Current status of charm mixing at LHCb & inputs to charm-phase determination

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On behalf of the LHCb Collaboration

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Outline

- Overview of Charm Mixing/CPV
- Some recent measurements
  - Mixing and CPV in $D^0 \to K^+\pi^-$
  - $A_\Gamma(D^0 \to hh)$
- Some uses of quantum correlated measurements
- Global fit outlook

Mixing in a nutshell

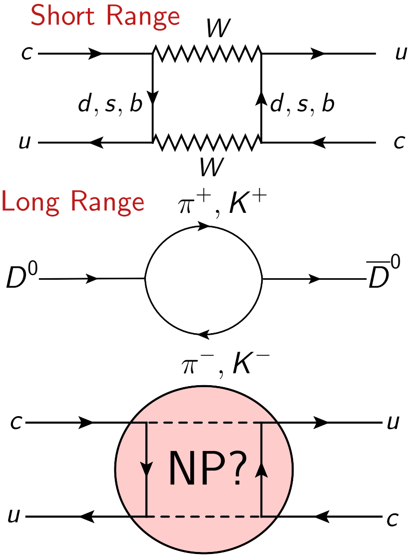
- Mixing in Neutral Mesons: mass≠flavor eigenstates
- Mass Eigenstates: $|D_{1,2}\rangle = p|D^0\rangle \pm q|\overline{D}^0\rangle$, $|p|^2 + |q|^2 = 1$
  $x = \frac{m_2 - m_1}{\Gamma}$, $y = \frac{\Gamma_2 - \Gamma_1}{2\Gamma}$, $\Gamma = \frac{\Gamma_1 + \Gamma_2}{2}$
- Time evolution written as
  $|D^0(t)\rangle = \frac{1}{2}\left(\left(e^{-i\lambda_1 t} + e^{-i\lambda_2 t}\right)|D^0\rangle + \frac{q}{p}\left(e^{-i\lambda_1 t} - e^{-i\lambda_2 t}\right)|\overline{D}^0\rangle\right)$
  $|\overline{D}^0(t)\rangle = \frac{1}{2}\left(\left(e^{-i\lambda_1 t} + e^{-i\lambda_2 t}\right)|\overline{D}^0\rangle + \frac{p}{q}\left(e^{-i\lambda_1 t} - e^{-i\lambda_2 t}\right)|D^0\rangle\right)$
  $\lambda_{1,2} = m_{1,2} - \frac{1}{2} i\Gamma_{1,2}$
- Other useful definitions:
  $$\begin{pmatrix} x' \\ y' \end{pmatrix} = \begin{pmatrix} \cos\delta & \sin\delta \\ -\sin\delta & \cos\delta \end{pmatrix} \begin{pmatrix} x \\ y \end{pmatrix}$$

CP Violation

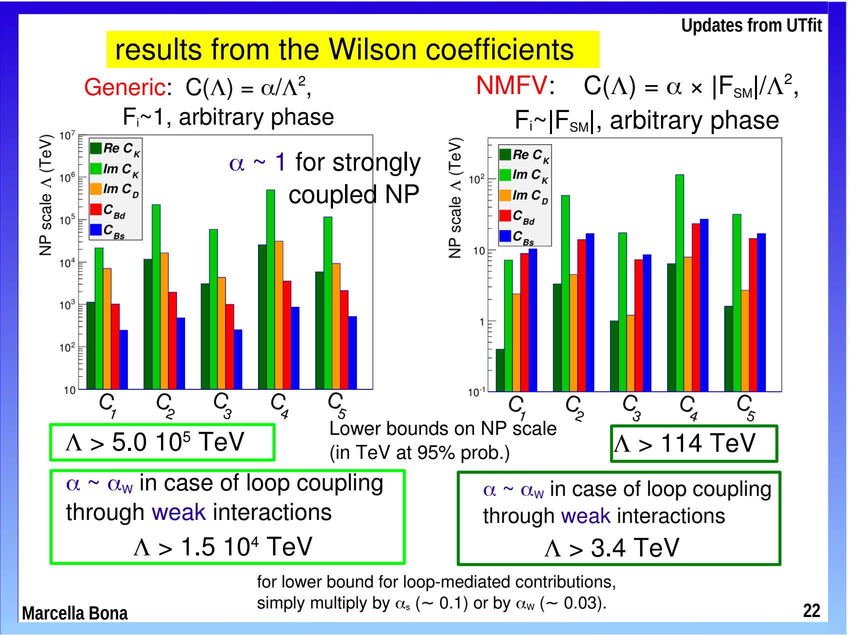
- Direct CPV: $\left|\frac{\overline{\mathcal{A}}_{\overline{f}}}{\mathcal{A}_f}\right| \neq 1$ → See Talk by E. Gersabeck
  $\mathcal{A}_f = \langle f|\mathcal{H}|D\rangle$, $\overline{\mathcal{A}}_{\overline{f}} = \langle \overline{f}|\mathcal{H}|\overline{D}\rangle$
- CPV in Mixing: $\left|\frac{q}{p}\right| \neq 1$
  Weak Phase: $\phi = \arg\left(\frac{q}{p}\right) \neq 0$
- CPV in Interference between Mixing and Decay:
  $\arg\left(\frac{q}{p}\frac{\overline{\mathcal{A}}_f}{\mathcal{A}_f}\right) \neq 0$

Mixing/CPV Expectations

- Only up-type quark system with mixing
- Mixing enters at 1 loop level in SM, GIM and CKM suppressed
- Non-perturbative long-range effects may dominate short-range interactions, difficult to calculate
- x, y expected to be $\lesssim 0.5\%$
- CPV expected to be $\mathcal{O}(10^{-3})$ in SM
- If enhancement of CPV is seen, could be caused by New Physics (NP)



Why is it important?



- From Marcella Bona, EPS 2017,
- $C_i(\Lambda) = \frac{L \times F_i}{\Lambda^2}$
- Use $F_i \simeq L \simeq 1$
  bounds on C_i
  give lower bound on Λ

$$\mathcal{H}_{\text{eff}}^{\Delta F=2} = \sum_{i=1}^{5} C_i Q_i^{q_j q_k} + \sum_{i=1}^{3} \tilde{C}_i \tilde{Q}_i^{q_j q_k}$$

$$\begin{aligned}
Q_1^{q_i q_j} &= \bar{q}_{jL}^{\alpha} \gamma_\mu q_{iL}^{\alpha} \bar{q}_{jL}^{\beta} \gamma^\mu q_{iL}^{\beta} \\
Q_2^{q_i q_j} &= \bar{q}_{jR}^{\alpha} q_{iL}^{\alpha} \bar{q}_{jR}^{\beta} q_{iL}^{\beta} \\
Q_3^{q_i q_j} &= \bar{q}_{jR}^{\alpha} q_{iL}^{\beta} \bar{q}_{jR}^{\beta} q_{iL}^{\alpha} \\
Q_4^{q_i q_j} &= \bar{q}_{jR}^{\alpha} q_{iL}^{\alpha} \bar{q}_{jL}^{\beta} q_{iR}^{\beta} \\
Q_5^{q_i q_j} &= \bar{q}_{jR}^{\alpha} q_{iL}^{\beta} \bar{q}_{jL}^{\beta} q_{iR}^{\alpha}
\end{aligned}$$

Definitions from [0707.0636]

Mixing and CPV in $D^0 \to K^+\pi^-$

Mixing and CPV in $D^0 \to K^+\pi^-$

[LHCb-PAPER-2017-046]

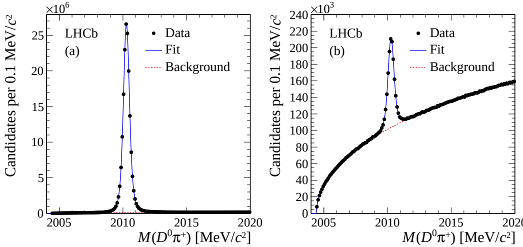
- Restricting to $D^0 \to K\pi$, time dependence of WS/RS ratio

$$\frac{\mathrm{WS}^{\pm}(t)}{\mathrm{RS}^{\pm}(t)} \equiv R^{\pm}(t) \approx R_D^{\pm} + \sqrt{R_D^{\pm}}y'^{\pm}\Gamma t + \frac{(x'^{\pm})^2 + (y'^{\pm})^2}{4}(\Gamma t)^2$$

$$x'^{\pm} = \left(+\left|\frac{q}{p}\right|, -\left|\frac{p}{q}\right|\right) \times (x' \cos\phi \pm y' \sin\phi)$$

$$y'^{\pm} = \left(+\left|\frac{q}{p}\right|, -\left|\frac{p}{q}\right|\right) \times (x' \sin\phi \mp y' \cos\phi)$$

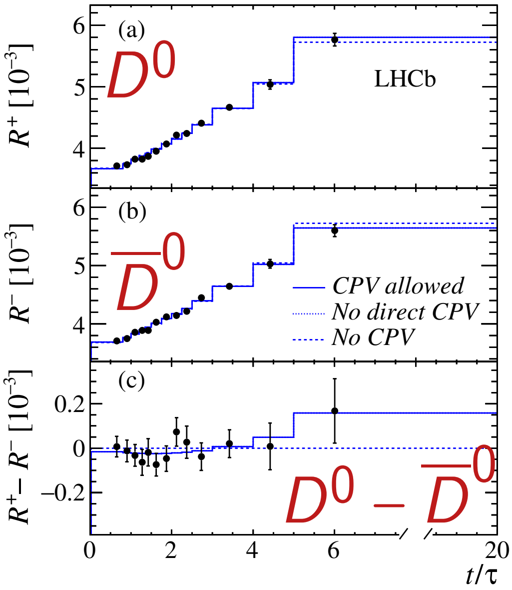
- Three fits:
  1. No CPV$\to$ $R^+ = R^-$, $x'^+ = x'^-$, $y'^+ = y'^-$
  2. No Direct CPV $\to$ $R^+ = R^-$
  3. All CPV allowed
- Use prompt $D^{*+} \to D^0\pi_s^+$, updated with Run I + 2015 + 2016 Data
- Detector Asymmetries, peaking backgrounds included in the fit



$N(RS) = 1.77 \times 10^8$ $\quad$ $N(WS) = 7.22 \times 10^5$

Mixing and CPV in $D^0 \to K^+\pi^-$

[LHCb-PAPER-2017-046]



- No evidence of CPV
- Precision increased by a factor of 2 w.r.t. Run I analysis

Parameter	Value	Correlations					
Direct and indirect *CP* violation							
Parameter	Value	R_D^+	y'^+	$(x'^+)^2$	R_D^-	y'^-	$(x'^-)^2$
R_D^+	$3.454 \pm 0.040 \pm 0.020$	1.000	−0.935	0.843	−0.012	−0.003	0.002
y'^+	$5.01 \pm 0.64 \pm 0.38$		1.000	−0.963	−0.003	0.004	−0.003
$(x'^+)^2$	$0.061 \pm 0.032 \pm 0.019$			1.000	0.002	−0.003	0.003
R_D^-	$3.454 \pm 0.040 \pm 0.020$				1.000	−0.935	0.846
y'^-	$5.54 \pm 0.64 \pm 0.38$					1.000	−0.964
$(x'^-)^2$	$0.016 \pm 0.033 \pm 0.020$						1.000
No direct *CP* violation							
Parameter	Value	R_D	y'^+	$(x'^+)^2$	y'^-	$(x'^-)^2$	
R_D	$3.454 \pm 0.028 \pm 0.014$	1.000	−0.883	0.745	−0.883	0.749	
y'^+	$5.01 \pm 0.48 \pm 0.29$		1.000	−0.944	0.758	−0.644	
$(x'^+)^2$	$0.061 \pm 0.026 \pm 0.016$			1.000	−0.642	0.545	
y'^-	$5.54 \pm 0.48 \pm 0.29$				1.000	−0.946	
$(x'^-)^2$	$0.016 \pm 0.026 \pm 0.016$					1.000	
No *CP* violation							
Parameter	Value	R_D	y'	x'^2			
R_D	$3.454 \pm 0.028 \pm 0.014$	1.000	−0.942	0.850			
y'	$5.28 \pm 0.45 \pm 0.27$		1.000	−0.963			
x'^2	$0.039 \pm 0.023 \pm 0.014$			1.000			

The header row of the table reads "Results [10^{-3}]" over the Parameter and Value columns and "Correlations" over the rest.

A_Γ from $D^0 \to KK$ and $D^0 \to \pi\pi$

$A_\Gamma(D^0 \to hh)$

[LHCb-PAPER-2016-063]

- For decays to CP eigenstates, expand time dependent asymmetry to

$$A = \frac{\Gamma(D^0 \to f) - \Gamma(\overline{D}^0 \to f)}{\Gamma(D^0 \to f) + \Gamma(\overline{D}^0 \to f)} \simeq a_{CP}^{\text{Direct}} + a_{CP}^{\text{Indirect}} \frac{t}{\tau}$$

- In the case of small direct CPV, $\Gamma \propto e^{-\hat{\Gamma} t}$, $a_{CP}^{\text{Indirect}} = -A_\Gamma$

$$A_\Gamma = \frac{\hat{\Gamma}(D^0 \to f) - \hat{\Gamma}(\overline{D}^0 \to f)}{\hat{\Gamma}(D^0 \to f) + \hat{\Gamma}(\overline{D}^0 \to f)} = \frac{y}{2}\left(\left|\frac{q}{p}\right| - \left|\frac{p}{q}\right|\right)\cos\phi - \frac{x}{2}\left(\left|\frac{q}{p}\right| + \left|\frac{p}{q}\right|\right)\sin\phi$$

- Measure $A_\Gamma(D^0 \to KK), A_\Gamma(D^0 \to \pi\pi)$ in two different ways

- Measure effective lifetime from unbinned maximum likelihood fit,
- Combine with previous 7 TeV result PRL 112(2014)041801

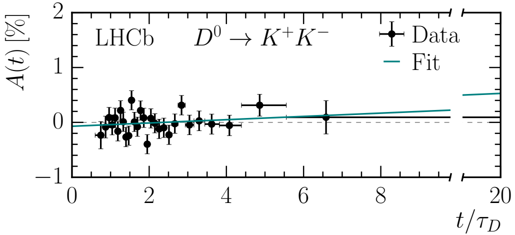
- Measure asymmetry of signal events in bins of lifetime, fit with a straight line
- 7+8 TeV measurement

- From prompt $D^{*\pm} \to D^0 \pi_s^\pm$
- Use $D^0 \to K^-\pi^+$ to validate ($A_\Gamma(D^0 \to K^-\pi^+) = 0$)

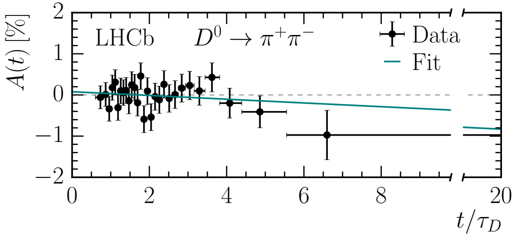
$A_\Gamma(D^0 \to hh)$

[LHCb-PAPER-2016-063]

$A_\Gamma(KK) = (-0.30 \pm 0.32 \pm 0.10) \times 10^{-3}$



$A_\Gamma(\pi\pi) = (0.46 \pm 0.58 \pm 0.12) \times 10^{-3}$



- Consistent with no CPV, both methods consistent with another
- Precision is at the level of 10^{-4}
- Statistics limited

Where are Quantum Correlated Measurements useful?

PRD.82.112006

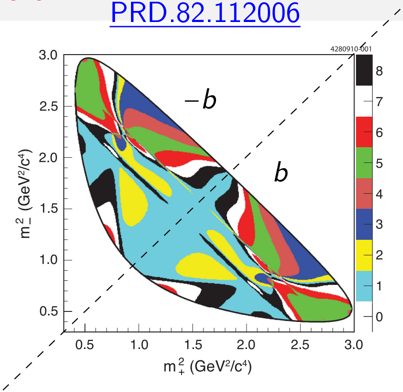
- Example: Bin flip in $D^0 \to K_s^0\pi^+\pi^-$ or $D^0 \to K_s^0 K^+ K^-$
- Define Dalitz plot in terms of $m_+ = m(K_s^0\pi^+)$ and $m_- = m(K_s^0\pi^-)$
- Bin dependent probability is

$$\mathcal{P}_{D^0}(t) = \Gamma e^{-\Gamma t}[T_b + r_{CP}\Gamma t\sqrt{T_b T_{-b}} \times \{y(s_b \sin\phi + c_b\cos\phi) + x(s_b\cos\phi - c_b\sin\phi)\}]$$

$$T_b = \int_b a_{12,13}^2 dm_{12}^2 dm_{13}^2$$

$$c_b = \frac{1}{\sqrt{T_b T_{-b}}}\int_b a_{12,13}a_{13,12}\cos(\delta_{12}-\delta_{13})dm_{12}^2 dm_{13}^2$$

$$s_b = \frac{1}{\sqrt{T_b T_{-b}}}\int_b a_{12,13}a_{13,12}\sin(\delta_{12}-\delta_{13})dm_{12}^2 dm_{13}^2$$



- ratio of bin b and $-b$ in time bin j is for $D^0/\overline{D}^0$

$$R_{bj}^{\pm} = \frac{r_b[1+\Re(z_{CP}^2-\Delta z^2)t_j^2/4] + |z_{CP}\pm\Delta z|^2 t_j^2/4 + \sqrt{r_b}\Re[X_b^*(z_{CP}\pm\Delta z)]t_j}{1+\Re(z_{CP}^2-\Delta z^2)t_j^2/4 + r_b|z_{CP}\pm\Delta z|^2 t_j^2/4 + \sqrt{r_b}\Re[X_b(z_{CP}\pm\Delta z)]t_j}$$

$X_b = c_b - i s_b$, $z_{CP}\pm\Delta z = \left(\frac{q}{p}\right)^{\pm 1} z$, $z_{(CP)} = -(y_{(CP)} + i x_{(CP)})$

- No efficiency, no amplitudes here

- either fix or gaussian constrain c_i and s_i to external measurements

$$x_{CP} = -\operatorname{Im}(z_{CP}) = \frac{1}{2}\left[x\cos\phi\left(\left|\frac{q}{p}\right| + \left|\frac{p}{q}\right|\right) - y\sin\phi\left(\left|\frac{q}{p}\right| - \left|\frac{p}{q}\right|\right)\right]$$

$$\Delta x = -\operatorname{Im}(\Delta z) = \frac{1}{2}\left[x\cos\phi\left(\left|\frac{q}{p}\right| - \left|\frac{p}{q}\right|\right) - y\sin\phi\left(\left|\frac{q}{p}\right| + \left|\frac{p}{q}\right|\right)\right]$$

$$y_{CP} = -\operatorname{Re}(z_{CP}) = \frac{1}{2}\left[y\cos\phi\left(\left|\frac{q}{p}\right| + \left|\frac{p}{q}\right|\right) - x\sin\phi\left(\left|\frac{q}{p}\right| - \left|\frac{p}{q}\right|\right)\right]$$

$$\Delta y = -\operatorname{Re}(\Delta z) = \frac{1}{2}\left[y\cos\phi\left(\left|\frac{q}{p}\right| - \left|\frac{p}{q}\right|\right) - x\sin\phi\left(\left|\frac{q}{p}\right| + \left|\frac{p}{q}\right|\right)\right]$$

Where are Quantum Correlated Measurements useful?

- Use toys for $D^0 \to K_s^0 KK$ to estimate impact of c_i, s_i measurements, Thesis of O. Lupton

Table 7.4: Estimated sensitivities to the observables z_{CP}, Δz and τ_{D^0} using different binning schemes, $\mathcal{N}$, and configurations. The configurations are described in the main text. In brief, they correspond to the dataset collected during 2012, or to dataset that is expected at the end of Run 2, and in each case both the normal, decay-time-biasing, selection and the "lifetime unbiased" selection described in Chapter 4 are simulated. In each case both the total uncertainty and the component of it due to uncertainties in the CLEO measurement of the strong-phase parameters X_i is given. When this component is small, the procedure used to extract it does not always succeed.

			Uncertainty								
			2012 biased		2012 unbiased		Run 2 biased		Run 2 unbiased		
	Observable	$\mathcal{N}$	Total	CLEO	Total	CLEO	Total	CLEO	Total	CLEO	
	τ_{D^0}	2	1.45 ± 0.04	0.50 ± 0.13	1.35 ± 0.04	0.36 ± 0.16	0.329 ± 0.009	0.173 ± 0.019	0.467 ± 0.013	0.10 ± 0.07	[fs]
		3	1.46 ± 0.04	—	1.318 ± 0.035	—	0.329 ± 0.009	0.160 ± 0.021	0.471 ± 0.012	0.04 ± 0.17	[fs]
		4	1.45 ± 0.04	0.27 ± 0.26	1.338 ± 0.035	0.25 ± 0.24	0.321 ± 0.009	0.129 ± 0.025	0.479 ± 0.012	0.17 ± 0.04	[fs]
y_{CP}	$\Re(z_{CP})$	2	3.73 ± 0.10	—	4.11 ± 0.10	0.8 ± 0.7	0.924 ± 0.025	0.53 ± 0.05	1.54 ± 0.04	0.76 ± 0.10	[‰]
		3	4.40 ± 0.12	1.2 ± 0.6	4.87 ± 0.14	0.9 ± 0.9	0.994 ± 0.026	0.48 ± 0.06	1.73 ± 0.05	0.67 ± 0.15	[‰]
		4	3.92 ± 0.11	0.8 ± 0.7	4.27 ± 0.11	—	0.904 ± 0.024	0.48 ± 0.05	1.54 ± 0.04	0.54 ± 0.14	[‰]
	$\Im(z_{CP})$	2	10.29 ± 0.26	1.4 ± 2.5	11.95 ± 0.30	4.3 ± 1.0	2.70 ± 0.07	1.81 ± 0.11	4.16 ± 0.11	0.9 ± 0.6	[‰]
		3	8.93 ± 0.23	4.2 ± 0.6	9.94 ± 0.27	4.6 ± 0.7	2.14 ± 0.06	1.41 ± 0.09	3.86 ± 0.10	2.49 ± 0.17	[‰]
		4	11.05 ± 0.28	7.6 ± 0.4	11.48 ± 0.29	6.9 ± 0.5	2.39 ± 0.06	1.70 ± 0.09	3.88 ± 0.10	2.31 ± 0.19	[‰]
A_Γ	$\Re(\Delta z)$	2	1.53 ± 0.04	—	1.95 ± 0.05	0.2 ± 0.6	0.299 ± 0.008	—	0.605 ± 0.015	—	[‰]
		3	1.80 ± 0.05	0.44 ± 0.25	2.29 ± 0.06	0.67 ± 0.26	0.361 ± 0.009	0.11 ± 0.04	0.777 ± 0.021	0.20 ± 0.10	[‰]
		4	1.45 ± 0.04	—	1.96 ± 0.05	0.44 ± 0.30	0.345 ± 0.010	0.135 ± 0.029	0.665 ± 0.017	—	[‰]
	$\Im(\Delta z)$	2	4.26 ± 0.11	0.9 ± 0.7	5.79 ± 0.15	2.0 ± 0.5	1.136 ± 0.029	0.74 ± 0.05	2.01 ± 0.05	0.98 ± 0.12	[‰]
		3	3.64 ± 0.09	1.57 ± 0.25	4.32 ± 0.12	1.5 ± 0.4	1.002 ± 0.026	0.74 ± 0.04	1.75 ± 0.04	1.09 ± 0.08	[‰]
		4	4.20 ± 0.11	2.55 ± 0.20	5.40 ± 0.14	3.24 ± 0.26	0.974 ± 0.025	0.70 ± 0.04	2.02 ± 0.05	1.44 ± 0.08	[‰]

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Even in Run 2
will be one of the largest systematics

Projection from $D^0 \to K_s^0\pi\pi$ toys

- Same idea for $D^0 \to K_s^0\pi\pi$, but for underlying parameters
- Try to assess current BESIII dataset as well, $\mathcal{L} \simeq 4 \times \mathcal{L}_{\text{CLEO}}$
- New measurement of c_i and s_i will have a large impact

From N. Jurik

	Run I			Run II			100M		
Parameter	1.5 M G	1.5M $\sqrt{G^2-F^2}$	1.5M, errors/2	12M G	12M $\sqrt{G^2-F^2}$	12M, errors/2	100M G	100M $\sqrt{G^2-F^2}$	100M, errors/2
$\sigma(x)$ $[10^{-3}]$	2.43	0.87	0.75	0.94	0.48	0.40	0.44	0.32	0.25
$\sigma(y)[10^{-3}]$	4.80	1.50	0.87	1.90	1.01	0.81	1.01	0.83	0.71
$\sigma(\lvert q/p\rvert)$	0.200	0.062	0.059	0.085	0.040	0.036	0.040	0.030	0.024
$\sigma(\phi)$[rad]	0.157	0.063	0.052	0.063	0.029	0.025	0.040	0.034	0.030

Table: $D^0 \to K_s^0\pi\pi$ projections for errors in Run I and Run II using bin-flip method, and the uncertainty from the measurement of the strong phase differences c_i and s_i. Estimated by gaussian constraining the strong phases for the column labeled G, and error estimated by the difference in quadrature between gaussian constraining and fixing. The third column for each set of statistics assumes the same central value, but decreases the error on c_i and s_i by a factor of 2.

Outlook from Global Fits

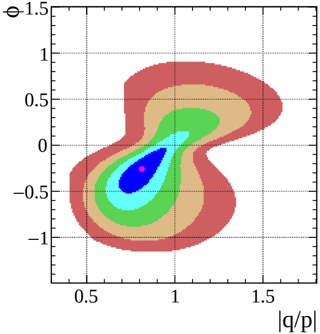
- Do HFLAV like fits to charm system
- Minimize $\chi^2 = \vec{\epsilon}^T \sigma^{-1} \vec{\epsilon}$
- Use subset of information: HFLAV COMBOS y_{CP}, A_Γ, Belle $K_s\pi\pi$, BaBar $K_s\pi\pi$, CLEO $\cos/\sin\delta_{K\pi}$, LHCb $K\pi$
- Fit for All CPV allowed, No DCPV using Superweak assumption ($\tan\phi = (1-|q/p|)(x/y)$)
- Assumptions: Central values unchanged
- For $\delta_{K\pi}$, use CLEO CV, scale error by $\sqrt{\mathcal{L}}$

Outlook from Global Fits

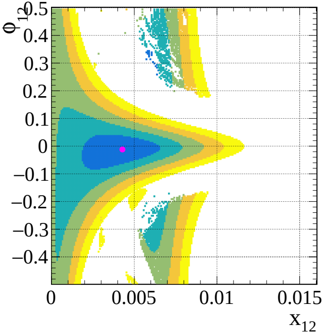
- Do HFLAV like fits to charm system
- Minimize $\chi^2 = \vec{\epsilon}^T \sigma^{-1} \vec{\epsilon}$
- Use subset of information: HFLAV COMBOS y_{CP}, A_Γ, Belle $K_s\pi\pi$, BaBar $K_s\pi\pi$, CLEO $\cos/\sin\delta_{K\pi}$, LHCb $K\pi$
- Fit for All CPV allowed, No DCPV using Superweak assumption ($\tan\phi = (1-|q/p|)(x/y)$)
- Assumptions: Central values unchanged
- For $\delta_{K\pi}$, use CLEO CV, scale error by $\sqrt{\mathcal{L}}$

Inputs from CKM 2016 (Last HFLAV update)

All CPV allowed



No DCPV



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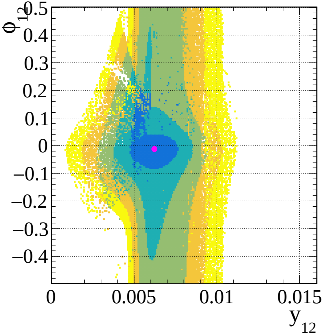
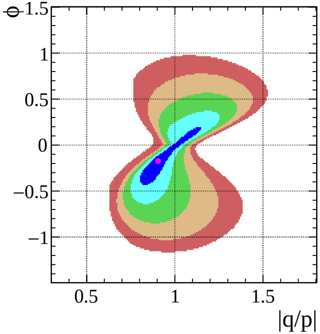


Reproduces shapes of HFLAV 2016

With new LHCb $K\pi$

All CPV allowed



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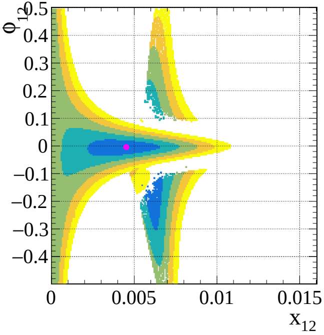

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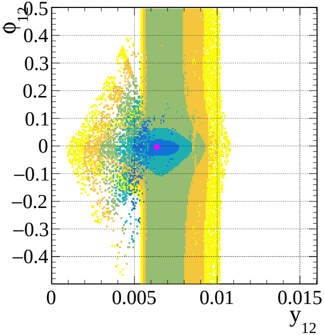
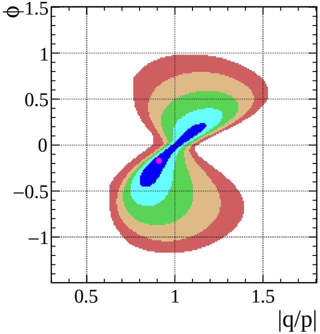


All CPV allowed



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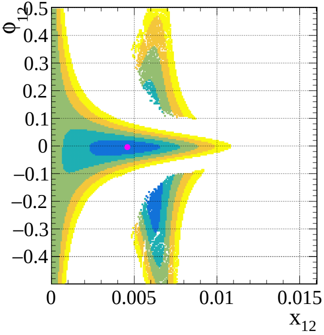

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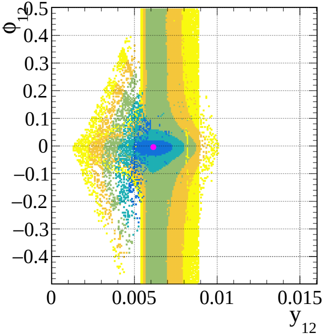
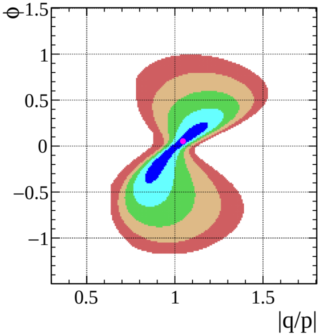


LHCb $K\pi$, BESIII measurement of $\sin/\cos\delta_{K\pi}$, $\mathcal{L} = 25\times$CLEO

All CPV allowed



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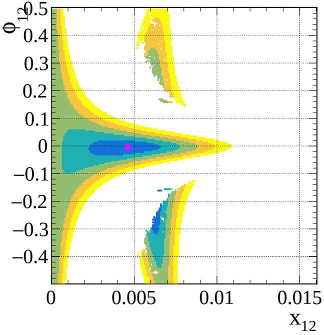

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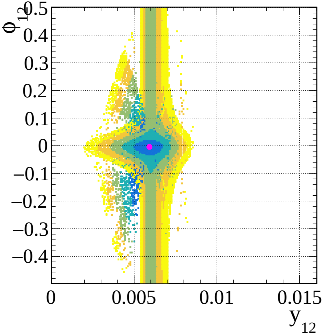

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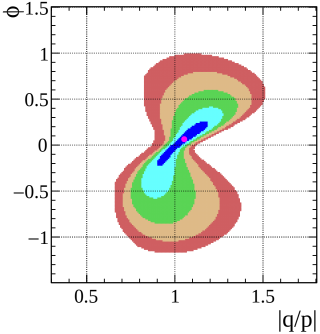

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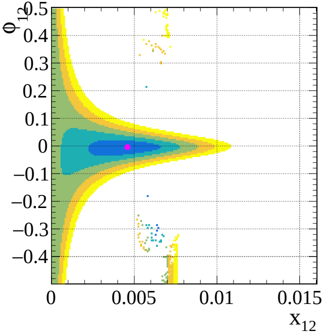

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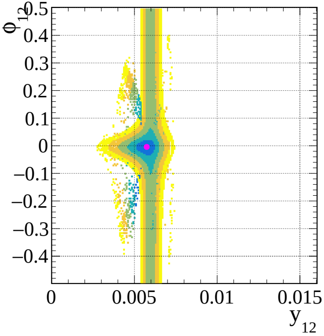
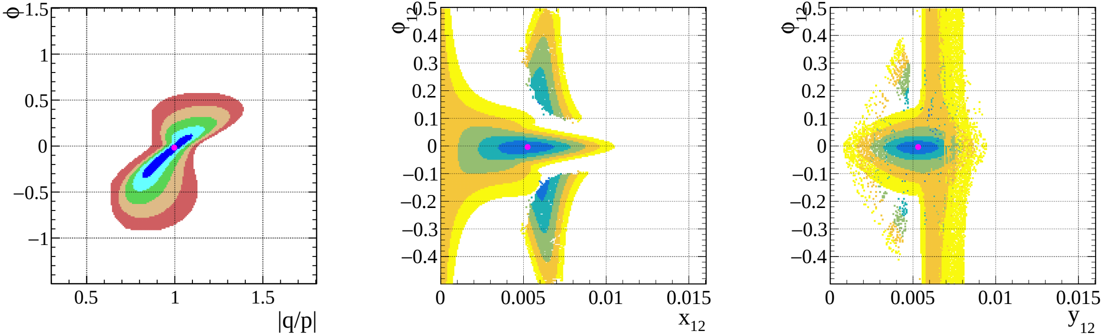


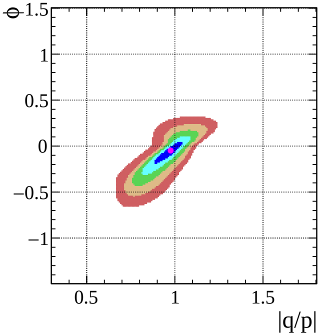
LHCb $K\pi$, $K_s\pi\pi$ Run I

All CPV allowed | No DCPV | No DCPV

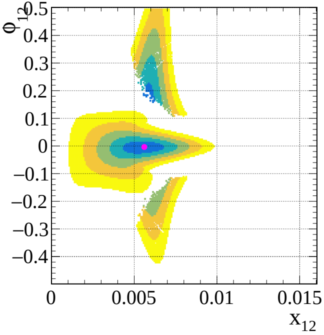


LHCb $K\pi$, $K_s\pi\pi$ Run II

All CPV allowed



No DCPV



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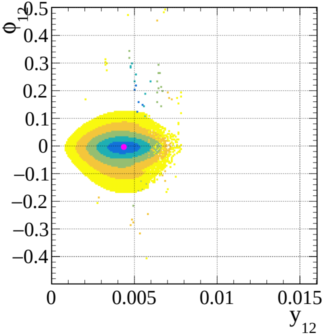


Conclusions

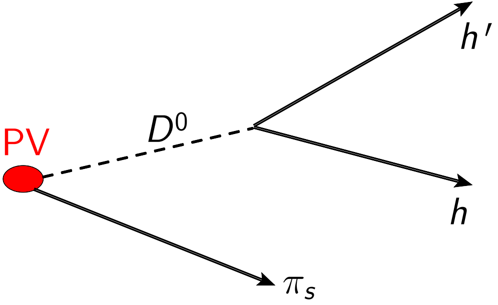
- Charm physics is a vibrant field with precision approaching the standard model expectations
- Measurements of strong phase differences from quantum correlated measurements will play an important role in future CPV measurements
- Measurement of strong phases in $D^0 \to K_s hh$, etc, decays will help limit systematics in indirect CPV analyses
- From naïve global fit projections, making measurements of strong phase differences without assumptions on underlying parameters will impact underlying fit parameters

Backup Slides

Experimental Strategies

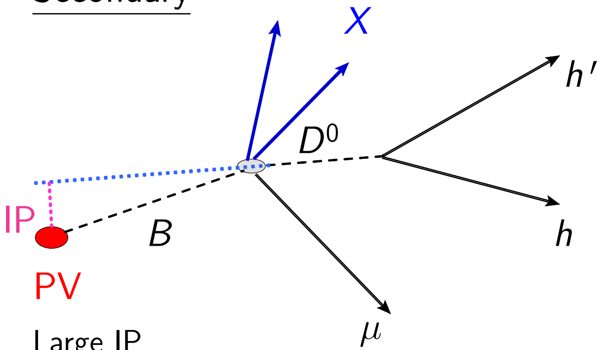
- Reconstruct charm decays with two topologies

Prompt



Impact Parameter (IP)~ 0

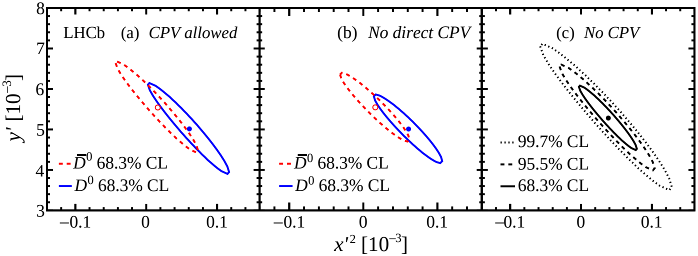
Secondary

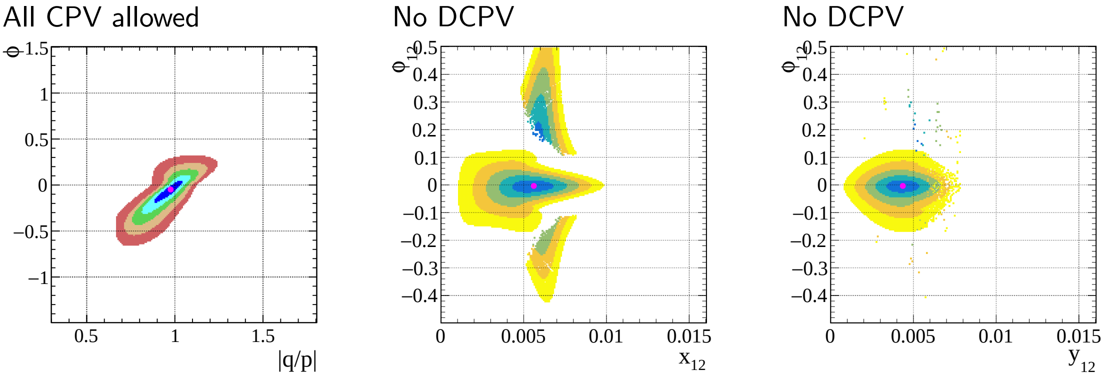


Large IP

- Use IP and related quantities to distinguish prompt and secondaries

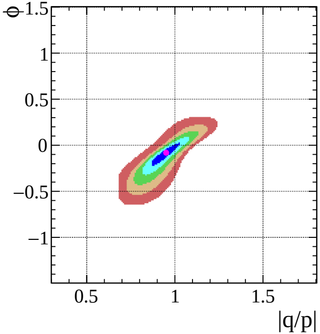
$D^0 \to K^+\pi^-$ contours



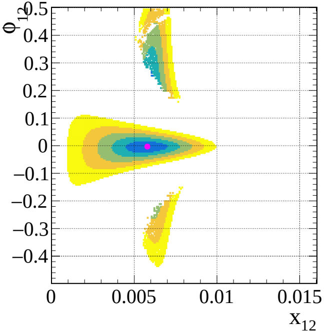


Run II measurement errors will increase without c_i, s_i measurements

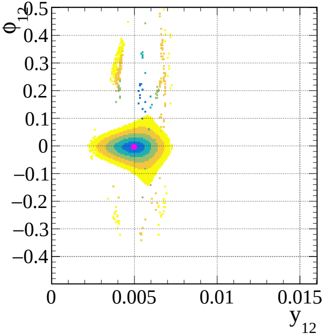
All CPV allowed



No DCPV



No DCPV



Run II measurement errors will increase without c_i, s_i measurements