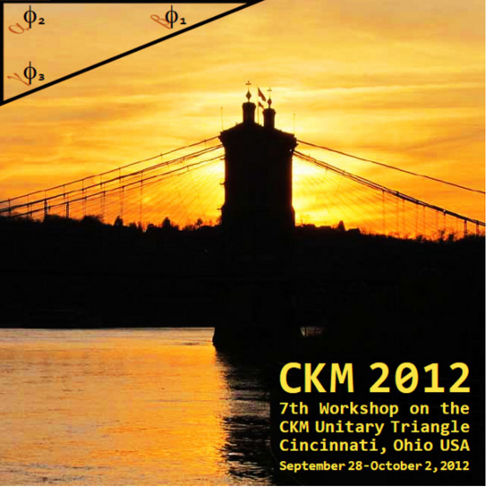


Summary of WG VII (charm mixing/CPV)

Mat Charles, Ray Cowan, Alexey Petrov, Svjetlana Fajfer

First

- Many thanks to the speakers for an excellent set of talks
- and to the audience for lively discussion
- and to the organisers for the opportunity to listen to the above
- and to the Westin for sustaining us with cookies

Summary^2

Sunday 30 September 2012

WG VII - Harding (08:30-10:30)

time	title	presenter
08:30	CPV and Mixing in the Charm Sector at Belle, and HFAG Averages	KO, Byeong Rok
09:08	CPV and Mixing in the Charm Sector at BaBar	CENCI, Riccardo
09:41	Charm Mixing at Threshold (Quantum Correlations) at CLEO	SUN, Werner
10:00	Charm Mixing in the Standard Model: Short Distance Approach	BOBROWSKI, Markus

WG VII - McKinley (16:30-18:30)

time	title	presenter
16:30	Charm Mixing in the Standard Model: Long Distance Approach	LIGETI, Zoltan
16:55	CPV and Mixing in the Charm Sector at LHCb	PARKES, Chris
17:20	CPV and Mixing in the Charm Sector at CDF	MATTSON, Mark Edward
17:40	Direct CPV in Non-leptonic Charm Decays I	BHATTACHARYA, Bhubanjyoti
18:00	Direct CPV in Non-leptonic Charm Decays II	BROD, Joachim

Monday 01 October 2012

WG VII - Hays (11:00-13:00)

time	title	presenter
11:00	Direct CPV in Non-leptonic Charm Decays: New Physics	KAMENIK, Jernej
11:25	Status and Prospects for Mixing/CPV Using Charm at Threshold	BRIERE, Roy
11:45	Prospects for Charm Mixing and CPV at SuperB	BRANCHINI, Paolo
12:05	Prospects for Charm Mixing and CPV at Belle II	ASNER, David
12:25	Prospects for Charm Mixing and CPV at the LHCb Upgrade	SPRADLIN, Patrick
12:40	Charm Mixing and CPV: Measurements We Need	GROSSMAN, Yuval

- 5 talks on current experimental results
- 5 on state of theory
- 4 on experimental prospects (next decade)
- 1 on where to go next

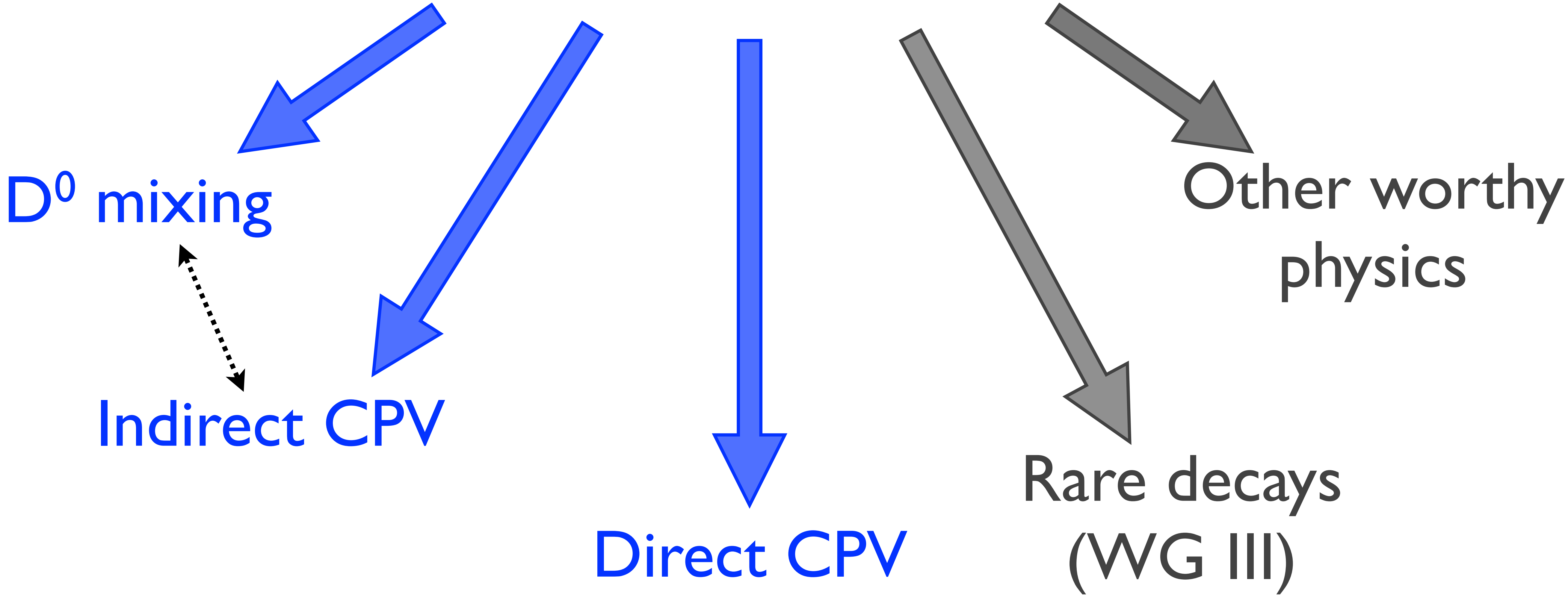
Alarr, Wikimedia

Caveat

or: why experimentalists should not give summary talks

Apologies to G. Larson

Charm physics



D^0 mixing

- Tremendous advances in the last decade
- ... but still a long way to go

D^0–$\overline{D}^0$ transitions observables

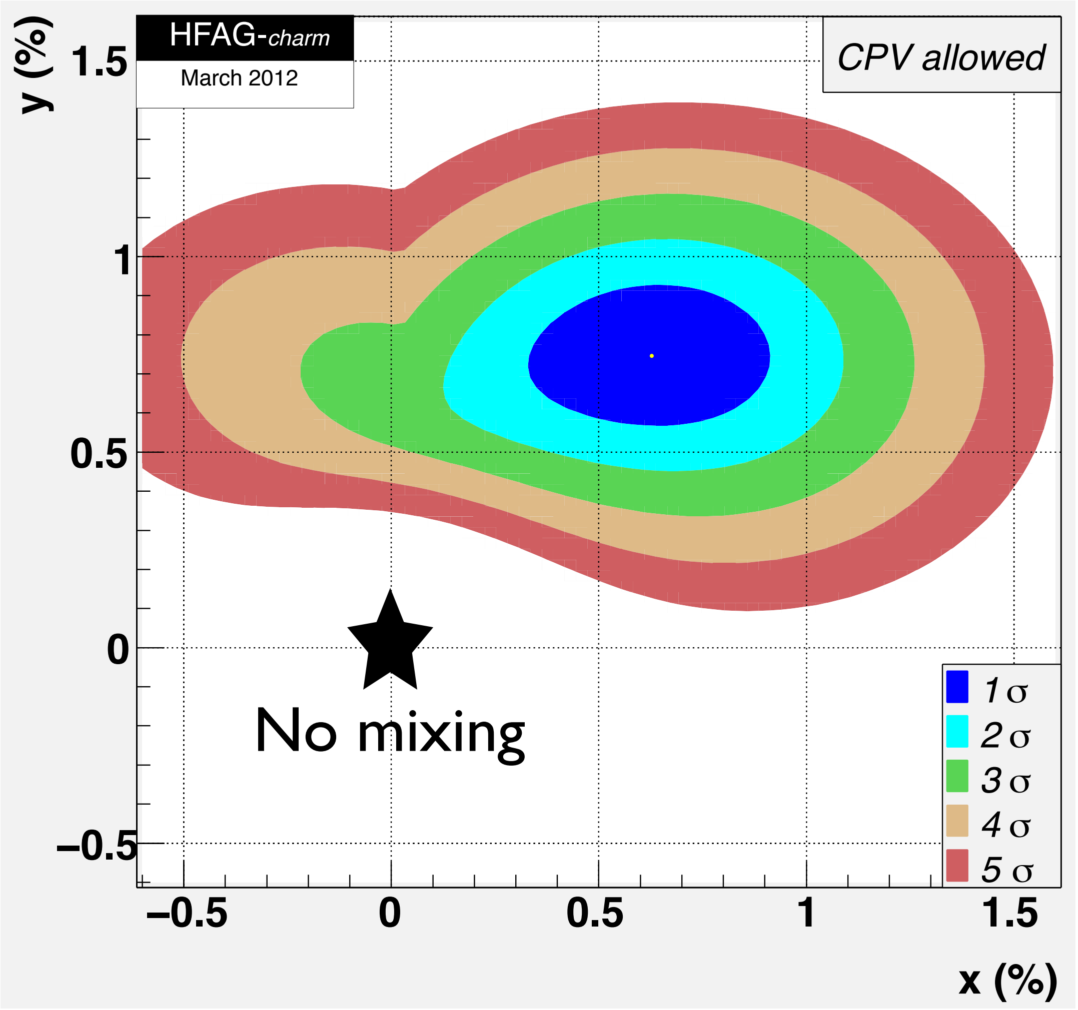
$$x = \frac{\Delta M}{\Gamma}, \quad y = \frac{\Delta \Gamma}{2\Gamma} \qquad R_M = \frac{1}{2}\left(x^2 + y^2\right)$$

$$x' = x\cos\delta_{K\pi} + y\sin\delta_{K\pi}$$
$$y' = y\cos\delta_{K\pi} - x\sin\delta_{K\pi}$$

$$\left|\frac{q}{p}\right| \qquad Arg\left(\frac{q}{p}\right)$$

$$y_{CP} = \frac{\tau(D^0 \to K^-\pi^+)}{2}\left(\frac{1}{\tau(D^0 \to K^-K^+)} + \frac{1}{\tau(\overline{D^0} \to K^-K^+)}\right) - 1 \approx \frac{\tau(D^0 \to K^-\pi^+)}{\tau(D^0 \to K^-K^+)} - 1$$

Mixing: experiment



HFAG average from March shown here.
Several new measurements not yet included.

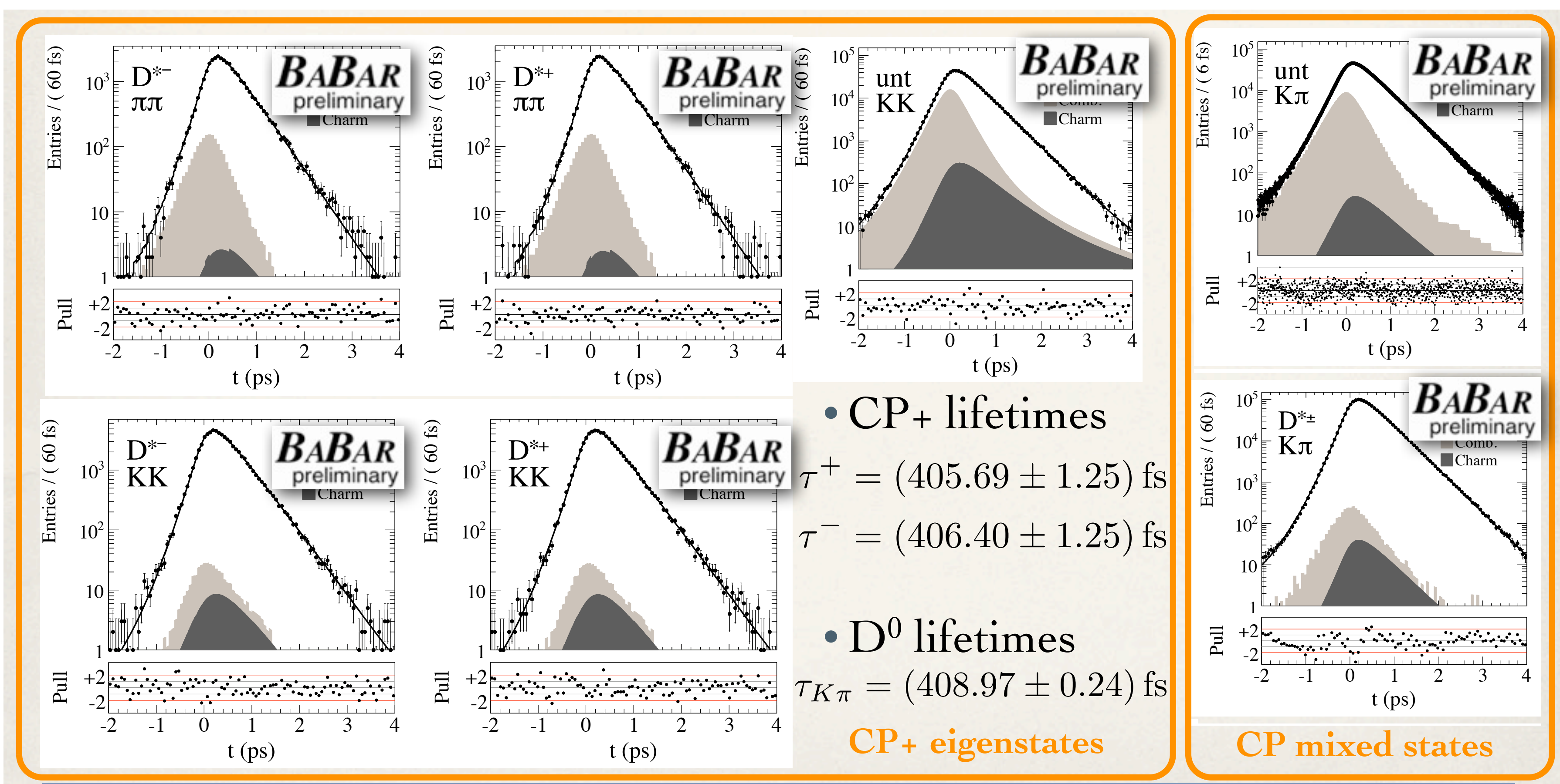
- No-mixing point now excluded at > 10σ
- Sign(x/y) likely positive
- General scale of mixing now very clear.
- Individual parameters still uncertain (esp. x).

Ko, Cenci, Parkes

New & recent results (1)

- Updates on y_{CP} from Belle & BaBar.
  Both use simultaneous fit to Kπ, KK, ππ samples

Belle preliminary, 976/fb	$y_{CP} = (+1.11 \pm 0.22 \pm 0.11)\%$
BaBar preliminary, 470/fb	$y_{CP} = (+0.720 \pm 0.180 \pm 0.124)\%$
LHCb, 0.03/fb JHEP 04 (2012) 129	$y_{CP} = (+0.55 \pm 0.63 \pm 0.41)\%$

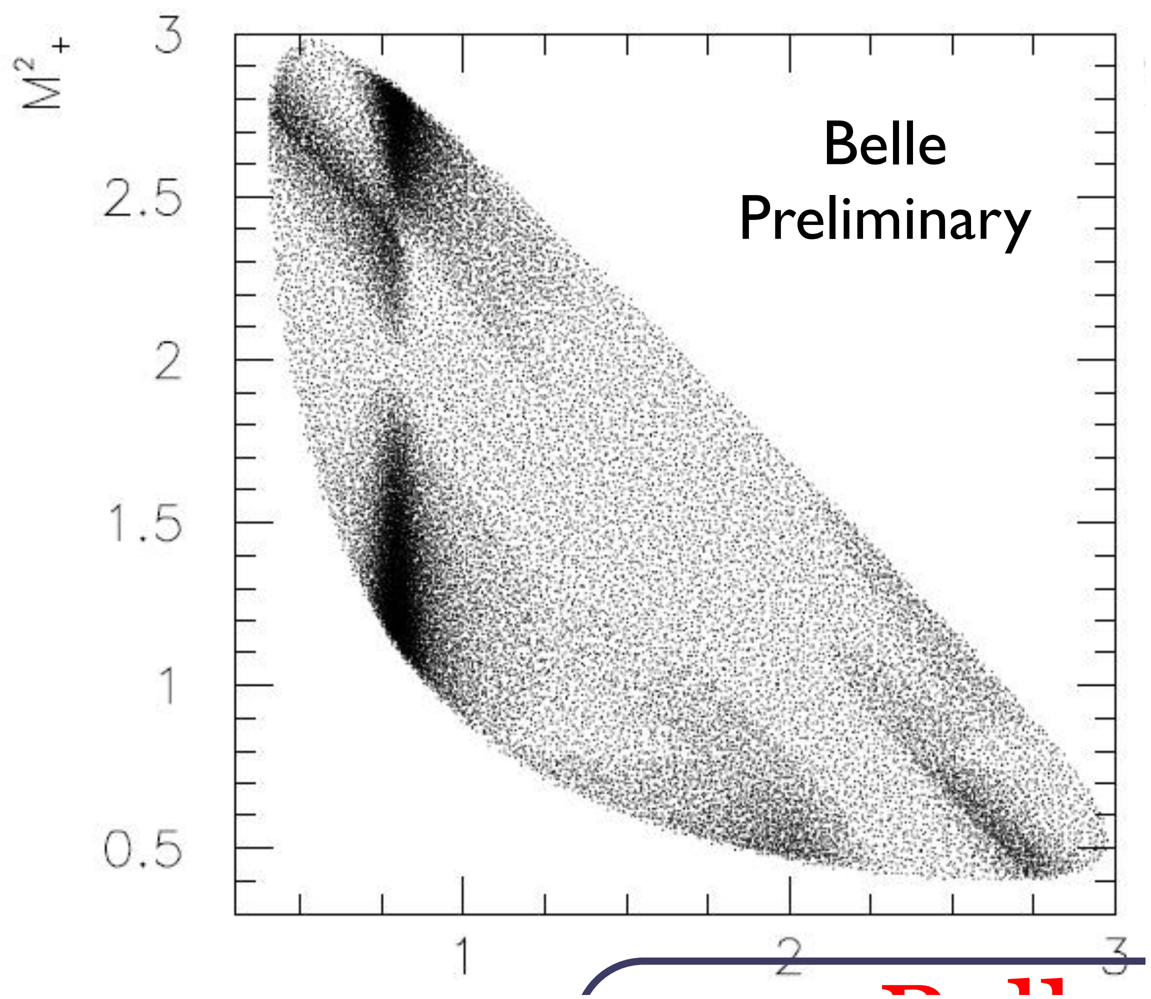


Ko

New & recent results (2)

- Belle update of time-dependent Dalitz plot analysis of $D^0 \to K_S \pi^+ \pi^-$ to 920/fb
- Preliminary results:

	result (%)
x	$(0.56 \pm 0.19^{+0.03+0.06}_{-0.09-0.09})$
y	$(0.30 \pm 0.15^{+0.04+0.03}_{-0.05-0.06})$

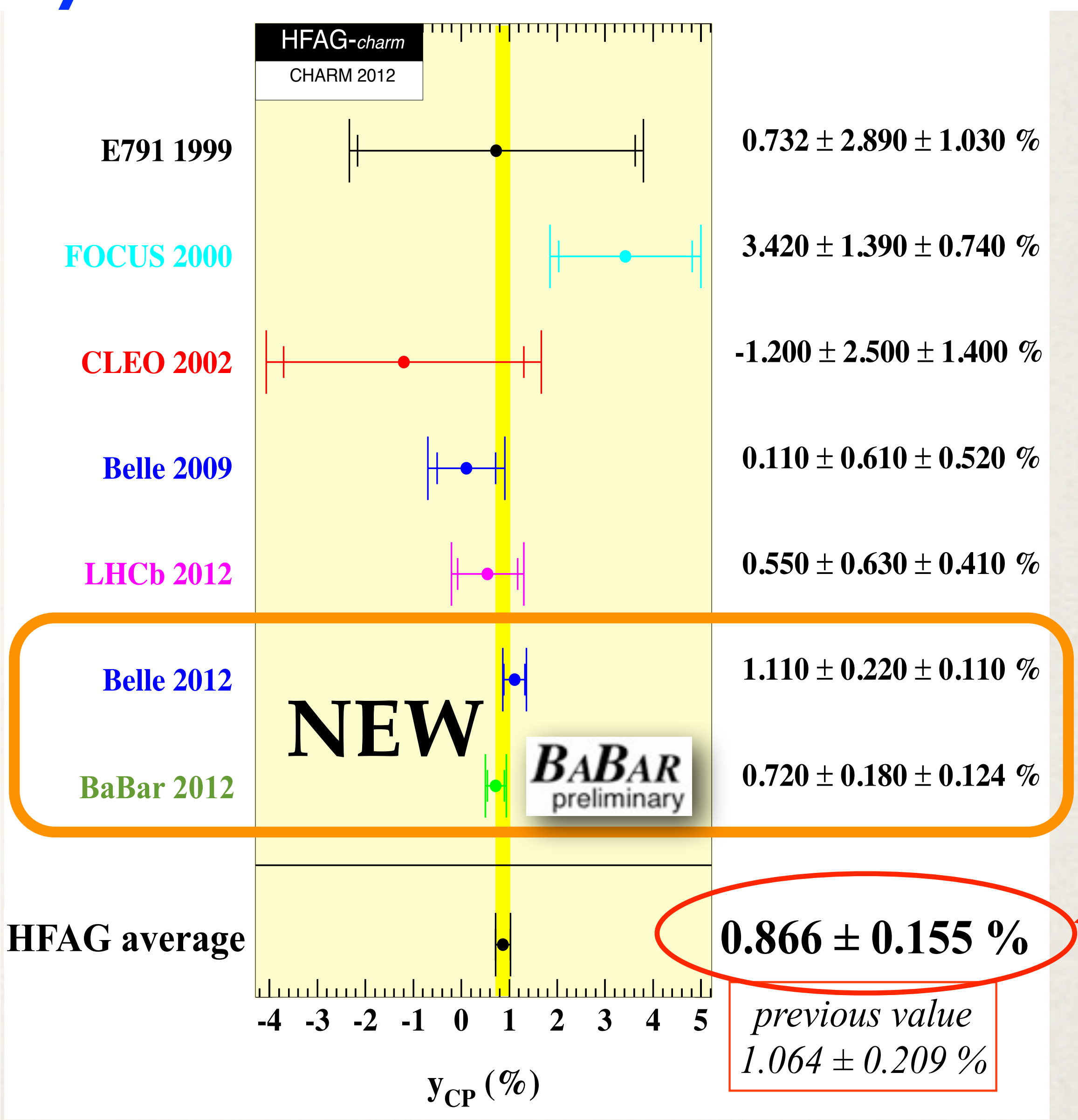


Ko, Cenci

Aside

- Mild tension between y_{CP} & y from these methods:

y_{CP} from lifetime ratios



y from t-dep Dalitz plot:

Belle 920/fb (preliminary)

$$y = (+0.30 \pm 0.15\,^{+0.04}_{-0.05}\,^{+0.03}_{-0.06})\%$$

BaBar 470/fb

$$y = (+0.57 \pm 0.20 \pm 0.13 \pm 0.07)\%$$

PRL 106:081803 (2010)

My naive average

$$y \approx (+0.38 \pm 0.13)\%$$

New & recent results (3)

- Mixing parameters extracted with quantum-correlated decays at CLEO-c
- Updated results with full CLEO-c dataset (818/pb)

Parameter	HFAG 2010 CLEO 2008	Fit: no ext. meas. (standard)	Fit: w/ ext. *y*, *x*, *y'* (extended)
y (10^{-2})	0.79 ± 0.13	$4.2 \pm 2.0 \pm 1.0$	**0.636 ± 0.114**
x^2 (10^{-3})	0.037 ± 0.024	$0.6 \pm 2.3 \pm 1.1$	0.022 ± 0.023
$r_{K\pi}^2$ (10^{-3})	3.32 ± 0.08	$5.33 \pm 1.07 \pm 0.45$	3.33 ± 0.08
$\cos\delta_{K\pi}$	1.10 ± 0.36	**$0.81\ ^{+0.22}_{-0.18}\ ^{+0.07}_{-0.05}$**	**$1.15\ ^{+0.19}_{-0.17}\ ^{+0}_{-0.08}$**
$\sin\delta_{K\pi}$	---	**$-0.01 \pm 0.41 \pm 0.04$**	**$0.56\ ^{+0.32}_{-0.31}\ ^{+0.21}_{-0.20}$**
$\delta_{K\pi}$ (°) [derived]	$22\ ^{+11}_{-12}\ ^{+9}_{-11}$	$10\ ^{+28}_{-53}\ ^{+13}_{-0}$	$18\ ^{+11}_{-17}$

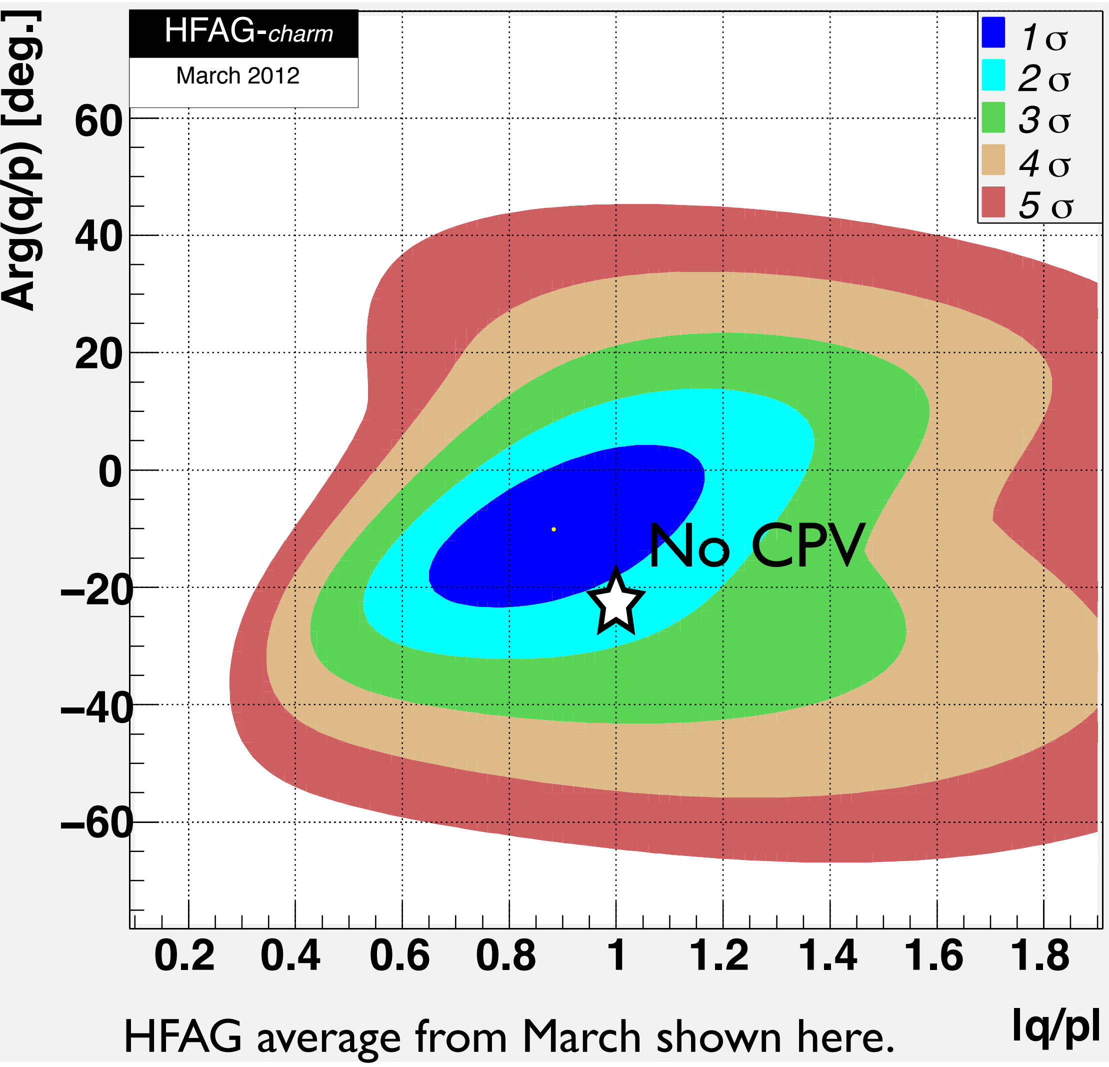
Average of y and $y' = y\cos\delta_{K\pi} - x\sin\delta_{K\pi}$

2.5σ diff. due to fluctuations in r^2 and y, correlated with $\cos\delta_{K\pi}$

CLEO only ↑ (standard fit)

External measurements used as inputs ↑ (extended fit)

Indirect CPV: experiment



HFAG average from March shown here.
New measurements not yet included.

- Poorly constrained due to smallness of x, y.
- Large CPV still allowed.
- New & recent results below

Belle preliminary, 976/fb	$A_\Gamma = (-0.03 \pm 0.20 \pm 0.08)\%$
BaBar preliminary, 470/fb	$\Delta Y = (0.088 \pm 0.255 \pm 0.058)\%$
LHCb, 0.03/fb JHEP 04 (2012) 129	$A_\Gamma = (-0.59 \pm 0.59 \pm 0.21)\%$

Mixing: theory

- Mixing in SM is just plain hard to calculate.
- Short-distance picture discussed by Markus Bobrowski
- Long-distance picture discussed by Zoltan Ligeti

Bobrowski

Mixing (short-distance)

- Operator product expansion in $1/m_c$
- Naive prediction (D=6) for y is horribly wrong

$$|y| \equiv |\Gamma_{12}| \cdot \tau(D^0) \simeq 10^{-6}$$

▷ MB, Lenz, Riedl, & Rohrwild ('10)

JHEP 1003 (2010) 009

- ... but this is not because m_c is too small. Instead, comes from delicate cancellation:

$$\Gamma_{12}\left(D^0\right) = -\mathcal{O}\left(\lambda^2\right) \underbrace{\left(\Gamma_{12}^{ss} - 2\Gamma_{12}^{sd} + \Gamma_{12}^{dd}\right)}_{m_s^4/m_c^4} + \mathcal{O}\left(\lambda^6\right) \underbrace{\left(\Gamma_{12}^{sd} - \Gamma_{12}^{dd}\right)}_{m_s^2/m_c^2} + \mathcal{O}\left(\lambda^{10}\right) \underbrace{\Gamma_{12}^{dd}}_{\sim 1}$$

- Cancellation less exact when including higher-dimension operators => y can be much larger.

Bobrowski

Mixing (short-distance)

- Going to D=9:

■ SU(3) cancellations softer in the condensate contribution

$$\Gamma_{12} = -\lambda_s^2 \underbrace{\left(\Gamma_{12}^{ss} - 2\Gamma_{12}^{ds} + \Gamma_{12}^{dd}\right)}_{1.15\, m_s^4/m_c^4} + 2\lambda_s\lambda_b \underbrace{\left(\Gamma_{12}^{ds} - \Gamma_{12}^{dd}\right)}_{-2.75\, m_s^2/m_c^2} - \lambda_b^2 \underbrace{\Gamma_{12}^{dd}}_{1.96}$$

$$\delta\Gamma_{12} = -\lambda_s^2 \underbrace{\delta\left(\Gamma_{12}^{ss} - 2\Gamma_{12}^{ds} + \Gamma_{12}^{dd}\right)}_{0.43\, m_s^3/m_c^3} + 2\lambda_s\lambda_b \underbrace{\delta\left(\Gamma_{12}^{ds} - \Gamma_{12}^{dd}\right)}_{0.19\, m_s/m_c} - \lambda_b^2 \underbrace{\delta\Gamma_{12}^{dd}}_{0}$$

$\times 13$ $\times 0.66$

■ flavour symmetry breaking:

$\Gamma_{12}^{ss}/\mathrm{ps}^{-1} = 1.908 + 0.036$ $(+1.9\%)$

$\Gamma_{12}^{sd}/\mathrm{ps}^{-1} = 1.935 + 0.018$ $(+0.9\%)$

$\Gamma_{12}^{dd}/\mathrm{ps}^{-1} = 1.962 + 0$

$y = (0.86 + 7.3) \cdot 10^{-6}$

$\times 8.5$

▷ MB, Lenz, & Nierste

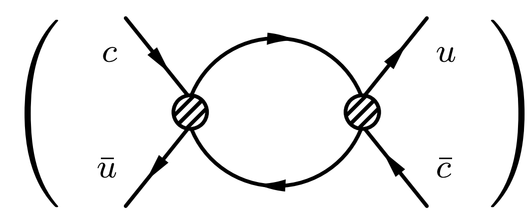
Was 0.86×10^{-6}
Grows by 7.3×10^{-6}
Extra is 8.5x base
i.e. overall x9.5

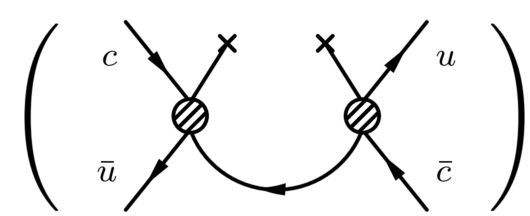
⟶ additional SU(3) breaking induced from the soft QCD background

- Guess another large factor going to D=12.
- Another one (non-factorization?) and we're done!

Mixing (short-distance)

- What does this tell us about indirect CPV?
- O(1) weak phase in short-distance Hamiltonian
- So conceivably SM $\phi \sim O(10^{-3})$ overall

$M_{12} = \text{Re}$


$\delta M_{12} = \text{Re}$


weak phase in the SD-Hamiltonian

$$\phi = \arg\left(-\frac{M_{12}}{\Gamma_{12}}\right) \simeq \mathcal{O}(1)$$

Mixing (long-distance)

- Contributions large & hard to calculate
- But not hopeless: SU(3) breaking due to phase-space tractable.
- Naturally obtain x, y ~ O(1%)

2-body final states

Final state representation		$y_{F,R}/s_1^2$
(PP)s-wave	$\mathbf{8}$	-0.0038
	$\mathbf{27}$	-0.00071
(PV)p-wave	$\mathbf{8}_S$	0.031
	$\mathbf{8}_A$	0.032
	$\mathbf{10}$	0.020
	$\overline{\mathbf{10}}$	0.016
	$\mathbf{27}$	0.040
(VV)s-wave	$\mathbf{8}$	-0.081
	$\mathbf{27}$	-0.061
(VV)p-wave	$\mathbf{8}$	-0.10
	$\mathbf{27}$	-0.14
(VV)d-wave	$\mathbf{8}$	0.51
	$\mathbf{27}$	0.57

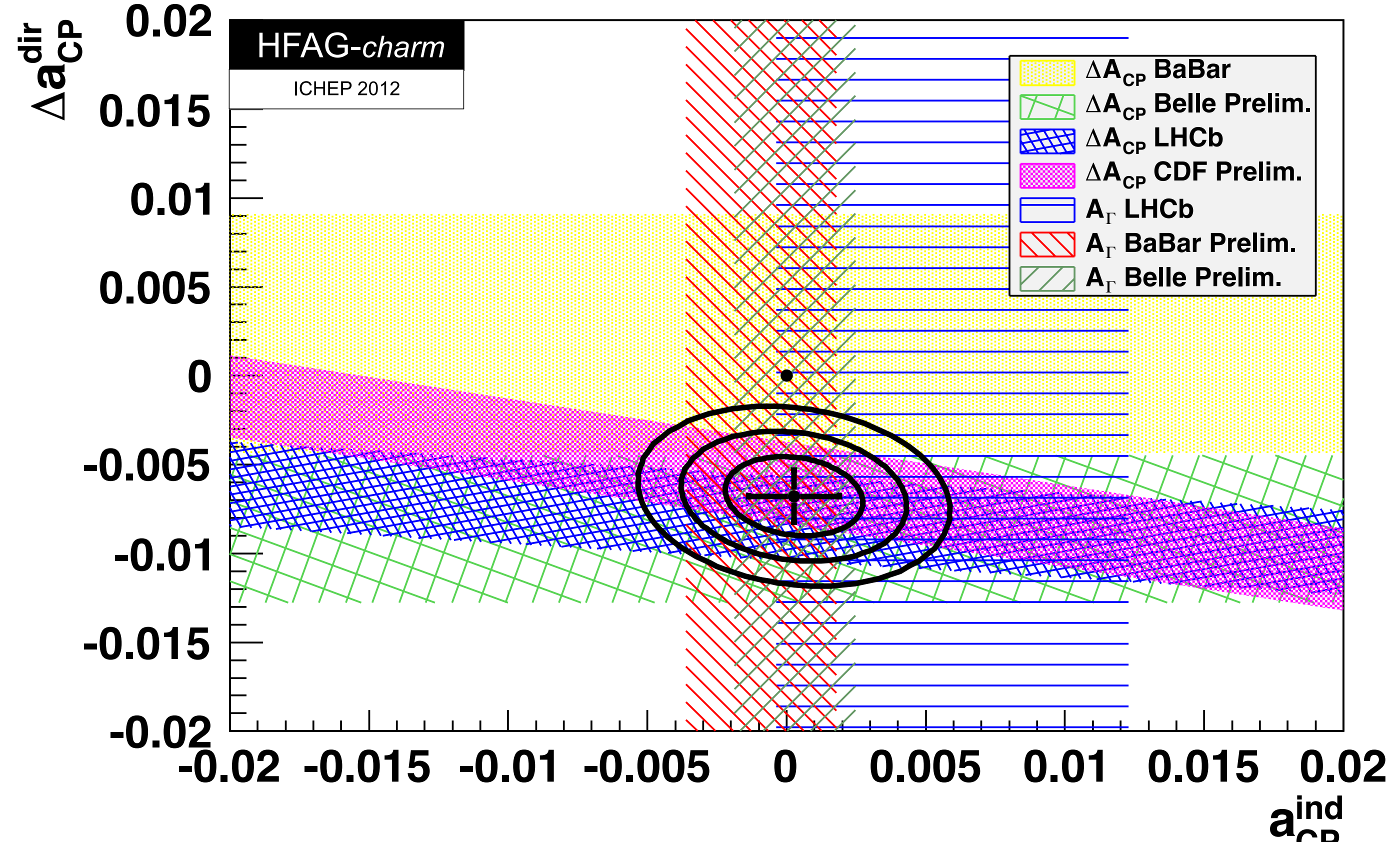
Multi-body final states

Final state representation		$y_{F,R}/s_1^2$
$(3P)_{s\text{-wave}}$	$\mathbf{8}$	-0.48
	$\mathbf{27}$	-0.11
$(3P)_{p\text{-wave}}$	$\mathbf{8}$	-1.13
	$\mathbf{27}$	-0.07
$(3P)_{\text{form-factor}}$	$\mathbf{8}$	-0.44
	$\mathbf{27}$	-0.13
$4P$	$\mathbf{8}$	3.3
	$\mathbf{27}$	2.2
	$\mathbf{27'}$	1.9

- Look for CP violation in mixing, which remains a potentially robust signal of NP

Direct CPV: ΔA$_{CP}$

- ΔA$_{CP}$: Is there something there?
- If so, is it SM?
- If not, what could it be?



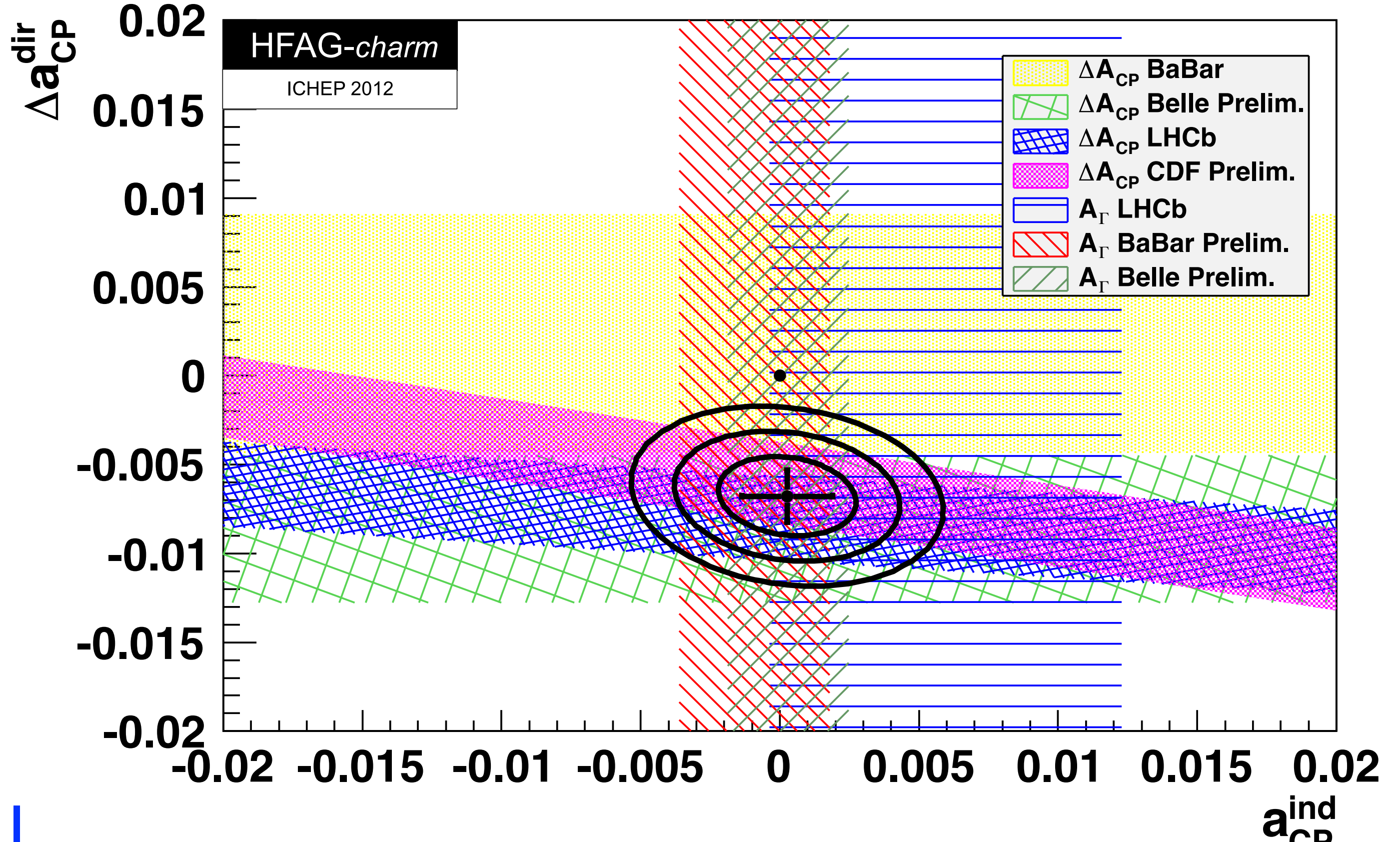
$$\Delta a_{CP}^{\rm dir} = (-0.678 \pm 0.147)\,\%$$

p-value for no CPV: 0.002%

Ko, Mattson, Parkes

Direct CPV: ΔA$_{CP}$

- ΔA$_{CP}$: Is there something there?
- Effect seen by LHCb, CDF, Belle with similar central values, significances between 2.1-3.5σ.
- Smells interesting, but we are not at 5σ.



CDF: Phys.Rev. D85 (2012) 012009
CDF: Phys.Rev.Lett. 109 (2012) 111801
LHCb: Phys. Rev. Lett. 108 (2012) 111602
Belle preliminary (976/fb)

$$\Delta a_{CP}^{\rm dir} = (-0.678 \pm 0.147)\,\%$$

p-value for no CPV: 0.002%

Bhattacharya, Brod

Direct CPV: ΔA$_{CP}$

- Is it SM?
- Consensus: it can be accommodated.
- Contributions from penguin & tree:

$$A_f \equiv A(D^0 \to f) = A_f^T \left[1 + r_f e^{i(\delta_f - \phi_f)}\right],$$
$$\bar{A}_f \equiv A(\overline{D^0} \to f) = A_f^T \left[1 + r_f e^{i(\delta_f + \phi_f)}\right]$$

r_f relative magnitude of subleading (penguin) amplitude with relative strong phase δ_f, weak phase ϕ_f.

$$\mathcal{A}_f^{\rm dir} := \frac{|A_f|^2 - |\bar{A}_f|^2}{|A_f|^2 + |\bar{A}_f|^2} = 2 r_f \sin\phi_f \sin\delta_f$$

How large can r_f be?

Direct CPV: ΔA_{CP}

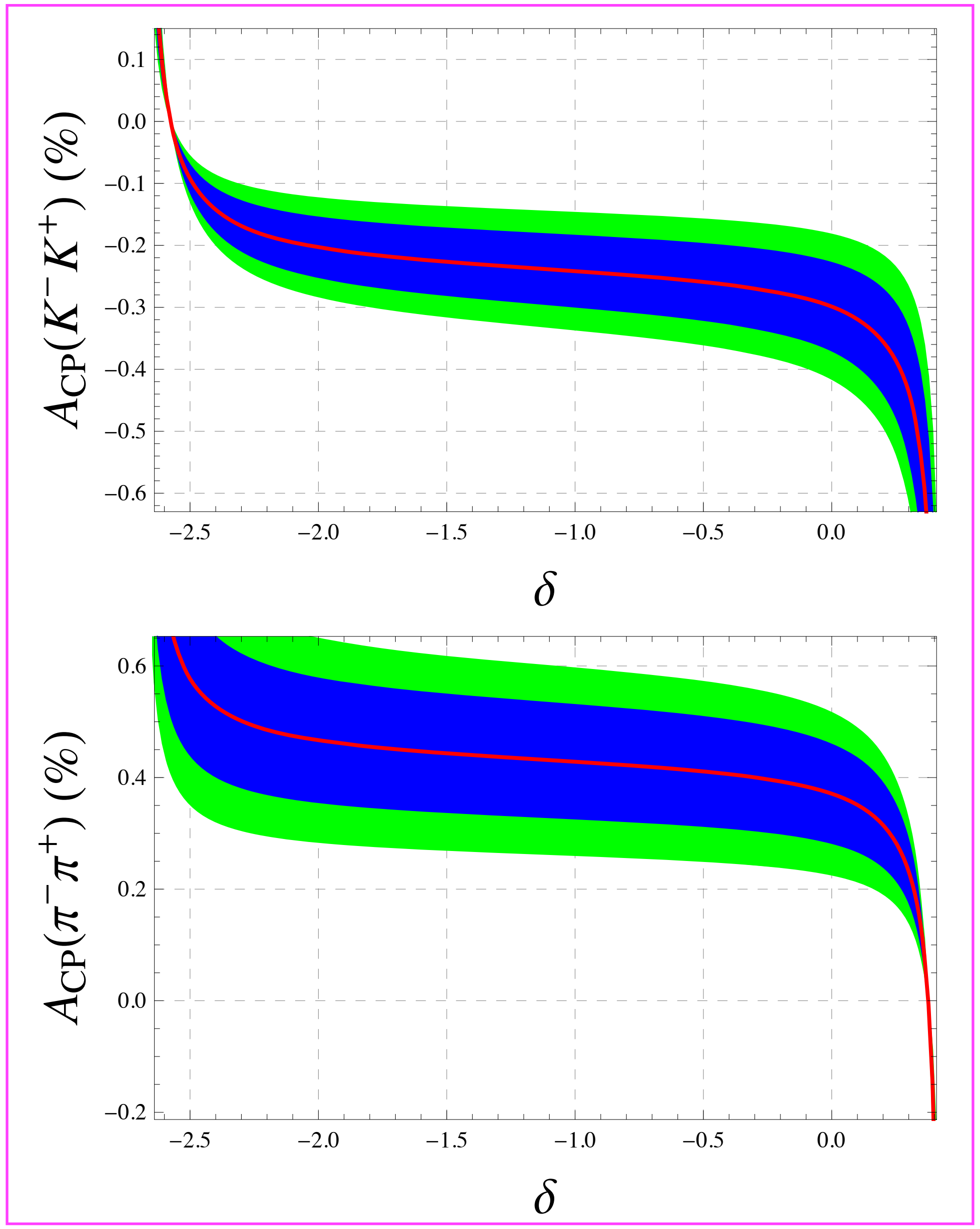
- Clue: odd pattern of BRs (e.g. $D^0 \rightarrow K^+K^- >> D^0 \rightarrow \pi^+\pi^-$)
- Several papers come to broadly the same answer: large penguin amplitude drives BOTH apparent U-spin breaking in BRs AND large ΔA_{CP}.

e.g. Feldmann et al, JHEP 1206 (2012) 007

Bhattacharya
Phys. Rev. D 85, 054014

Direct CPV: ΔA_{CP}

- Bhattacharya et al fit to cocktail of BRs to extract Penguin, Penguin Annihilation amplitudes.
- Penguin enhanced by an order of magnitude compared to naive estimate.
- $\Delta A_{CP} \sim -0.6\%$ projected
- $|A(K^+K^-)| < |A(\pi^+\pi^-)|$ likely



Direct CPV: ΔA_{CP}

- Brod et al: posit nominal U-spin breaking
- Then $D^0 \to h^+h^-$ BRs demand large penguin amplitude

$$
\begin{aligned}
A(\bar{D}^0 \to K^+\pi^-) &= V_{cs}V_{ud}^* T(1 - \tfrac{1}{2}\epsilon'_{1T}),\\
A(\bar{D}^0 \to \pi^+\pi^-) &= -V_{cs}V_{us}^*\left[T(1 + \tfrac{1}{2}\epsilon_{1T}) - P_{\mathrm{break}}(1 - \tfrac{1}{2}\epsilon_{sd}^{(2)})\right]\\
&\quad - V_{cb}^*V_{ub}(T/2(1 + \tfrac{1}{2}\epsilon_{1T}) + P(1 - \tfrac{1}{2}\epsilon_P)),\\
A(\bar{D}^0 \to K^+K^-) &= V_{cs}V_{us}^*\left[T(1 - \tfrac{1}{2}\epsilon_{1T}) + P_{\mathrm{break}}(1 + \tfrac{1}{2}\epsilon_{sd}^{(2)})\right]\\
&\quad - V_{cb}^*V_{ub}(T/2(1 - \tfrac{1}{2}\epsilon_{1T}) + P(1 + \tfrac{1}{2}\epsilon_P)),\\
A(\bar{D}^0 \to \pi^+K^-) &= V_{cd}V_{us}^* T(1 + \tfrac{1}{2}\epsilon'_{1T}).
\end{aligned}
$$

- Implies large r_f => large ΔA_{CP} allowed

Direct CPV: ΔA_{CP}

- But still room for NP here:
  - SM estimates rather uncertain
  - We haven't explained WHY the penguin amplitudes are large
- Suppose that central value for ΔA_{CP} is correct and that SM doesn't saturate it. What NP could contribute without violating existing constraints?

Kamenik

Phys.Lett. B711 (2012) 46-51

Direct CPV: ΔA_{CP}

- Generically, what operators can contribute?

$$\mathcal{H}^{\mathrm{eff-NP}}_{|\Delta c|=1} = \frac{G_F}{\sqrt{2}} \sum_i C_i^{\mathrm{NP}} Q_i$$

- **LL 4q operators:** excluded
- **LR 4q operators:** ajar - potentially visible effects in D-$\overline{\text{D}}$ and/or ε'/ε
- **RR 4q operators:** unconstrained in EFT - UV sensitive contributions?

Model example:
Da Rold et al., 1208.1499

Dipole operators only weakly constrained (edm's)

esp. chromo-magnetic dipole operators

Direct CPV: ΔA_{CP}

- What about specific models? Considered:
  - SUSY
  - Warped extra dimensions
  - 4th generation
- Interesting implications/features for each
- See refs in Jernej's slides for details

Ko, Cenci, Mattson, Parkes

Direct CPV: Other results

- Measurements in other modes vital to understand what's going on. Several new & recent results.

$A_{CP}^{D^+\to\overline{K}^0\pi^+}$ = (-0.024±0.094±0.067)% Belle PRL 109, 021601 (2012)

$$A_{CP}(D^+ \to K^0_S K^+) = (+0.46 \pm 0.36 \pm 0.25)\%$$
$$A_{CP}(D^+_s \to K^0_S K^+) = (+0.28 \pm 0.23 \pm 0.24)\%$$
$$A_{CP}(D^+_s \to K^0_S \pi^+) = (+0.3 \pm 2.0 \pm 0.3)\%$$

BABAR preliminary

Time-integrated search for CPV in $D^0 \to K_S \pi^+ \pi^-$
incl. searches in Dalitz plot distribution
Overall ACP = -0.0005 ± 0.0057 ± 0.0054

CDF Phys. Rev. D 86, 032007 (2012)

Search for CPV in $D^+ \to K^- K^+ \pi^-$
(see next slide)

BABAR preliminary

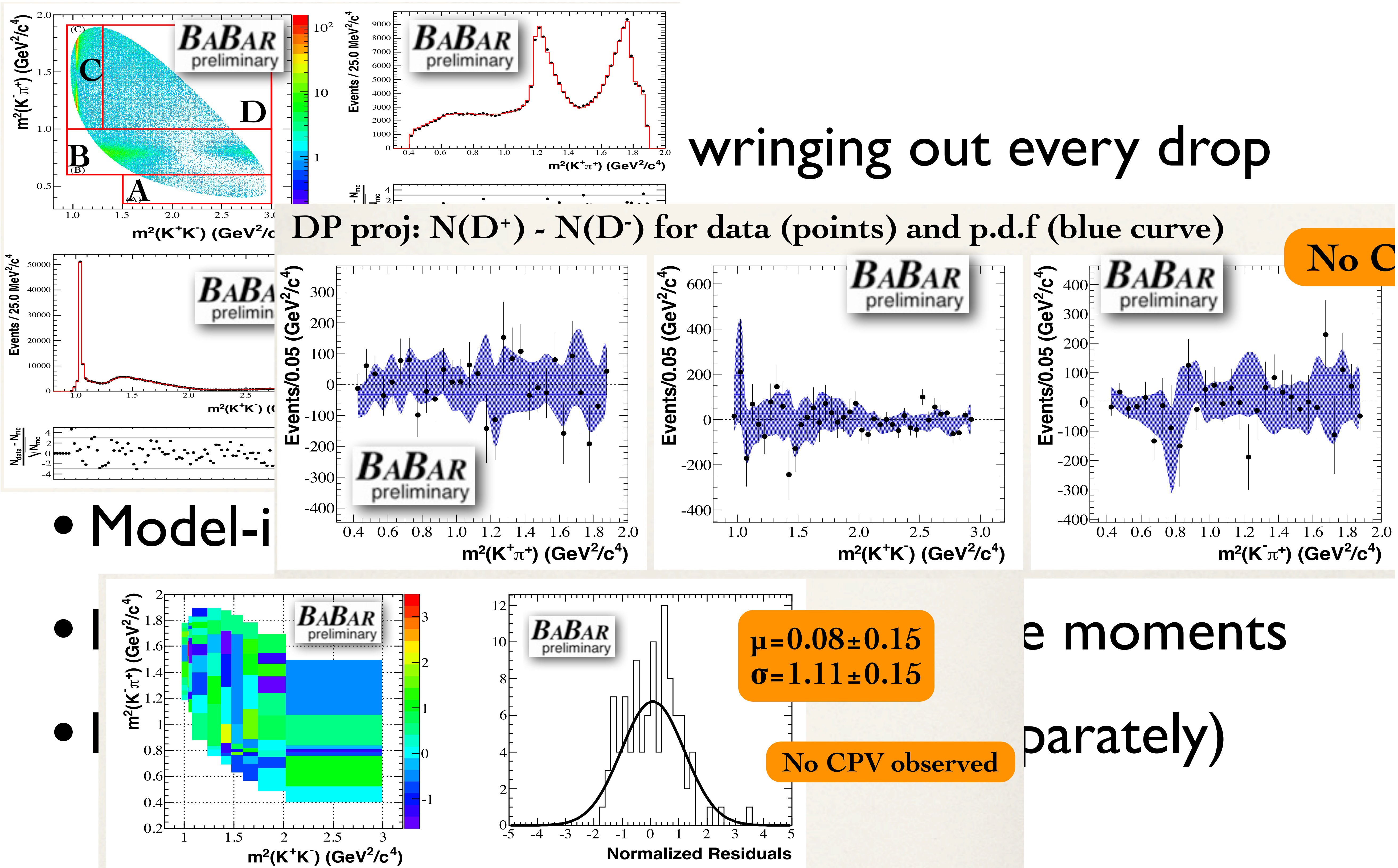
Direct CPV: Other results

- Really thorough analysis, wringing out every drop of sensitivity.
- Overall ACP
- Model-independent search in big bins
- Model-independent search in fine bins
- Model-independent search w/ Legendre moments
- Model-dependent search (fit D^+, D^- separately)

Cenci

Direct CPV: Other results

wringing out every drop



- Model-i
- I … e moments
- I … parately)

Grossman + more

What next?

- Theory talks identified important modes to probe.
- Several now checked or in progress...
- ... though Murphy's law in effect: many compelling modes are experimentally tough.

Isospin-related $\Delta I = 3/2$ modes

$D^0 \to K^+ \overline{K^0}$

$D^0 \to \pi^0 \pi^0$

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

$D^0 \to K^0 \overline{K^0}$

$D^0 \to (X)\gamma$

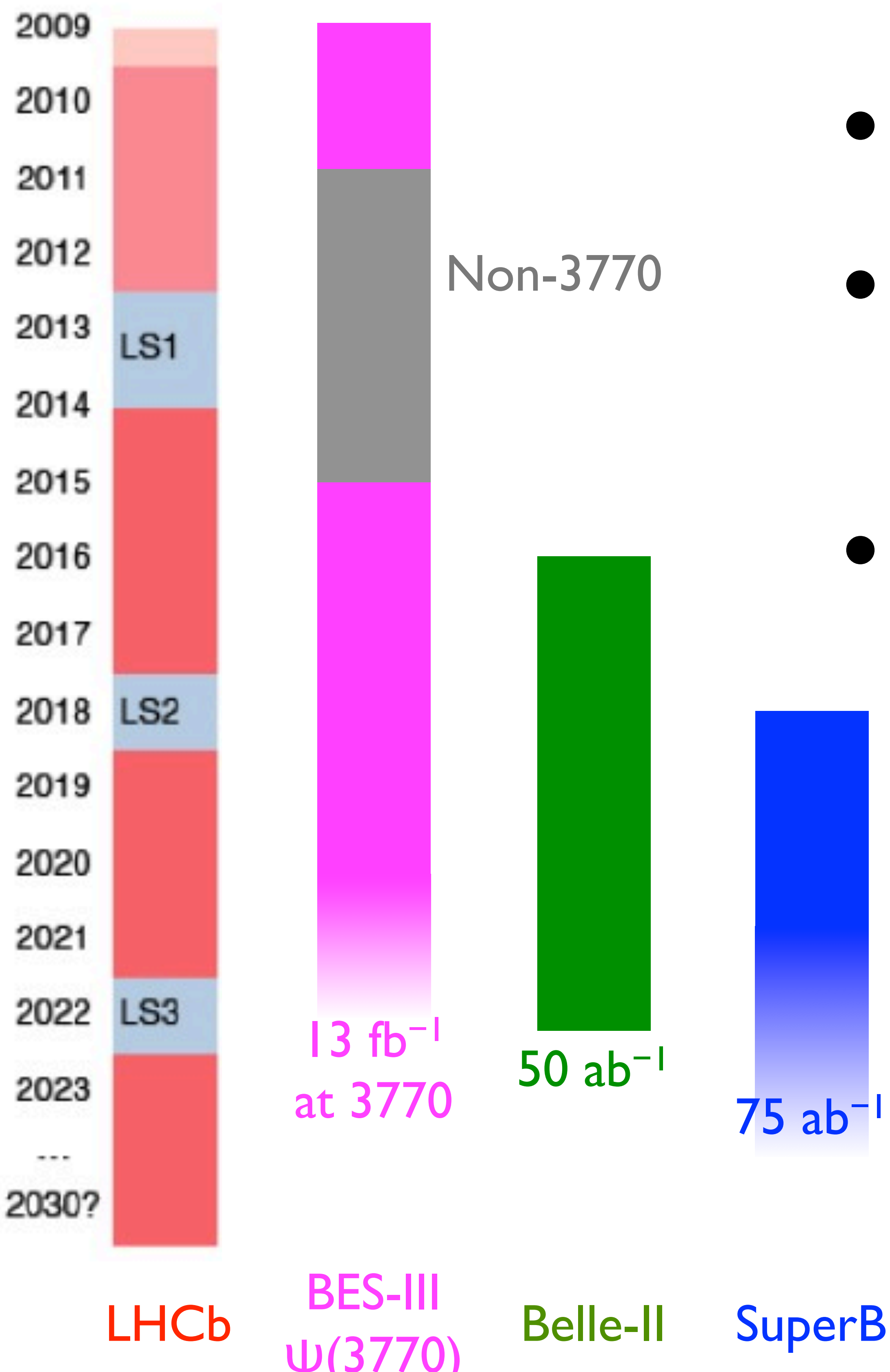
$D^0 \to (X)l^+ l^-$

$D^0 \to P^+ P^- \gamma$ (esp. near ϕ, ρ)

$D^0 \to \eta' \eta'$ ("not very practical")

Briere, Branchini, Asner, Spradlin

Into the future

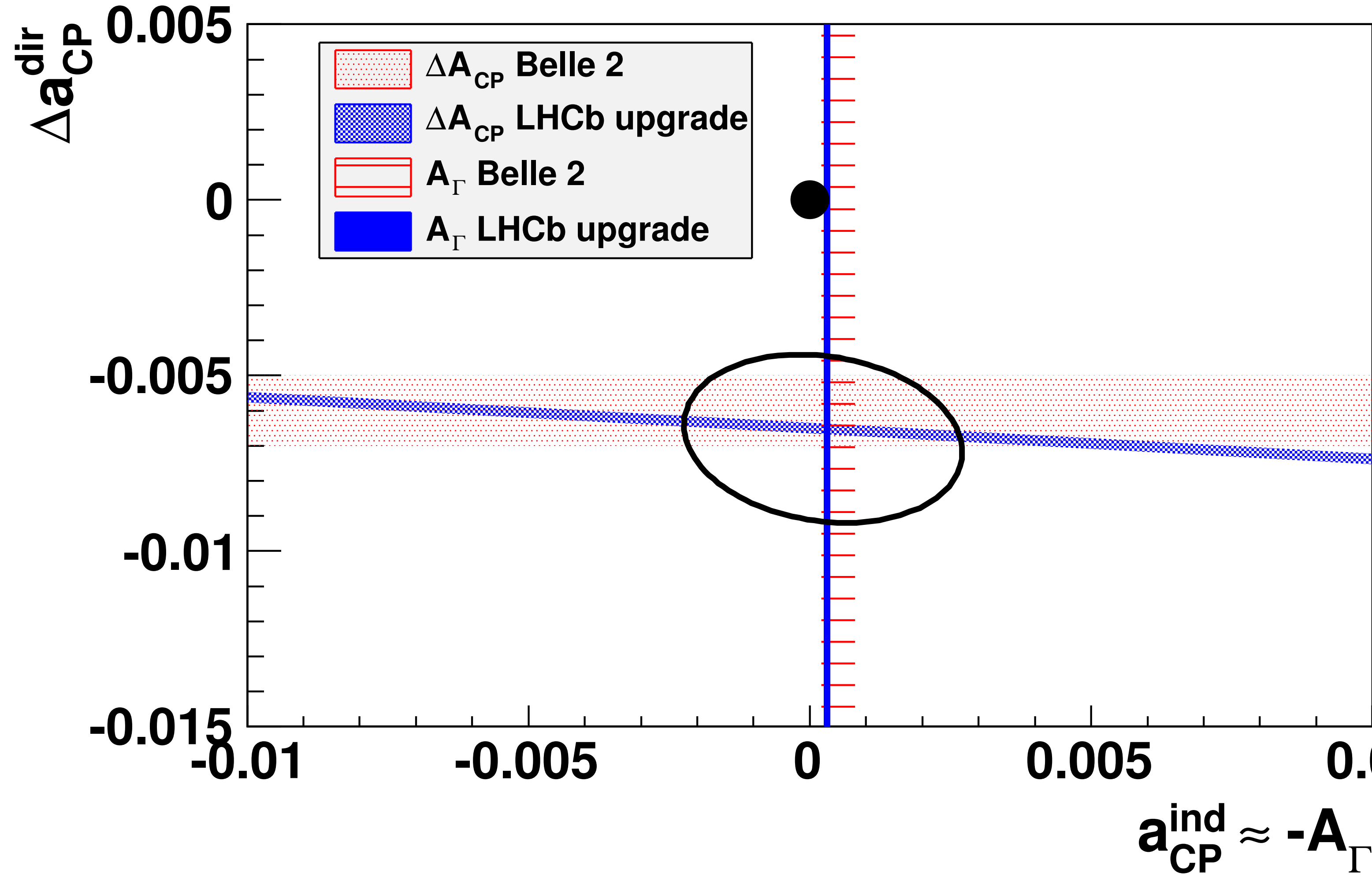


- Caution: my rough projection!
- Important complementarity between hadron & e^+e^- machines
- Statistical reach of LHCb upgrade staggering

Charm@threshold has an important role to play. Tau-charm factory not shown but highly desirable.

LHCb upgrade

Control of systematics is going to be the name of the game.



Extrapolating to the statistical sensitivity of the LHCb upgrade

Mode	Parameter(s)	Precision
$D^{*+} \to D^0\pi^+;\ D^0 \to K^-K^+, (\pi^-\pi^+)$	y_{CP}	0.004% (0.008%)
$D^{*+} \to D^0\pi^+;\ D^0 \to K^-K^+, (\pi^-\pi^+)$	A_Γ	0.004% (0.008%)
WS/RS $K\pi$	(x'^2, y')	$\mathcal{O}[(10^{-5}, 10^{-4})]$
WS/RS $K\mu\nu$	R_M	$\mathcal{O}(5\times10^{-7})$
$D^{*+} \to D^0\pi^+;\ D^0 \to K^0_s\pi^-\pi^+$	(x, y)	(0.015%, 0.010%)

Extrapolating to the statistical sensitivity of the LHCb upgrade

Mode	Parameter(s)	Precision
$D^{*+} \to D^0\pi^+;\ D^0 \to K^-K^+, (\pi^-\pi^+)$	A_Γ	0.004% (0.008%)
$D^{*+} \to D^0\pi^+;\ D^0 \to K^-K^+, \pi^-\pi^+$	ΔA_{CP}	0.015%
$D^+ \to K^0_s K^+$	A_{CP}	10^{-4}
$D^+ \to K^-K^+\pi^+$	A_{CP}	5×10^{-5}
$D^+ \to \pi^-\pi^+\pi^+$	A_{CP}	8×10^{-5}
$D^+ \to h^-h'^+\pi^+$	CPV in phases	$(0.01-0.10)^\circ$
$D^+ \to h^-h'^+\pi^+$	CPV in fractions	$(0.01-0.10)$%

Conclusions

- Plenty of surprises since CKM 2010
- Lots more to do on both theory & experiment
  - More use of Lattice?
- Charm important in the game of model-killing
  - esp. D mixing (Golowich et al, Phys.Rev. D79 (2009) 114030; Phys.Rev. D76 (2007) 095009)
- Avalanche of data in the coming decade -- should clear up many questions (and surely raise new ones)

MANCHESTER 1824

The University of Manchester

CHARM2013: The 6th International Workshop on Charm Physics

31 Aug - 4 Sept 2013; Manchester, England

- Home
- Scientific Programme
- Registration
- Abstract Submission
- Venue
- Accommodation
- Social Events
- Travel and Local Information
- Participants
- Organisers
- Contact

CHARM 2013
will be held at
the University of Manchester (England)
31 Aug - 4 Sept 2013