Constraining charm penguins

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Prologue

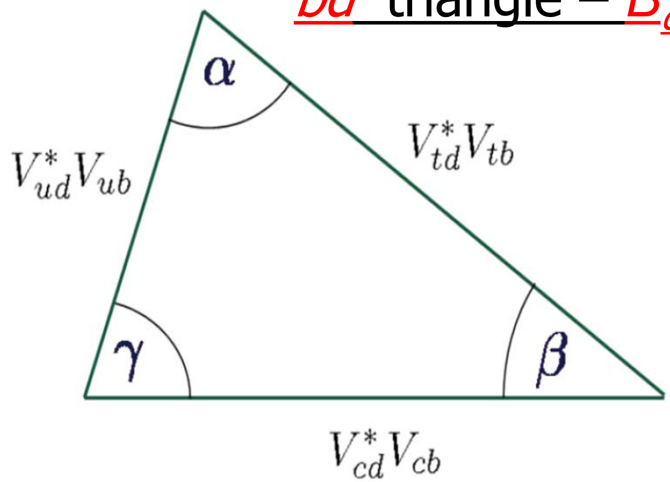
AD 1999:

"A comprehensive program of CP studies in heavy flavour decays has to go beyond observing large CP asymmetries in nonleptonic B decays and finding that the sum of the three angles of the unitarity triangle is consistent with 180°. There are many more correlations between observables encoded in the KM matrix; those can be expressed through five unitarity triangles in addition to the one usually considered."

-- Ikaros Bigi and A. Sanda
http://arxiv.org/abs/hep-ph/9909479

Weak phases in B_d and D decays

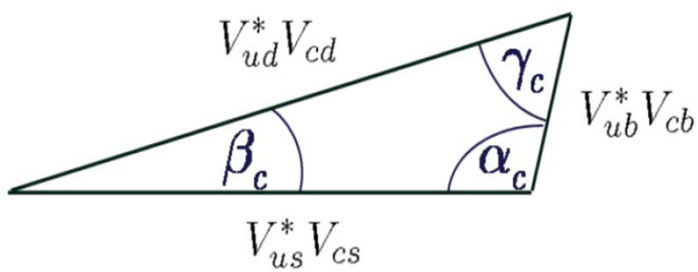
bd triangle – B_d decays. All three phases are large.



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

Tree phases β_c are tiny
BUT penguin phase
$\gamma_c = \gamma = 67^0$ is large.

cu triangle – *D* decays



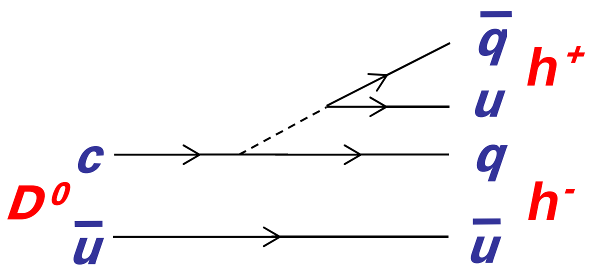
$$\begin{aligned}
\alpha_c &= \left[V_{ub}^*V_{cb}/V_{us}^*V_{cs}\right] = (111.5 \pm 4.2)^\circ \\
\beta_c &= \left[V_{ud}^*V_{cd}/V_{us}^*V_{cs}\right] = (0.0350 \pm 0.0001)^\circ \\
\gamma_c &= \left[V_{ub}^*V_{cb}/V_{ud}^*V_{cd}\right] = (68.4 \pm 0.1)^\circ
\end{aligned}$$

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

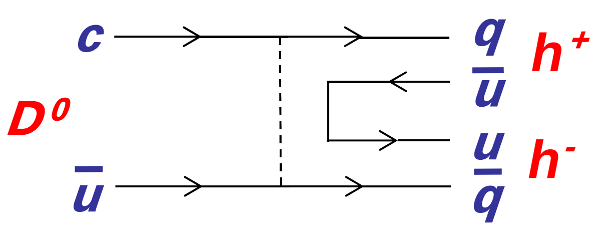
- It is probably beyond experimental ability to measure β_c
  - But it is important to check that it is very small.
  - Also interesting to check other phases in the "cu" triangle.

- B-factory methods are possible approach.
  - Make *t*-dependent measurement of *CP* asymmetry for decays to *CP* eigenstates *TDCPV*. (Talk by G. Inguglia).
  - Comparison of *TDCPV* for 2 modes can also provide measurement of D^0 mixing phase.
  - Effect of penguins will need to be estimated – an interesting measurement in any case.

$D^0 \rightarrow h^+h^-$ $(K^+K^-, \pi^+\pi^-$ or $\rho^+\rho^-)$

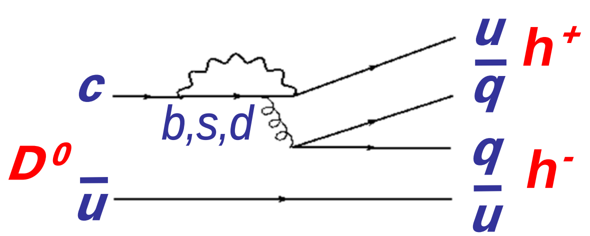


Tree (T): CKM phase $\begin{cases} K^+K^-: & \text{zero} \\ \pi^+\pi^-: & \beta_c \end{cases}$



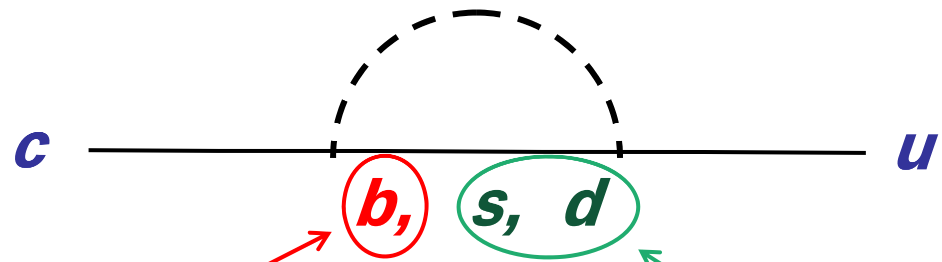
Exchange (E): CKM phase <u>same</u> as T

So $\rightarrow$ Combine T and E as "T"



Penguin (P): CKM phase γ_c

Standard Model Penguins



"cu" triangle condition

SM: $P_b \propto V_{cb} V_{ub}^*$

$$\frac{P_b}{T} \propto \frac{\alpha_s}{\pi} \frac{V_{cb} V_{ub}^*}{V_{cq} V_{uq}^*}$$

$$\simeq 10^{-4} e^{i67^0}$$

$$P_s + P_d \propto \boxed{V_{cs} V_{us}^* + V_{cd} V_{ud}^* = -V_{cb} V_{ub}^*}$$

U-spin breaking $\sim (m_s^2 - m_d^2)/m_c^2$ a tunable parameter controls level of P_s, P_d effect on P.

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

SM Penguins:

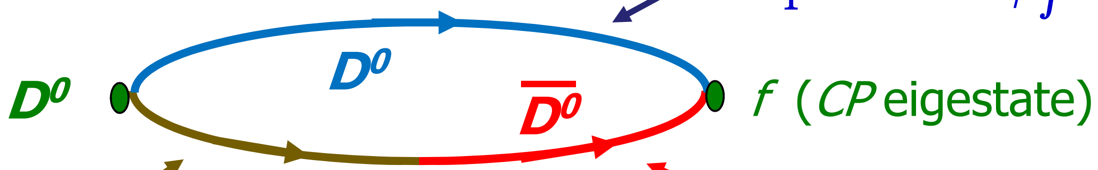
- Small - could be larger with *U*-spin or *QCD* effects
- Weak phase large (~ γ)
- Change iso-spin $\Delta I = ½$ ($c \to u$)

TDCPV in D^0 decays

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

- Mixing allows D^0 and $\bar{D}^0$ to interfere, exposing weak phases.
- Assume only T amplitude:

$\mathcal{A}_f \equiv \langle f|H|D^0\rangle$
phase $= \phi_f^{\text{weak}} + \delta_f^{\text{strong}}$



Mixing phase
$Arg\{q/p\} = \phi_M$

$\bar{\mathcal{A}}_f \equiv \langle f|H|\bar{D}^0\rangle$
phase $= -\phi_f^{\text{weak}} + \delta_f^{\text{strong}}$

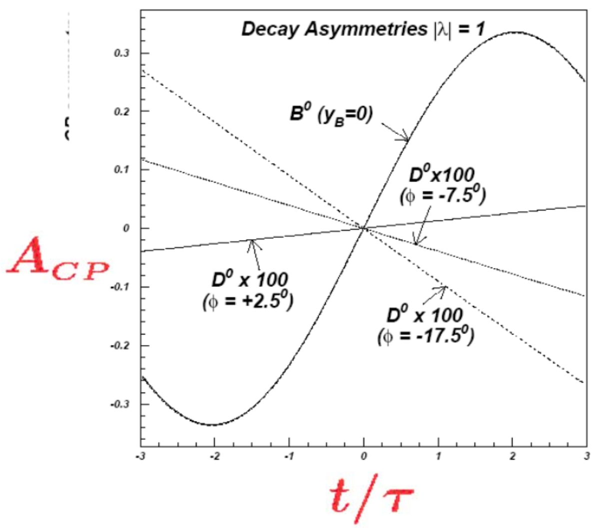
- Define $\lambda_f = \dfrac{q\bar{\mathcal{A}}_f}{p\mathcal{A}_f}$, then $\mathrm{Arg}\{\lambda_f\} = \phi_{\mathrm{M}} - 2\phi_f^{\text{weak}}$
- Measure λ_f using time-dependent CP asymmetry.

See Gianluca Inguglia's talk

Time-Dependent CP Asymmetry (TDCP)

- D^0 and $\overline{D^0}$ oscillations leads to time-dependent CP asymmetry.

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



Asymmetry grows with $|t/\tau|$:

- A_{CP} for D^0 is much smaller than for B^0 and is almost linear in t.
- Slope of line $\propto$ arg $\{\lambda_f\}$
- $|A_{CP}|$ is largest for large t

Direct CPV shifts asymmetry at t=0

- For $D^0 \to h^+h^-$ we expect $\arg\{\lambda_f\} = \phi_M - 2(\beta_c + \delta\beta_c)$

(h = π or ρ)

Effect of Penguin

Penguins in $D \rightarrow \pi\pi$ or $\rho\rho$ decays

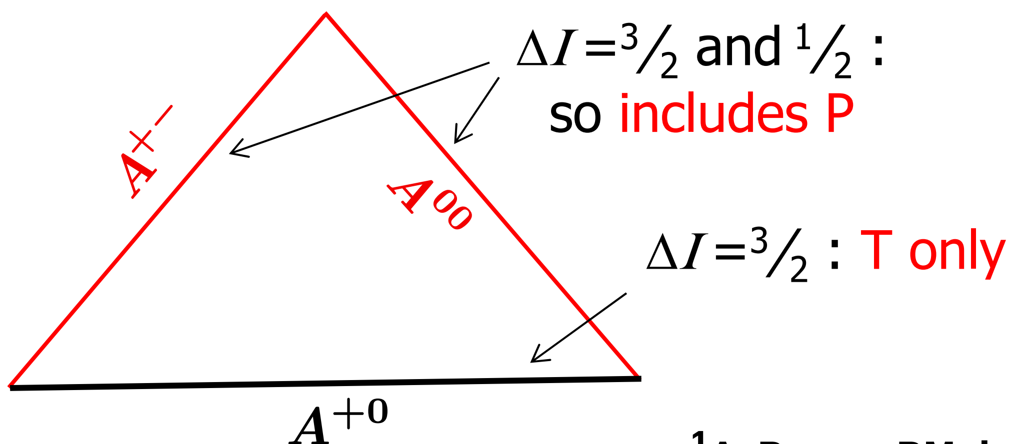
- Penguin contributions, $\delta\beta_c$, to $\mathrm{Arg}\{\lambda_f\}$ can be estimated from I-spin relations between the amplitudes for different charge modes:

$$\begin{array}{lcll} A^{+-} & : & D^0 \rightarrow \pi^+\pi^- & (\rho^+\rho^-) \\ A^{00} & : & D^0 \rightarrow \pi^0\pi^0 & (\rho^0\rho^0) \\ A^{+0} & : & D^+ \rightarrow \pi^+\pi^0 & (\rho^+\rho^0) \end{array}$$

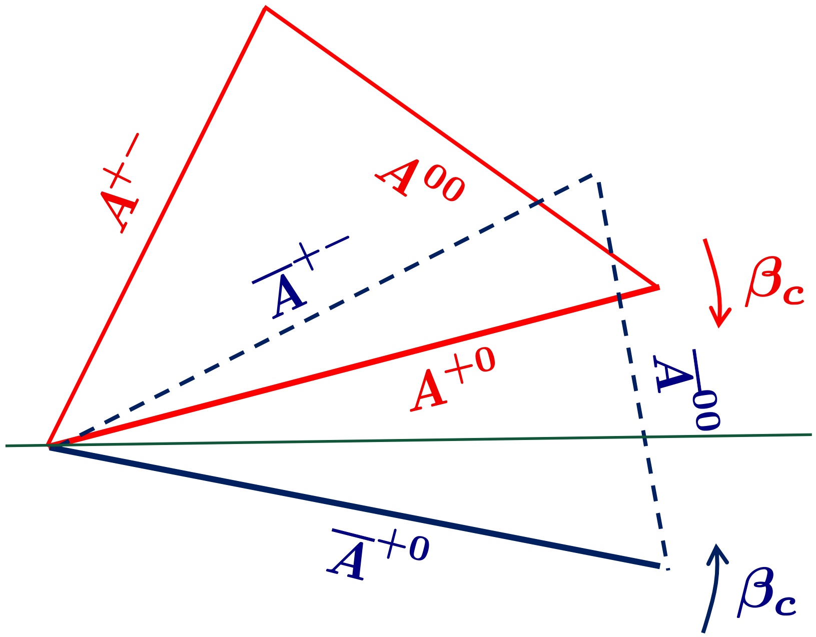
With similar definitions for CP Conjugate modes $\overline{A},^{+-}$ $\overline{A},^{00}$ $\overline{A}^{+0}$

- Bose symmetry allows only $\Delta I = ½$ and $\Delta I = {}^3\!/_2$ amplitudes. The former is possible for T and P but the latter only for T.

$$A^{+-}/\sqrt{2} = A^{+0} - A^{00}$$
$$\overline{A}^{+-}/\sqrt{2} = \overline{A}^{+0} - \overline{A}^{00}$$

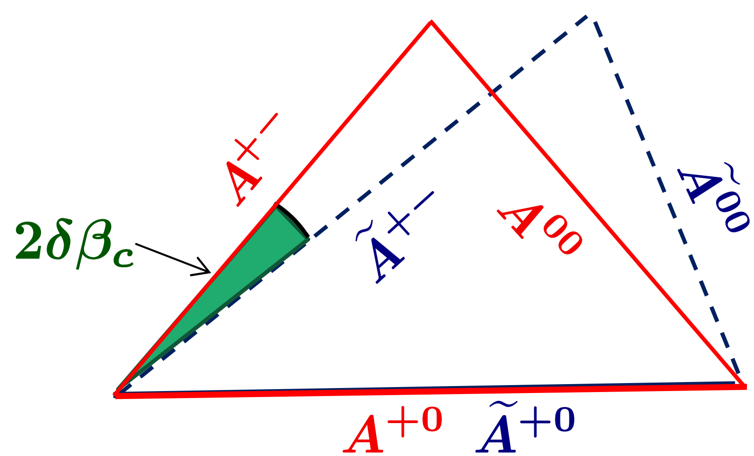


[1]A. Bevan, BM, in progress



- In $D^{\pm}\rightarrow\pi^{\pm}\pi^{0}$ only T contributes so phase of A^{+0} is + β_c and for $\overline{A}^{+0}$ it is – β_c
- We rotate these to coincide
  Then re-label $\overline{A}$'s as $\widetilde{A}$'s

- The "+-" and "00" amplitudes include penguins.
- Any phase difference between A^{+-} and $\widetilde{A}^{+-}$, therefore, is $2\delta\beta_c$ (due to penguins).



Apply to current charm data

- Take current information on $\pi\pi$ decay rates (from PDG):

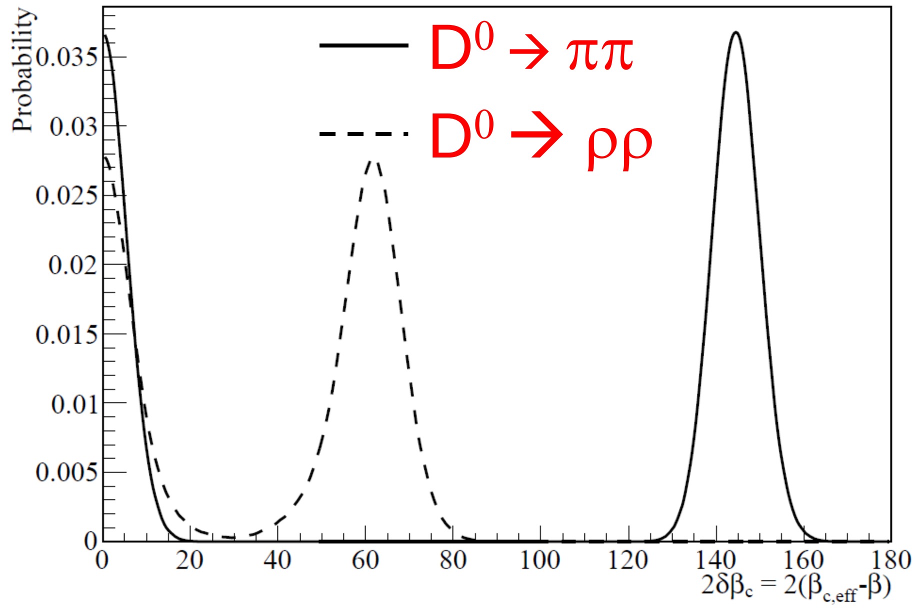
Parameter	Measured Value
τ_{D^0}	0.4101 ± 0.0015 (ps)
$\tau_{D^\pm}$	1.040 ± 0.007 (ps)
$\mathcal{B}(D^0 \to \pi^+\pi^-)$	$(1.400 \pm 0.026) \times 10^{-3}$
$\mathcal{B}(D^\pm \to \pi^+\pi^0)$	$(1.19 \pm 0.06) \times 10^{-3}$
$\mathcal{B}(D^0 \to \pi^0\pi^0)$	$(0.80 \pm 0.05) \times 10^{-3}$

From these values, we create ensembles of MC simulated amplitudes, based on their magnitudes and uncertainties.

We assume no *CP* asymmetry (yet, at least!)

For each sample, we compute $2\delta\beta_c$ noting the ambiguity in relative orientation between D^0 and $\overline{D}^0$ triangles.

- Both solutions are clearly visible in distributions of the resulting values of $\delta\beta_c$ with a width that suggests an uncertainty in $\delta\beta_c$ of about 2.7^0 for $\pi\pi$ and 4.6^0 for $\rho\rho$.



- When, eventually, an asymmetry becomes evident in any of these modes, the positions of the peaks may be more interesting.

$D \rightarrow \rho\rho$ decays

- Analysis is similar to that for $D \rightarrow \pi\pi$ but with complications. Again, there are mostly $I=1$ or $I=2$ final states. BUT
  - The ρ^0 interferes with ω^0, introducing an $I=1$ component
  - ρ resonances are broad and interfere with other resonances and each another.
  - Transversity amplitudes for $\rho\rho$ have different *CP* and could have different penguin contributions. Therefore they require separate treatment.
- *So proper amplitude analyses of $D \rightarrow 4\pi$ modes are required*

Our study assumes that just one transversity state dominates and ignores all the above complications.

Current data on $D \rightarrow \rho\rho$

Small $\rho^0\rho^0$ rate a hint that P is small ?

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

Large f_L justifies use of a single spin state.

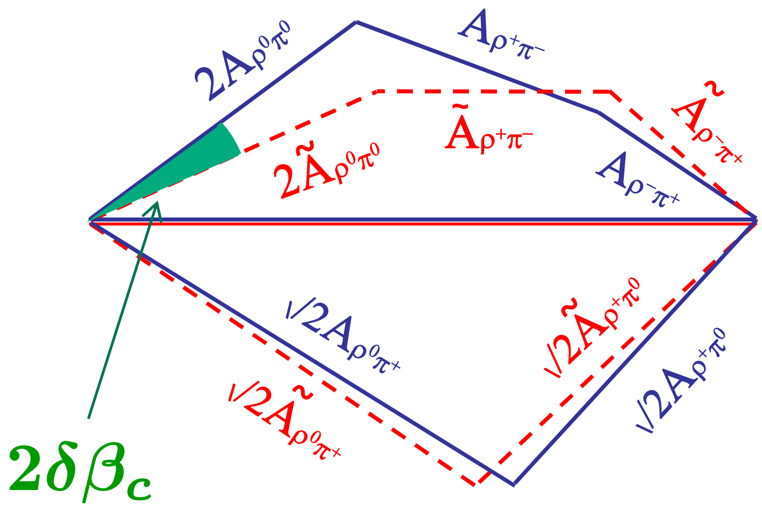
†We assume that $D \to 4\pi$ channels quoted by PDG are dominated by resonant $\rho\rho$
⋆Theoretical assumption.
See *B*A*B*AR: Phys.Rev. D84 (2011) 114009.

I-spin analysis of $D \rightarrow \rho\pi$ decays

- For $\rho\pi$, Bose statistics does not apply, so there are five I-spin amplitudes contributing to a pentagonal relationship:

$$\underbrace{2A^{00} + A^{+-} + A^{-+}}_{\Delta I = {}^3/_2 \text{ only}} = \underbrace{\sqrt{2}(A^{0+} + A^{+0})}_{\Delta I = {}^3/_2 \text{ only}}$$

Neither side of the equation has a P component.

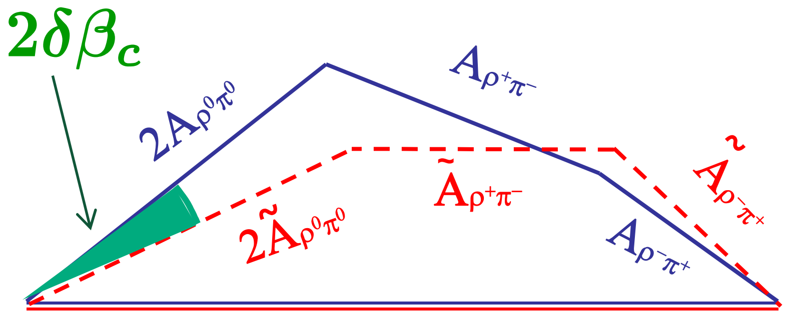


D^0 amplitudes A have been rotated by weak decay phase $+\beta_c$

$\overline{D^0}$ amplitudes $\tilde{A}$ have been rotated by weak decay phase $-\beta_c$

$$\boxed{\rightarrow 2\delta\beta_c = \arg \tilde{A}_{\rho^0\pi^0} / A_{\rho^0\pi^0}}$$

β_c from $D^0 \rightarrow \rho\pi$ decays alone



- A time-dependent Dalitz plot fit to D^0 (and $\overline{D^0}$) → $\pi^+\pi^-\pi^0$ decays provides all the required information.

  [Quinn, Snyder, Phys.Rev.D48(1993) 2139-2144]

- This determines 26 invariant quantities related to $D^0 \rightarrow \rho\pi$ amplitudes

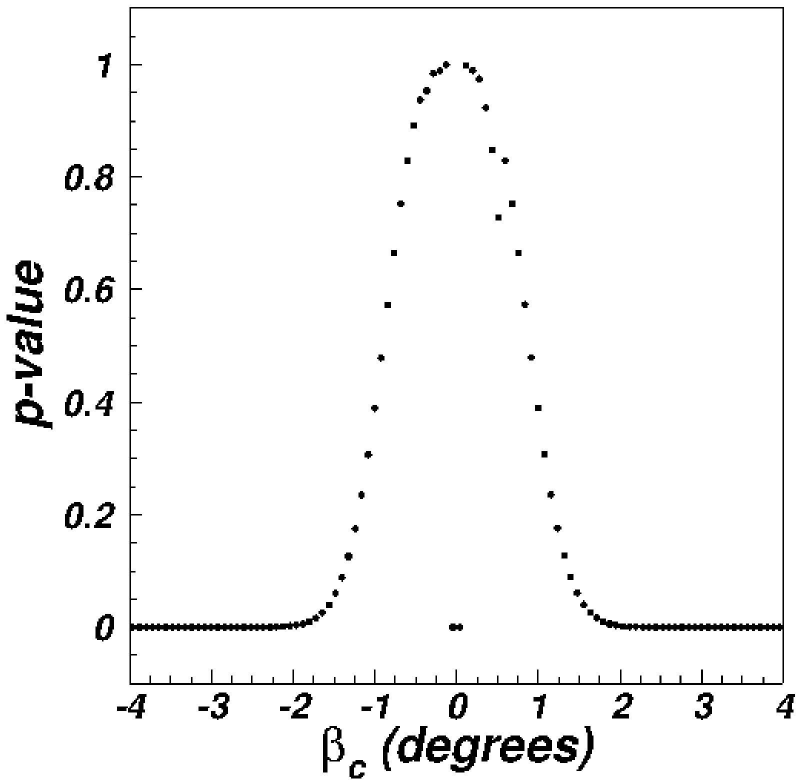
$$
\begin{array}{rcrcl}
A(D^0 \rightarrow \rho^+\pi^-) & : & A^{+-} & = & T^{+-}e^{-i\beta_c} + P^{+-} \\
A(D^0 \rightarrow \rho^-\pi^+) & : & A^{-+} & = & T^{-+}e^{-i\beta_c} + P^{-+} \\
A(D^0 \rightarrow \rho^0\pi^0) & : & A^{00} & = & T^{00}\, e^{-i\beta_c} + P^{00} \\
q/p\, A(\overline{D}^0 \rightarrow \rho^+\pi^-) & : & \overline{A}^{+-} & = & T^{-+}e^{+i\beta_c} + P^{-+} \\
q/p\, A(\overline{D}^0 \rightarrow \rho^-\pi^+) & : & \overline{A}^{-+} & = & T^{+-}e^{+i\beta_c} + P^{+-} \\
q/p\;\, A(\overline{D}^0 \rightarrow \rho^0\pi^0) & : & \overline{A}^{00} & = & T^{00}\, e^{+i\beta_c} + P^{00}\,,
\end{array}
$$

  their magnitudes and relative phases, and their time-dependences.

- These determine β_c and the magnitudes and phases of the *P*'s and *T*'s.

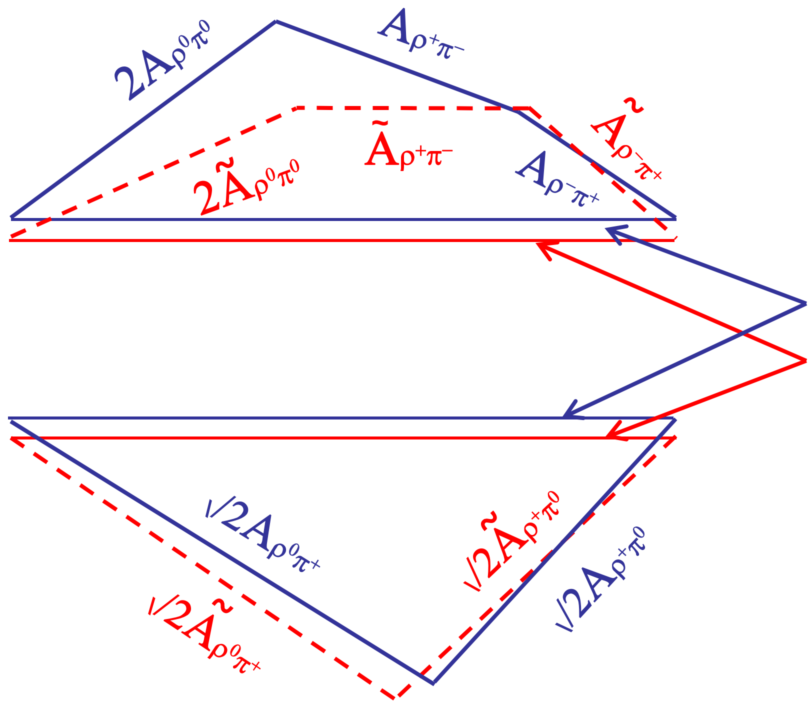
Toy "β_c scan" on BaBar $D^0 \rightarrow \rho\pi$ data

- Using the complex *A*'s from the BaBar fit to time-integrated $D^0 \rightarrow 3\pi$ decays, we make fits for *P* and *A* at various β_c values and plot the *p*-value for the best fit at each point.
- Two peaks are observed, respectively at $\beta_c = 0$ and $\pi/2$, each with a half-width of $\sim 1^0$.



Precision for $\beta_c \approx 1°$

I -spin constraints in $D \rightarrow \rho\pi$ decays



I -spin conservation requires these 4 lines to have same lengths.

Systematic Limitations

- These studies rely on experimental determination of the relative magnitudes of D^0 and D^+ decay amplitudes.
  - Systematic limitations should be from π^0 efficiency and will probably be reached by Belle2 or by 5 ab^{-1} τ-charm.

Modes	$\#\pi^0$ required	Comment
$\pi^+\pi^- : \pi^0\pi^0 : \pi^+\pi^0$	$0 : 1 : 1$	Normalize $\pi^0\pi^0$ to $K_s\pi^0$
$\rho^+\rho^- : \rho^0\rho^0 : \rho^+\rho^0$	$2 : 0 : 1$	3 distinct Dalitz plots
$\rho^+\pi^- : \rho^0\pi^0 : \rho^+\pi^0$	$0 : 0 : 0$	Use just $\pi^+\pi^-\pi^0$ Dalitz plot

- For BaBar, systematic is ~3% per π^0.

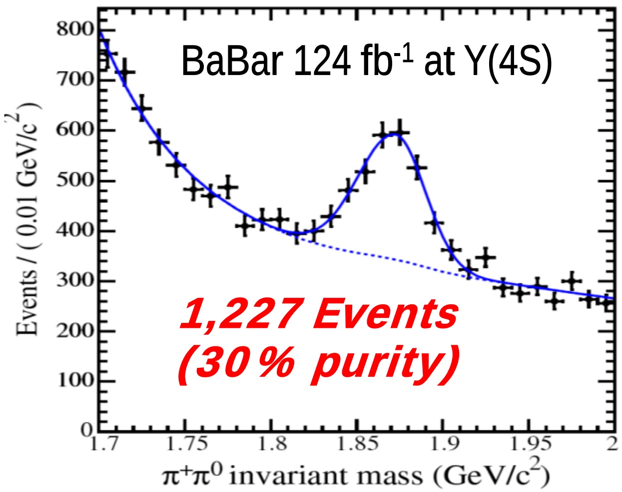
  BUT, if $e^+e^-\gamma$ (Dalitz) decays are used, this is only ~0.6%

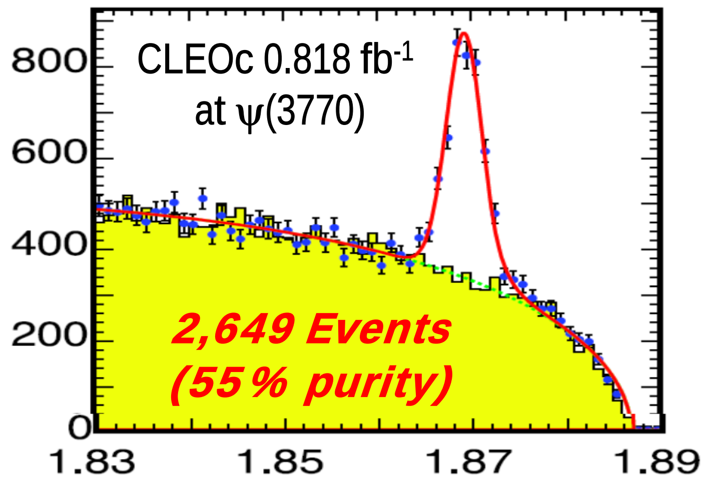
  However we lose a factor 80 in sample size.

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





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

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

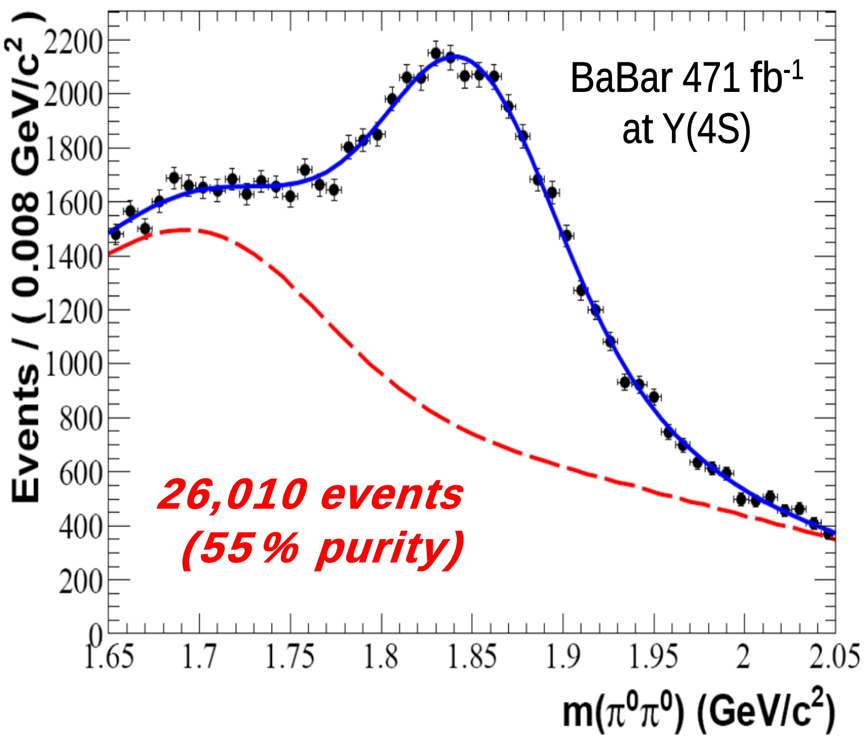
Phys.Rev. D74 (2006) 011107

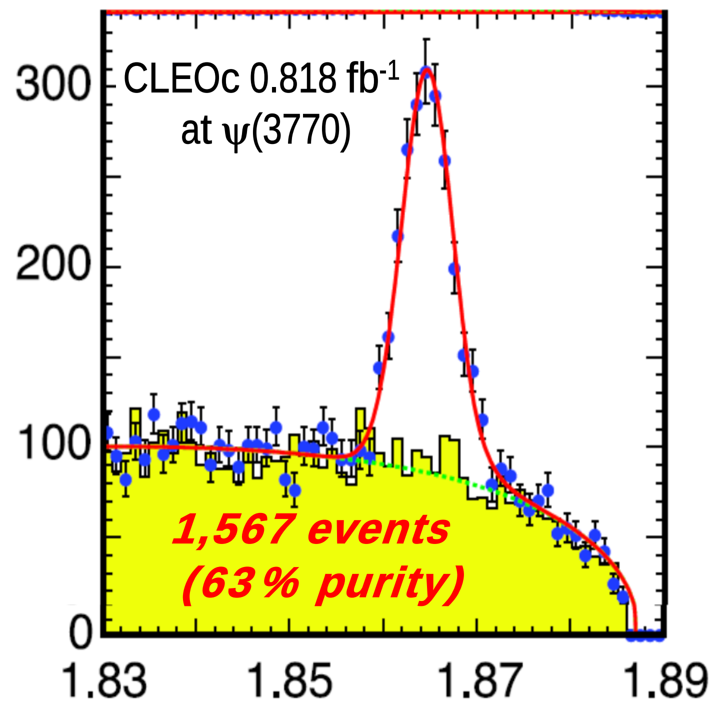
$B_{\pi^+\pi^0} / B_{K^-\pi^+\pi^+} = (1.29 \pm 0.04 \pm 0.05) \times 10^{-2}$

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

Phys.Rev. D81 (2010) 052013

$\pi^0\pi^0$ BF and asymmetry





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

A^{CP} ~ (xxx ± 1.2) x10^{-2}

Submitted to Phys.Rev. D

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

A^{CP} - *NOT possible*

Phys.Rev. D81 (2010) 052013

Projections for A^{CP} Measurements

- 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.
  - So we assume these will shrink with the sqrt of 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
$\pi^+\pi^-$	0.1?	–	–	–	± 0.6	± 0.04
$\pi^0\pi^0$	–	–	–	–	± 1.2	± 0.10
ΔA^{CP}	± 0.07					± 0.05

Summary

- Time-integrated *CPV* asymmetries have yet to be seen but, when they are, a look at the effect of penguins should be possible with a precision within the 1-2 degree range.
- *LHCb* is working extremely well, and is clearly ready to lead the way in measurements of *D* decays with charged tracks,
  - but it will leave much for e^+e^- machines to do with the modes with π^0's and other neutrals.
- Experiments at charm threshold have a particular role to play in studies with *D* decays with one or more π^0 or γ, and should be optimized for this role.

Backup Slides

The triangles

See Bigi and Sanda, hep-phy/9909479 (1999)

B_d decays

BaBar/Belle

~1 (28^0)

B_s decays

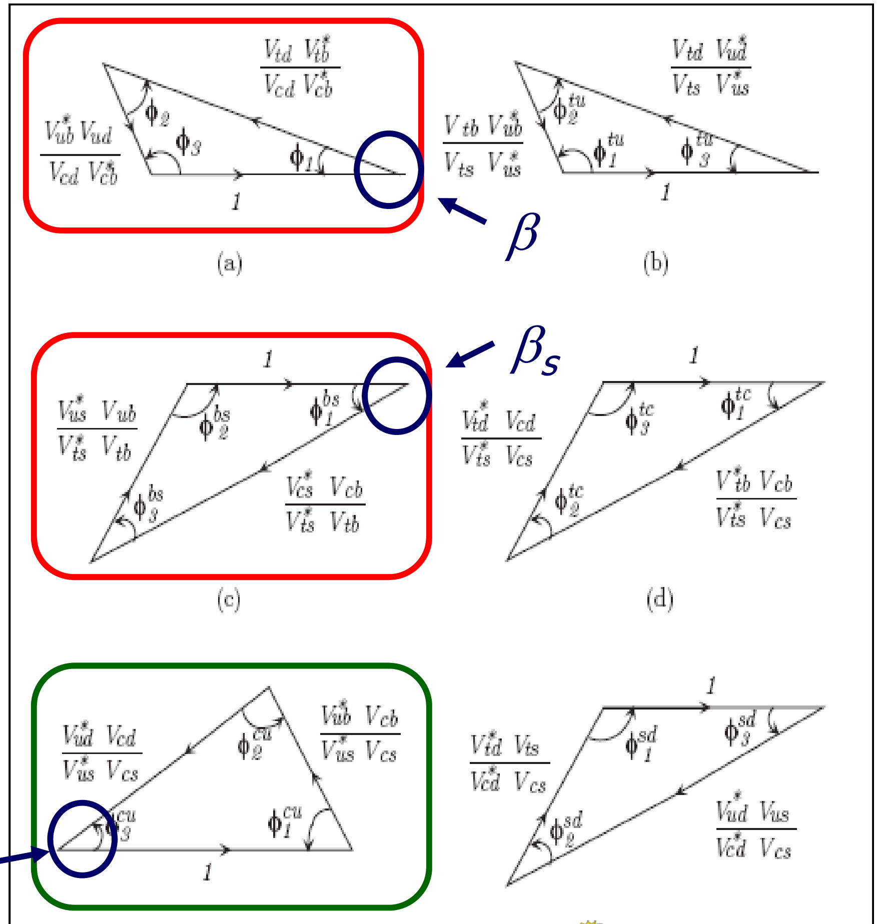
LHCb/CDF/D0

~λ^2 (1^0)

cu triangle

D decays

~λ^4 ($.05^0$)



β_c

Bigi and Sanda:

In addition to α, β and γ, the angles, β_c and β_s should be measured also, if possible.

LHCb is working on β_s using $B_s \rightarrow \psi\phi(f^0)$ decays.

SuperB and Belle2 should also be able to study $B_s \rightarrow \psi\eta^{(\prime)}$ at Y(5S)

What is Interesting about Charm

- Charm was "invented" to account for small FCNC interactions in nature (GIM mechanism).
- In this scenario, for the charm sector,
  - Mixing is also greatly suppressed;
  - Many charm particle decays are also extremely small.
  - *CP* violation (*CPV*) is also expected to be small, mostly because weak phases are small (Arg{V_{cd}} ~ λ^4);
- With "SM backgrounds" so small, charm is a good place to look for new physics (*NP*).
- Charm also allows study of the role of the up-type quarks.

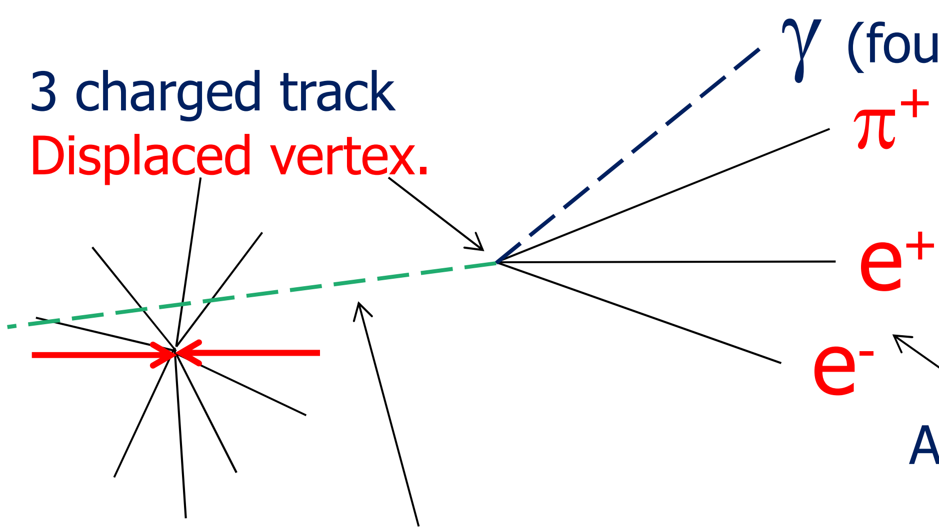
A π^o Trigger ?

Consider $D^+ \rightarrow \pi^+\pi^o$ 1/80 π^o's decay thus.

$\quad\quad\quad\quad\quad\quad\quad\quad\quad\quad \lfloor\_\_\_ e^+e^-\gamma$

Need to trigger back up

3 charged track
Displaced vertex.



γ (found offline)

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

Three tracks do not point back to PV

Invariant mass < D^+