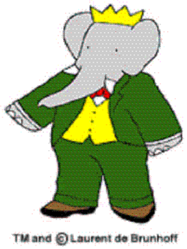
CP Violation and all that.



Brian Meadows

University of Cincinnati

Lecture IV

- *CP* Violation and mixing for *D* vs. *B*.
- *TDCPV* measurement at a *D* factory too ?
  - Unitarity triangles
- Time-integrated and direct *CPV* – evidence from *LHCb.*
- Is this evidence for *NP* ?

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CPV in *D*'s and *B*'s

- The ability to search for CPV in the charm sector is distinguished sharply from that in B and B_s mesons in several important ways.
  - Weak phases in the charm quark sector of the CKM are small ($\sim\lambda^4$).

V_{cd} acquires a phase at order λ^4

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

  - *D^0* mixing is also heavily suppressed and evidence for it has only recently been found (by BaBar and Belle).

D^0-$\overline{D}^0$ mixing-induced oscillations

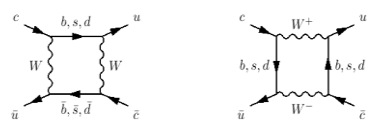
- Mixing milestones

BABAR: PRL 98 211802 (2007)	$D^0 \to K^+\pi^-$ decay time analysis	3.9σ
BELLE: PRL 98 211803 (2007)	$D^0 \to K^+K^-$, $\pi^+\pi^-$ vs $K^+\pi^-$ lifetime difference analysis	3.2σ
BELLE: PRL 99 131803 (2007)	$D^0 \to K_s\pi^+\pi^-$ time dependent Dalitz analysis	2.2σ
CDF: PRL 100, 121802 (2008)	$D^0 \to K^+\pi^-$ decay time analysis	3.8σ
BABAR: arXiv:0712.2249 (2007), accepted by PRD-RC	$D^0 \to K^+K^-$, $\pi^+\pi^-$ vs $K^+\pi^-$ lifetime difference analysis	3σ
	all mixing results combined by HFAG:	**6.7σ**

- Of all neutral mesons, the D^0 system exhibits the least mixing

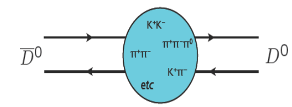
System:	x:	y:
K^0 (1956)	0.95	0.99
B_d (1987)	0.78	≈0
B_s (2006)	26	0.15
D^0 (2007)	0.0098	0.0075

- Short distance $\Delta C=2$ SM suppression:



D mixing loop involves d-type quarks
  - b quark loop suppressed: $|V_{ub}^* V_{cb}| \ll 1$
  - s and d quark loops: GIM suppressed
  - Mass difference ampl. < O(10^{-5})

- Long distance mixing amplitudes



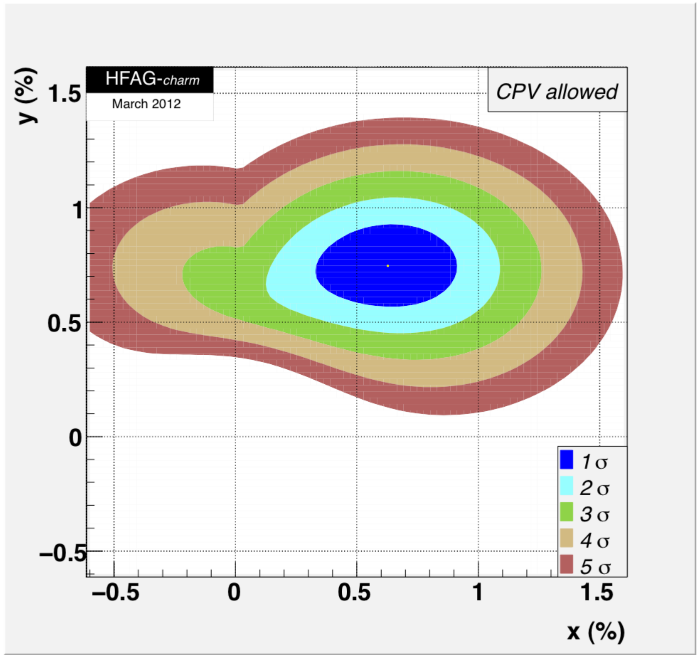
predominant but hard to quantify

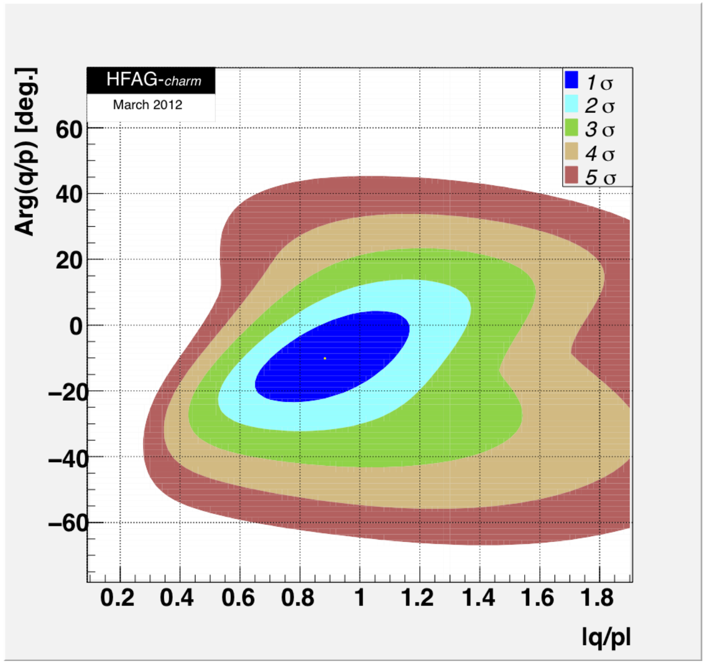
Recent estimates are typically
$|x| \leq 1\%, \quad |y| \leq 1\%$
(consistent with current observation)

Signals for New Physics would be $|x| >> |y|$ or Evidence for *CPV*

Golowich, Hewett, Pakvasa an Petrov, PR 76, 095009(2007)

Current World Averages (HFAG)





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

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A "*B factory*" for *D*'s Too ?

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

- The SM predicts any weak phase to be tiny - a TDCPV analysis is a way to see if this is actually.
- We explore the potential to study the *"cu"* triangle at the LHCb at SuperB/Belle2 at *Y(4S)* or SuperB at $\psi(3770)$.
  - It is unlikely we can measure β_c(<0.1 degrees) to high precision
  - However, a larger value could signify evidence for new physics.
- SuperB in Italy is planning to include an option to run ~1 ab^{-1} at psi(3770) with a CM boost.

The triangles

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

B_d decays

BaBar/Belle

~1 (28^0)

B_s decays

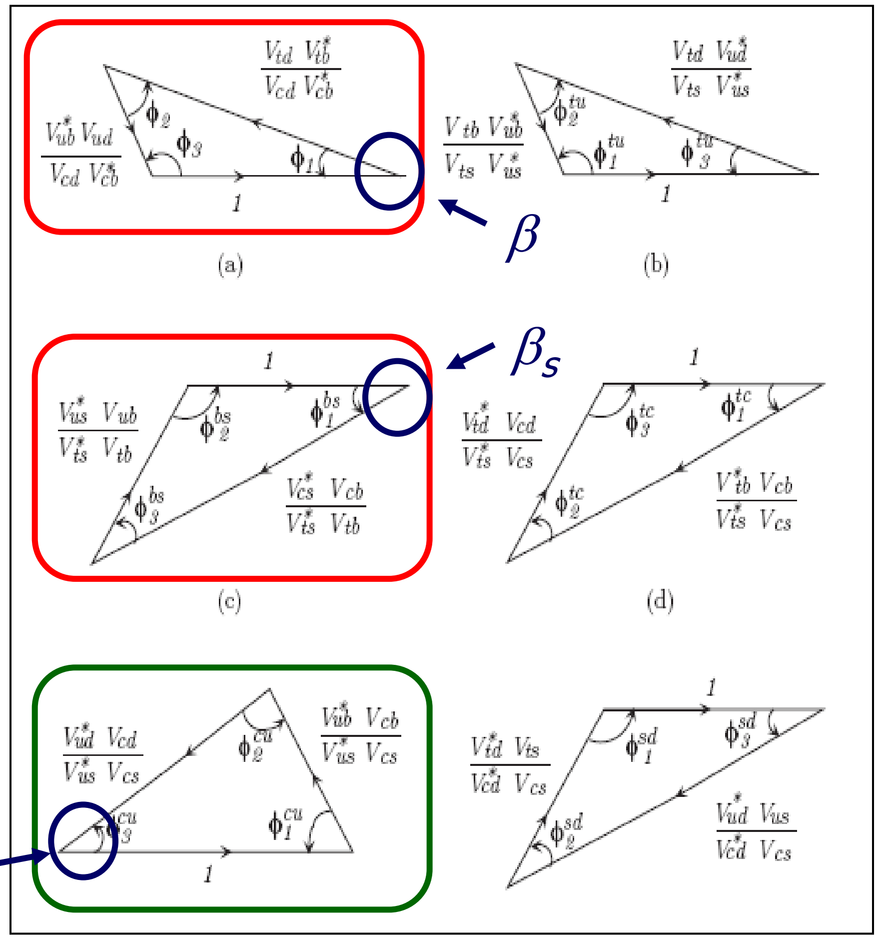
LHCb/CDF/D0

~λ^2 (1^0)

cu triangle

D decays

~λ^4 ($.05^0$)



β_c

Bigi and Sanda:

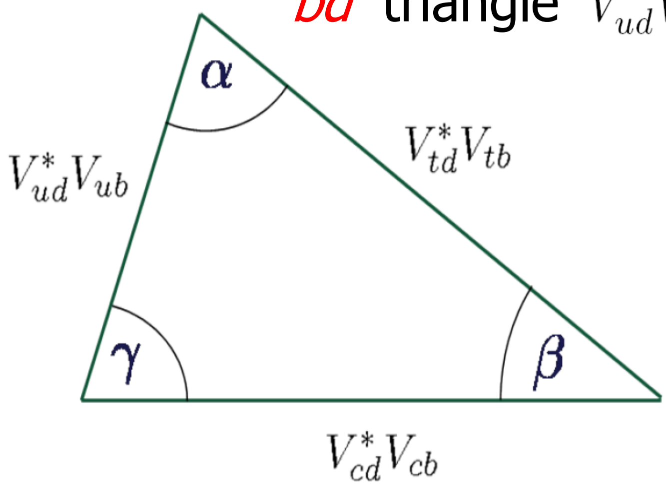
In addition to α, β and γ, the angles, β_c and β_s should be measured also, if possible.

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

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

Unitarity Triangles from CKM Fits

bd triangle $V_{ud}^* V_{ub} + V_{cd}^* V_{cb} + V_{td}^* V_{tb} = 0$

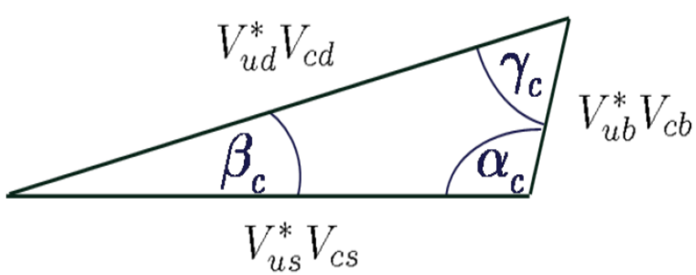


$$\alpha = [V_{td}V_{tb}^*/V_{ud}V_{ub}^*] = (89.4 \pm 4.3)^\circ$$
$$\beta = [V_{cd}V_{cb}^*/V_{cd}V_{cb}^*] = (22.1 \pm 0.6)^\circ$$
$$\gamma = [V_{ud}V_{ub}^*/V_{cd}V_{cb}^*] = (68.4 \pm 3.7)^\circ$$

NOTE that

- γ_c is equal to γ
- $\alpha_c + \gamma_c \sim 90^0$

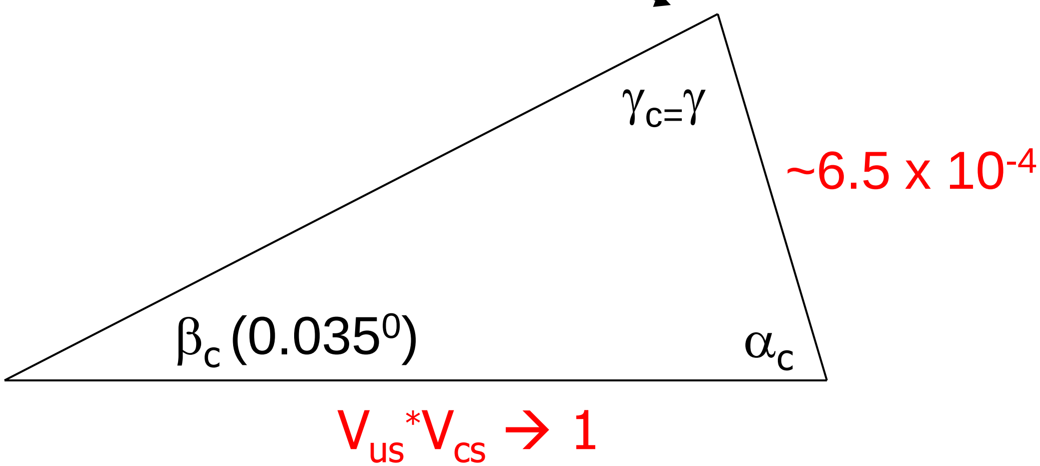
cu triangle $V_{ud}^* V_{cd} + V_{us}^* V_{cs} + V_{ub}^* V_{cb} = 0$



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

Constraint on cu Triangle ?

- $$1+\frac{A^2\lambda^5(\bar{\rho}+i\bar{\eta})}{\lambda-\lambda^3/2-\lambda^5(1/8+A^2/2)} = 1.00025 + i1.00062$$



Lengths of sides:

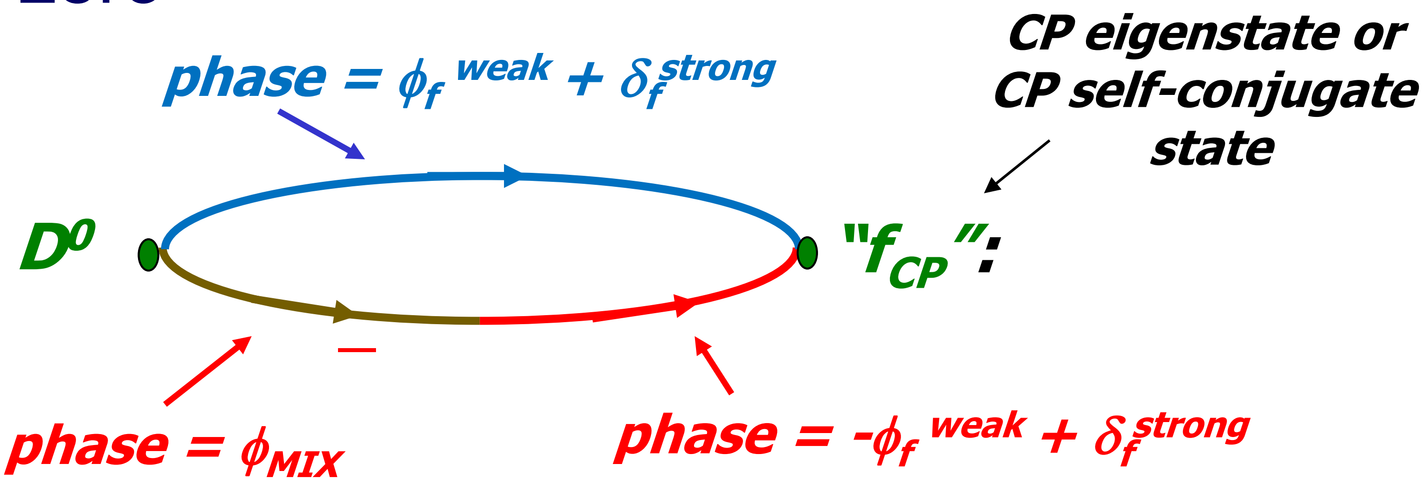
CKM	Uncertainty
$\lvert V_{ud}\rvert$	0.022%
$\lvert V_{cd}\rvert$	4.8%
$\lvert V_{ub}\rvert$	11%
$\lvert V_{cb}\rvert$	3.2%
$\lvert V_{us}\rvert$	1%
$\lvert V_{cs}\rvert$	3.5%

Might improve SL decays of D_s
With SuperB run at D_s threshold ?

→ BUT some measurement of β_c is needed to test CKM

Decays to *CP* eigenstates

- For decays to CP eigenstates, strong phase δ_f in λ_f is zero

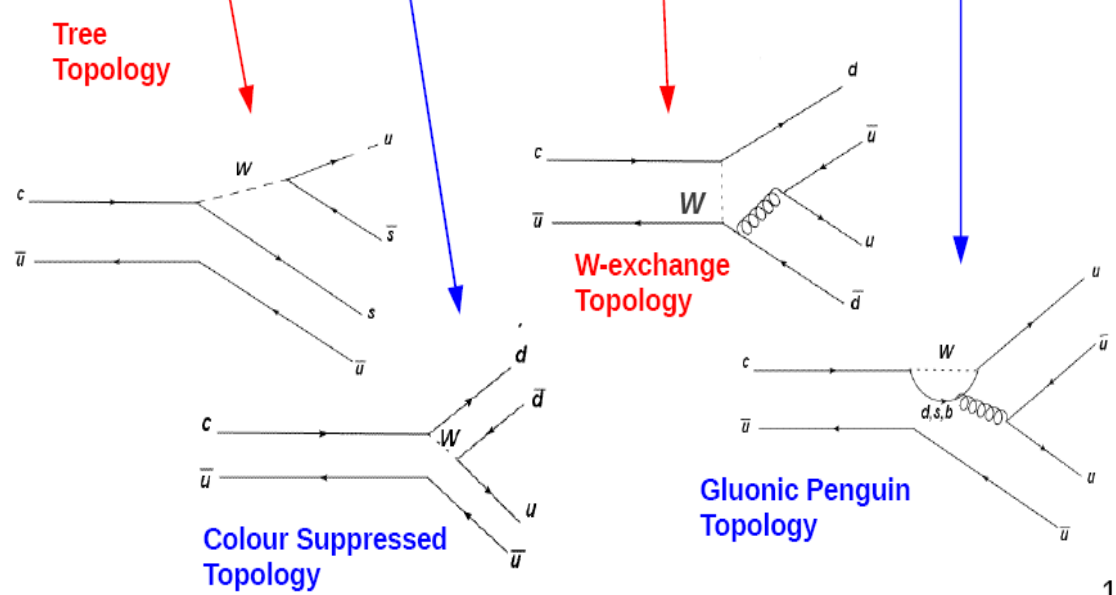


$$\boxed{\text{Phase of } \lambda_f : \ \phi_{MIX} - 2\phi_f^{weak}}$$

Decays of *D* mesons to *CP* eigenstates

- For decays to CP eigenstates, strong phase δ in λ_f is zero

$$A = \boxed{|T|}\, e^{i(\phi_T+\delta_T)} + \boxed{|CS|}\, e^{i(\phi_{CS}+\delta_{CS})} + \boxed{|W|}\, e^{i(\phi_W+\delta_W)} + \sum_{q=d,s,b} \boxed{|P_q|}\, e^{(i\phi_q+\delta_q)}$$



Several amplitudes could, however, contribute to the decays.

- Some information on the magnitude of **P**, the penguin contribution can be obtained from an isospin analysis if all charge modes have well measured **BF**'s, including neutral modes $\pi^0\pi^0$, $\rho^0\rho^0$ and all the $\rho\pi$ modes too.

This could be done at the electron machines.

$D^0 \rightarrow f_{CP}$ Decay Amplitudes

- To order λ^6 these are:

Four out of five are complex !

$$V_{cs}V_{us}^* = \lambda - \frac{\lambda^3}{2} - \left(\frac{1}{8} + \frac{A^2}{2}\right)\lambda^5$$

Real

$$V_{cs}V_{ud}^* = 1 - \lambda^2 - \frac{A^2\lambda^4}{2} + A^2\lambda^6\left[\frac{1}{2} - \bar\rho - i\bar\eta - \bar\eta^2 - \bar\rho^2\right]$$

Phase is $O(\lambda^6)$

$$\boxed{V_{cd}V_{ud}^* = -\lambda + \frac{\lambda^3}{2} + \frac{\lambda^5}{8} + \frac{A^2\lambda^5}{2}[1 - 2(\bar\rho + i\bar\eta)]}$$

Phase is π-β_c

$$V_{cd}V_{us}^* = -\lambda^2 + \frac{A^2\lambda^6}{2}[1 - 2(\bar\rho + i\bar\eta)]$$

Phase is π-β_c but $\sim\lambda^6$

$$V_{cb}V_{ub}^* = A^2\lambda^5(\bar\rho + i\bar\eta)$$

Phase is γ_c, but only found in penguin amplitude
$\rightarrow$unlikely to be able to check that $\gamma_c = \gamma$

Most promising ?
$D^0 \rightarrow hh$ ($h = \pi, K, \rho, f_0, \ldots$)

Amplitudes for Decays to CP Eigenstates

mode	η_{CP}	T	CS	P_q	W_{EX}
$D^0 \to K^+K^-$	$+1$	$V_{cs}V_{us}^*$		$V_{cq}V_{uq}^*$	
$D^0 \to K_S^0 K_S^0$	$+1$				$V_{cs}V_{us}^* + V_{cd}V_{ud}^*$
$D^0 \to \pi^+\pi^-$	$+1$	$V_{cd}V_{ud}^*$		$V_{cq}V_{uq}^*$	$V_{cd}V_{ud}^*$
$D^0 \to \pi^0\pi^0$	$+1$		$V_{cd}V_{ud}^*$	$V_{cq}V_{uq}^*$	$V_{cd}V_{ud}^*$
$D^0 \to \rho^+\rho^-$	$+1$	$V_{cd}V_{ud}^*$		$V_{cq}V_{uq}^*$	$V_{cd}V_{ud}^*$
$D^0 \to \rho^0\rho^0$	$+1$		$V_{cd}V_{ud}^*$	$V_{cq}V_{uq}^*$	$V_{cd}V_{ud}^*$
$D^0 \to \phi\pi^0$	$+1$		$V_{cs}V_{us}^*$	$V_{cq}V_{uq}^*$	
$D^0 \to \phi\rho^0$	$+1$		$V_{cs}V_{us}^*$	$V_{cq}V_{uq}^*$	
$D^0 \to f^0(980)\pi^0$	-1		$V_{cs}V_{us}^* + V_{cd}V_{ud}^*$	$V_{cq}V_{uq}^*$	
$D^0 \to \rho^0\pi^0$	$+1$		$V_{cd}V_{ud}^*$	$V_{cq}V_{uq}^*$	$V_{cd}V_{ud}^*$
$D^0 \to a^0\pi^0$	-1		$V_{cd}V_{ud}^*$	$V_{cq}V_{uq}^*$	$V_{cd}V_{ud}^*$
$D^0 \to K_S^0 K_S^0 K_S^0$	$+1$				$V_{cs}V_{ud}^* + V_{cd}V_{us}^*$
$D^0 \to K_L^0 K_S^0 K_S^0$	-1				$V_{cs}V_{ud}^* + V_{cd}V_{us}^*$
$D^0 \to K_L^0 K_L^0 K_S^0$	$+1$				$V_{cs}V_{ud}^* + V_{cd}V_{us}^*$
$D^0 \to K_L^0 K_L^0 K_L^0$	-1				$V_{cs}V_{ud}^* + V_{cd}V_{us}^*$

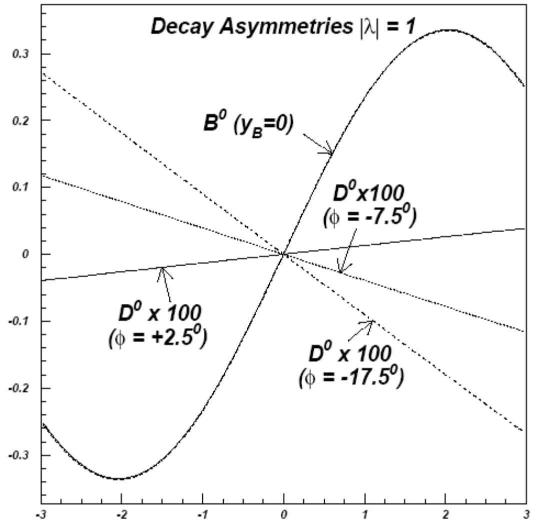
Dominated by real T

Dominated by T with $\phi_f = \pi - \beta_c$

Time-Dependent CP Asymmetry

- For *D* decay we measure CP asymmetry vs. decay time

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



- The D^0 asymmetry is much smaller than that for B^0
- $|A_{CP}|$ is almost linear in *t* while, for B^0 it is sinusoidal
- Slope of line depends upon $\phi = \text{Arg}\{\lambda\}$

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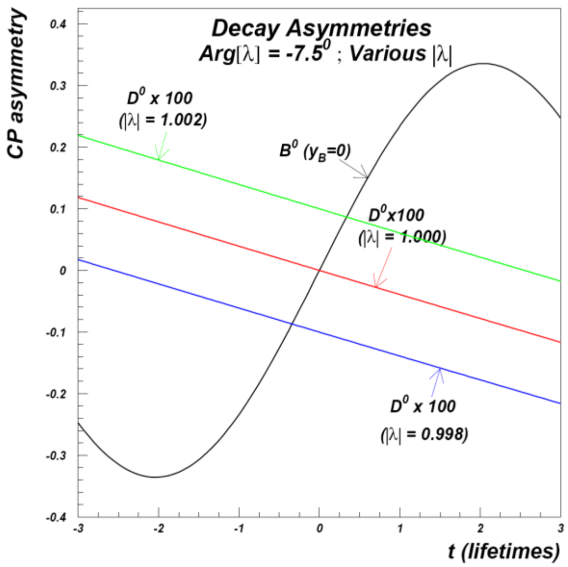

- Intercept of line depends upon $|\lambda|$

  Any asymmetry at t~0 is from direct CPV

- $|A_{CP}|$ is small, but it grows and is largest at large $|t|$
- BUT, as $|t|$ grows larger, the number of events falls off exponentially.

Mis-Tagging

- Effect of mis-tagging probability ω is to reduce the D^0-$\overline{D}^0$ asymmetry

- Effect of *CP* asymmetry in ω is to shift the asymmetry.
  - Direct *CPV* asymmetry is measured at *t=0* ! So shift can be particularly serious in this case.

$$\boxed{\begin{aligned}\mathcal{A}^{\rm Phys}(\Delta t) &= \frac{\bar{\Gamma}^{\rm Phys}(\Delta t) - \Gamma^{\rm Phys}(\Delta t)}{\bar{\Gamma}^{\rm Phys}(\Delta t) + \Gamma^{\rm Phys}(\Delta t)} \\ &= -\Delta\omega + (1 - 2\omega + \Delta\omega)\mathcal{A}(\Delta t)\end{aligned}}$$

$\Delta\omega$ is difference In ω for D^0 vs. $\overline{D}^0$

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- Effect of *CP* asymmetry in ω is to shift the asymmetry.
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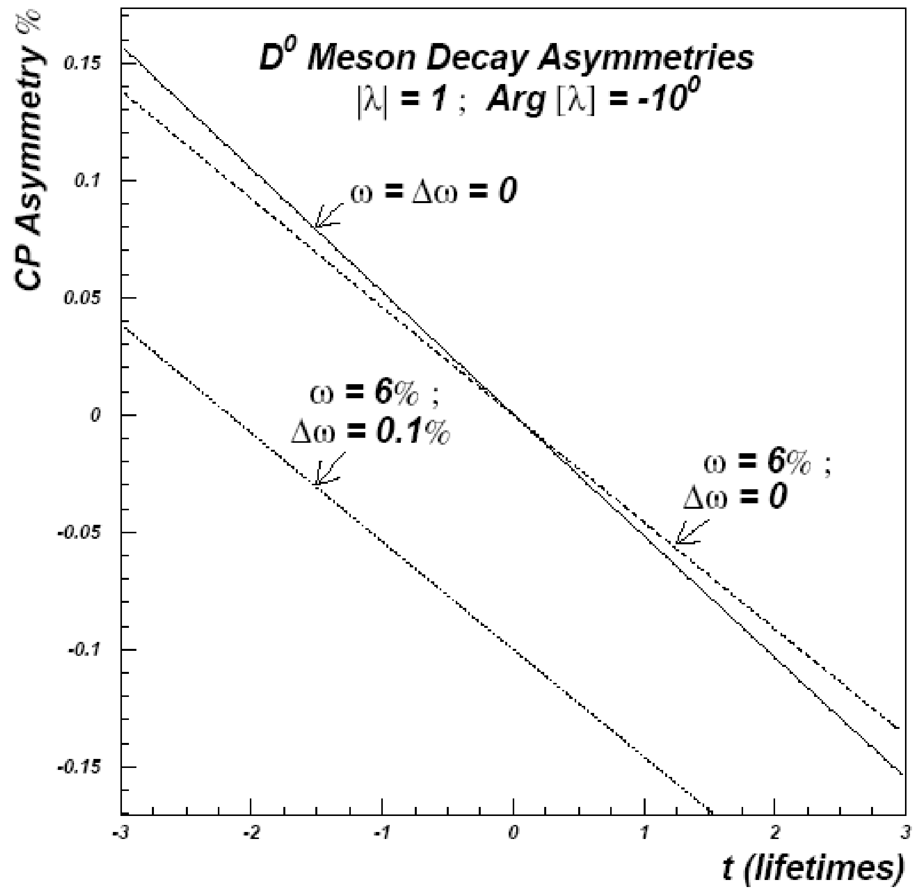
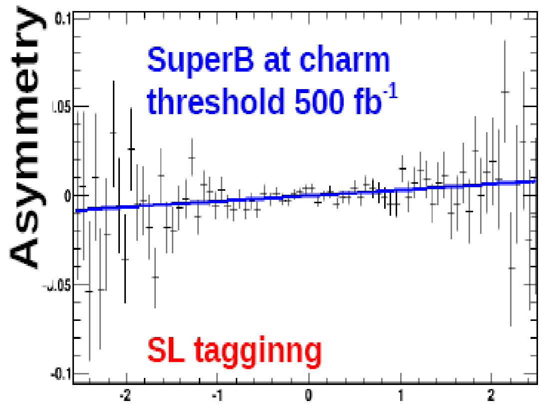


Results – “as good as (they) get”

- A toy MC study was made to study how well we might measure $\phi=\text{Arg}\{\lambda\}$
  - Events were generated with the distributions $\Gamma(\Delta t)$ and $\Gamma(\Delta t)$
  - Perfect time resolution was assumed
- Unbinned likelihood fits were made to study $\sigma(\phi)$.

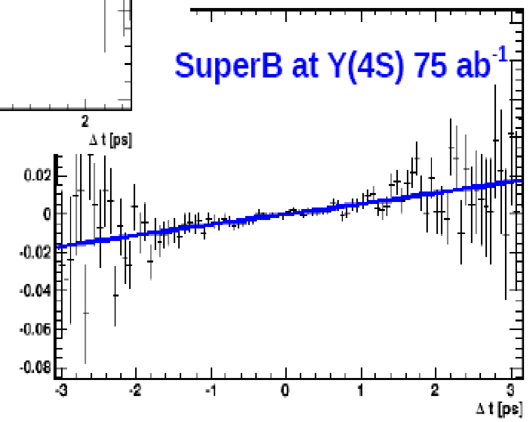


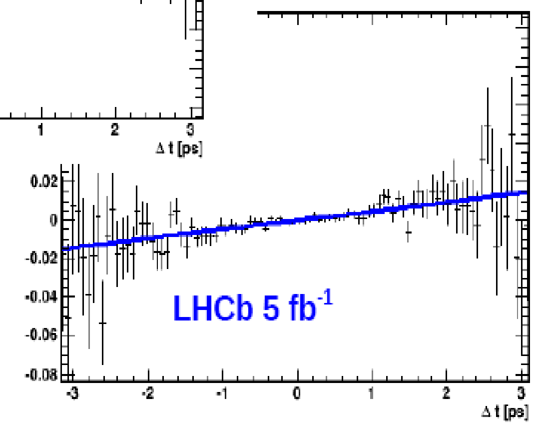
Mis-tag assumptions

- SuperB (charm thresh.) $\omega=\Delta\omega=0$
- SuperB @ Y(4S) $\omega=1\%$, $\Delta\omega = 0$
- LHCb $\omega = 6\%$, $\Delta\omega = 0.1\%$

$$f_{cp} = \pi^+\pi^-$$

$$D^0 \rightarrow f_{cp}$$





Numbers of events scaled

- from CLEO c to 500 fb^{-1}
- from BaBar to 75 ab^{-1}
- from LHCb 35 pb^{-1}

Results – "as good as (they) get"

- The K^+K^- mode is dominated by a tree diagram that is real.
- Therefore, this mode can be used to find arg $(q/p) = \phi_M$
- Then $\pi^+\pi^-$ mode (for which $\arg(\lambda_f\} = \phi_M - 2\beta_{c,eff}$) can give $\beta_{c,eff}$

Parameter	SuperB SL	SuperB SL + K	SuperB $\Upsilon(4S)$	LHCb
$\phi(\pi\pi) = \arg(\lambda_{\pi\pi})$	8.0°	3.4°	2.2°	2.3°
$\phi(KK) = \arg(\lambda_{KK})$	4.8°	2.1°	1.3°	1.4°
$\phi_{CP} = \phi_{KK} - \phi_{\pi\pi}$	9.4°	3.9°	2.6°	2.7°
$\beta_{c,eff}$	4.7°	2.0°	1.3°	1.4°

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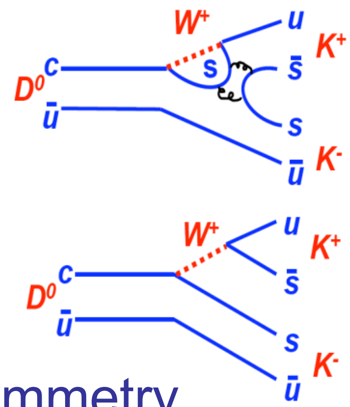
- Is this evidence for *NP* ?

Time-Integrated *CPV* in *D* decays

- For many years, it has been (almost) axiomatic that direct *CPV* in charm particle decays would be a sure sign of NP.
- In November 2011, such evidence (3.5σ significance) was found by the LHCb collaboration, supported by results from the CDF collaboration, but with only 2.6σ significance
- Despite this, doubts now exist about whether details of SM physics are the real source of this *CPV* arising from the presence of penguin contributions to SCS decays.
- If so, evidence for NP has yet to be found.

- In the SM, *CPV* in the charm sector is due to SM penguin tree interference, and should be at about the 0.1% level.

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

- Experimentally we measure the decay rate asymmetry

$$A^f_{CP} = \frac{\Gamma(D^0 \to f) - \Gamma(\bar{D}^0 \to \bar{f})}{\Gamma(D^0 \to f) + \Gamma(\bar{D}^0 \to \bar{f})} = a^f_{\text{direct}} + a_{\text{indirect}}$$

$= A_\tau \sim 0.01\%$

which includes both direct and indirect contributions.

- New insights on systematics, improve uncertainties → ~(0.2-0.4)%.
  - Previous asymmetries were ~0% with uncertainties ~(1-10)%

An experimental milestone

- Until 2007, precision of *D* decay asymmetry measurements were limited to ~1% by two main factors:
  - Charge asymmetry in the efficiencies of "slow pion" tags ($D^{\pm} \rightarrow D^0 \pi^{\pm}$), estimated from MC studies, were unreliable.
  - *D*(*D*) production asymmetries were not well predicted by theory.
- In 2007, BaBar set out to measure $D^0 \rightarrow K^+ K^-$ and $\pi^+\pi^-$ decay asymmetries. They
- introduced a way to measure tagging efficiencies from data rather than MC.
  - The asymmetry in the target h^+h^- channels, subject only to the tagging efficiency, was then measured.
- were able to separate azimuthal asymmetry into odd and even to distinguish forward-backward from CP components.

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

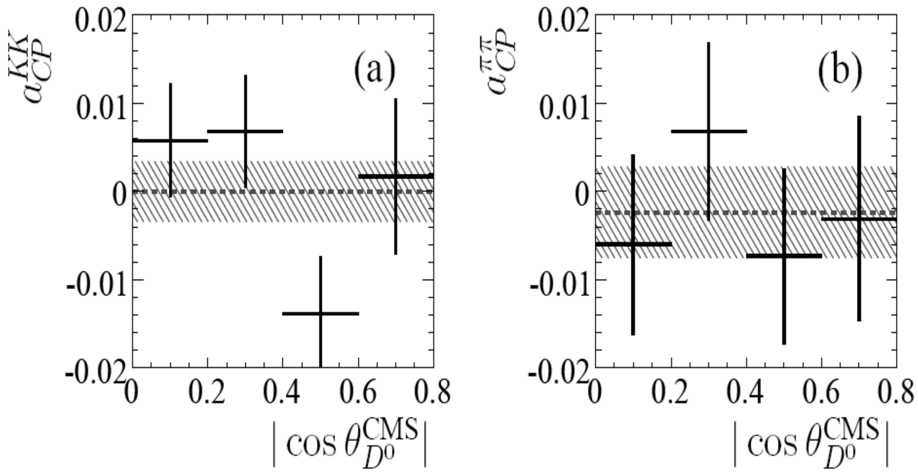
- *D^0*'s produced in e^+e^- collisions at B factories are tagged by the sign of the slow pion from *D^** decay

- Efficiencies for π_s^+ and π_s^- are not the same (low energy $\sigma_{\pi N}$, etc).
  So, use DATA rather than MC to find the asymmetry:
  - Use (several x10^6) untagged $K^-\pi^+$ to map (4-dimensional) efficiency asymmetry for K^- and for π^+ momenta and azimuth.
  - Use this efficiency on tagged $K^-\pi^+$ to map isolated 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, higher order or QCD effects)
  - Take average of each $\cos\theta^*$ range for $|\cos\theta^*| > 0$ and < 0 $\rightarrow A_{CP}$
  - Take difference of each $\cos\theta^*$ range for $|\cos\theta^*| > 0$ and < 0 $\rightarrow A_{FB}$

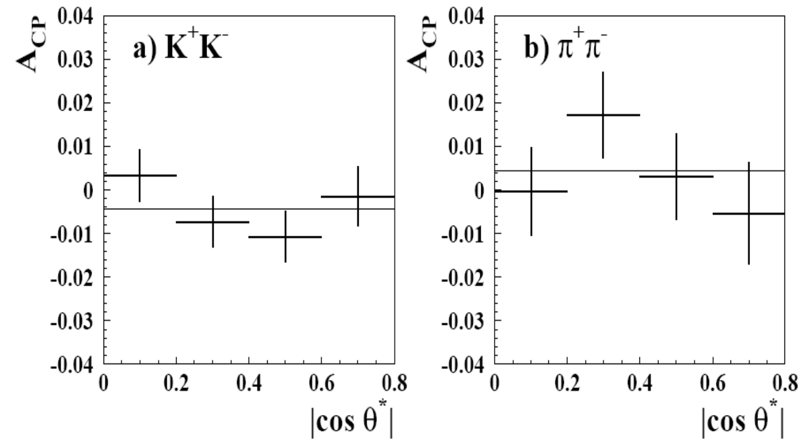
$D^0 \rightarrow K^+K^-$ and $\pi^+\pi^-$

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



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

PLB670, 190-195 (2008)



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

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

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

- For comparison, results on the CPV asymmetry measurement, integrated over the 3-body phase space for these channels are:

Phys.Rev. D78 (2008) 051102
384 fb^{-1}

Phys.Lett.B662 (2008) 102-110
532 fb^{-1}

$$A_{CP}^{KK\pi^0} = [\ 1.00 \pm 1.67(\text{stat.}) \pm 0.25(\text{syst.})]\%$$

$$A_{CP}^{\pi\pi\pi^0} = [-0.31 \pm 0.41(\text{stat.}) \pm 0.17(\text{syst.})]\%$$

$$A_{CP}^{\pi\pi\pi^0} = [-0.43 \pm 0.41(\text{stat.}) \pm 1.23(\text{syst.})]\%$$

Babar used the technique described to correct for tracking asymmetries.

Belle's (earlier paper), did not do this.

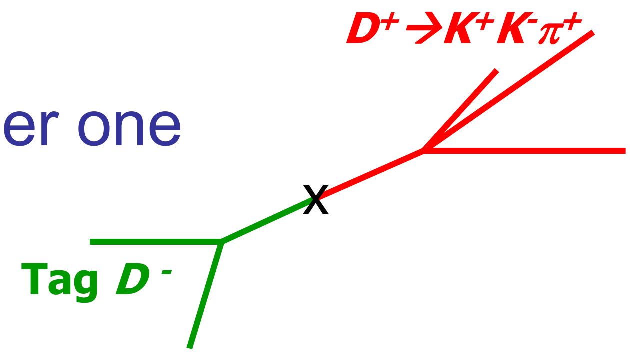
- No evidence for CPV
- Systematic uncertainties ~ 0.2% *(Likely scale with luminosity$^{-1/2}$)* !!
- No significant difference between $KK\pi^0$ and $\pi\pi\pi^0$

- See Ryan White's talk on other more recent 3-body *CPV* measurements.

Example at charm threshold - $D^+ \to K^- K^+ \pi^+$

Phys.Rev. D78 (2008) 072003
818 pb^{-1}

- CLEO-c used 818 pb^{-1} e^+e^- at the $\psi(3770)$ – near D^+D^- threshold.
- One $D^\pm$ (self-tagged) identifies the other one
  - no asymmetry from D^* tagging!
  - no production asymmetry.



- Overall asymmetry

$$A_{CP} = (-0.03 \pm 0.84 \pm 0.29)\%$$

- Amplitude analysis of Dalitz plot – integrated asymmetry

$$A_{CP} = (-0.4 \pm 2.0^{+0.2+0.6}_{-0.5-0.3})\%$$

CPV measurements at hadron machines

- Pretty soon, CDF and then LHCb devised ways to beat or finesse the slow pion tagging efficiency to reach precision in asymmetry measurements in the "per mille" range.
- LHCb also has a special problem with production asymmetry, since the uses $p+p \to D^0+X$ rather than $\bar{p}+p \to D^0+X$ interactions so that the BaBar odd-even trick will not work .
- Both experiments can, however, finesse these problems by measuring

$$\Delta_{CP} = A_{CP}^{KK} - A_{CP}^{\pi\pi}$$

- Most interesting, was the observation by CDF that the asymmetry measured is of the form

$$\Delta_{CP}^{f} = \frac{\Gamma^{(D^0\to f)} - \Gamma^{(\bar{D}^0\to f)}}{\Gamma^{(D^0\to f)} + \Gamma^{(\bar{D}^0\to f)}} \approx A_{CP}^{\text{direct}} + \frac{\langle t \rangle}{\tau} A_{CP}^{\text{indirect}}$$

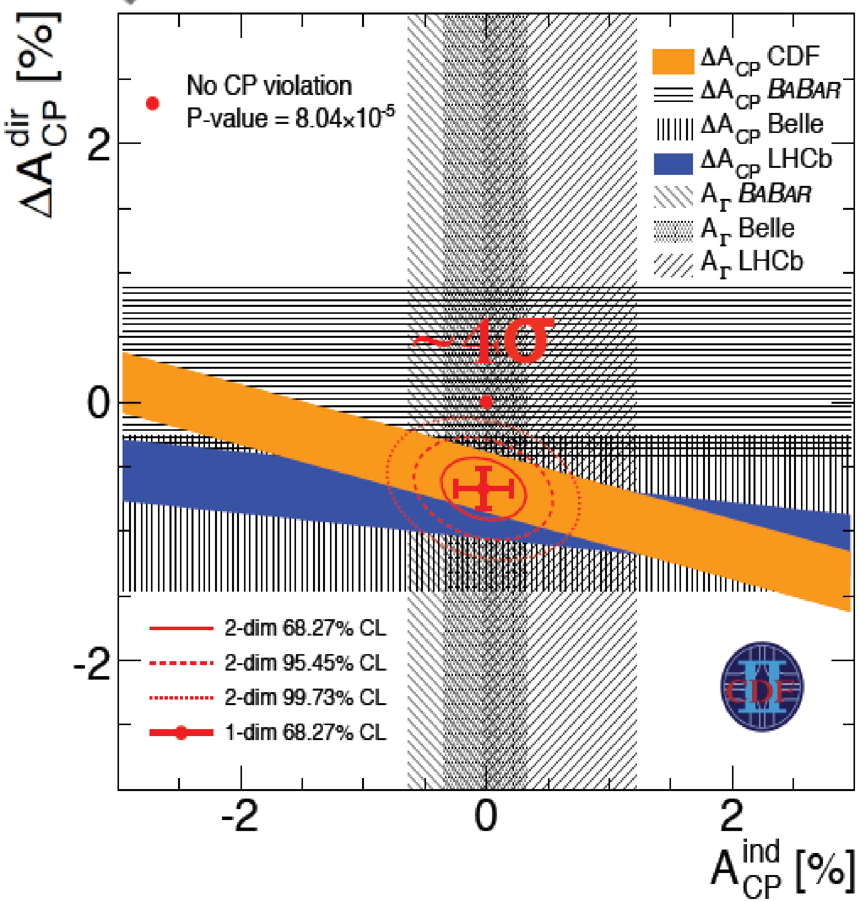
and to note that CDF, LHCb and BaBar/Belle have different time integration periods over which <t> is computed.

CDF asymmetry measurements

NEW

$\Delta A_{CP} = (-0.62 \pm 0.21(\text{stat}) \pm 0.10(\text{syst}))\%$

CDF Note 10784



Confirm LHCb result

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

When combining à la HFAG

No CPV point is at

$\sim 4\sigma$ from zero

$\Delta A_{CP}^{dir} = (-0.67 \pm 0.16)\%$

$A_{CP}^{ind} = (-0.02 \pm 0.22)\%$

Mirco Dorigo (CDF)
Moriond QCD, 2012

Evidence for direct CPV in *D* decay LHCb

Jonas Rademacker (Bristol) talk at Moriond EW

Direct CPV in D→KK, D→ππ

0.62/fb, arXiv:1112.0938
PRL **108,** 111602 (2012)

$$A_{CP}(K^+K^-) \equiv \frac{\Gamma(D^0 \to K^+K^-) - \Gamma(\overline{D}^0 \to K^+K^-)}{\Gamma(D^0 \to K^+K^-) + \Gamma(\overline{D}^0 \to K^+K^-)} \qquad A_{CP}(\pi^+\pi^-) \equiv \frac{\Gamma(D^0 \to \pi^+\pi^-) - \Gamma(\overline{D}^0 \to \pi^+\pi^-)}{\Gamma(D^0 \to \pi^+\pi^-) + \Gamma(\overline{D}^0 \to \pi^+\pi^-)}$$

Tag initial state with D*: $D^{*-} \to \overline{D}^0 \pi_s^-$, $D^{*+} \to D^0 \pi_s^+$

$$A_{RAW}(f)^* = A_{CP}(f) + \cancel{A_D(f)} + A_D(\pi_s) + A_P(D^{*+})$$

what we want

~~f's detection asymmetry.~~

π_s detection asymmetry

Production asymmetry

- Initial state subject to production and π_s detection asymmetry.
  Cancel in the difference: $\Delta A_{CP} \equiv A_{CP}(KK) - A_{CP}(\pi\pi)$
- Nice: U-spin suggests that $A_{CP}(KK) \approx -A_{CP}(\pi\pi)$ (Grossmann Kagan Nir Phys.Rev.D75:036008,2007)
- Measures CPV in decay only, other forms of CPV cancel (to very good approx)

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

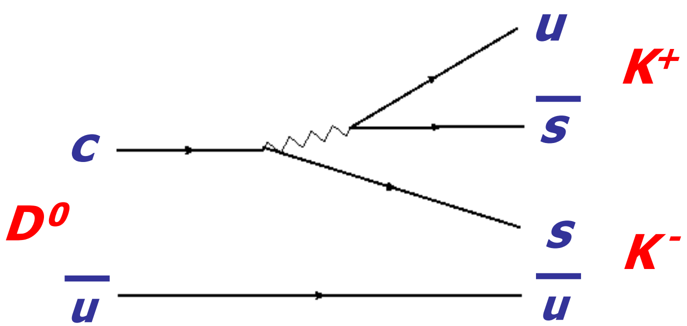
0.62 fb^{-1} Needs confirmation

Lecture IV

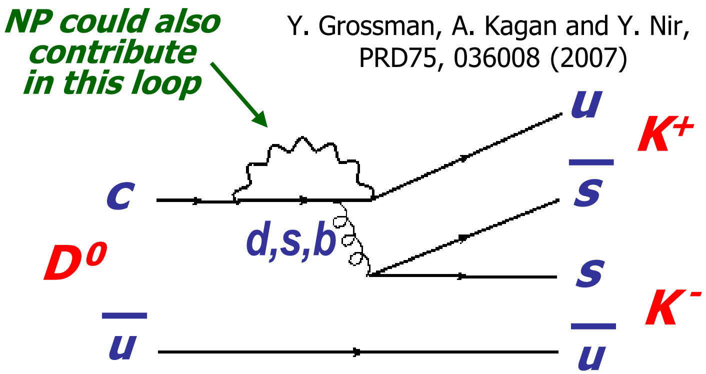
- *CP* Violation and mixing for *D* vs. *B*.
- *TDCPV* measurement at a *D* factory too ?
  - Unitarity triangles
- Time-integrated and direct *CPV* – evidence from *LHCb*.
- Is this evidence for *NP* ?

Direct CPV in SCS D^0 Decays

- In the *SM*, *CPV* comes from penguin amplitudes *P* interfering with tree amplitudes *T*.
- Large *CP* asymmetries ~1% could come from NP particles in penguin loops, new scalar exchanges, … (many ideas!)



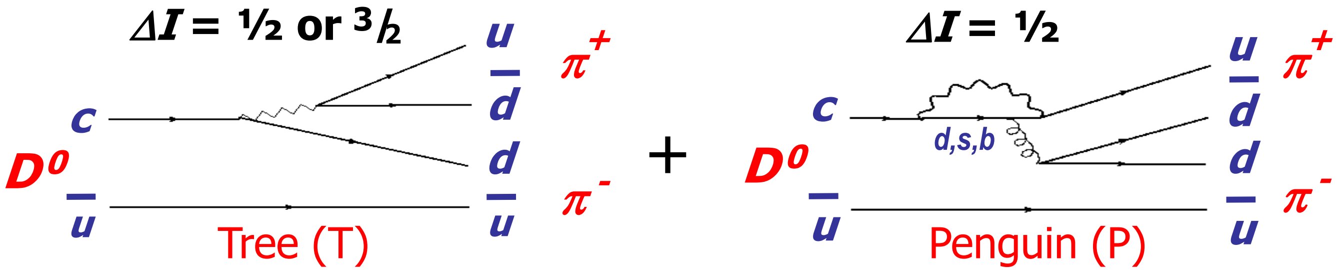
Y. Grossman, A. Kagan and Y. Nir, PRD75, 036008 (2007)



- It is hard for the SM to account for asymmetries of ~1%, but not impossible. How can we tell if NP is required?

CPV in *SCS* decays in the SM

- *SM* penguin and Tree contributions.

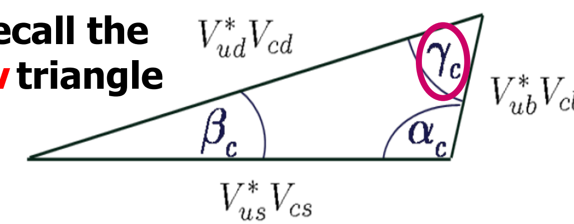


- The largest penguin amplitude comes from the *b* quark, so the SM ratio between tree and penguin amplitudes is

$$P/T = \frac{V_{cb}V_{ub}}{V_{cs}V_{us}} = r_P e^{-i\gamma} \sim 10^{-3} e^{-i68^\circ}$$

The phase of *P/T* is γ (=68^0)

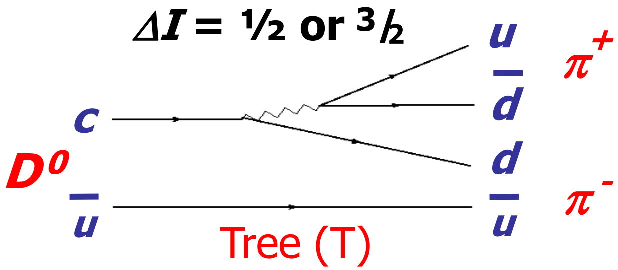
Recall the *cu* triangle



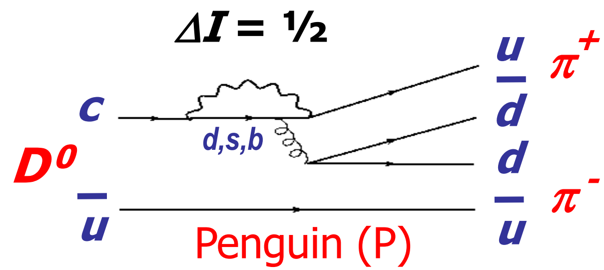
- The magnitude r_P must include QCD power corrections, etc., that are notoriously difficult to compute.

Include (some kind of) NP

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



+



NP

+ ???

$\Delta I = {}^3/_2$?

- Decay amplitudes for D^0 and $\overline{D}^0 \to \pi^+\pi^-$ are

$$A = T + Pe^{i(\delta_P-\gamma)} + Ne^{i(\delta_N-\phi)}$$

$$\bar{A} = T + Pe^{i(\delta_P+\gamma)} + Ne^{i(\delta_N+\phi)}$$

[We choose: $\delta_T = 0$]

SM weak phase $\sim\lambda^5$

SM phase $\gamma \sim 67^0$

NP contribution Weak phase ϕ

- This leads to an asymmetry

$$\mathcal{A}_{CP} = \frac{\Gamma-\bar{\Gamma}}{\Gamma+\bar{\Gamma}} \simeq 2r_P \sin\gamma \sin\delta_P + 2r_N \sin\phi \sin\delta_N$$

$\Delta I = 1/2 \sim 10^{-3}$ $\qquad$ $\Delta I = 1/2$ or $3/2$

I- spin Tests for NP

- It is hard for the SM to account for asymmetries of ~1%, but maybe not impossible. 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.

http://arxiv.org/abs/1204.3557

$D^{0,+} \rightarrow \pi\pi$ and $\rho\rho$ (GZK)

- Bose statistics requires only $I = 0$ or 2 in each of these final states so there are two reduced I-spin decay amplitudes A_1 ($\Delta I = ½$) and A_3 ($\Delta I = {}^3/_2$) so that

$$
\begin{aligned}
A_{\pi^+\pi^-} &= \sqrt{2}A_3 + \sqrt{2}A_1 \\
A_{\pi^0\pi^0} &= 2A_3 - A_1 \\
A_{\pi^+\pi^0} &= 3A_3
\end{aligned}
$$

CP conjugate decays are similar with $A_f \rightarrow \bar{A}_{\bar{f}}$.

- Split these amplitudes into SM (S) and NP (N) components:

$$A_k = S_k e^{i(\delta_k^S - \phi_k^S)} + N_k e^{i(\delta_k^N - \phi_k^N)}$$

(k = 1 or 3)

- In the SM, A_3 comes only from the tree diagram ($V_{cd}V_{ud}$) with weak phase $\phi_3^S \sim 0$

[Actually $\sim\lambda^4$]

CP Asymmetry in $D^+ \to \pi^+\pi^0$

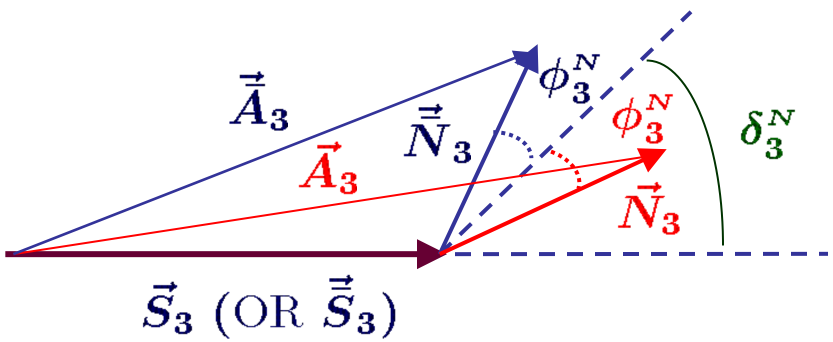
- We can also choose the strong phase $\delta_3^S = 0$ so that

$$A_3 = S_3 + N_3 e^{i(\delta_3^N - \phi_3^N)}$$

Real

So, for $D^+ \to \pi^+\pi^0$, the *CP* difference

$$\Delta_2(\pi^+\pi^0) = \left(|A_{\pi^+\pi^0}|^2 - |\bar{A}_{\pi^-\pi^0}|^2\right) = 36 S_3 N_3 \sin\delta_3^N \sin\phi_3^N .$$



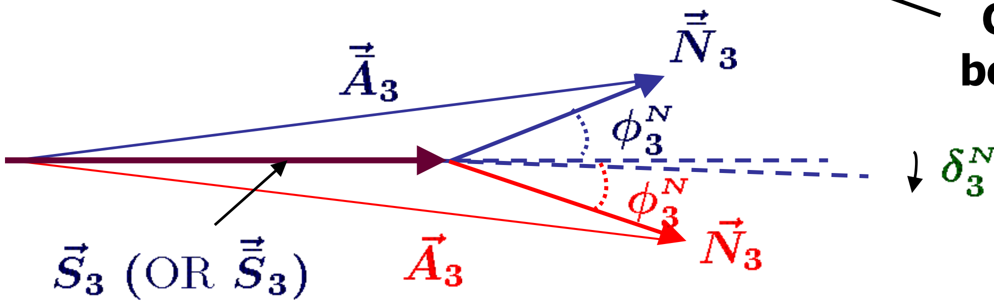
$\to$ *CP* asymmetry in $D^0 \to \pi^+\pi^0$ requires NP !

- BUT absence of measurable *CP* asymmetry in $D^+ \rightarrow \pi^+\pi^0$ does not eliminate need for a $\Delta I = {}^3/_2$ *NP* amplitude

$$\Delta_2\left(\pi^+\pi^0\right) = 36 S_3 N_3 \sin\delta_3^N \sin\phi_3^N .$$

Could be small

(Could also be small).



- So GZK suggest testing

$$Q_1 = \Delta_2(\pi^+\pi^-) + \Delta_2(\pi^0\pi^0) - \frac{2}{3}\Delta_2(\pi^+\pi^0) = 3\left(|A_1|^2 - |\bar{A}_1|^2\right) .$$

- If Q_1 not zero, there are $\Delta I = {}^1/_2$ contributions to *CPV*

  (Could be either *NP* or *SM*).

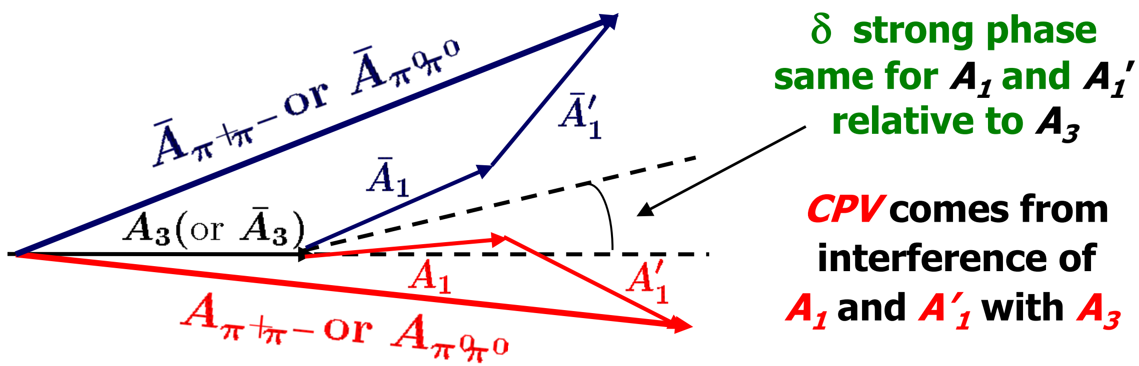
- **BUT if**

$$Q_1 = \underbrace{\Delta_2(\pi^+\pi^-)}_{\neq 0} + \underbrace{\Delta_2(\pi^0\pi^0)}_{\neq 0} - \frac{2}{3}\Delta_2(\pi^+\pi^0) = 3(\underbrace{|A_1|^2 - |\bar{A}_1|^2}_{= 0}) .$$

- **Either** the *CP* differences observed come from A_3

Evidence for *NP*

- **Or** the $\Delta I = {}^1/_2$ amplitudes for *T* and *P* have the same strong phase but different weak phases (no *CPV* in $\Delta I = ½$)



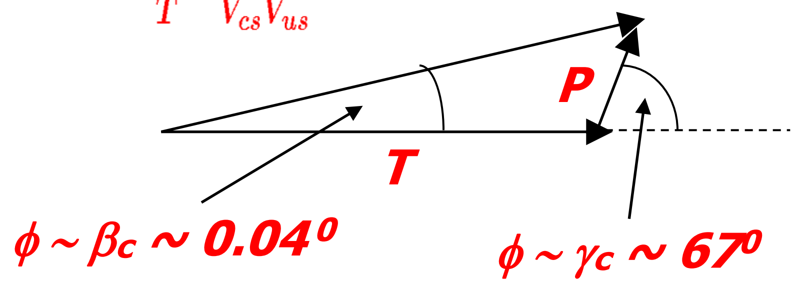
No need for *NP*

- Time-dependent CP asymmetry measurements are required to distinguish these.

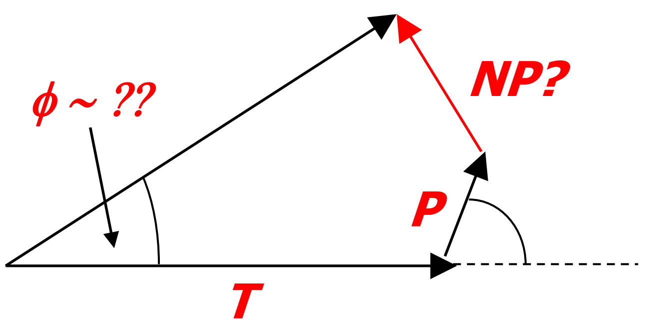
Time-dependent *CPV* asymmetry

- 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 $D^0 \to \pi^+\pi^-$ and $D^0 \to K^+K^-$ 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: $\frac{P}{T} = \frac{V_{cb}V_{ub}}{V_{cs}V_{us}} = r_P e^{-i\gamma} \sim 10^{-3} e^{-i\,68^0}$

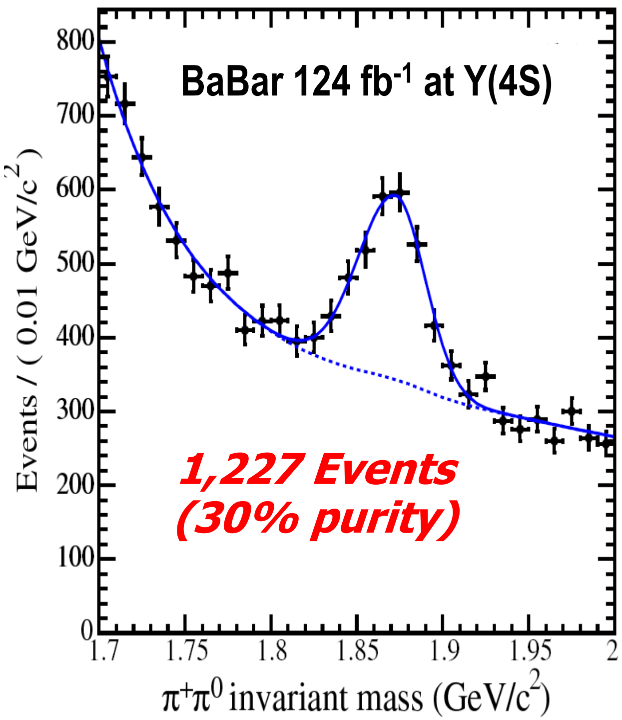


NP:



Prospects for Measuring $D^+ \to \pi^+\pi^0$ Asymmetry

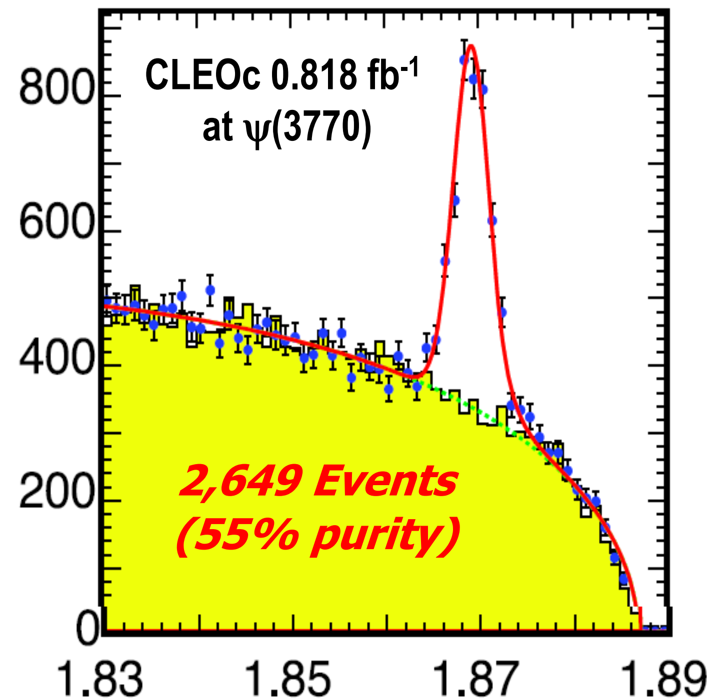
- BaBar and CLEO measured this mode relative to $D^+ \to K^-\pi^+\pi^+$



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

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

Phys.Rev. D74 (2006) 011107

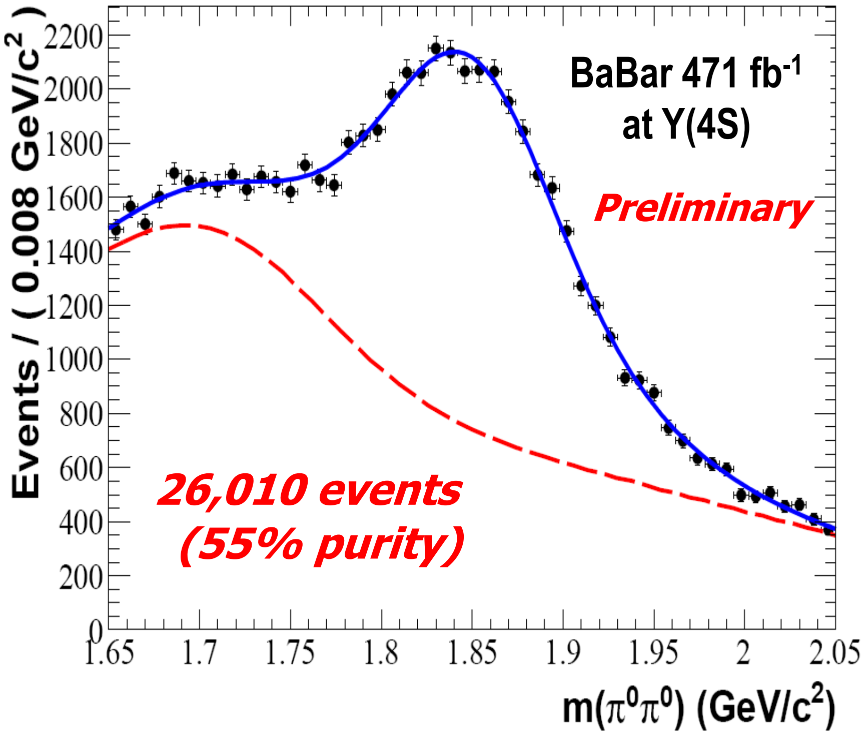


$B_{\pi^+\pi^0} \,/\, B_{K^-\pi^+\pi^+} = (1.29 \pm 0.04 \pm 0.05) \times 10^{-2}$

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

Phys.Rev. D81 (2010) 052013

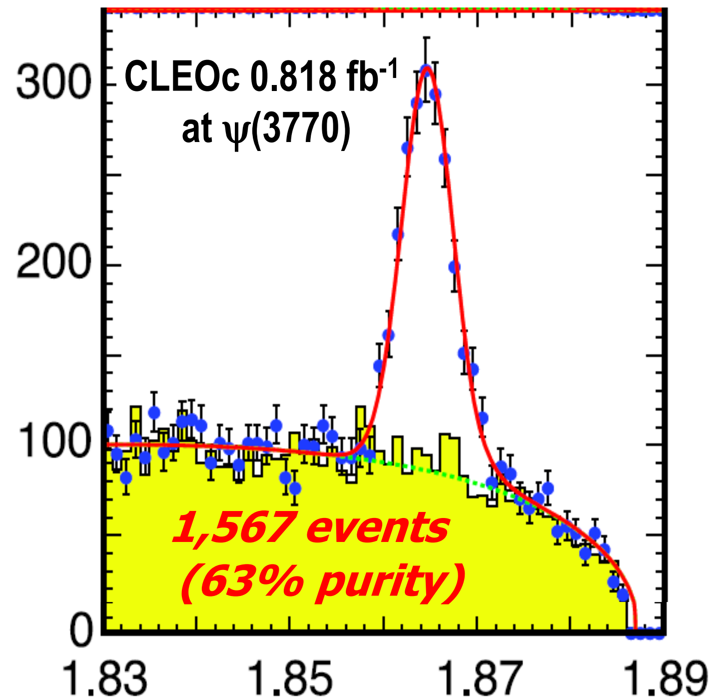
Prospects for Measuring other ππ Asymmetries



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

A^{CP} ~ (xxx ± 1.2) x10^{-2}

Submitted to Phys.Rev. D



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

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