Work in process, for submission soon…

From Beauty to Charm…

Bounding hadronic uncertainties in c to u decays

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Based on work in progress by AB and Brian Meadows

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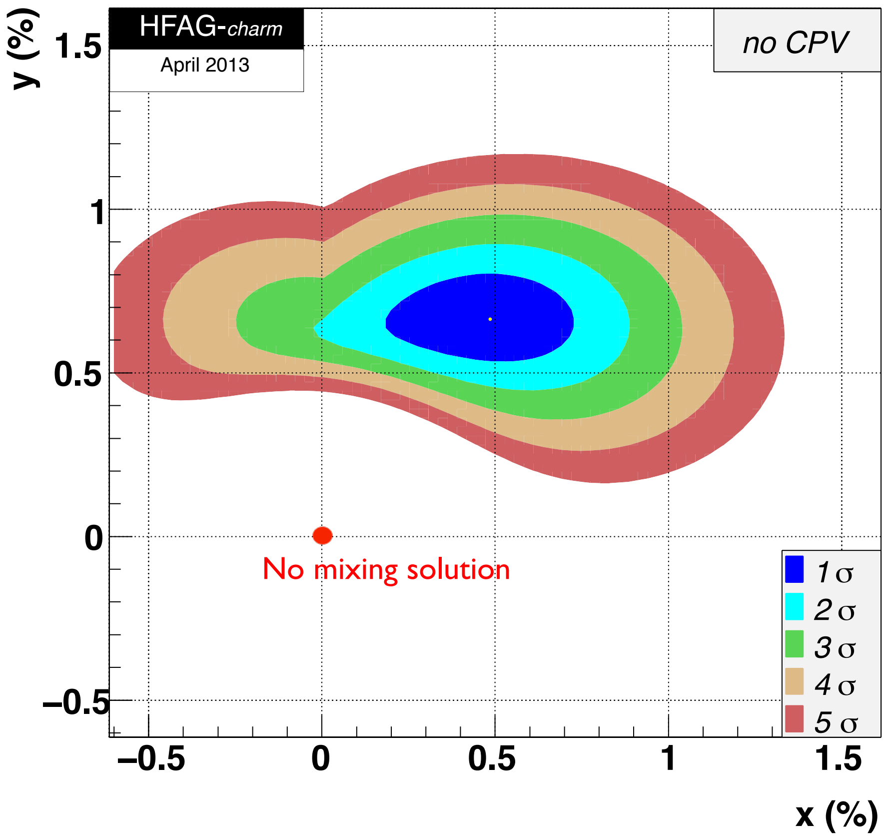
Overview

- From mixing to CP violation
- The experimental stage
- Isospin relations
  - D to $\pi\pi$
  - D to $\rho\rho$
  - D to $\pi^+\pi^-\pi^0$
- Conclusions

From mixing to CP violation

- Experimentalists have been chasing neutral meson mixing in the charm sector for decades…
  - Both of the B Factories saw this in 2007 via different observables.
  - More recently LHCb has produced a beautiful demonstration of this quantum mechanical effect.



From mixing to CP violation

- Experimentalists have been chasing neutral meson mixing in the charm sector for decades…
  - Now that mixing is under-control… we can look for:
    - CP violation in mixing.

$$|q/p| \neq 1$$

Hard to find, but important

    - Direct CP violation.

$$|A|^2 \neq |\overline{A}|^2$$

Hard to interpret, but should be there

    - Recall the conditions required for direct CP violation place constraints on what we can learn from such observables.

$$A_{CP} = \frac{\overline{\Gamma} - \Gamma}{\overline{\Gamma} + \Gamma} \propto A_1 A_2 \sin(\phi_1 - \phi_2) \sin(\delta_1 - \delta_2)$$

e.g. for two interfering amplitudes

    - CP violation in the interference between mixing and decay.

$$\lambda_f = \frac{q}{p}\frac{\overline{A}}{A} \neq 1$$

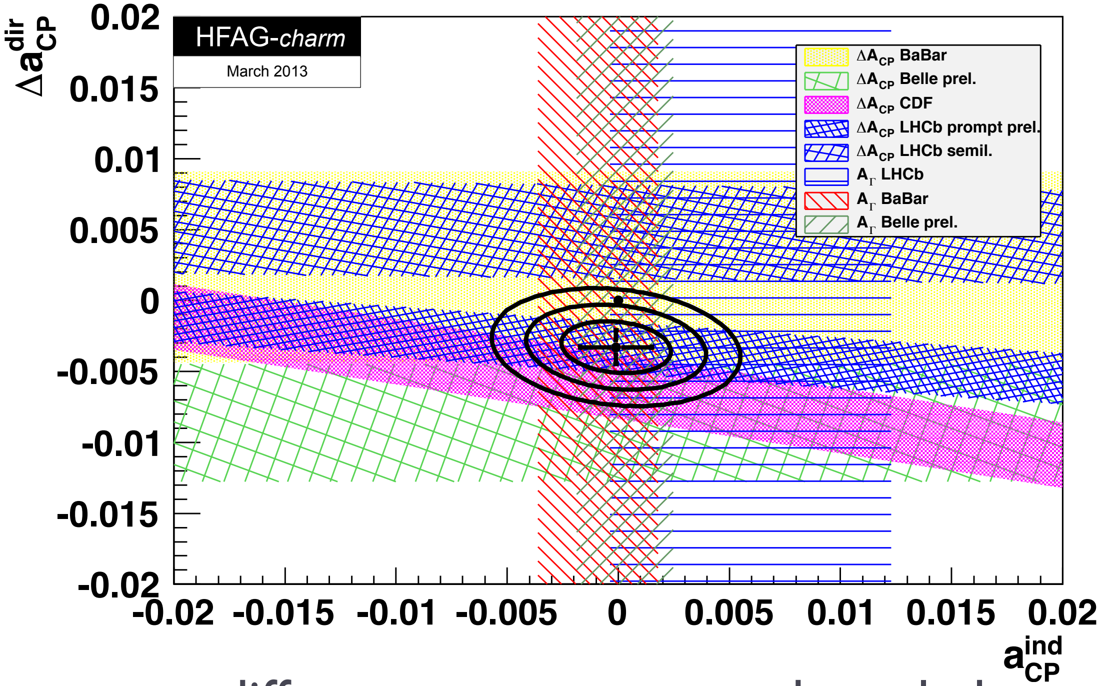
Hard to find, but important, test CPV in the CKM matrix

From mixing to CP violation

- HFAG follows the formalism from Gersback et al. J.Phys. G39 (2012) 045005.
  - Good way to interpret current data ... but.
- Another more general approach is summarised in AB, Meadows, Inguglia PRD **84** 114009 (2011). This breaks down the different contributions in terms of the CKM phase contributions to different amplitudes.
  - In order to learn about the standard model from CP violation measurements we need to understand:
    - mixing: i.e. q/p;
    - decay contributions in $\overline{A}/A$;
    - hadronic uncertainties that contribute to the interference between these two terms. *This means that eventually we will need to understand the CKM contributions to different amplitudes to understand the types of CP violation in charm.*

The experimental stage

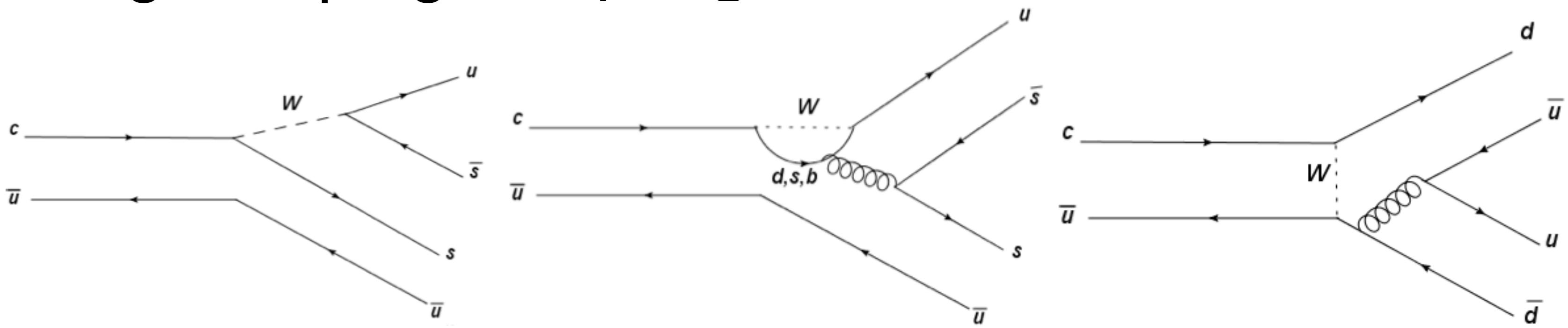
- LHCb, the Tevatron and B Factories have been searching for direct CP violation.
  - Focus on the ΔA_{CP} measurement: A_{KK}-$A_{\pi\pi}$



  - ΔA_{CP} is a direct CP asymmetry different measurement – knowledge of interfering amplitudes and *strong phase* differences are required to relate measurement back to the CKM matrix, A_Γ is related to ΔA_{CP} via λ_f, but measured independently (not optimal use of information)

The experimental stage

- These decays have contributions from (mixing+) tree, exchange and penguin topologies:



$D \to K^+K^-$ (Use this mode to measure the phase of D mixing)

$\propto V_{cs}V_{us}^*$ O(1) $\propto V_{cq}V_{uq}^*$ O(1) + O(1) + O(10^{-3})

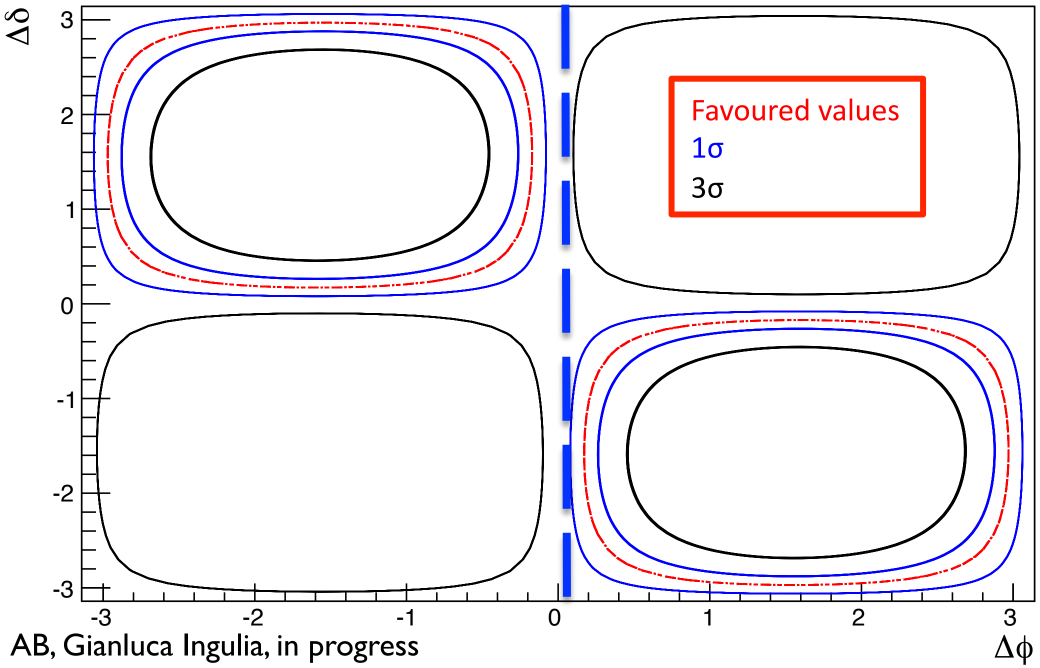
$D \to \pi^+\pi^-$ (Use this mode to measure the phase of D mixing + a weak phase β_c)

$\propto V_{cd}V_{ud}^*$ O(1) $\propto V_{cq}V_{uq}^*$ O(1) + O(1) + O(10^{-3}) $\propto V_{cd}V_{ud}^*$ O(1)

The experimental stage

- Can we find new physics via ΔA_{CP}?

e.g. Interpreting pion tag data from LHCb, this example assumes penguins (NP) amplitudes are 1% of the tree. Exact value of $r=A_1/A_2$ doesn't change the conclusion.



AB, Gianluca Ingulia, in progress

• SM solution is well defined at tree level.

• With one observable (=constraint) you can't constrain the three parameters of relevance (r, $\Delta\delta$, $\Delta\phi$) to search for NP.

• Need a more complicated experimental approach: time-dependent CP asymmetry measurements, including $\overline{A}/A$.

• Hadronic uncertainties from penguins play a role in interpreting the results of time-dependent

$$c \longrightarrow d$$

transitions .... that is the rest of this talk.

The experimental stage

- Can we find new physics via ΔA_{CP}? Not with this observable

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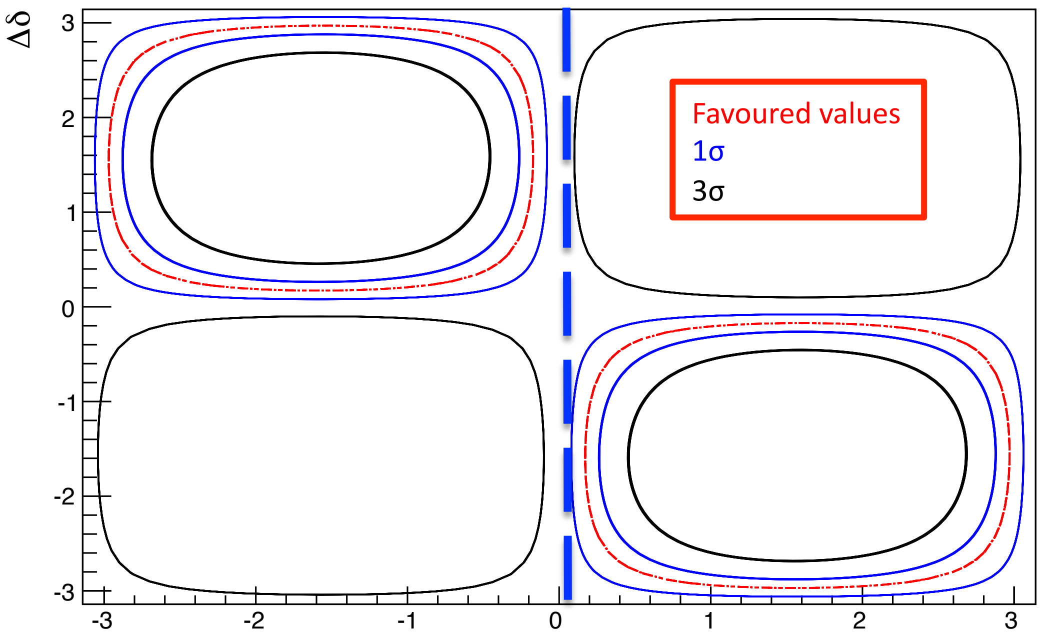

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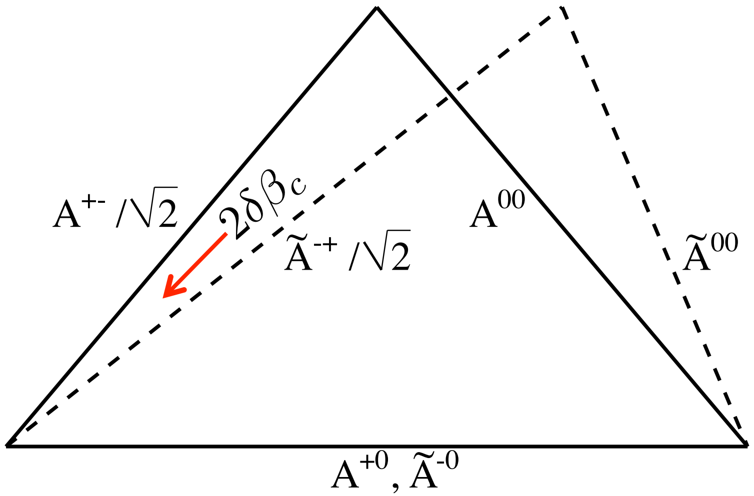
Isospin relations

- As with K and B decays the decays D to ππ are related by Isospin symmetry:

$$\frac{1}{\sqrt{2}}A^{+-} = A^{+0} - A^{00},$$
$$\frac{1}{\sqrt{2}}\overline{A}^{-+} = \overline{A}^{-0} - \overline{A}^{00},$$

• Similarly on can extend to ρπ and ρρ decays, with the corresponding additional complexity.



e.g. see Gronau & London Phys. Rev. Lett. 65, 3381 (1990)

- Following from this it is straightforward to constrain the shift from penguins on the weak phase measurement that can be made in D to hh decays (h = π, ρ) using existing data.

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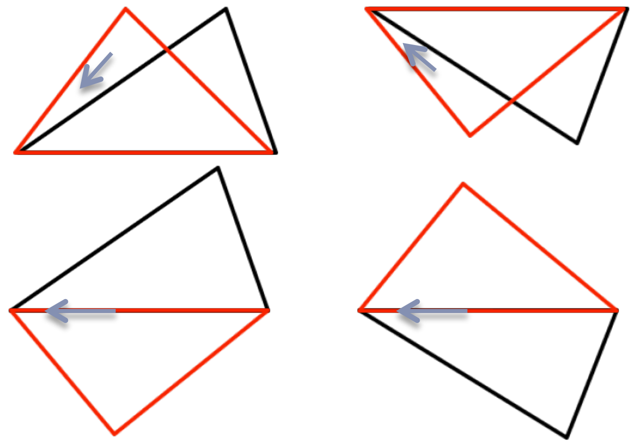

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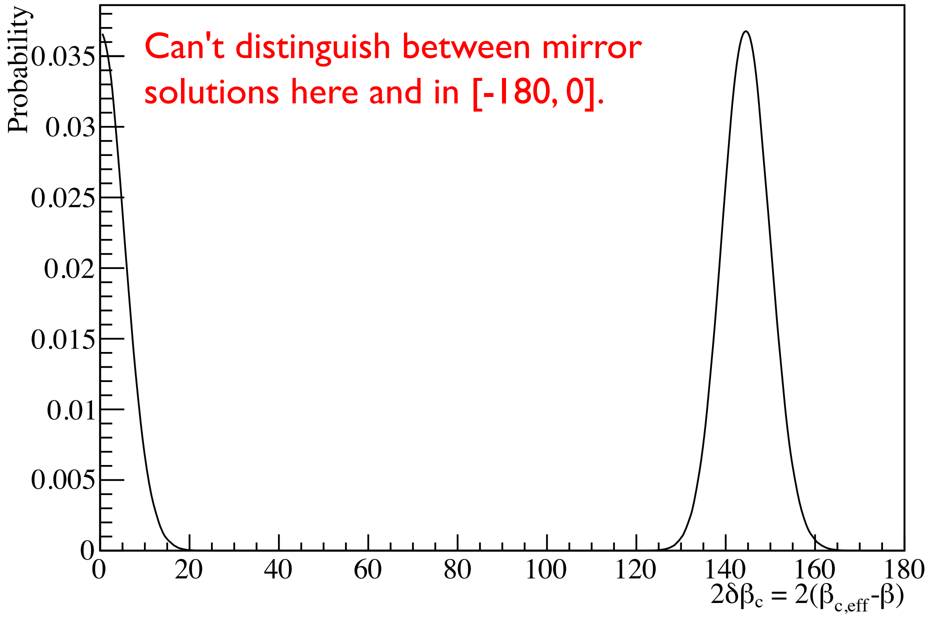
$D \to \pi\pi$

- Using inputs from the PDG we can estimate the effect of penguin pollution in $D \to \pi\pi$ decays, ignoring long distance and electroweak penguin effects.
  - Require branching ratios and CP asymmetries for $\pi\pi$ decays (assume A_{CP}=0).

Parameter	Measured Value
$\mathcal{B}(D^0 \to \pi^+\pi^-)$ $(\times 10^{-3})$	1.400 ± 0.026
$\mathcal{B}(D^\pm \to \pi^+\pi^0)$ $(\times 10^{-3})$	1.19 ± 0.06
$\mathcal{B}(D^0 \to \pi^0\pi^0)$ $(\times 10^{-3})$	0.80 ± 0.05



Experimentally limited by modes with neutrals in the final state.

Current data limits $\delta\beta_c$ to 2.7°.

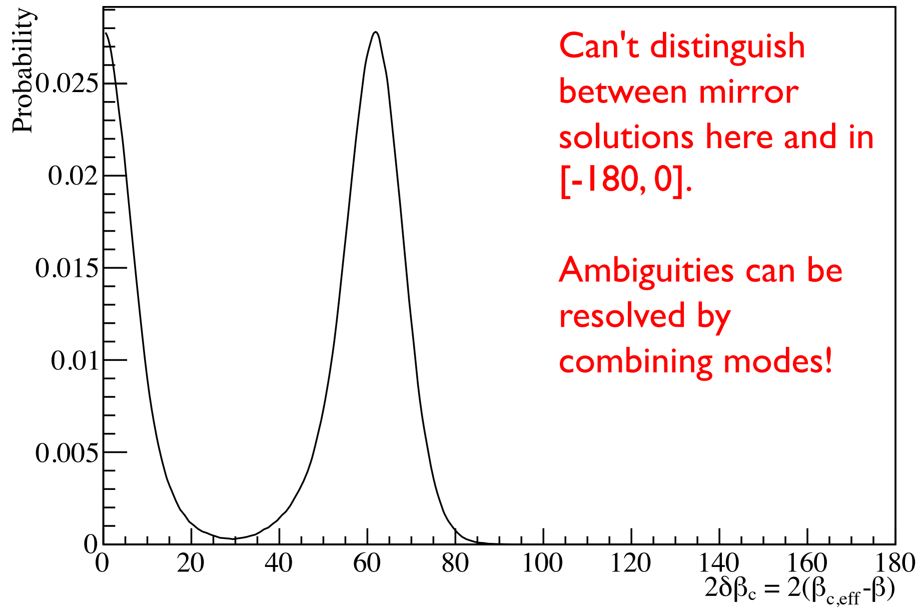
$D \to \rho\rho$

- Taking a similar approach for $D \to \rho\rho$ decays, and ignoring possible I=1 amplitudes one can try to estimate penguin pollution in these decays (needs an angular analysis of the data!).
  - PDG data highlight one clear point:
    - There is a lack of good experimental data in this set of decays.
  - CLEO measured $D^0 \to \rho^0\rho^0$ explicitly – but measurements of the other modes have not been done (they were treated as an inclusive 4 body final state).
    - Here we assume that the 4 body final state decays to $\pi^+\pi^0\pi^-\pi^0$ and $\pi^+\pi^-\pi^+\pi^0$ are dominated by $\rho^+\rho^-$ and $\rho^+\rho^0$.
    - Also assume naive factorisation to estimate f_L~0.83 for these decays, and analyse only the longitudinal polarisation.

$D \rightarrow \rho\rho$

- Under these assumptions we get:

Parameter	Measured Value
$\mathcal{B}(D^0 \to \rho^+\rho^-)$ $(\times 10^{-3})$	$10.0 \pm 0.9\dagger$
$\mathcal{B}(D^\pm \to \rho^+\rho^0)$ $(\times 10^{-3})$	$11.3 \pm 0.8\dagger$
$\mathcal{B}(D^0 \to \rho^0\rho^0)$ $(\times 10^{-3})$	1.82 ± 0.13
$f_L(D^0 \to \rho^+\rho^-)$ $(\times 10^{-3})$	$0.83\star$ (Ref. [3])
$f_L(D^\pm \to \rho^+\rho^0)$ $(\times 10^{-3})$	$0.83\star$ (Ref. [3])
$f_L(D^0 \to \rho^0\rho^0)$ $(\times 10^{-3})$	0.69 ± 0.08



Can't distinguish between mirror solutions here and in [-180, 0].

Ambiguities can be resolved by combining modes!

- Current data limits δβc to 4.6°.
- It is important that BES III and the B Factories perform angular analyses of these decays to understand if this estimate is robust.

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

- The D to 3π Dalitz structure is well known from BaBar and CLEO.
  - This means one can use the Snyder and Quinn approach to constrain penguins in these decays.

Gronau et al., Phys. Lett. B606,95 (2005)
Snyder, Quinn Phys. Rev. D48, 2139 (1993)

I = 2 is T only.
I= 0, 1 are T and P.

Amplitude subscripts relate to the Δ I value (I = ½ etc.).

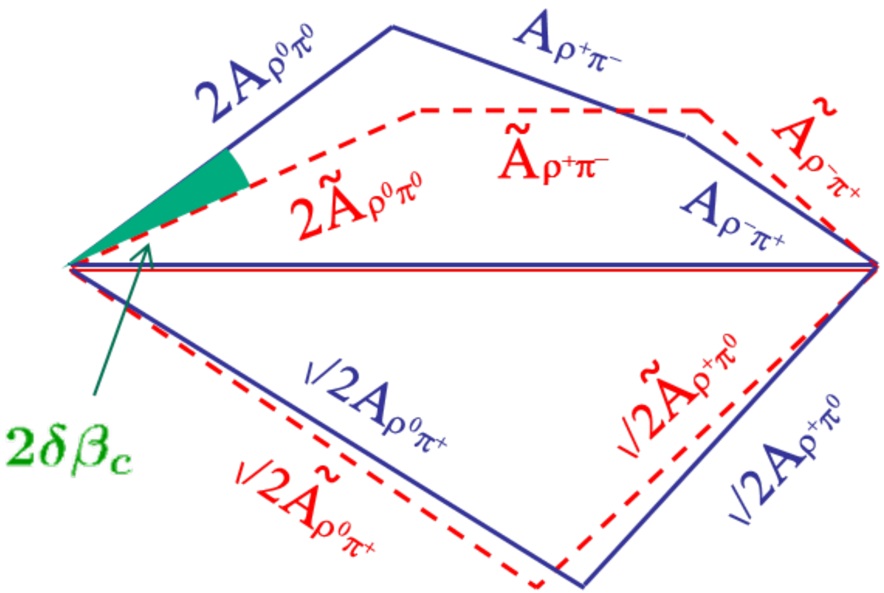
Δ I=1/2 transitions are I=0, 1.

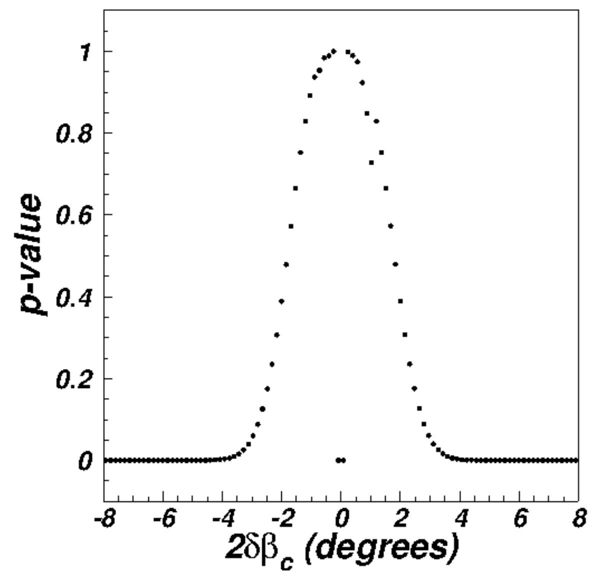
Δ I=3/2 transitions are I=1, 2, and SM penguins can't contribute to these.

$$
\begin{aligned}
A^{+-} &= \mathcal{A}_3 + \mathcal{B}_3 + \frac{1}{\sqrt{2}}\mathcal{A}_1 + \mathcal{B}_1 \\
&= T^{+-} + P_1 + P_0 \\
A^{-+} &= \mathcal{A}_3 - \mathcal{B}_3 - \frac{1}{\sqrt{2}}\mathcal{A}_1 + \mathcal{B}_1 \\
&= T^{-+} - P_1 + P_0 \\
A^{00} &= 2\mathcal{A}_3 - \mathcal{B}_1 \\
&= [T^{+-} + T^{-+} - T^{+0} - T^{0+}]/2 - P_0 \\
A^{+0} &= \frac{3}{\sqrt{2}}\mathcal{A}_3 - \frac{1}{\sqrt{2}}\mathcal{B}_1 + \mathcal{A}_1 \\
&= [T^{+0} + 2P_1]/\sqrt{2} \\
A^{0+} &= \frac{3}{\sqrt{2}}\mathcal{A}_3 + \frac{1}{\sqrt{2}}\mathcal{B}_1 - \mathcal{A}_1 \\
&= [T^{0+} - 2P_1]/\sqrt{2}
\end{aligned}
$$

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

- So instead of triangles one has pentagons.





Here the charged modes are observed in different Dalitz plots and don't bring anything to the table.

A priori one doesn't know the relative strong phase between charged and neutral modes.

- Current data limits $2\delta\beta c$ to 1°.
- We estimate a time-dependent measurement from BaBar would yield $\sigma(\beta_{c,\,eff}) \sim 1°$.

Conclusions

- Hadronic uncertainties arising from penguin pollution in D decays to hh (h=π, ρ), and the $\pi^+\pi^-\pi^0$ Dalitz plot can be controlled to the (few) degree level.

- A step toward understanding precision of CKM angle tests that can be done with time-dependent CP asymmetry measurements in the charm sector.

- These hadronic uncertainties also play a role in understanding approximate observables such as A_Γ in D to $\pi\pi$.

- BES III, LHCb and the other e^+e^- machines can help improve experimental constraints in this area.
  - Measure rates and direct CP asymmetries of D decays to hh and 3π final states (h=π, ρ).
  - Perform time-dependent measurements to access information from λ_f.

- It will be interesting to see what LHCb and BES III can bring to the table with data already in hand.
  - We're looking forward to finding out what we can learn about CP violation and the CKM matrix from charm in the coming decade.

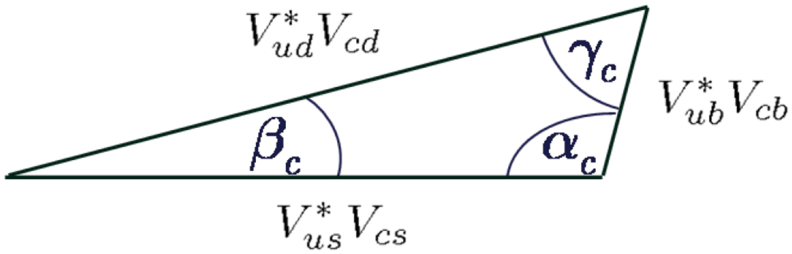
CKM

- CKM > O(λ^3) is model dependent: we choose Buras et al.

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

- Note:
  - At this order in λ, V_{cd} is complex
  - Correspondence between β and arg(V_{td}) and γ and arg(V_{ub}) is not exact any more
  - Direct angle measurements from B decays, and indirect constraints lead to a prediction of the cu triangle:

$$V^*_{ud}V_{cd} + V^*_{us}V_{cs} + V^*_{ub}V_{cb} = 0$$

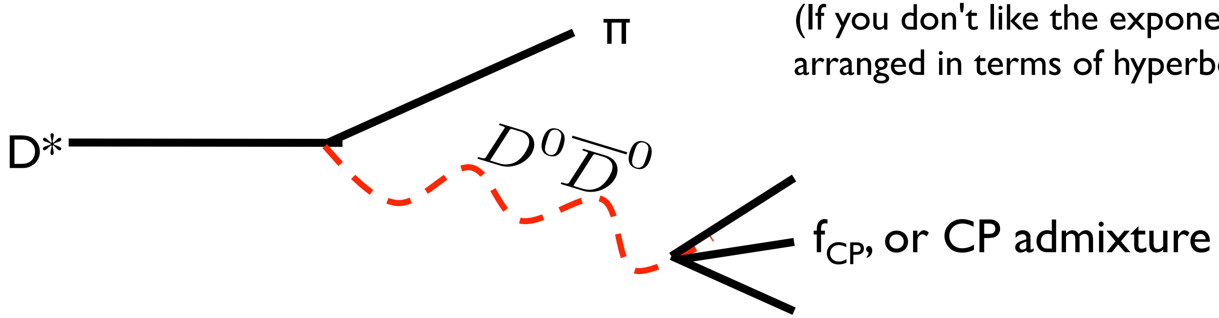


$$\begin{aligned} \alpha_c &= (111.5 \pm 4.2)^\circ \\ \beta_c &= (0.0350 \pm 0.0001)^\circ \\ \gamma_c &= (68.4 \pm 0.1)^\circ \end{aligned}$$

  - Can try to constrain this.

Formalism: D* tagged events

(If you don't like the exponentials, this can be re-arranged in terms of hyperbolic functions)



- The time dependence is familiar

$$\Gamma(P^0 \to f) \propto e^{-\Gamma_1 t}\left[\frac{(1+e^{\Delta\Gamma t})}{2} + \frac{Re(\lambda_f)}{1+|\lambda_f|^2}(1-e^{\Delta\Gamma t}) + e^{\Delta\Gamma t/2}\left(\frac{1-|\lambda_f|^2}{1+|\lambda_f|^2}\cos\Delta M t - \frac{2Im(\lambda_f)}{1+|\lambda_f|^2}\sin\Delta M t\right)\right]$$

$$\Gamma(\overline{P}^0 \to f) \propto e^{-\Gamma_1 t}\left[\frac{(1+e^{\Delta\Gamma t})}{2} + \frac{Re(\lambda_f)}{1+|\lambda_f|^2}(1-e^{\Delta\Gamma t}) + e^{\Delta\Gamma t/2}\left(-\frac{1-|\lambda_f|^2}{1+|\lambda_f|^2}\cos\Delta M t + \frac{2Im(\lambda_f)}{1+|\lambda_f|^2}\sin\Delta M t\right)\right]$$

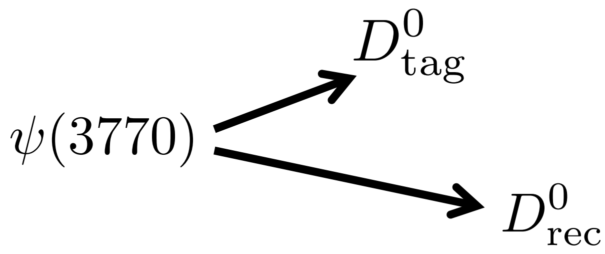
- Recall $\Delta\Gamma \neq 0$ as and

$$x = \frac{\Delta M}{\Gamma}, \text{ and } y = \frac{\Delta\Gamma}{2\Gamma}$$

$$\lambda_f = \left|\frac{q}{p}\right| e^{i\phi_{MIX}} \left|\frac{\overline{A}}{A}\right| e^{i\phi_{CP}}$$

The aim is to understand what mixing **AND** decay can teach us.

Formalism: threshold tagged events



(If you don't like the exponentials, this can be re-arranged in terms of hyperbolic functions)

- The time dependence is familiar

$$\Gamma(P^0 \to f) \;\propto\; e^{-\Gamma_1|\Delta t|}\left[\frac{h_+}{2} + \frac{Re(\lambda_f)}{1+|\lambda_f|^2}h_- + e^{\Delta\Gamma|\Delta t|/2}\left(\frac{1-|\lambda_f|^2}{1+|\lambda_f|^2}\cos\Delta M\Delta t - \frac{2Im(\lambda_f)}{1+|\lambda_f|^2}\sin\Delta M\Delta t\right)\right],$$

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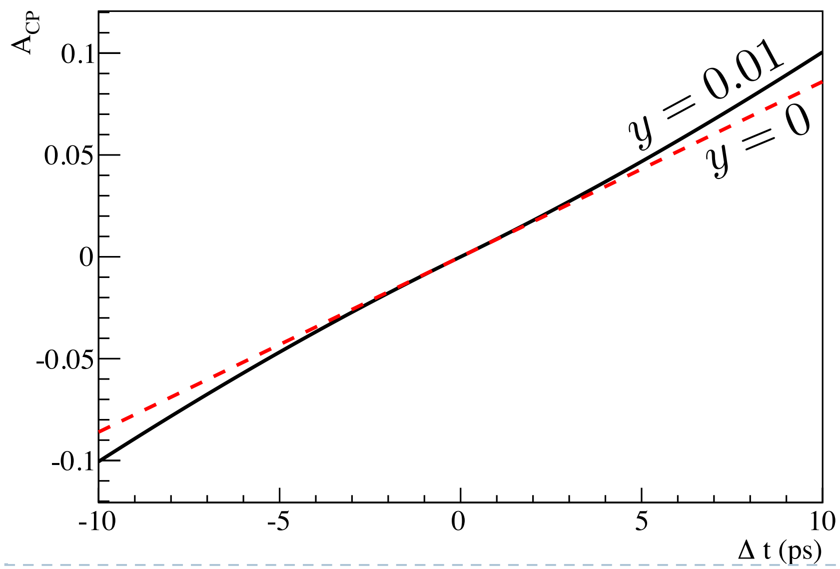
The aim is to understand what mixing **AND** decay can teach us.

Formalism: threshold events

- Can construct an asymmetry from these rates in the usual way:

(If you don't like the exponentials, this can be re-arranged in terms of hyperbolic functions, or in terms of x and y)

$$\mathcal{A}(\Delta t) = \frac{\overline{\Gamma}(\Delta t) - \Gamma(\Delta t)}{\overline{\Gamma}(\Delta t) + \Gamma(\Delta t)} = 2e^{\Delta\Gamma|\Delta t|/2} \frac{(|\lambda_f|^2 - 1)\cos\Delta M\Delta t + 2Im\lambda_f \sin\Delta M\Delta t}{(1+|\lambda_f|^2)h_+ + 2h_- Re\lambda_f}$$



The asymmetry is slowly varying

Won't see oscillation maxima as in the case of B decays.

Effect of $\Delta\Gamma$ is seen in the difference between solid ($\Delta\Gamma \neq 0$) and dashed ($\Delta\Gamma = 0$) curves.