Mixing and CP-Violation in Charm at LHCb

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Why Study Charm Mixing and CPV

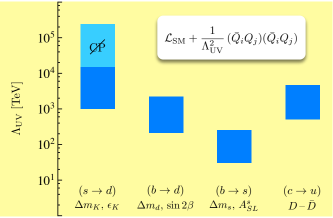
What should you remember tomorrow, or a year from now?

- Flavor physics, generically, allows searches for manifestations of **New Physics at the highest energy scales** by studying rare and forbidden decays and and searching for *CP* violation beyond that described by the Kobayashi-Maskawa phase of the CKM matrix.
  - ***CP* violation in** D^0, K^0, B_d and B_s **mixing** provide complementary sensitivities to BSM physics;
  - We are collecting fully reconstructed charm samples **100× to 1000×** larger than previous experiments, and expect to collect another 10× to 50× more in Run 3;
  - We are already probing mass scales **higher** than can be searched for directly at the LHC.
- **Direct CPV** may provide complementary insights related to new amplitudes. SM predictions are notoriously variable; observations at the edge of our sensitivities might (or might not) signal BSM physics. In any case, these measurements will anchor our understanding of CPV in the interference of suppressed and mixing amplitudes.

Flavor Constrains BSM Physics

Operator	Bounds on Λ in TeV ($c_{\mathrm{NP}}=1$)		Bounds on c_{NP} ($\Lambda=1$ TeV)		Observables
	Re	Im	Re	Im	
$(\bar{s}_L\gamma^\mu d_L)^2$	9.8×10^2	1.6×10^4	9.0×10^{-7}	3.4×10^{-9}	$\Delta m_K;\quad \epsilon_K$
$(\bar{s}_R\,d_L)(\bar{s}_L d_R)$	1.8×10^4	3.2×10^5	6.9×10^{-9}	2.6×10^{-11}	
$(\bar{c}_L\gamma^\mu u_L)^2$	1.2×10^3	2.9×10^3	5.6×10^{-7}	1.0×10^{-7}	$\Delta m_D;\quad \lvert q/p\rvert_D,\,\phi_D$
$(\bar{c}_R\,u_L)(\bar{c}_L u_R)$	6.2×10^3	1.5×10^4	5.7×10^{-8}	1.1×10^{-8}	
$(\bar{b}_L\gamma^\mu d_L)^2$	6.6×10^2	9.3×10^2	2.3×10^{-6}	1.1×10^{-6}	$\Delta m_{B_d};\ \sin(2\beta)$ from $B_d\to\psi K$
$(\bar{b}_R\,d_L)(\bar{b}_L d_R)$	2.5×10^3	3.6×10^3	3.9×10^{-7}	1.9×10^{-7}	
$(\bar{b}_L\gamma^\mu s_L)^2$	1.4×10^2	2.5×10^2	5.0×10^{-5}	1.7×10^{-5}	$\Delta m_{B_s};\ \sin(\phi_s)$ from $B_s\to\psi\phi$
$(\bar{b}_R\,s_L)(\bar{b}_L s_R)$	4.8×10^2	8.3×10^2	8.8×10^{-6}	2.9×10^{-6}	

Flavor Structure in the SM and Beyond



Generic bounds without a flavor symmetry

$$\Delta\mathcal{L}^{\Delta F=2} = \sum_{i\neq j}\frac{c_{ij}}{\Lambda^2}(\overline{Q}_{Li}\gamma^\mu Q_{Lj})^2\ ,$$

- Table above from Isidori and Teubert, Eur.Phys.J.Plus **129**, 40 (2014). Bounds on representative dimension-six $\Delta F=2$ operators.
- Image to the left from M. Neubert, EPS-HEP-2011.

Direct CP Violation

adapted from Khodjamirian and Petrov, PLB 774 (2017) 235 - 242

Observables sensitive to CP-violation are most often written in terms of asymmetries

$$a_{\mathrm{CP}}(f) = \frac{\Gamma(D \to f) - \Gamma(\overline{D} \to \overline{f})}{\Gamma(D \to f) + \Gamma(\overline{D} \to \overline{f})}, \tag{1}$$

formed from the partial rates of a D-meson decay to a final state f and of its CP-conjugated counterpart. $\cdots$ the asymmetry in Eq. (1) could be a function of time, if $D^0\overline{D}^0$-mixing is taken into account. The measured time-integrated asymmetry contains a *direct* component, [which] occurs when the absolute values of the $D \to f$ decay amplitude, which we denote by $A_f \equiv A(D \to f)$, and of the corresponding CP-conjugated amplitude $\overline{A}_{\overline{f}} \equiv A(\overline{D} \to \overline{f})$ are different. This can be realized if the decay amplitude A_f can be separated into at least two different parts,

$$A_f = A_f^{(1)} e^{i\delta_1} e^{i\phi_1} + A_f^{(2)} e^{i\delta_2} e^{i\phi_2}, \tag{2}$$

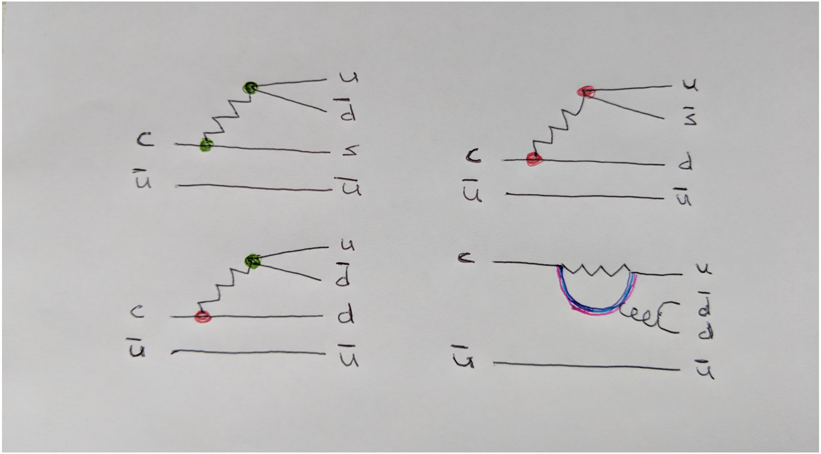
where $\phi_1 \neq \phi_2$ are the weak phases (odd under CP), and $\delta_1 \neq \delta_2$ are the strong phases (even under CP). The CP-violating asymmetry is then given by

$$a_{\mathrm{CP}}^{\mathrm{dir}}(f) \propto \frac{A_f^{(1)}}{A_f^{(2)}} \sin(\delta_1 - \delta_2) \sin(\phi_1 - \phi_2). \tag{3}$$

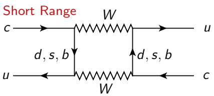
The amplitude pattern of Eq. (2) naturally emerges in SCS nonleptonic decays such as $D^0 \to K^-K^+$ and $D^0 \to \pi^-\pi^+$. [as penguin amplitudes augment tree amplitudes]

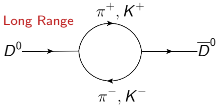
Tree Amplitudes and Penguin Amplitudes

Strong and Weak Phases



Neutral Meson Oscillation and *CP* Violation in Mixing

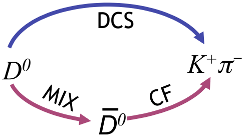




$$|P_{1,2}\rangle = p|P^0\rangle \pm q|\overline{P}^0\rangle\,; \qquad p^2 + q^2 = 1$$

$$x \equiv \frac{\Delta m}{\Gamma} \qquad y \equiv \frac{\Delta\Gamma}{2\Gamma}$$

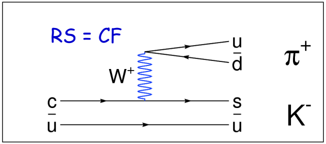
$$\begin{aligned} |\mathcal{M}|^2 \quad \propto \quad & \frac{1}{2}\, e^{-\Gamma t} \Big\{ |\mathcal{A}_\alpha|^2 \Big(\cosh y\,\Gamma t + \cos x\,\Gamma t \Big) \\ & + |\overline{\mathcal{A}}_\alpha|^2 \left|\frac{q}{p}\right|^2 \Big(\cosh y\,\Gamma t - \cos x\,\Gamma t \Big) \\ & + 2 \left[\Re\left(\left(\frac{q}{p}\right)^* \mathcal{A}_\alpha \overline{\mathcal{A}}^*_\alpha \right) \sinh y\,\Gamma t - \Im\left(\left(\frac{q}{p}\right)^* \mathcal{A}_\alpha \overline{\mathcal{A}}^*_\alpha \right) \sin x\,\Gamma t \right] \Big\}\,. \end{aligned}$$

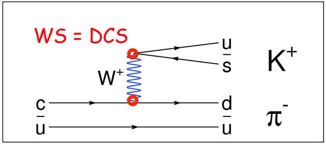


for x, $y \ll 1$ (valid for D^0, not for B_s):

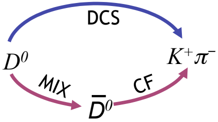
- **doubly Cabibbo-Suppressed (DCS) $\approx \propto e^{-\Gamma t}$;**
- **pure mixing $\propto e^{-\Gamma t} \times (\Gamma t)^2$**
- **interference $\approx \propto e^{-\Gamma t} \times \Gamma t$**

Time Evolution of $D^0 \to K\pi$





DCS and mixing amplitudes interfere to give a "quadratic" WS decay rate (x, y << 1):



$$\frac{\Gamma_{WS}(t)}{e^{-t/\tau}} \propto R_D + \sqrt{R_D}y'\left(\frac{t}{\tau}\right) + \left(\frac{x'^2 + y'^2}{4}\right)\left(\frac{t}{\tau}\right)^2$$

where $x' = x\cos\delta + y\sin\delta$ $y' = y\cos\delta - x\sin\delta$

and δ is the phase difference between DCS and CF decays.

m_i, Γ_i ⇔ weak eigenstates ; $x \equiv \frac{\Delta m}{\langle\Gamma\rangle}$; $y \equiv \frac{\Delta m}{2\langle\Gamma\rangle}$; $\tau \equiv \frac{1}{\langle\Gamma\rangle}$

CPV in Mixing

$$\langle D^0|H|\overline{D^0}\rangle = M_{12} - \frac{i}{2}\Gamma_{12}\ ; \quad \langle\overline{D^0}|H|D^0\rangle = M_{12}^* - \frac{i}{2}\Gamma_{12}^*\,,$$

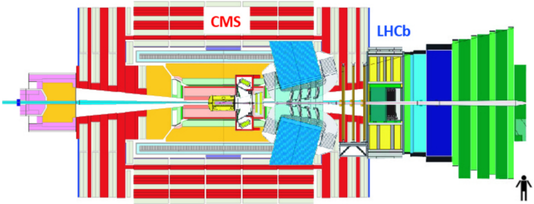
$$\frac{q}{p} = \frac{-2\,(M_{12}^* - \frac{1}{2}\Gamma_{12}^*)}{\Gamma\,(x - iy)}\ ; \quad \lambda_f \equiv \frac{q}{p}\frac{\overline{A}_f}{A_f} = -\left|\frac{q}{p}\right| R_f\, e^{i(\phi+\Delta_f)} \quad \left(\to -\eta_f^{CP}\left|\frac{q}{p}\right| e^{i\phi}\right)$$

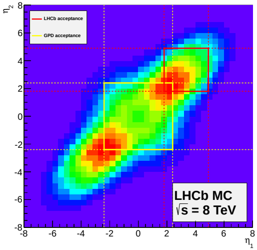
$$\left|\langle f|H\left|\overline{D}^{\,0}(t)\right\rangle\right|^2 \approx \frac{e^{-\Gamma t}}{2}\,|\mathcal{A}_f|^2\Big\{R_D + \left|\frac{p}{q}\right|\sqrt{R_D}\,\Big[y\cos(\delta+\varphi) - x\sin(\delta+\varphi)\Big](\Gamma t) + \left|\frac{p}{q}\right|^2\frac{x^2+y^2}{4}(\Gamma t)^2\Big\}$$

$$\left|\langle\overline{f}|H\left|D^0(t)\right\rangle\right|^2 \approx \frac{e^{-\Gamma t}}{2}\,|\overline{\mathcal{A}}_{\overline{f}}|^2\Big\{\overline{R}_D + \left|\frac{q}{p}\right|\sqrt{\overline{R}_D}\,\Big[y\cos(\delta-\varphi) - x\sin(\delta-\varphi)\Big](\Gamma t) + \left|\frac{q}{p}\right|^2\frac{x^2+y^2}{4}(\Gamma t)^2\Big\}\,.$$

no direct CPV $+\,x,\ y \ll 1 \ \to$ $\tan\varphi \approx \left(1 - \left|\frac{q}{p}\right|\right)\frac{x}{y}$ $\quad\left[|M_{12}|,\ |\Gamma_{12}|,\ \arg\left(\frac{\Gamma_{12}}{M_{12}}\right) \to x,\ y,\ \left|\frac{q}{p}\right|,\ \arg\left(\frac{q}{p}\right)\right]$

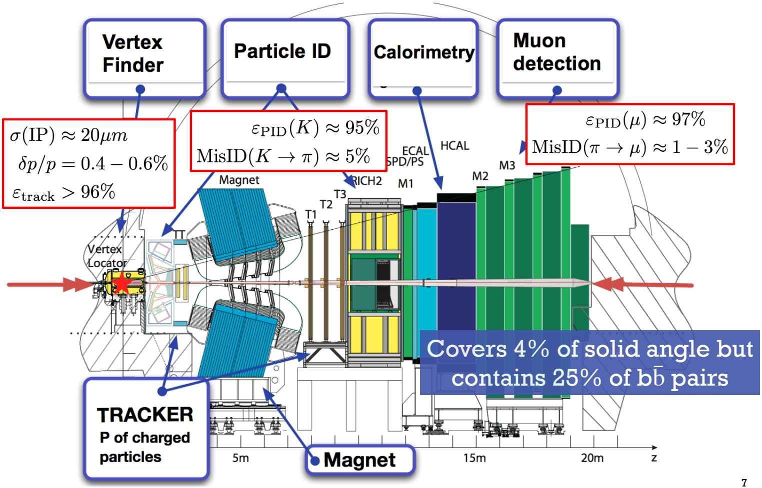
LHC Detector Acceptances for $b\bar{b}$ Production





- LHCb is a forward spectrometer, optimized for accepting both B and $\overline{B}$ hadrons in an event;
- accepts about $10\times$ as many triggers as ATLAS or CMS;
- $\sigma(c\,\overline{c}) \sim 20 \times \sigma(b\,\overline{b})$;
- acceptance in η complements ATLAS and CMS for many electro-weak studies.

LHCb Detector [2008 JINST 3 S08005]



Vertex Finder

$\sigma(\text{IP}) \approx 20\mu m$

$\delta p/p = 0.4 - 0.6\%$

$\varepsilon_{\text{track}} > 96\%$

Particle ID

$\varepsilon_{\text{PID}}(K) \approx 95\%$

$\text{MisID}(K \to \pi) \approx 5\%$

Calorimetry

Muon detection

$\varepsilon_{\text{PID}}(\mu) \approx 97\%$

$\text{MisID}(\pi \to \mu) \approx 1 - 3\%$

TRACKER

P of charged particles

Magnet

Covers 4% of solid angle but contains 25% of $b\bar{b}$ pairs

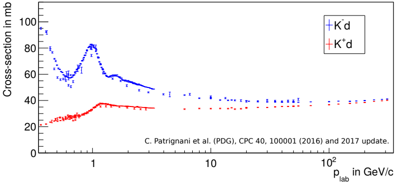
Some Experimental Issues

The experimental observable is not directly A_{CP}, but A_{raw} :

$$A_{\mathrm{raw}} = A_{CP} + A_P + A_D + A_{\mathrm{tag}}$$

- The production asymmetry A_P : *pp* collisions have an initial anti-quark deficit
- The detection asymmetry A_D : meson and anti-meson cross-sections differ
- The tagging asymmetry A_{tag} : efficiencies depend on charge of tagging particles
- The *CP* asymmetry A_{CP} : What we want to measure

- Detection asymmetry reduced by flipping magnet polarity regularly
- Residual detection asymmetry due to intrinsic different cross-section between particles of opposite charge when interacting with the detector's material



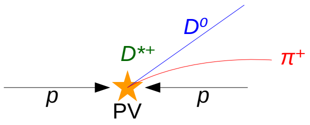
C. Patrignani et al. (PDG), CPC 40, 100001 (2016) and 2017 update.

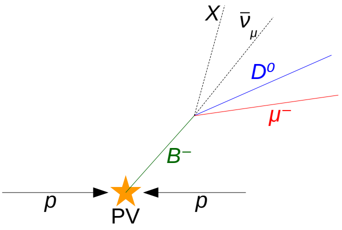
Production and tagging asymmetries

At LHCb, we use 2 independent tagging methods :

Prompt
$D^{*+} \rightarrow D^0\pi^+$

Semileptonic
$B^- \rightarrow D^0\mu^-\overline{\nu}_\mu X$





Prior Measurements of Direct CPV

- Most precise measurements to date
  - Based on Run 1 data
  - Updated analyses with Run 2 data under way

$$A_{CP}(D^0 \to K^+K^-) = (0.4 \pm 1.2 \pm 1.0) \times 10^{-3}$$ [Phys. Lett. B 767 (2017), 177-187]

$$A_{CP}(D^0 \to \pi^+\pi^-) = (0.7 \pm 1.4 \pm 1.1) \times 10^{-3}$$ [Phys. Lett. B 767 (2017), 177-187]

$$\Delta A_{CP}(D^0 \to h^+h^-) = (1.0 \pm 0.8 \pm 0.3) \times 10^{-3}$$ [Phys. Rev. Lett. 116, 191601 (2016)]

- ΔA_{CP} measured first; then $A_{CP}(KK)$; then $A_{CP}(\pi\pi)$ extracted;
- systematic errors for ΔA_{CP} are smaller than for either channel alone;
- statistical errors are also smaller – we had to use tighter cuts to extract the absolute $A_{CP}(KK)$.

→ **on to the latest results: direct CPV first, then time-dependent**

ΔA_{CP} in Λ_c^+ decays

[JHEP 03 (2018) 182]

- Dataset : $3.0\,\text{fb}^{-1}$, Run 1
- Production mode : $\Lambda_b^0 \rightarrow \Lambda_c^+ \mu^- X$
- Raw asymmetry :

$$A_{\text{raw}}(f) = A_{CP}(f) + A_P(\Lambda_b^0) + A_{\text{tag}}(\mu) + A_D(f)$$

$$\text{where f} = pK^+K^-,\ p\pi^+\pi^-$$

- Removing experimental asymmetries by taking the difference between the two final states

$$\begin{aligned}\Delta A_{CP} &= A_{\text{raw}}(pK^+K^-) - A_{\text{raw}}(p\pi^+\pi^-)\\ &= A_{CP}(pK^+K^-) - A_{CP}(p\pi^+\pi^-)\end{aligned}$$

  - Assuming the kinematics is the same for the two final states

ΔA_{CP} in Λ_c^+ decays

[JHEP 03 (2018) 182]

- The kinematics of the two final states are not the same

→ Reweight the kinematics of $p\pi^+\pi^-$ to pK^+K^-

  - Reweight with decision trees with gradient boosting (GBDT)
  - Reweight for Λ_c^+ transverse momentum and pseudorapidity and p transverse momentum
  - limited by statistics of pK^+K^- final state

- Quote a weighted asymmetry:

$$\Delta A_{CP}^{\mathrm{wgt}} = A_{\mathrm{raw}}(pK^+K^-) - A_{\mathrm{raw}}^{\mathrm{wgt}}(p\pi^+\pi^-)$$

  - Weight function published in order to compare with theoretical predictions

ΔA_{CP} in Λ_c^+ decays

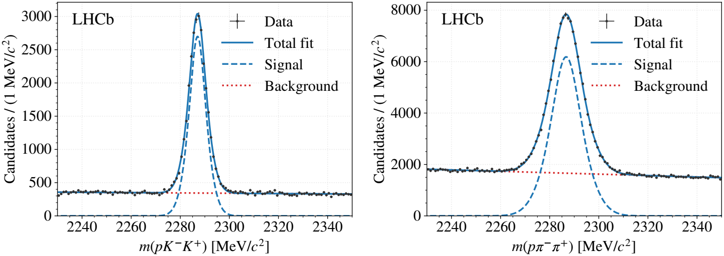
[JHEP 03 (2018) 182]

$\Lambda_c^+ \to pK^-K^+$

$N_{\rm sig} = 25190 \pm 200$

$\Lambda_c^+ \to p\pi^-\pi^+$

$N_{\rm sig} = 161390 \pm 580$



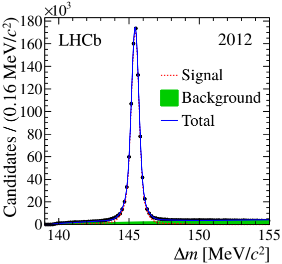
$$\Delta A_{CP}^{\rm wgt} = (3.0 \pm 9.1 \pm 6.1) \times 10^{-3}$$

- First measurement of *CPV* parameters in 3-body Λ_c^+ decays.
- No *CPV* observed

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

[Phys. Lett. B 769 (2017) 345-356]

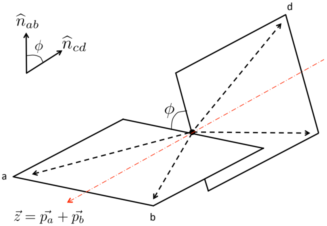
- Dataset : $3.0\,\text{fb}^{-1}$, Run 1
- Production mode : $D^{*+} \to D^0\pi^+$
- $N_{\text{sig}} = (1008 \pm 1) \times 10^3$



- Ordering of the particles:
  - For the D^0: $\pi_1\pi_2\pi_3\pi_4 = \pi^+\pi^-\pi^+\pi^-$, where largest $m(\pi^+\pi^-) = m(\pi_3\pi_4)$
  - For the $\bar{D}^0$: *CP* is applied $\pi_1\pi_2\pi_3\pi_4 = \pi^-\pi^+\pi^-\pi^+$
- 5D phase space:
  - $m(\pi_1\pi_2), m(\pi_1\pi_4), m(\pi_2\pi_3), m(\pi_1\pi_2\pi_3), m(\pi_1\pi_2\pi_4)$

Triple Product Asymmetry Math

Parity reversing and parity preserving amplitudes interfere - producing parity violation



- $C_{\widehat{T}} = \vec{p}_a \cdot (\vec{p}_c \times \vec{p}_d)$ $[P]$
- $\overline{C}_{\widehat{T}} = \vec{p}_{\overline{a}} \cdot (\vec{p}_{\overline{c}} \times \vec{p}_{\overline{d}})$ $[\overline{P}]$
- **$\vec{p}_a \cdot (\vec{p}_c \times \vec{p}_d) \propto \sin\phi$**
- NB: $\vec{p}_a \cdot (\vec{p}_c \times \vec{p}_d) = -\vec{p}_a \cdot (\vec{p}_b \times \vec{p}_c)$

$$A_{\widehat{T}}(C_{\widehat{T}}) = \frac{N(C_{\widehat{T}} > 0) - N(C_{\widehat{T}} < 0)}{N(C_{\widehat{T}} > 0) + N(C_{\widehat{T}} < 0)} \quad \overline{A}_{\widehat{T}}(\overline{C}_{\widehat{T}}) = \frac{\overline{N}(-\overline{C}_{\widehat{T}} > 0) - \overline{N}(-\overline{C}_{\widehat{T}} < 0)}{\overline{N}(-\overline{C}_{\widehat{T}} > 0) + \overline{N}(-\overline{C}_{\widehat{T}} < 0)}$$

$$a_{P}^{\widehat{T}\text{-odd}} = \frac{1}{2}\left(A_{\widehat{T}} + \overline{A}_{\widehat{T}}\right) \qquad a_{CP}^{\widehat{T}\text{-odd}} = \frac{1}{2}\left(A_{\widehat{T}} - \overline{A}_{\widehat{T}}\right)$$

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

[Phys. Lett. B 769 (2017) 345-356]

The energy test [J. Stat. Comput. Simul. 75 (2005) 109]

- Sensitive to local *CPV* in the phase space
- Model independent unbinnned method
- Define a metric to compute the distance between 2 points in the phase space
- Define a test statistic, T

$$T = \sum_{i,j>i}^{n} \frac{\psi_{ij}}{n(n-1)} + \sum_{i,j>i}^{\bar{n}} \frac{\psi_{ij}}{\bar{n}(\bar{n}-1)} - \sum_{i,j}^{n,\bar{n}} \frac{\psi_{ij}}{n\bar{n}}$$

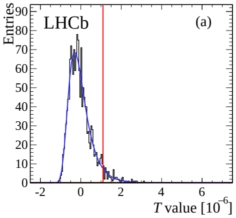
- Build the "no *CPV* " hypothesis as a set of random permutations of the data
- Compare the value in data to the "no *CPV* " hypothesis

This is the first application of the energy test to a 4-body decay

CPV in $D^0 \to \pi^+\pi^-\pi^+\pi^-$: *Results*

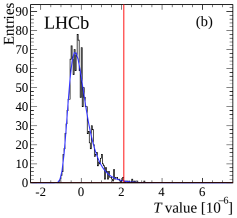
[Phys. Lett. B 769 (2017) 345-356]

P-even test statistic



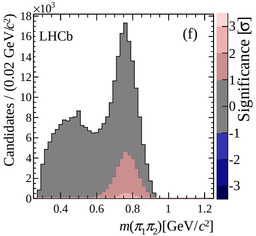
p-value $= (4.6 \pm 0.5)\%$

P-odd test statistic



p-value $= (0.6 \pm 0.2)\%$

P-odd details for $m(\pi_1\, \pi_2)$

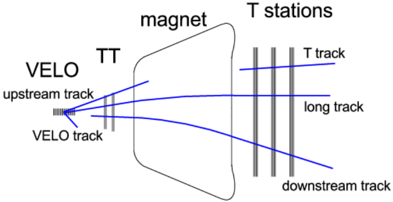


- data are marginally consistent with CP symmetry hypothesis
- more data and full amplitude analysis may be able to observe direct CPV in this SCS decay

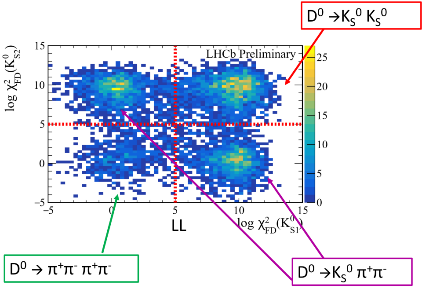
A_{CP} in $D^0 \rightarrow K^0_S K^0_S$ decays

[arXiv:1806.01642]

Track and K^0_S categories



removing backgrounds



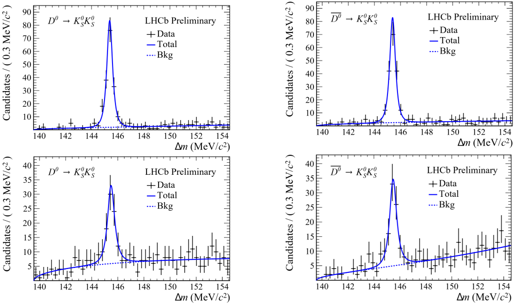
For this analysis:

- dataset: 2.0 fb^{-1} 2015 - 2016
- production + tagging: prompt D^{*+}
- LL: the two K^0_S decay in the VELO and both form long tracks
- LD: one K^0_S decays inside and one decays downstream of the VELO

A_{CP} in $D^0 \to K^0_S K^0_S$ decays

[arXiv:1806.01642]

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



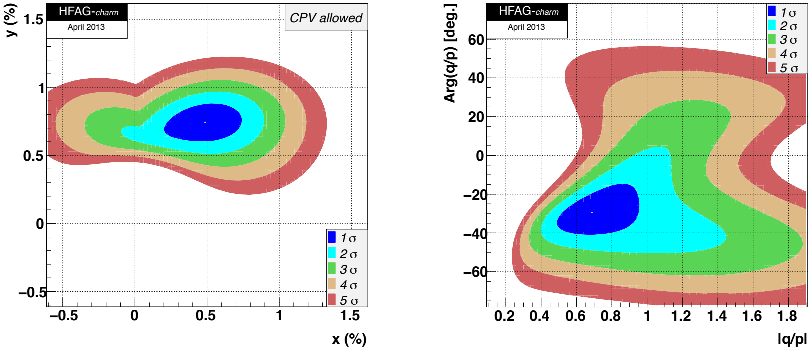
$N_{sig}^{LL} = (759 \pm 32)$ LL

$N_{sig}^{LD} = (308 \pm 26)$ LD

- $A_{CP} = (4.2 \pm 3.4 \pm 1.0)\%$
- Compatible with Run 1 result: $A_{CP} = (-2.9 \pm 5.2 \pm 2.2)\%$
- Average : $A_{CP} = (2.0 \pm 2.9 \pm 1.0)\%$

→ Catching up with Belle: [$A_{CP} = (-0.0 \pm 1.5 \pm 0.2)\%$ [PRL 119 (2017) 171801]]

Mixing + CPV: Context and History



The interpretation of experimental results often depends on prior knowledge and impact on underlying physics parameters.

These plots illustrate the status of charm mixing/CPV results compiled by the Heavy Flavor Averaging Group, circa April 2013 (before LHCb's first $K\pi$ mixing + CPV results were announced [PRL 111 (2013) 251801].

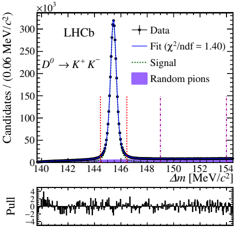
A_Γ with $D^0 \to hh$ decays

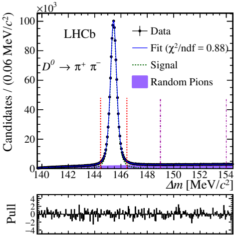
Phys. Rev. Lett 118, 261803 (2017)

$$A_{CP}(h^+h^-;t) \;\approx\; A_{CP}^{\rm dir}(h^+h^-) + A_\Gamma(h^+h^-)\left(\frac{t}{\tau}\right) + \left[<\mathcal{O}(10^{-6})\left(\frac{t}{\tau}\right)^2\right]$$

$$A_{CP}^{\rm dir}(h^+h^-) \;\equiv\; A_{CP}(t=0) = \frac{\left|\mathcal{A}(D^0\to h^+h^-)\right|^2 - \left|\mathcal{A}(\bar{D}^0\to h^+h^-)\right|^2}{\left|\mathcal{A}(D^0\to h^+h^-)\right|^2 + \left|\mathcal{A}(\bar{D}^0\to h^+h^-)\right|^2},$$

$$A_\Gamma(h^+h^-) = \frac{\eta_{\not{C}\not{P}}}{2}\left[y\left(\left|\frac{q}{p}\right| - \left|\frac{p}{q}\right|\right)\cos\varphi - x\left(\left|\frac{q}{p}\right| + \left|\frac{p}{q}\right|\right)\sin\varphi\right],$$



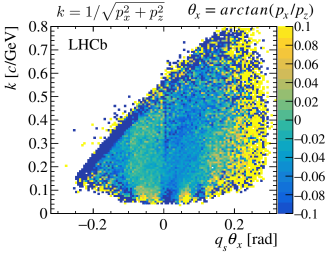


Dataset

- 9.0 M $D \to K^-K^+$ & 3.0 M $D \to \pi^-\pi^+$ from 3 fb^{-1} of Run 1 data (collected 2011-2012)
- prompt $D^{*+} \to D^-\pi^+$ + cc
- cut on $m(K\pi)$; study Δm
- combinatorial background is sideband-subtracted
- asymetry is measured in decay time intervals spanning $[0.6,\ 20]\ \tau(D^0)$.

A_Γ with $D^0 \to hh$ decays: Experimental Challenges

Phys. Rev. Lett 118, 261803 (2017)

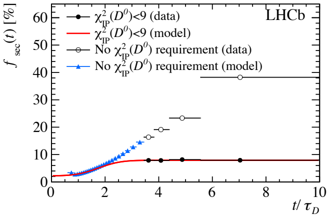


Instrumental Asymmetries

- **Soft pion charge reconstruction asymmetry**
  Time dependent correction due to correlation between soft pion kinematics and D^0 decay time
- **Reweighed the soft pion kinematic to recover left-right asymmetry of the detector**
  Validated on $D^0 \to K^-\pi^+$ decays

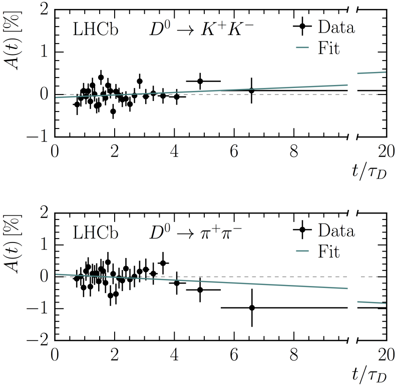
D^0 from B decays (Secondaries)

- **Undetected B decays mimic a larger D^0 decay time**
  Dilutes the asymmetry
- **Applied requirement of the D^0 pointing to PV**
  Residual background from B decays estimated with a model calibrated by the yield of secondaries at higher decay time



A_Γ with $D^0 \to hh$ decays: Results

Phys. Rev. Lett 118, 261803 (2017) + JHEP 04 (2015) 043



The data are consistent with hypothesis that *CP* symmetry is exact (in this measurement) at the level of 3×10^{-4}.

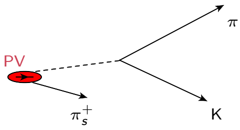
- $A_\Gamma(KK) = (-3.0 \pm 3.2 \pm 1.0) \times 10^{-4}$
- $A_\Gamma(\pi\pi) = (-4.6 \pm 5.8 \pm 1.2) \times 10^{-4}$

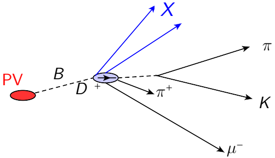
A complementary analysis of the same data using per-event acceptance calculations produces compatible results.

Combining these results with those from a statisically independent sample ($B \to D^0\mu^- X$)

- $A_\Gamma = (-2.9 \pm 2.8) \times 10^{-4}$

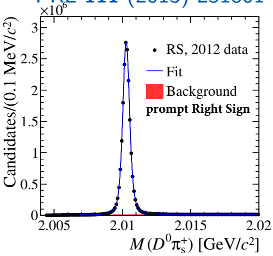
$D^0 \to K\pi$ Samples: Prompt and Doubly-Tagged (DT)



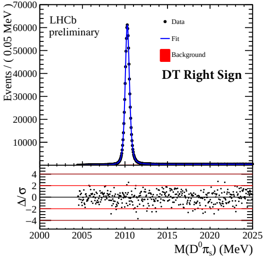


- prompt signal trigger becomes "fully" efficient well above one lifetime;
- doubly-tagged trigger is $\sim$ independent of D^0 decay time;

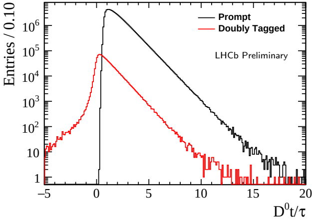
PRL **111** (2013) 251801



PRD 95, 052004 (2017)



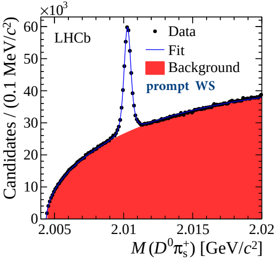
PRD 95, 052004 (2017)

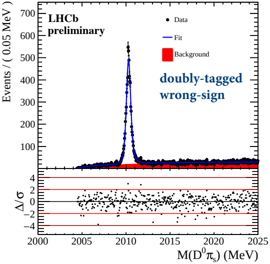


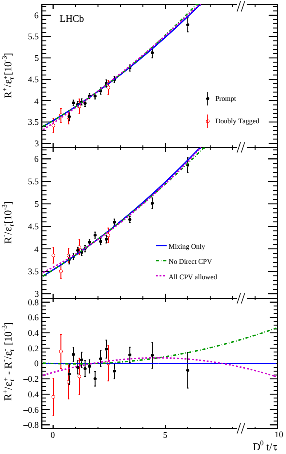
$D^0 \to K\pi$ Mixing and CPV Measurements

$$R^{\pm}(t) = \frac{\mathrm{WS}(t)}{\mathrm{RS}(t)} = R_D^{\pm} + \sqrt{R_D^{\pm}}\, y' \left(\frac{t}{\tau}\right) + \left(\frac{x'^{\pm 2} + y'^{\pm 2}}{4}\right)\left(\frac{t}{\tau}\right)^2$$

PRL **111** (2013) 251801; PRD 95, 052004 (2017)





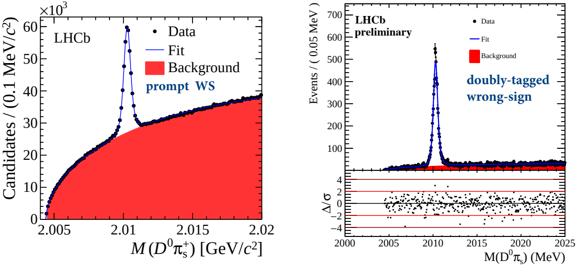


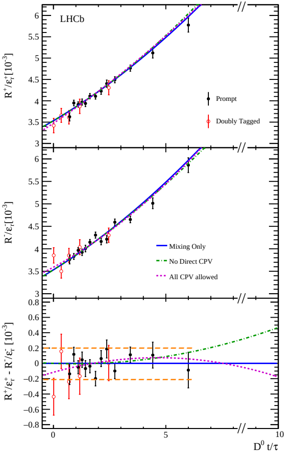
- $\sim$ 54 M prompt RS, $\sim$ 1.7 M DT RS;
- $\sim$ 230 K WS, $\sim$ 6 K WS DT;
- ***D^0, $\overline{D}^0$ mixing rates are equal, $\pm 5\%$.***
- adding DT sample [$\mathcal{O}(3\%)$] improves precision by $(10-20)\%$.

$D^0 \to K\pi$ Mixing and CPV Measurements

$$R^{\pm}(t) = \frac{\mathrm{WS}(t)}{\mathrm{RS}(t)} = R_D^{\pm} + \sqrt{R_D^{\pm}}\, y' \left(\frac{t}{\tau}\right) + \left(\frac{x'^{\pm 2} + y'^{\pm 2}}{4}\right)\left(\frac{t}{\tau}\right)^2$$

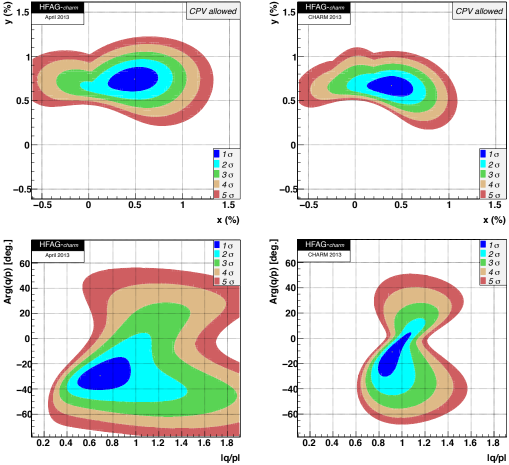
PRL **111** (2013) 251801; PRD 95, 052004 (2017)





- ∼ 54 M prompt RS, ∼ 1.7 M DT RS;
- ∼ 230 K WS, ∼ 6 K WS DT;
- **D^0, $\overline{D}^0$ mixing rates are equal, ±5%.**
- adding DT sample [$\mathcal{O}(3\%)$] improves precision by (10 − 20)%.

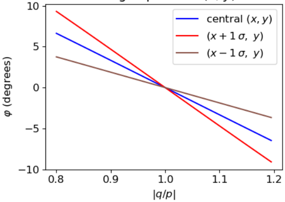
Impact: Run 1 $K\pi$ Mixing + CPV Measurement
[PRL 111 (2013) 251801]



HFLAV World Averages

April 2013	w/o constraint	with constraint
$\lvert q/p \rvert$	$0.69\,^{+0.17}_{-0.14}$	$1.04\,^{+0.07}_{-0.06}$
$\varphi\,(^\circ)$	$-29.6\,^{+8.9}_{-7.5}$	$-1.6\,^{+2.4}_{-2.5}$
Sept 2013		
$\lvert q/p \rvert$	$0.91\,^{+0.11}_{-0.09}$	$1.008\,^{+0.014}_{-0.014}$
$\varphi\,(^\circ)$	$-10.8\,^{+10.5}_{-12.3}$	$-0.3\,^{+0.5}_{-0.6}$

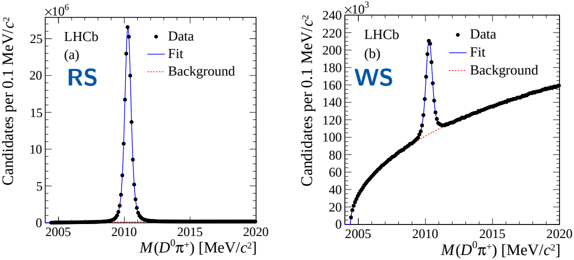
$\tan\varphi = (1 - |q/p|)\,(x/y)$
using Sept. 2013 (x, y)

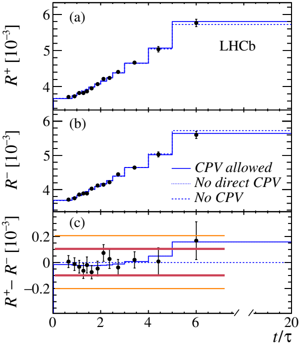


$D^0 \to K\pi$ Mixing and CPV Measurements – 2018 Update

$$R^{\pm}(t) = \frac{\mathrm{WS}(t)}{\mathrm{RS}(t)} = R_D^{\pm} + \sqrt{R_D^{\pm}}\,y'\left(\frac{t}{\tau}\right) + \left(\frac{x'^{\pm 2} + y'^{\pm 2}}{4}\right)\left(\frac{t}{\tau}\right)^2$$

PRD 97, 031101 (2018)

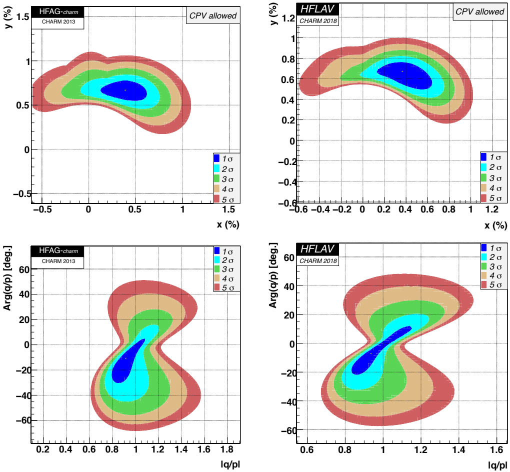




- 3 fb^{-1} @ 7/8 TeV $+$ 2 fb^{-1} @ 13 TeV;
- $\sim$ 177 M prompt RS, (was $\sim$ 54 M);
- $\sim$ 720 K prompt WS, (was $\sim$ 230 K);
- fit range extended to $t/\tau = 20$

Impact: 5 fb^{-1} $K\pi$ Mixing + CPV Measurement

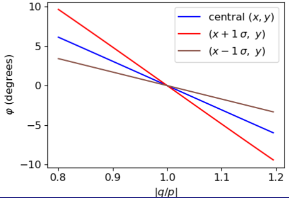
[PRD 97 (2018) 031101]



HFLAV World Averages

Sept 2013	w/o constraint	with constraint
$\lvert q/p\rvert$	$0.91\,^{+0.11}_{-0.09}$	$1.008\,^{+0.014}_{-0.014}$
$\varphi\,(^\circ)$	$-10.8\,^{+10.5}_{-12.3}$	$-0.3\,^{+0.5}_{-0.6}$
May 2018		
$\lvert q/p\rvert$	$0.94\,^{+0.17}_{-0.07}$	$0.998\,^{+0.007}_{-0.008}$
$\varphi\,(^\circ)$	$-7.2\,^{+14.7}_{-9.6}$	$0.09\,^{+0.32}_{-0.32}$

$\tan\varphi = (1 - |q/p|)\,(x/y)$
using Sept. 2013 (x, y)



To Take Away

- We are measuring **direct CPV** in charm decays with sensitivities in the range $\mathbf{10^{-3} - 10^{-2}}$. Standard Model predictions are in the range $10^{-4} - 10^{-3}$.
- We are measuring the particle – antiparticle **differences in mixing rates (CPV in mixing) in $D^0 \to K\pi$ at the few percent level.**
- The **super-weak constraint** (that all CPV in mixing originates in $|M_{12}|$, $|\Gamma_{12}|$, and $\arg(\Gamma_{12}/M_{12})$ **dramatically reduces the uncertainties on both $|q/p|$ and $\arg(q/p)$** . This constraint should apply for mixing with CF and DCS final states.
- The limits from these measurements **constrain BSM physics at high mass scales** and complement the limits from direct searches.
- We anticipate $> 4\times$ as much reconstructed charm in Run 2 as in Run 1, and **another $10\times - 50\times$** as much in Run 3.
- Flavor physics is fun.