar magnitude to *CPV* asymmetries, *Grossman, Kagan and* Zupan[1] have proposed a number of sum rules that could, when sufficient data are available, expose any *CPV* effects in $\Delta I = {}^3\!/_2$ amplitudes.
  - Grossman has also suggested many $SU(3)_F$ sum rule tests

    (see CKM 2012)

…………

[1] Phys.Rev. D85 (2012) 114036

Bias in time-integrated *CPV* measurements.

- *D^0*'s are usually required to be tagged by a slow pion from *D^** decay

  BaBar introduced a way round two main barriers to the "per mille" level:

- Efficiencies for π_s^+ and π_s^- are not the same

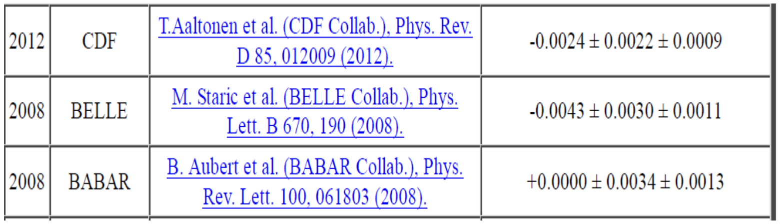
  Use DATA to find the asymmetry:
  - Use (several x10^6) untagged $K^-\pi^+$ to map efficiency asymmetry for K^- and for π^+
  - Repeat for tagged $K^-\pi^+$ to map π_s asymmetry

- *D^0*'s are produced with asymmetry in θ^* (relative to beam axis) and efficiency depends on θ^* (from Z^0/γ and higher order effects)
  - Take average of each $\cos\theta^*$ range for $|\cos\theta^*| > 0$ and < 0 as A_{CP}
  - Take difference in each $\cos\theta^*$ range for $|\cos\theta^*| > 0$ and < 0 as A_{FB}

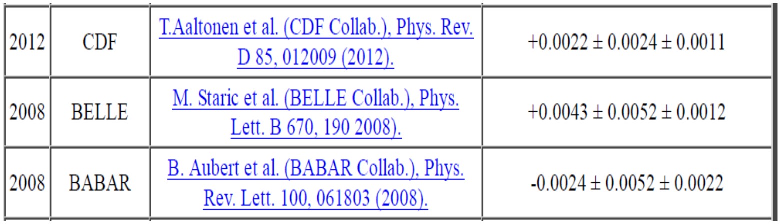
Measurements of A_{CP}

- Until 2008, systematic limit for precision of A_{CP} was $\gtrsim$ 1%.

Later

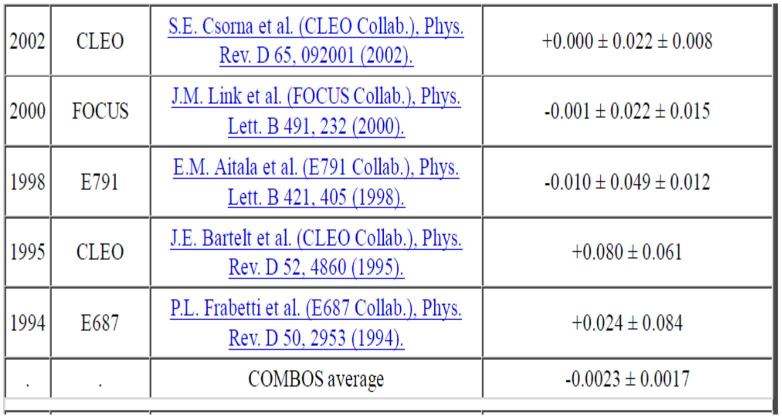


2012	CDF	T.Aaltonen et al. (CDF Collab.), Phys. Rev. D 85, 012009 (2012).	-0.0024 ± 0.0022 ± 0.0009
2008	BELLE	M. Staric et al. (BELLE Collab.), Phys. Lett. B 670, 190 (2008).	-0.0043 ± 0.0030 ± 0.0011
2008	BABAR	B. Aubert et al. (BABAR Collab.), Phys. Rev. Lett. 100, 061803 (2008).	+0.0000 ± 0.0034 ± 0.0013

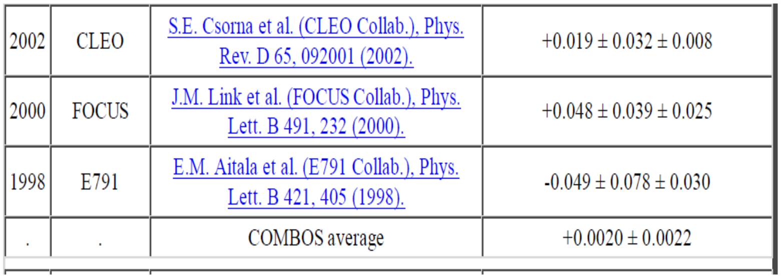


2012	CDF	T.Aaltonen et al. (CDF Collab.), Phys. Rev. D 85, 012009 (2012).	+0.0022 ± 0.0024 ± 0.0011
2008	BELLE	M. Staric et al. (BELLE Collab.), Phys. Lett. B 670, 190 2008).	+0.0043 ± 0.0052 ± 0.0012
2008	BABAR	B. Aubert et al. (BABAR Collab.), Phys. Rev. Lett. 100, 061803 (2008).	-0.0024 ± 0.0052 ± 0.0022

2008 -- BaBar insight - use data to improve uncertainties



2002	CLEO	S.E. Csorna et al. (CLEO Collab.), Phys. Rev. D 65, 092001 (2002).	+0.000 ± 0.022 ± 0.008
2000	FOCUS	J.M. Link et al. (FOCUS Collab.), Phys. Lett. B 491, 232 (2000).	-0.001 ± 0.022 ± 0.015
1998	E791	E.M. Aitala et al. (E791 Collab.), Phys. Lett. B 421, 405 (1998).	-0.010 ± 0.049 ± 0.012
1995	CLEO	J.E. Bartelt et al. (CLEO Collab.), Phys. Rev. D 52, 4860 (1995).	+0.080 ± 0.061
1994	E687	P.L. Frabetti et al. (E687 Collab.), Phys. Rev. D 50, 2953 (1994).	+0.024 ± 0.084
.	.	COMBOS average	-0.0023 ± 0.0017



2002	CLEO	S.E. Csorna et al. (CLEO Collab.), Phys. Rev. D 65, 092001 (2002).	+0.019 ± 0.032 ± 0.008
2000	FOCUS	J.M. Link et al. (FOCUS Collab.), Phys. Lett. B 491, 232 (2000).	+0.048 ± 0.039 ± 0.025
1998	E791	E.M. Aitala et al. (E791 Collab.), Phys. Lett. B 421, 405 (1998).	-0.049 ± 0.078 ± 0.030
.	.	COMBOS average	+0.0020 ± 0.0022

CLEO-c ran at charm threshold

- No D* tagging
- No production asymmetry (CMS=Lab)
- BUT sign of asymmetry unknown for D^0)

- Many

- More data-driven techniques for estimating charge asymmetries in detection and production angular efficiency have since been developed:
  - BaBar/Belle use the huge number of (carefully selected) tracks from B's, produced at rest in the Y(4S) CMS.
  - CDF measures asymmetries for the pion tag (from D^*) by combining charge asymmetry information for tagged and untagged $D^0 \to K^-\pi^+$ and $\pi^+\pi^-$ decays. LHCb also use additional techniques
- These all rely on basic $c\bar{c}$ production rate symmetry not present at LHC, yet LHCb also use data-driven approaches:
  - Reversing the spectrometer magnet.
  - Direct measurements of the $c\bar{c}$ production asymmetry.
  - Use of asymmetries between decay modes.

Direct *CPV* in $D^+(D_s^+)$ Decays to K_s

- Decays are self-tagging, no tag pion asymmetry, but:
  - Do not have charge symmetry among D^+ decay products
    → BaBar and Belle use *B* decay tracks to measure efficiency.
  - K_s can be K^0 or $\overline{K^0}$ and these have different interaction σ's
    → dilution correction (depends on momentum) up to 3 per mil.
  - K_s has unavoidable *CP* asymmetry $(-0.332 \pm 0.006) \times 10^{-2}$ (Nir and Grossman effect")

	$D^+ \to K_S^0 \pi^+ (\%)$	$D^+ \to K_S^0 K^+ (\%)$
Belle	$-0.363 \pm 0.094 \pm 0.067$	$-0.246 \pm 0.275 \pm 0.135$
BABAR	$-0.44 \pm 0.13 \pm 0.10$	$+0.13 \pm 0.36 \pm 0.25$

	$D_s^+ \to K_S^0 \pi^+ (\%)$	$D_s^+ \to K_S^0 K^+ (\%)$
Belle	$+5.45 \pm 2.50 \pm 0.33$	$--$
BABAR	$+0.6 \pm 2.0 \pm 0.3$	$(-0.05 \pm 0.23 \pm 0.24$

All consistent with *CPV* in K_s

No evidence for *CPV* in D^+ decays.

CPV in multi-body decay modes

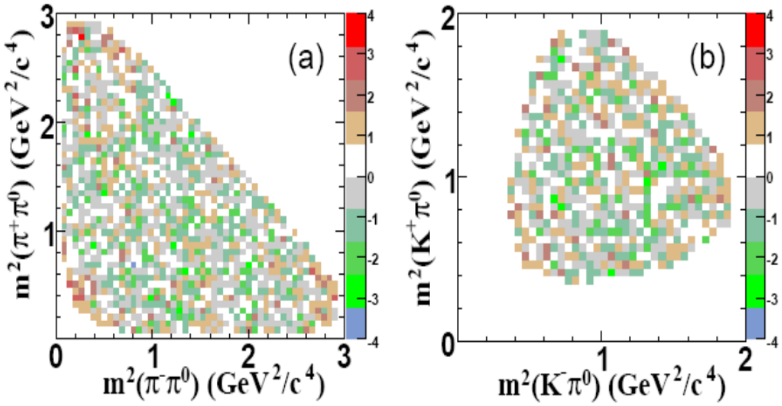
PhysRevD.78.051102
384 fb^{-1}

- Extended search within $h^+h^-\pi^o$ modes:
  - *CPV* is unlikely to be seen in all channels – but perhaps in one
    Search each channel - e.g. $D^0 \rightarrow \rho^0 + \pi^0$
  - Each channel can be normalized to whole Dalitz plot.
    Systematic uncertainties from π_s^+ tagging or from production asymmetries become 2nd o`rder effects
  - CPV is signalled by differences in phase behaviour between D^0 and $\overline{D}^0$.
    Dalitz plot for these 3-body final states yields information on phase behaviour between channels.

- BaBar, Belle and LHCb are using several search strategies
  - Model-independent searches for *CPV* in exclusive parts of phase space.
  - Model-dependent searches based on fits to the Dalitz plot distributions

Two Model-Independent Searches for CPV in $D^0 \rightarrow \pi^-\pi^+\pi^0$ and $K^-K^+\pi^0$ by BaBar

"Miranda method ?"



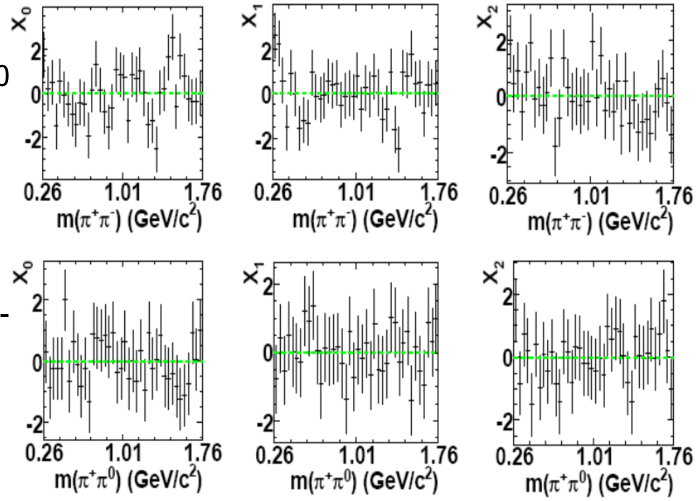
Phys.Rev.D (TBP, 2008)

Dalitz plots for D^0 and for $\overline{D}^0$ are normalized and compared, bin-for-bin

Unbiassed frequentist test yields 16.6% conf. level there is no difference.

$[\pi^+\pi^-] + \pi^0$ channel

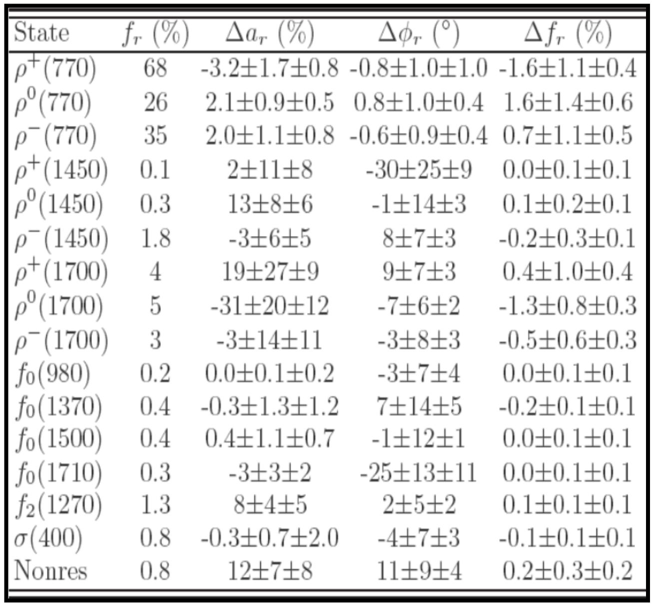
$[\pi^+\pi^0] + \pi^-$ channel



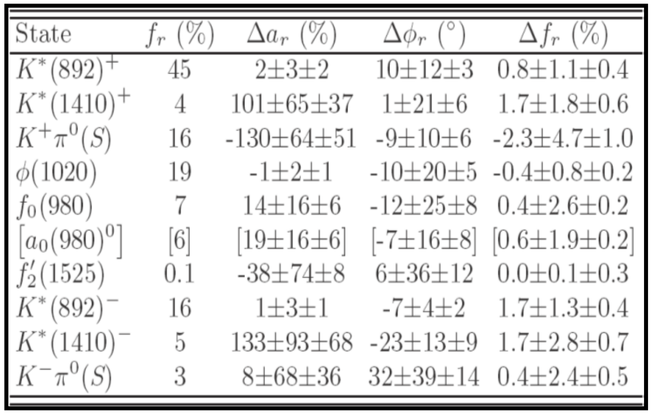
Legendre polynomial moments of D^0-$\overline{D}^0$ differences (to order 8) are normalized and compared, in each channel.

Unbiassed frequentist test indicates 23-66% conf. levels there are no differences in the various channels.

Model-dependent Search for CPV in $D^0 \rightarrow \pi^-\pi^+\pi^0$ and $K^-K^+\pi^0$

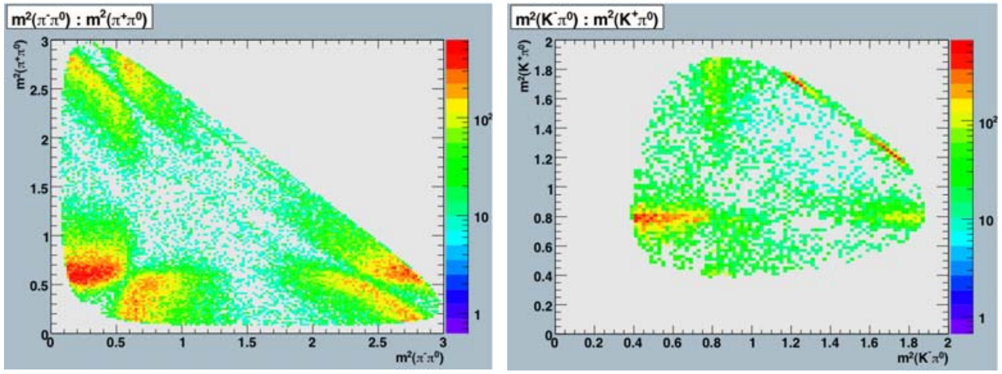


State	f_r (%)	Δa_r (%)	$\Delta\phi_r$ (°)	Δf_r (%)
$\rho^+(770)$	68	-3.2±1.7±0.8	-0.8±1.0±1.0	-1.6±1.1±0.4
$\rho^0(770)$	26	2.1±0.9±0.5	0.8±1.0±0.4	1.6±1.4±0.6
$\rho^-(770)$	35	2.0±1.1±0.8	-0.6±0.9±0.4	0.7±1.1±0.5
$\rho^+(1450)$	0.1	2±11±8	-30±25±9	0.0±0.1±0.1
$\rho^0(1450)$	0.3	13±8±6	-1±14±3	0.1±0.2±0.1
$\rho^-(1450)$	1.8	-3±6±5	8±7±3	-0.2±0.3±0.1
$\rho^+(1700)$	4	19±27±9	9±7±3	0.4±1.0±0.4
$\rho^0(1700)$	5	-31±20±12	-7±6±2	-1.3±0.8±0.3
$\rho^-(1700)$	3	-3±14±11	-3±8±3	-0.5±0.6±0.3
$f_0(980)$	0.2	0.0±0.1±0.2	-3±7±4	0.0±0.1±0.1
$f_0(1370)$	0.4	-0.3±1.3±1.2	7±14±5	-0.2±0.1±0.1
$f_0(1500)$	0.4	0.4±1.1±0.7	-1±12±1	0.0±0.1±0.1
$f_0(1710)$	0.3	-3±3±2	-25±13±11	0.0±0.1±0.1
$f_2(1270)$	1.3	8±4±5	2±5±2	0.1±0.1±0.1
$\sigma(400)$	0.8	-0.3±0.7±2.0	-4±7±3	-0.1±0.1±0.1
Nonres	0.8	12±7±8	11±9±4	0.2±0.3±0.2



State	f_r (%)	Δa_r (%)	$\Delta\phi_r$ (°)	Δf_r (%)
$K^*(892)^+$	45	2±3±2	10±12±3	0.8±1.1±0.4
$K^*(1410)^+$	4	101±65±37	1±21±6	1.7±1.8±0.6
$K^+\pi^0(S)$	16	-130±64±51	-9±10±6	-2.3±4.7±1.0
$\phi(1020)$	19	-1±2±1	-10±20±5	-0.4±0.8±0.2
$f_0(980)$	7	14±16±6	-12±25±8	0.4±2.6±0.2
$[a_0(980)^0]$	[6]	[19±16±6]	[-7±16±8]	[0.6±1.9±0.2]
$f_2'(1525)$	0.1	-38±74±8	6±36±12	0.0±0.1±0.3
$K^*(892)^-$	16	1±3±1	-7±4±2	1.7±1.3±0.4
$K^*(1410)^-$	5	133±93±68	-23±13±9	1.7±2.8±0.7
$K^-\pi^0(S)$	3	8±68±36	32±39±14	0.4±2.4±0.5

Phys.Rev.D (TBP, 2008)



Dalitz plots for D^0 and for $\overline{D}^0$ were fitted to isobar model expansions of interfering amplitudes in each channel.

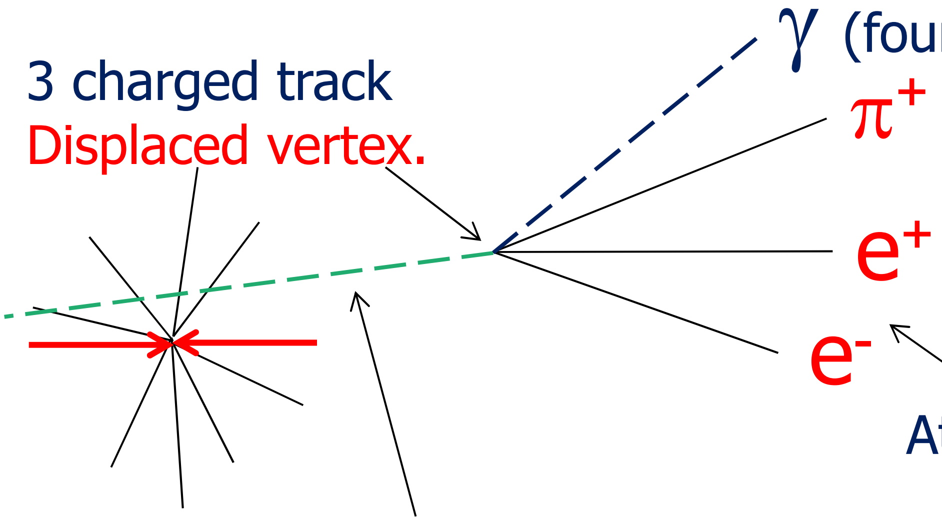
Differences in magnitudes and phases For each amplitude were insignificant.

A π^o Trigger ?

Consider $D^+ \rightarrow \pi^+\pi^o$ 1/84 π^o's decay thus.

$\llcorner\!\!\!\_\_\_\; e^+e^-\gamma$

Need to trigger
Back up



γ (found offline)

3 charged track
Displaced vertex.

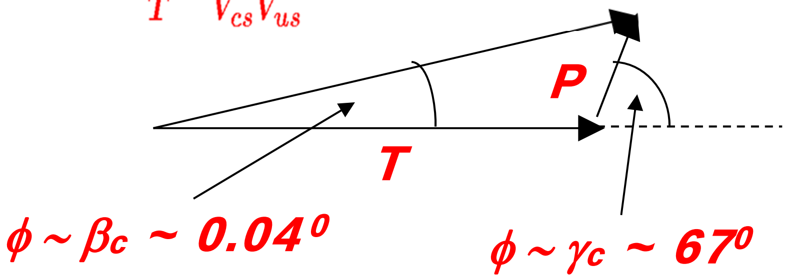
At least 1 (or 2)
e's ID'd.

Three tracks do not point
back to PV
Invariant mass < D^+

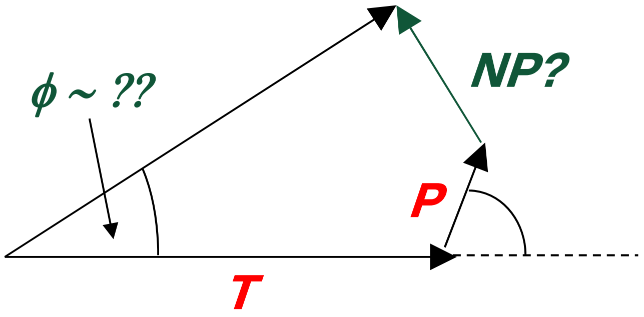
Measure TD *CPV* asymmetry

- The time-dependence of *CPV* asymmetry of weak decays of D^0 to a *CP* eigenstate measures the phase $\phi_M - 2\phi$ where ϕ_M is the mixing phase and ϕ is the weak decay phase.
- Differences between $D^0 \rightarrow \pi^+\pi^-$ and $D^0 \rightarrow K^+K^-$ can, therefore, be used to measure ϕ.
- This can be useful in understanding the difference between *SM* and *NP* for the differential asymmetry observed by LHCb between these two modes.

SM: $\frac{P}{T} = \frac{V_{cb}V_{ub}}{V_{cs}V_{us}} = r_P e^{-i\gamma} \sim 10^{-3} e^{-i\,68^0}$



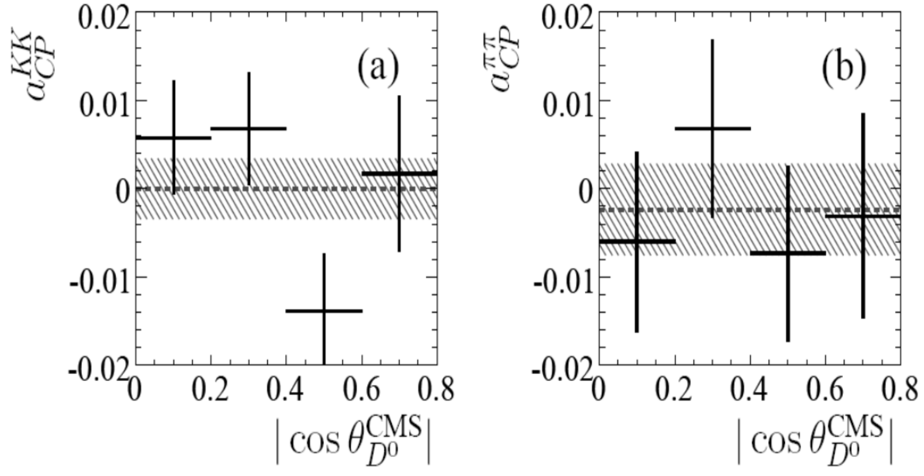
NP:

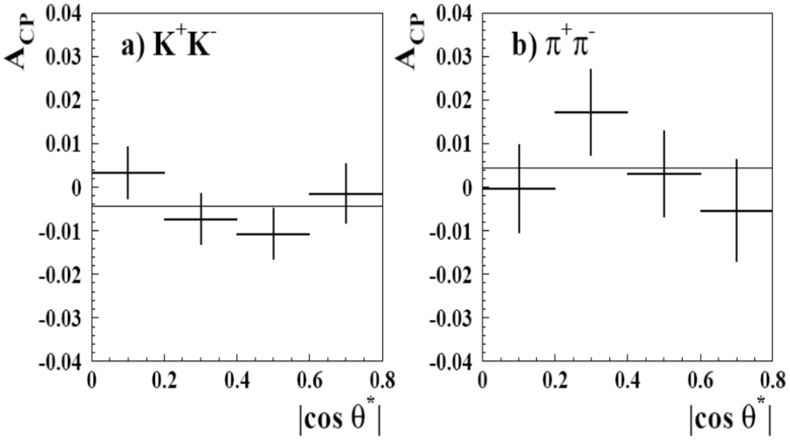


$D^0 \rightarrow K^+K^-$ and $\pi^+\pi^-$

Phys.Rev.Lett.100:061803 (2008)

Arxiv:0807.0148v1 (2008) **NEW**





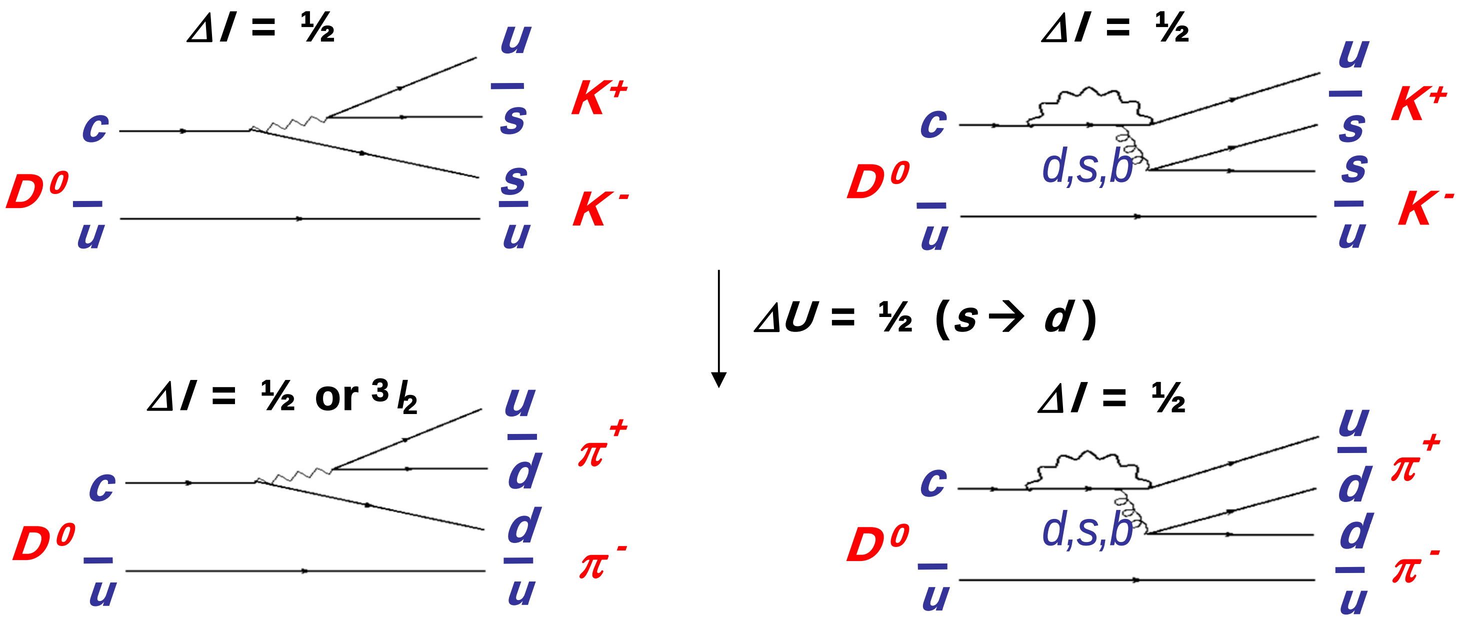
$$A_{CP}^{KK} = [\ 0.00 \pm 0.34(\text{stat.}) \pm 0.13(\text{syst.})]\%$$
$$A_{CP}^{\pi\pi} = [-0.24 \pm 0.52(\text{stat.}) \pm 0.22(\text{syst.})]\%$$

$$A_{CP}^{KK} = [\ 0.43 \pm 0.30(\text{stat.}) \pm 0.11(\text{syst.})]\%$$
$$A_{CP}^{\pi\pi} = [0.43 \pm 0.52(\text{stat.}) \pm 0.12(\text{syst.})]\%$$

- No evidence for CPV
- Systematic uncertainties ~ 0.1% (Likely scale with luminosity$^{-1/2}$) !!
- No significant difference between KK and $\pi\pi$

I-spin and U-spin

- There are differences in $I-$ and $U-$spin in each amplitude



- The relation between K^+K^- and $\pi^+\pi^-$ modes is a change $\Delta U=½$ ($s \rightarrow d$) that, if $SU(3)_{\text{flav.}}$ is not broken, results in a change in sign of the CP asymmetries.

I, U and V-spin Conservation

Three SU(2) sub-groups of flavour SU(3):

Lipkin:

"I-spin, U-spin, V-spin → V-all spin"

I-spin symmetry breaking sources:

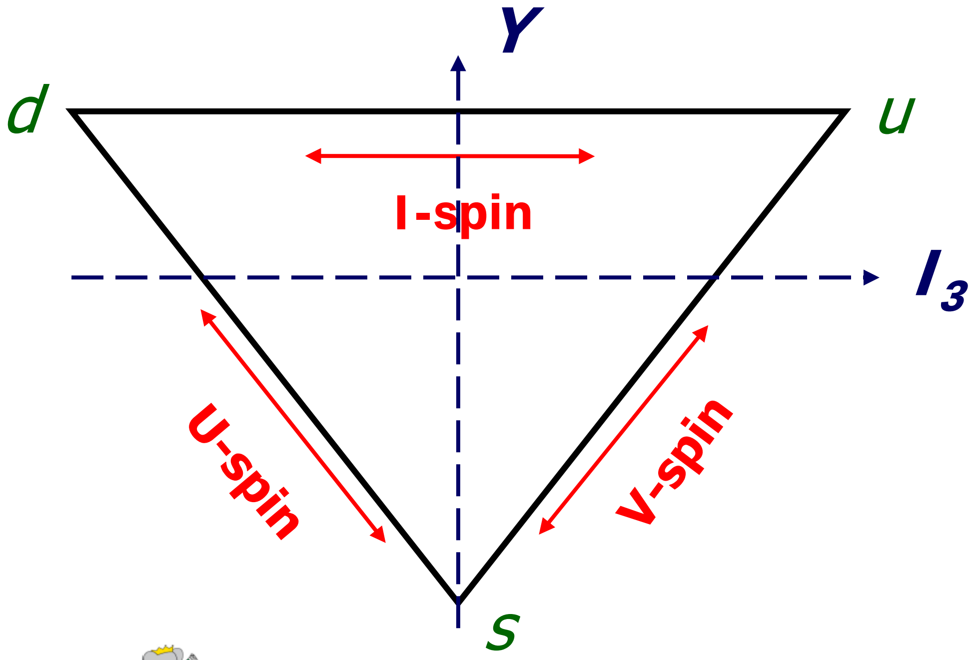
- *EW* penguins - suppressed by factor α_s/α.
- Different *u* and *d* quark masses.
- *E/M* interactions.

BUT Effects are O(1%) - comparable to some *CPV* asymmetries observed.

U-spin symmetry is probably broken.

- Ratios of D^0 decay rates to $K^-\pi^+$, K^-K^+ and $K^+\pi^-$ differ from Cabibbo suppression values.
- *U*-spin symmetry predicts that
  $$A_{CP}(\pi^+\pi^-) = -A_{CP}(K^+K^-)$$
  has yet to be experimentally tested.

Feldman, Nandi, Soni, arXiv: 1202.3795



- I-spin breaking, due to electromagnetic interactions and to u and d quark mass differences are CP conserving. That due to EW penguin amplitudes are suppressed by ~(α_s/α).

- GZK keep this breaking a 2nd *order* effect in comparison with predicted asymmetries, by writing their sum rules mostly in terms of CP differences of rates

$$\Delta_2(f) = (|A_f|^2 - |\bar{A}_{\bar{f}}|^2)$$

or amplitudes

$$\Delta(f) = (A_f - \bar{A}_{\bar{f}})$$

I- spin Tests for NP

- It is hard for the SM to account for ΔA_{CP} of ~1%, but maybe not impossible. But how can we tell if NP is required?

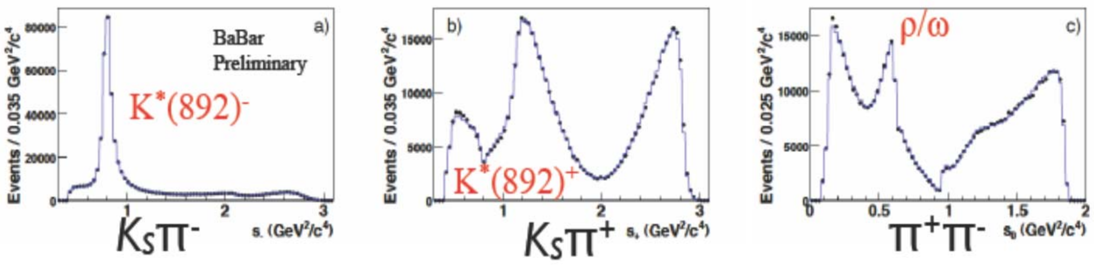
- In the SM, the *CPV* asymmetries come only from $\Delta I = {}^{1}\!/_{2}$ penguin amplitudes.
- So *CPV* symmetries from a $\Delta I = {}^{3}\!/_{2}$ decay amplitude would be a clear signal for NP.
- Recognizing that I–spin breaking has similar magnitude to *CPV* asymmetries, *Grossman, Kagan and Zupan* (GKZ) recently proposed a number of sum rules that could, when sufficient data are available, expose any *CPV* effects in $\Delta I = {}^{3}\!/_{2}$ amplitudes.

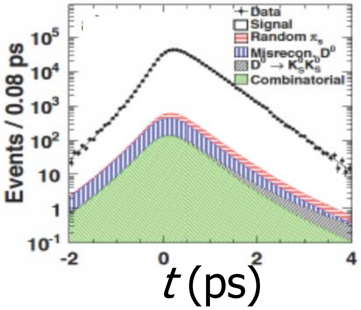
Phys.Rev. D85 (2012) 114036

Large and pure samples from $D^{*+} \to D^0 \pi^+$ decays fit to combined $K_s\pi\pi$ and K_sKK samples give most precise measurement to date

$K_s \pi^+\pi^-$

Signal : 541K
purity 98.5%





$\mathcal{A}_f$:

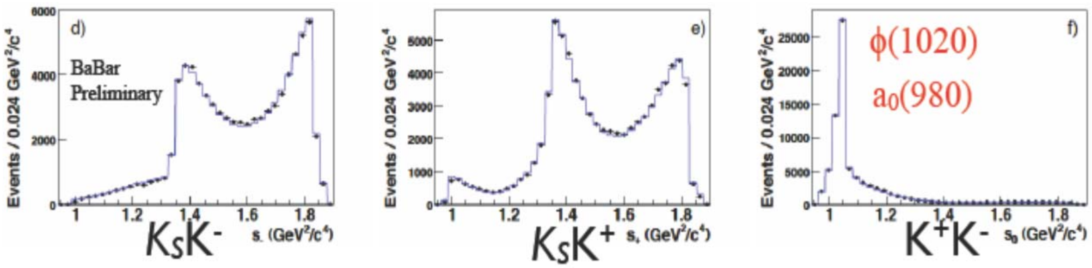
S-wave $\pi^+\pi^-$
K-matrix model

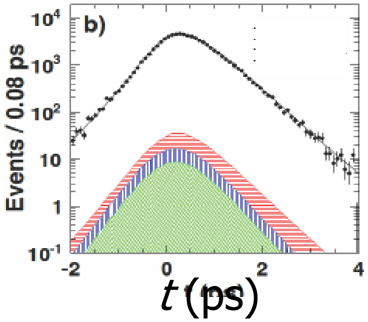
S-wave $K^0\pi^-$
LASS model

P- and D-waves
Breit-Wigner model

$K_sK^+K^-$

Signal : 80K
purity 99.2%





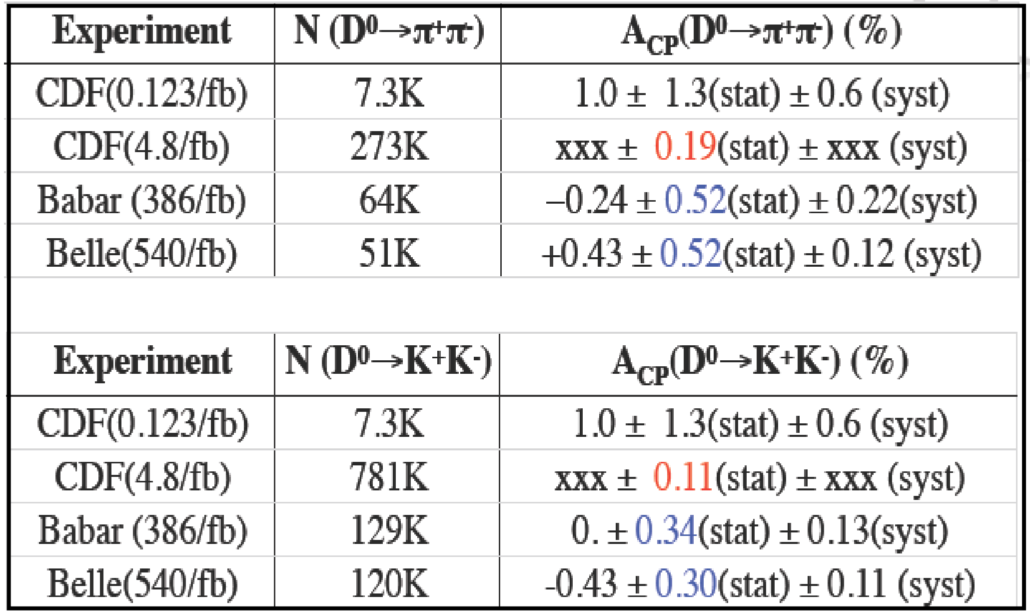
$\mathcal{A}_f$:

S-wave K^+K^- Coupled-channel Breit-Wigner a0(980)

All other waves Breit-Wigners

Time-Integrated CPV from TeVatron

Work in progress – Mark Mattson, ICHEP 2010



Experiment	N ($D^0 \to \pi^+\pi^-$)	$A_{CP}(D^0 \to \pi^+\pi^-)$ (%)
CDF(0.123/fb)	7.3K	1.0 ± 1.3(stat) ± 0.6 (syst)
CDF(4.8/fb)	273K	xxx ± 0.19(stat) ± xxx (syst)
Babar (386/fb)	64K	−0.24 ± 0.52(stat) ± 0.22(syst)
Belle(540/fb)	51K	+0.43 ± 0.52(stat) ± 0.12 (syst)

Experiment	N ($D^0 \to K^+K^-$)	$A_{CP}(D^0 \to K^+K^-)$ (%)
CDF(0.123/fb)	7.3K	1.0 ± 1.3(stat) ± 0.6 (syst)
CDF(4.8/fb)	781K	xxx ± 0.11(stat) ± xxx (syst)
Babar (386/fb)	129K	0. ± 0.34(stat) ± 0.13(syst)
Belle(540/fb)	120K	-0.43 ± 0.30(stat) ± 0.11 (syst)

Systematic uncertainty is expected to be O(0.1%), comparable to statistical uncertainty.

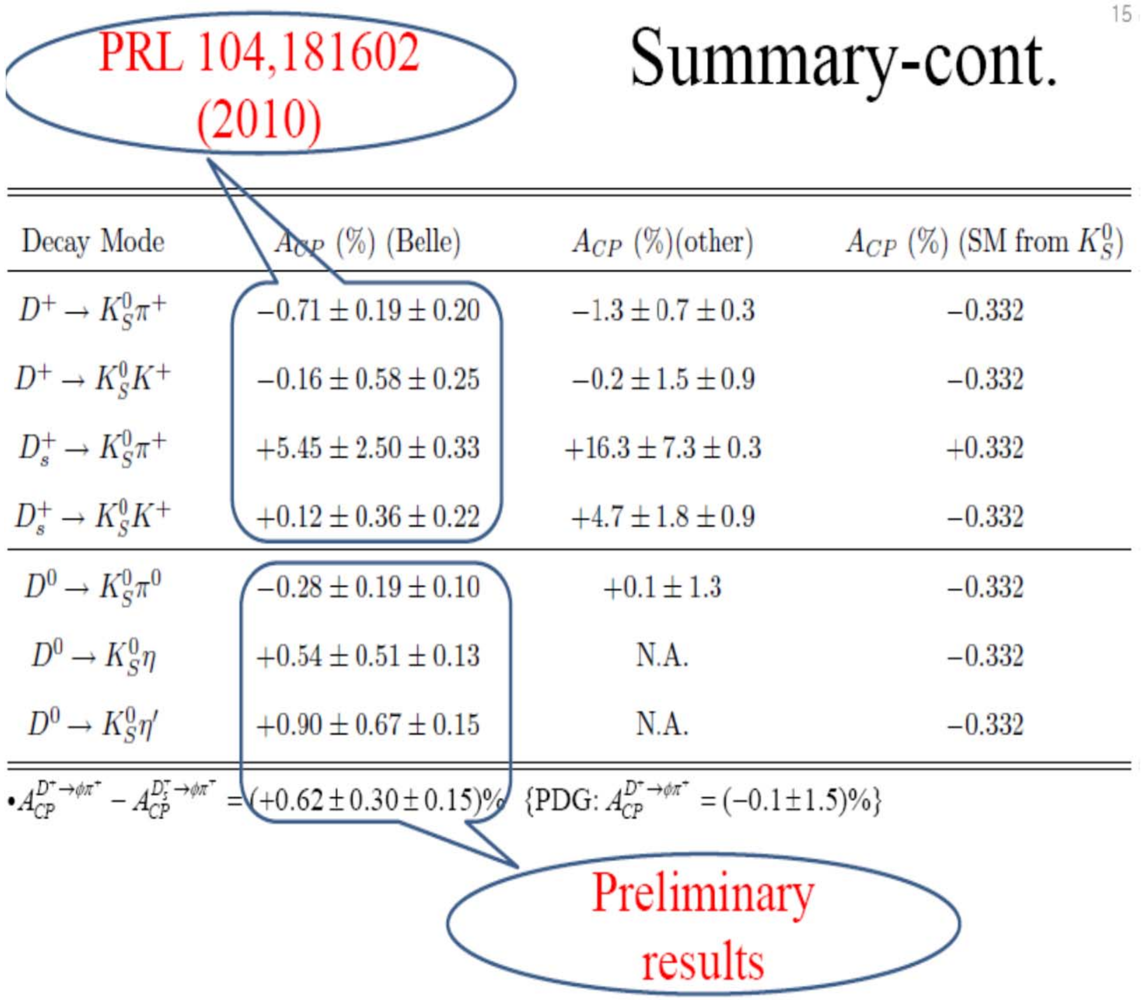
Techniques pioneered by Babar, extended and used by Belle, virtually eliminate major systematic effects:

- F-B production asymmetry
  - Use odd moments
- Charge efficiency asymmetry
  - Use data to calibrate, NOT Monte Carlo

Now used by CDF.

Interesting → interestinger …

New Time-Integrated CPV Results from Belle



15

Summary-cont.

PRL 104,181602 (2010)

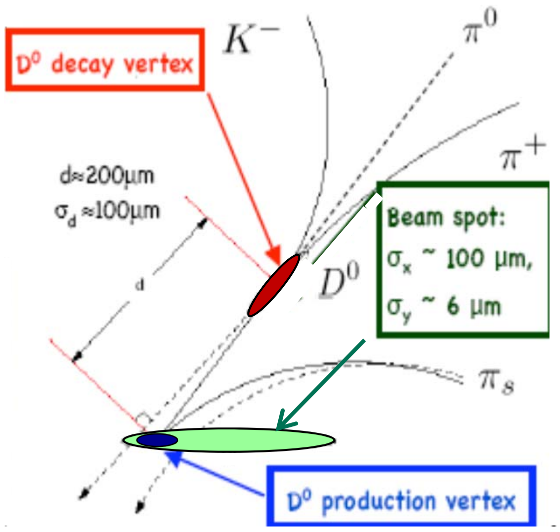
Decay Mode	A_{CP} (%) (Belle)	A_{CP} (%)(other)	A_{CP} (%) (SM from K_S^0)
$D^+ \to K_S^0 \pi^+$	$-0.71 \pm 0.19 \pm 0.20$	$-1.3 \pm 0.7 \pm 0.3$	-0.332
$D^+ \to K_S^0 K^+$	$-0.16 \pm 0.58 \pm 0.25$	$-0.2 \pm 1.5 \pm 0.9$	-0.332
$D_s^+ \to K_S^0 \pi^+$	$+5.45 \pm 2.50 \pm 0.33$	$+16.3 \pm 7.3 \pm 0.3$	$+0.332$
$D_s^+ \to K_S^0 K^+$	$+0.12 \pm 0.36 \pm 0.22$	$+4.7 \pm 1.8 \pm 0.9$	-0.332
$D^0 \to K_S^0 \pi^0$	$-0.28 \pm 0.19 \pm 0.10$	$+0.1 \pm 1.3$	-0.332
$D^0 \to K_S^0 \eta$	$+0.54 \pm 0.51 \pm 0.13$	N.A.	-0.332
$D^0 \to K_S^0 \eta'$	$+0.90 \pm 0.67 \pm 0.15$	N.A.	-0.332

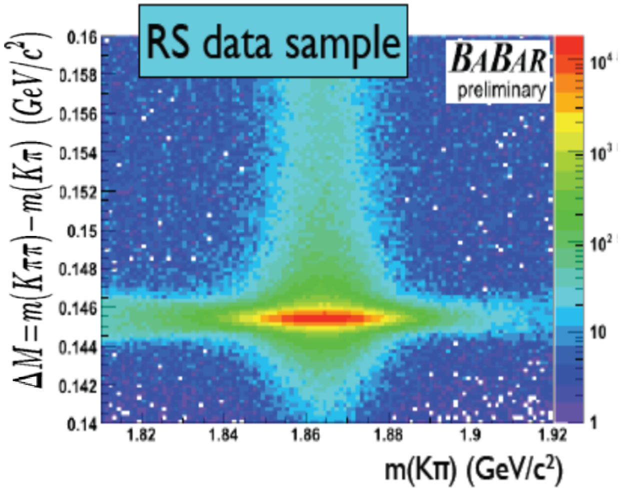
- $A_{CP}^{D^+ \to \phi\pi^+} - A_{CP}^{D_s^+ \to \phi\pi^+} = (+0.62 \pm 0.30 \pm 0.15)\%$ {PDG: $A_{CP}^{D^+ \to \phi\pi^+} = (-0.1 \pm 1.5)\%$}

Preliminary results

Mixing Measurements at *BaBar* and *Belle*

- Good vertex resolution allows measurement of time-dependence of D^0 decays.
- Can eliminate distortion from *B* decays by cutting low momentum D^0's
- Excellent particle ID (Dirc and dE/dx) allows clean K/π separation

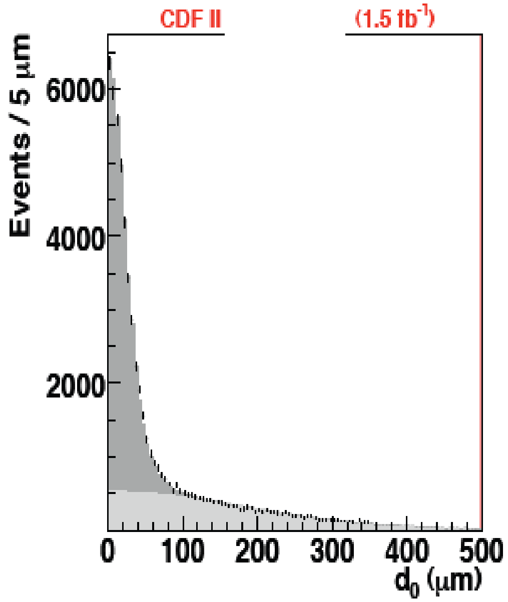


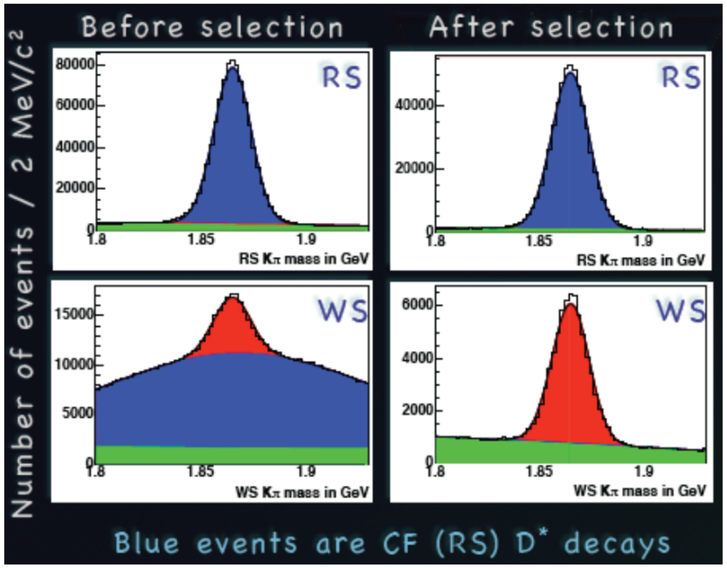


- D^0's from $D^{*+} \rightarrow D^0\pi^+$ decays:
  - Tag flavor of D^0 by the sign of the "slow pion" in D^* decays
  - Allow clean rejection of backgrounds
- **BUT untagged events can be used too !**

Mixing Measurements at *CDF*

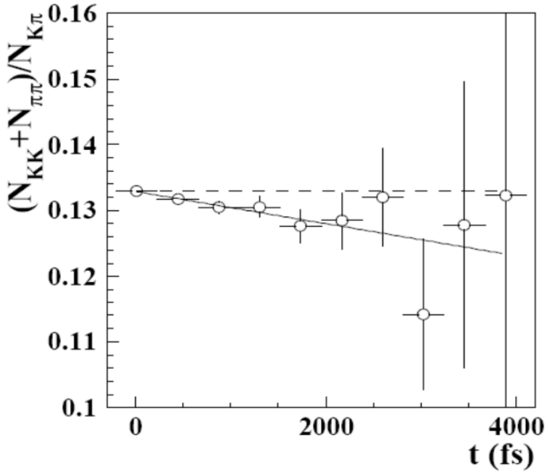
- Use 2-track displaced vertex trigger
- Must contend with *D^0* from *B* decay
- Can eliminate distortion from *B* decays by cutting out events with large impact parameter.

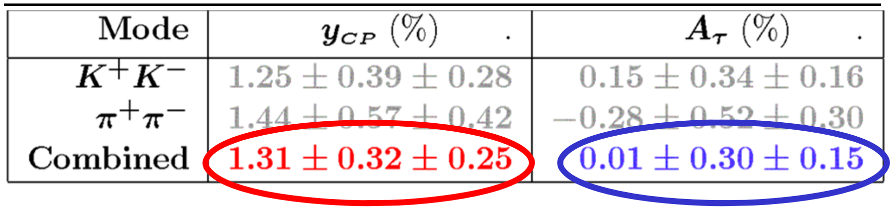




- Doubly mis-ID'd WS events require a RS mass cut
- *D^0*'s from *$D^{*+} \rightarrow D^0\pi^+$* decays: Untagged events are not used

Lifetime Ratio (*D**-tagged Samples)

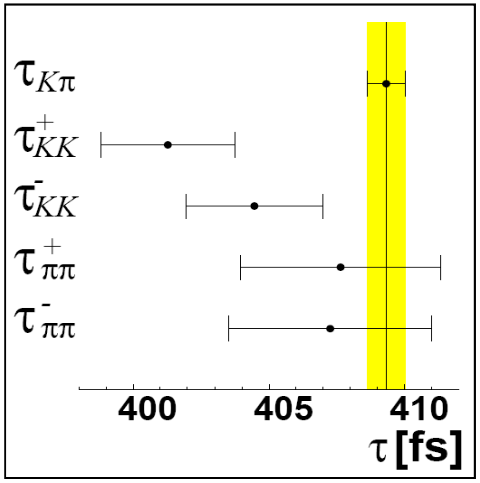


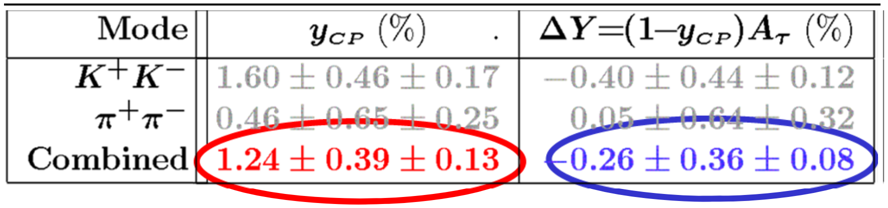


Mode	y_{CP} (%)	A_τ (%)
K^+K^-	$1.25 \pm 0.39 \pm 0.28$	$0.15 \pm 0.34 \pm 0.16$
$\pi^+\pi^-$	$1.44 \pm 0.57 \pm 0.42$	$-0.28 \pm 0.52 \pm 0.30$
Combined	$1.31 \pm 0.32 \pm 0.25$	$0.01 \pm 0.30 \pm 0.15$

3.2 σ evidence - no *CPV*

PRL 98:211803,2007 540 fb^{-1}





Mode	y_{CP} (%)	$\Delta Y = (1 - y_{CP}) A_\tau$ (%)
K^+K^-	$1.60 \pm 0.46 \pm 0.17$	$-0.40 \pm 0.44 \pm 0.12$
$\pi^+\pi^-$	$0.46 \pm 0.65 \pm 0.25$	$0.05 \pm 0.64 \pm 0.32$
Combined	$1.24 \pm 0.39 \pm 0.13$	$-0.26 \pm 0.36 \pm 0.08$

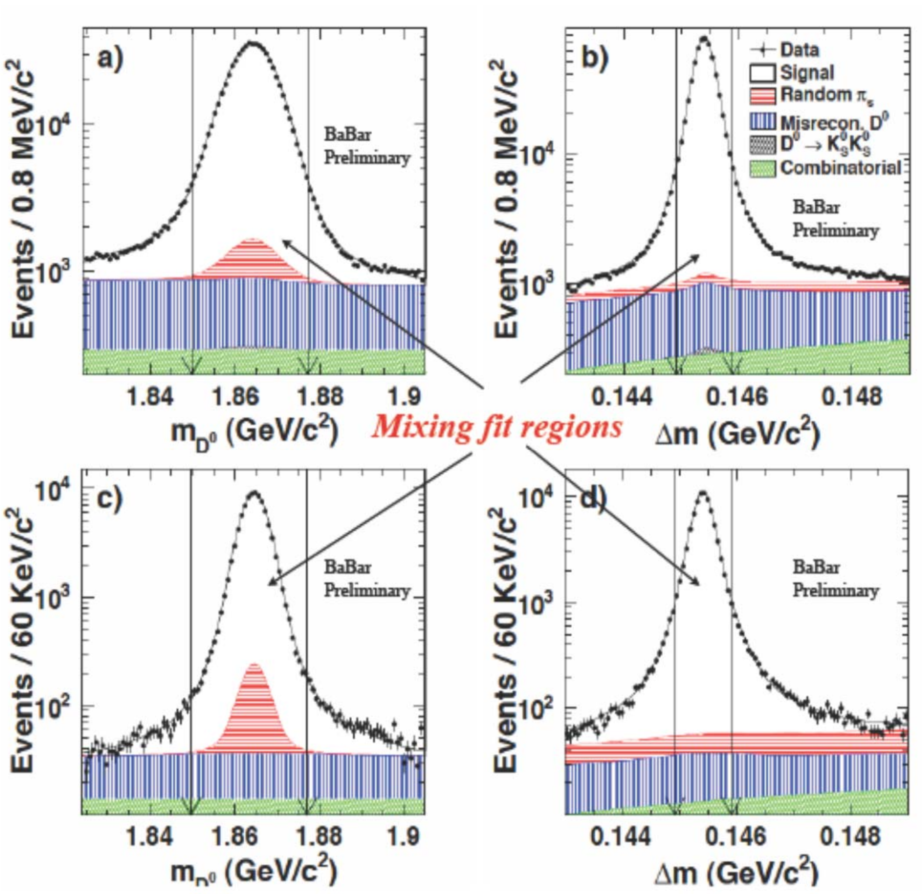
3.0 σ evidence - no *CPV*

Phys.Rev.D78:011105,2008 384 fb^{-1}

TD Amplitude Analysis of $D^0 \rightarrow K_S h^+ h^-$

Recent result

Phys.Rev.Lett.105:081803 (2010) – 468 fb^{-1}



Very clean samples
from $D^{*+} \rightarrow D^0 \pi^+$ decays

$K_S \pi^+ \pi^-$:
Signal (540.8±0.8) x 10^3 events
Purity 98.5 %

Fit to combined $K_S\pi\pi$ and K_SKK samples give

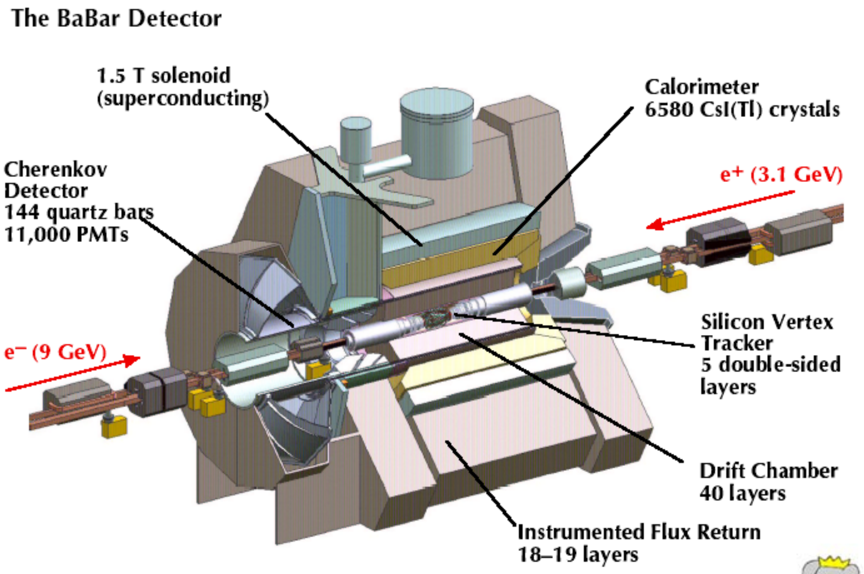
$x = [0.16 \pm 0.23(\text{stat.}) \pm 0.12(\text{syst.}) \pm 0.08(\text{model})]\%$

$y = [0.57 \pm 0.20(\text{stat.}) \pm 0.13(\text{syst.}) \pm 0.07(\text{model})]\%$

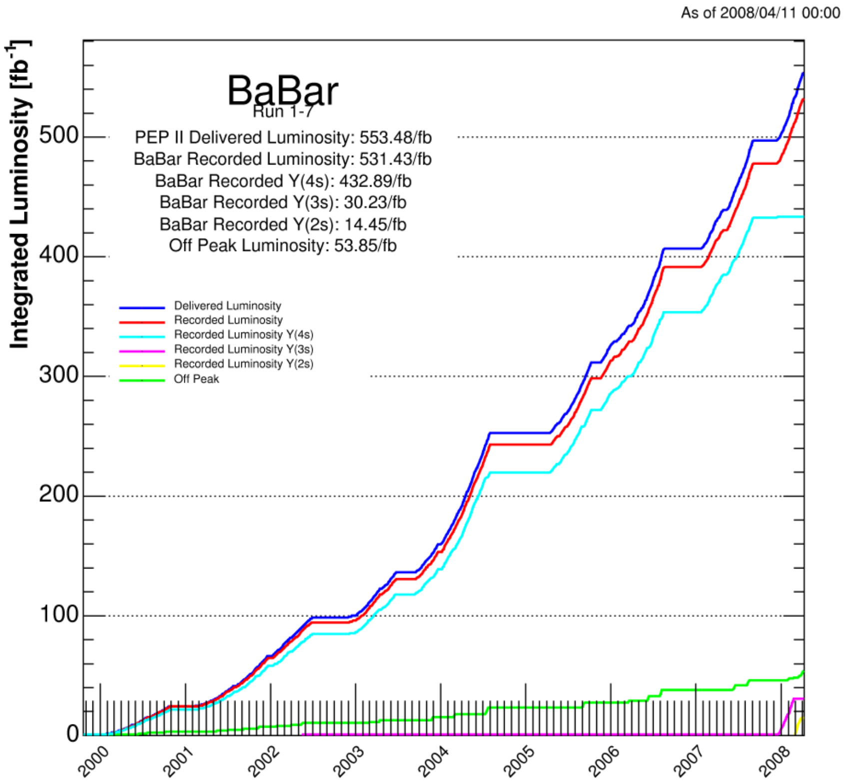
Most precise measurement to date:

$K_S K^+ K^-$:
Signal (79.9±0.3) x 10^3 events
Purity 99.2 %

BaBar



Peak luminosity $1.2\times10^{34}\,cm^{-2}s^{-1}$
Integrated luminosity 531 fb^{-1}



- Main purpose: Study CP violation in asymmetric e^+e^- □ Υ(4S) □ $B\bar{B}$
- Experiment far exceeded the design goals
  - Luminosity order of magnitude larger
  - Many more measurements and discoveries.