New results in CPV at LHCb

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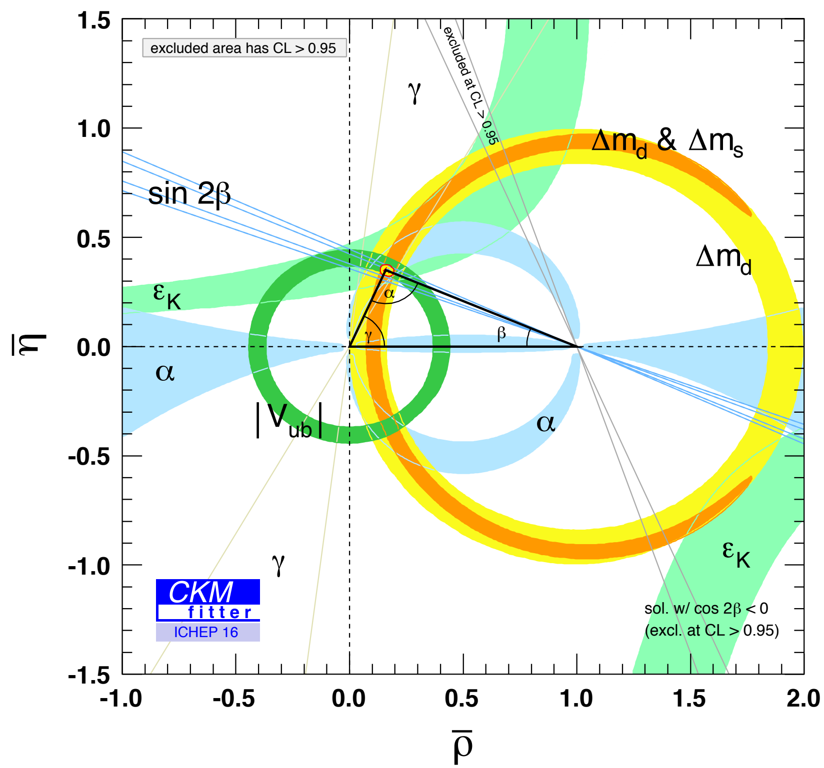
Outline

- Introduction to CP violation
- The LHCb experiment
- $\boldsymbol{\beta_{(s)}}$ **measurements** [arXiv:1709.03944] [JHEP 08 (2017) 055]
- $\boldsymbol{\gamma}$ **measurements** [arXiv: 1708.06370]
- **CPV in $\boldsymbol{b}$-baryon** [arXiv: 1609.05216]
- **CPV in charm sector** [PRL 118,261803 (2017)]
- Summary

CP violation

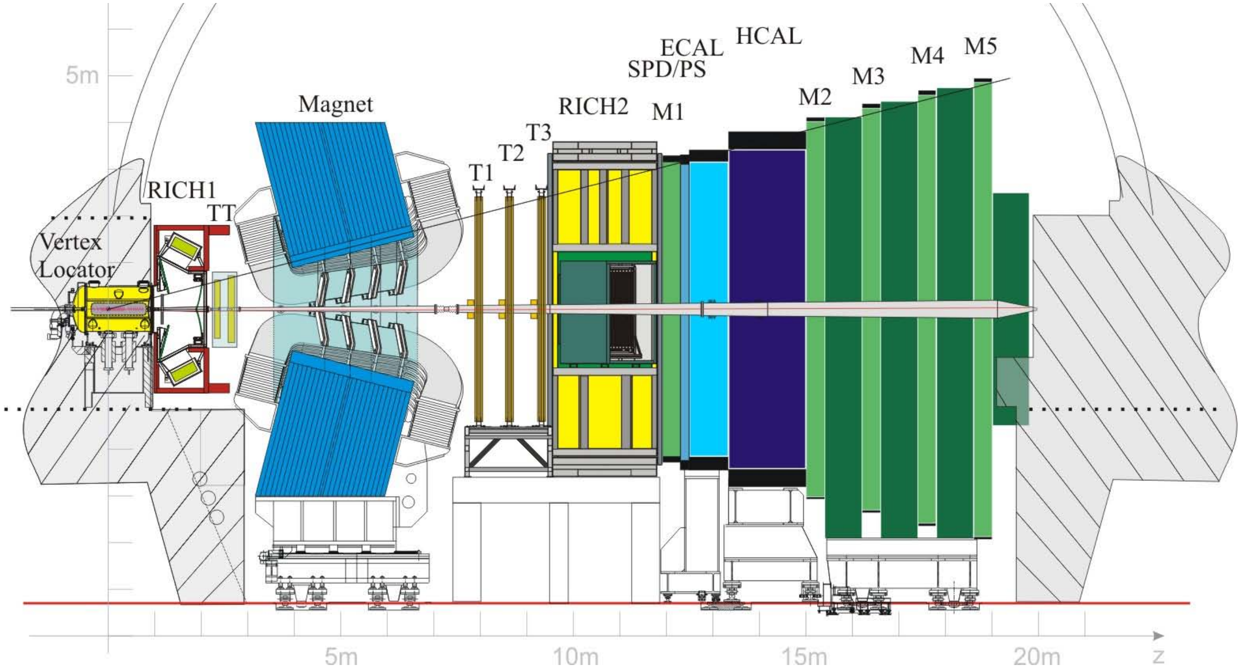
- The dominant source of CPV in SM is the complex phase in CKM
- New physics models predict additional sources of CPV
- Decays of heavy-flavored hadrons are the best laboratory to
  - ✓Overconstrain the unitarity triangle as a precision test of the SM
  - ✓Search for new sources of CPV
- Experimental status

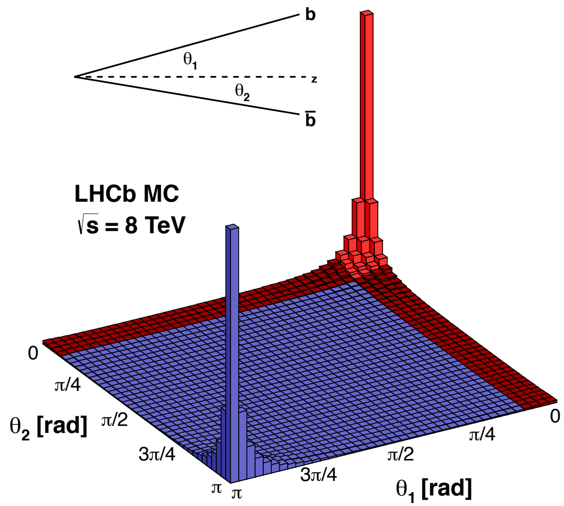
LHCb plays an important role!



The LHCb experiment

- A dedicated heavy flavor physics experiment
  - ✓ Large beauty and charm production cross-sections at the LHC
  - ✓ A single-arm forward region spectrometer covering $2 < \eta < 5$



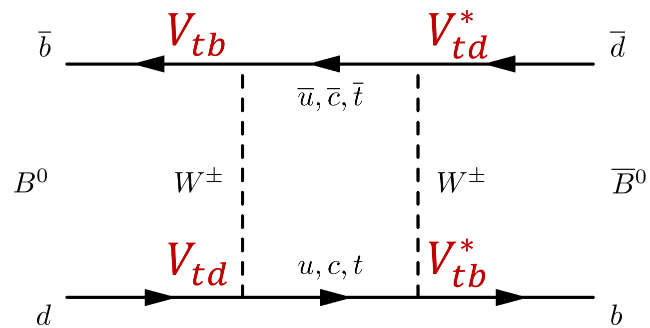


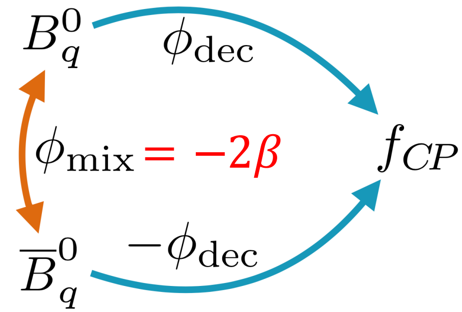
[JINST 3 (2008) S08005]

- **Excellent vertex resolution:** measure impact parameter; good decay time resolution
- **Good momentum resolution:** resolve heavy flavor decays; minimize background
- **Effective particle identification:** isolate similar decays; flavor tagging

β measurements

- $\beta = \arg\left(\frac{V_{td}V_{tb}^*}{V_{cd}V_{cb}^*}\right)$
- Decay rate depends on
  $\phi = \phi_{\text{mix}} - \cancel{2\phi_{\text{dec}}}$





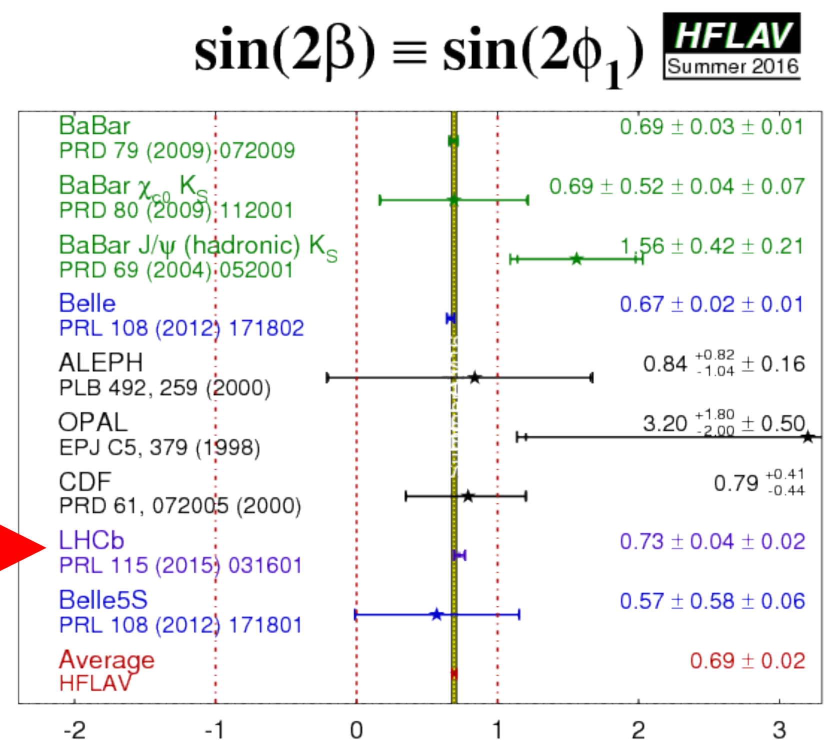
- Asymmetry between B^0 and $\bar{B}^0$ decay rates (with $\Delta\Gamma = 0$)

$$A_{f_{\text{CP}}}(t) = \frac{\Gamma(\bar{B}^0(t) \to f_{\text{CP}}) - \Gamma(B^0(t) \to f_{\text{CP}})}{\Gamma(\bar{B}^0(t) \to f_{\text{CP}}) + \Gamma(B^0(t) \to f_{\text{CP}})}$$
$$\approx S \times \sin(\Delta m \cdot t) - C \times \cos(\Delta m \cdot t)$$

✓ $S = \pm\sin\phi = \pm\sin(2\beta)$

[PRD 91 (2015) 073007]

- SM prediction $\sin(2\beta) = 0.771^{+0.017}_{-0.041}$
- B-factories still dominate the world average $\sin(2\beta) = 0.69 \pm 0.02$, but LHCb is quite close using $B^0 \to J/\psi(\mu^+\mu^-)K_S$ with RunI data



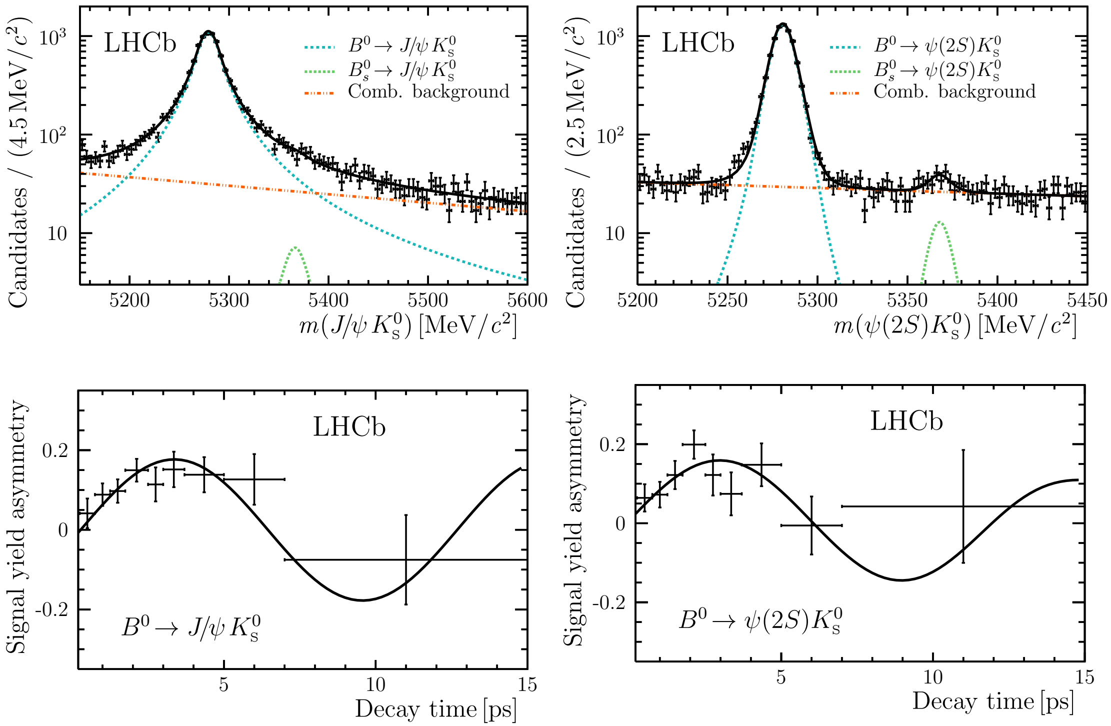
[HFLAV: arXiv:1612.07233]

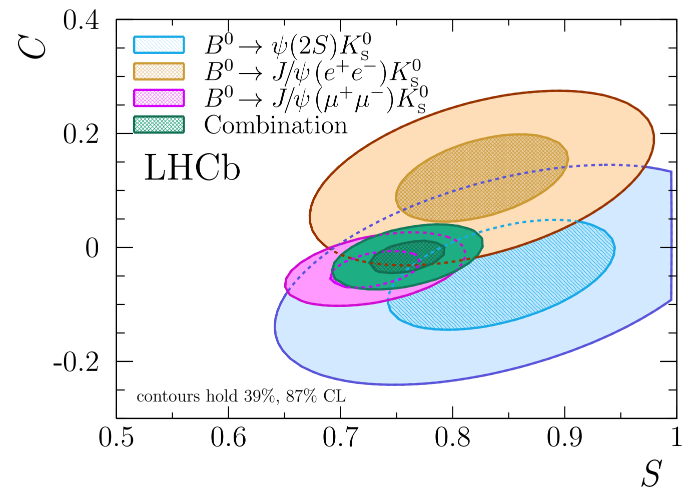
β from $B^0 \to [c\bar{c}]K_S$ decays

[arXiv:1709.03944]

- Additional channels with RunI data
- CP observables determined using fit to flavor-tagged decay-time distribution

$B^0 \to J/\psi(e^+e^-)K_S$ **$B^0 \to \psi(2S)(\mu^+\mu^-)K_S$**



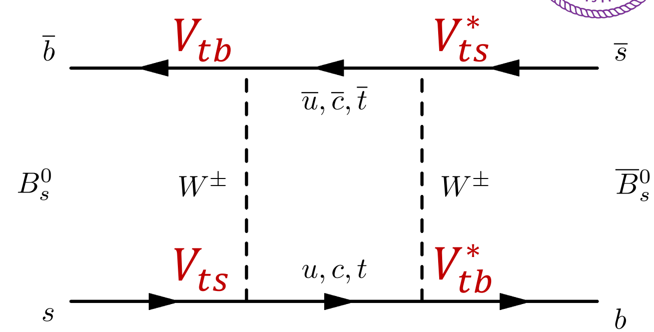


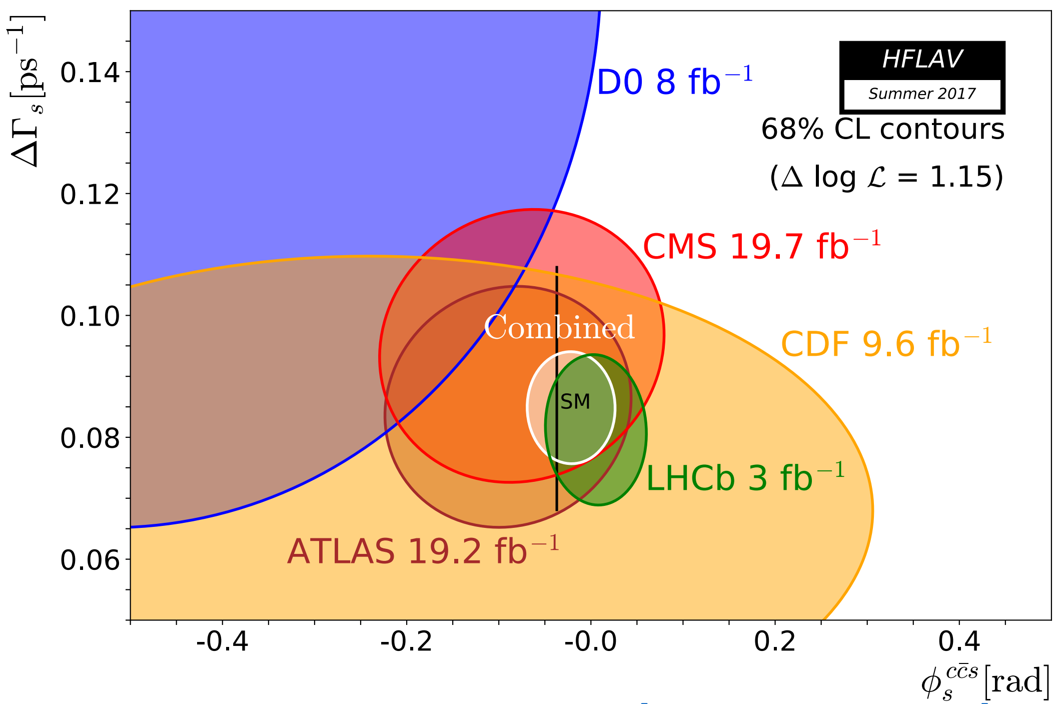
$$C(B^0 \to [c\bar{c}]K^0_S) = -0.017 \pm 0.029$$
$$S(B^0 \to [c\bar{c}]K^0_S) = 0.760 \pm 0.034$$

- Improve the precision of $\sin(2\beta)$ measurements at LHCb by 20%

β_s measurements

- $\beta_s = \arg\left(\frac{V_{ts}V_{tb}^*}{V_{cs}V_{cb}^*}\right)$
  - ✓ similar story as for β; $\Delta\Gamma \neq 0$
- SM prediction $\phi_s = -36.5^{+1.3}_{-1.2}$ mrad [PRD 91 (2015) 073007]
- World average $\phi_s = -21 \pm 31$ mrad





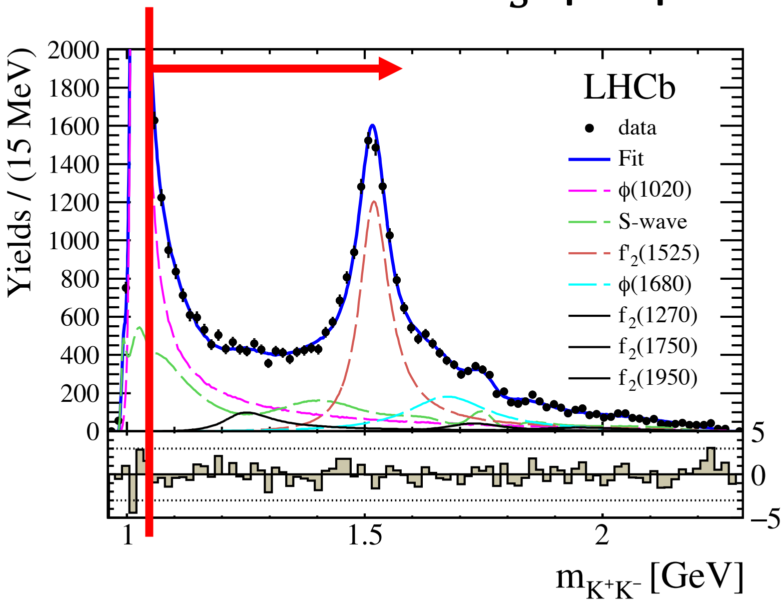
[HFLAV: arXiv:1612.07233]

- ✓ LHCb average dominate, with $J/\psi\phi$, $J/\psi\pi^+\pi^-$, $\psi(2S)\phi$, $D_s^+D_s^-$
- ✓ Far from SM precision; plenty of room for new physics

β_s from $\bar{B}_s^0 \to J/\psi K^+ K^-$ above $\phi(1020)$

[JHEP 08 (2017) 055]

- Supplementary to the previous RunI analysis with $m_{KK} < 1.05$ GeV
- CP observables determined using an amplitude analysis as a function of the $\bar{B}_s^0$ proper decay time with flavor tagged



Total amplitudes: $\begin{cases} \mathcal{A} = \sum A_i \\ \bar{\mathcal{A}} = |\lambda| e^{-i\phi_s} \sum \eta_i A_i \end{cases}$

Decay rate:

$$\Gamma(t) \propto e^{-\Gamma_s t} \left\{ \frac{|\mathcal{A}|^2 + |\overline{\mathcal{A}}|^2}{2} \cosh \frac{\Delta\Gamma_s t}{2} + \frac{|\mathcal{A}|^2 - |\overline{\mathcal{A}}|^2}{2} \cos(\Delta m_s t) - \mathcal{R}e\boxed{(\mathcal{A}^* \overline{\mathcal{A}})} \sinh \frac{\Delta\Gamma_s t}{2} - \mathcal{I}m\boxed{(\mathcal{A}^* \overline{\mathcal{A}})} \sin(\Delta m_s t) \right\}$$

$$\begin{aligned} \phi_s &= 119 \pm 107 \pm 34 \,\text{mrad}, \\ |\lambda| &= 0.994 \pm 0.018 \pm 0.006, \\ \Gamma_s &= 0.650 \pm 0.006 \pm 0.004 \,\text{ps}^{-1} \\ \Delta\Gamma_s &= 0.066 \pm 0.018 \pm 0.010 \,\text{ps}^{-1} \end{aligned}$$

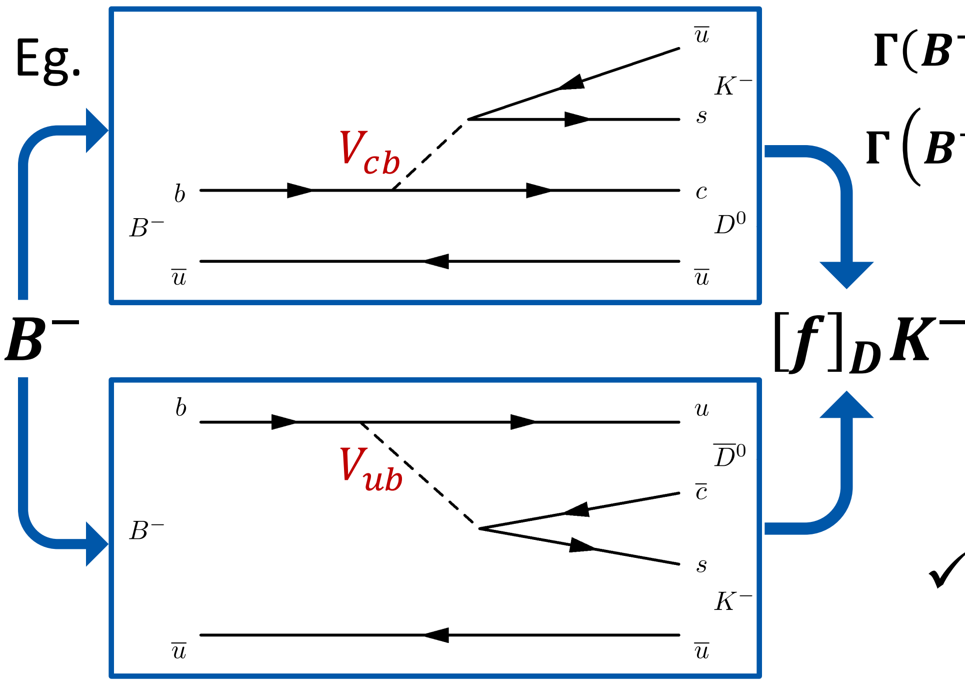
New LHCb average

$$\boxed{\phi_s = 1 \pm 37 \,\text{mrad}}$$

γ measurements

- $\gamma = \arg(-\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*})$
  - ✓Least well-known angle of the CKM unitarity triangle
  - ✓Tree-level determination with small theoretical uncertainties
- Direct measurements mainly through $B \to Dh$

Eg.



$$\Gamma(B^- \to [f]_D K^-) = \left|A_{cb}A_D + A_{ub}A_{\bar{D}}e^{i(\delta_B+\delta_D-\gamma)}\right|^2$$

$$\Gamma\left(B^+ \to [\bar{f}]_D K^+\right) = \left|A_{cb}A_D + A_{ub}A_{\bar{D}}e^{i(\delta_B+\delta_D+\gamma)}\right|^2$$

- Unknowns: $r_B = \frac{A_{ub}}{A_{cb}}, \delta_B, \gamma$
- CP observables: Partial width ratios R; CP asymmetries A

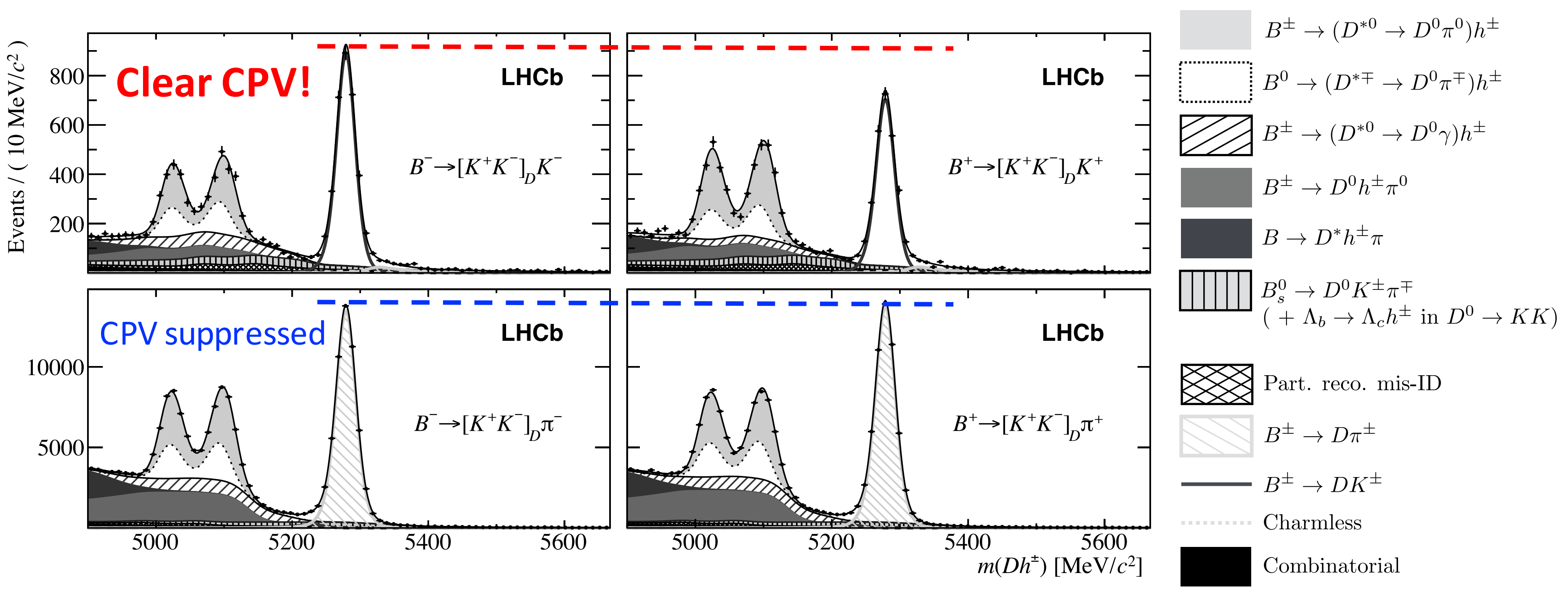
✓ World average $\gamma = (73.5^{+4.3}_{-5.0})°$; LHCb dominate [HFLAV: arXiv:1612.07233]

- Indirect measurement (fit from CKM triangle): $\gamma = (65.3^{+1.0}_{-2.5})°$

[CKMfitter: EPJC 41, 1-131 (2005)]

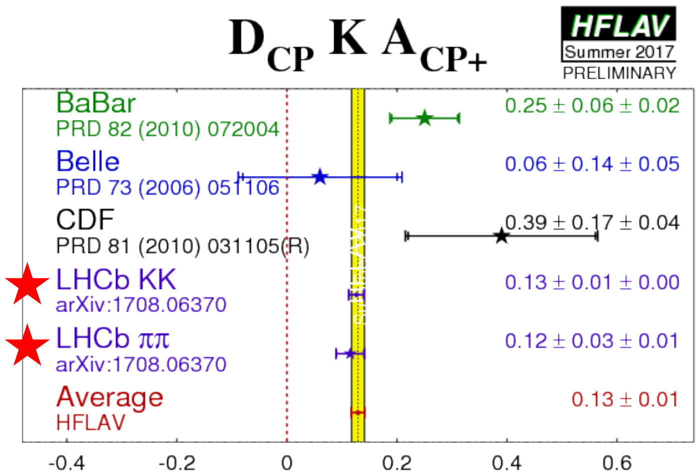
γ from $B^{\pm} \to D^{(*)}K^{\pm}/\pi^{\pm}$ [arXiv: 1708.06370]

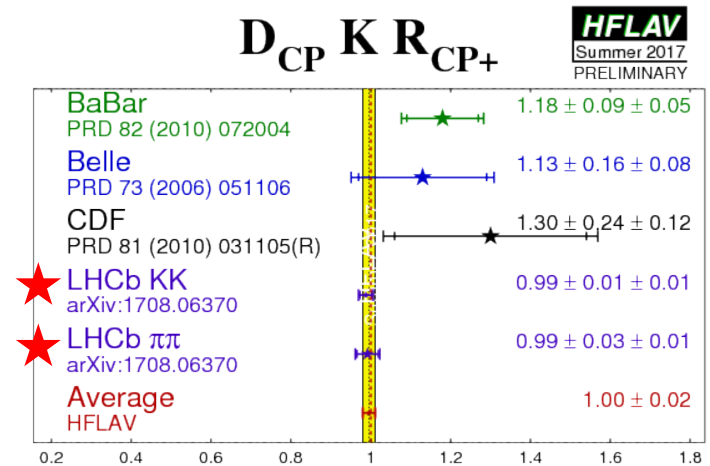
- Using 1.0, 2.0 and 2.0 fb^{-1} data at $\sqrt{s} = 7, 8$ and 13 TeV
- $D^* \to D\pi^0(\gamma)$, partially reconstructed without $\pi^0(\gamma)$
  - ✓ Partial reconstruction used for the first time
  - ✓ Strong phase difference of 180° between $D\pi^0$ and $D\gamma$
- D fully reconstructed using $K^{\pm}\pi^{\mp}, K^+K^-, \pi^+\pi^-$



γ from $B^{\pm} \to D^{(*)}K^{\pm}/\pi^{\pm}$ (cont.) [arXiv: 1708.06370]

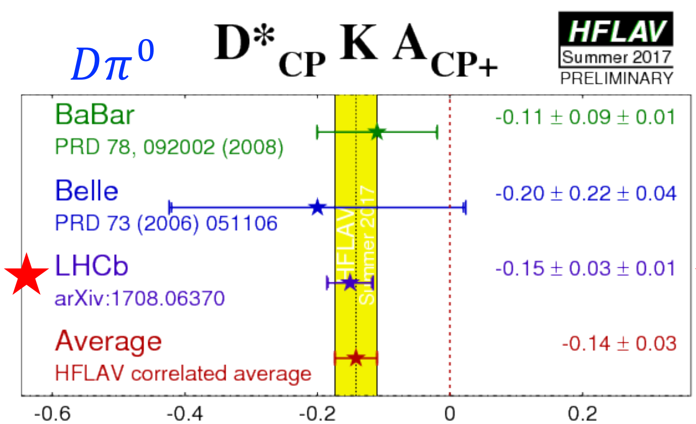
- $B^{-} \to Dh^{-}$: world-best CP observables with $K^{+}K^{-}$,$\pi^{+}\pi^{-}$

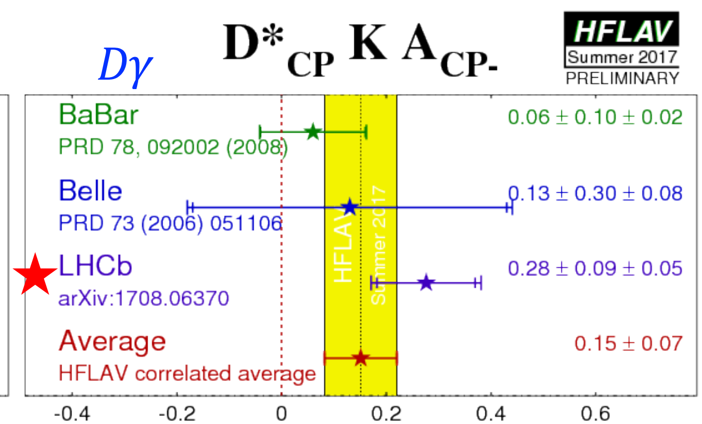


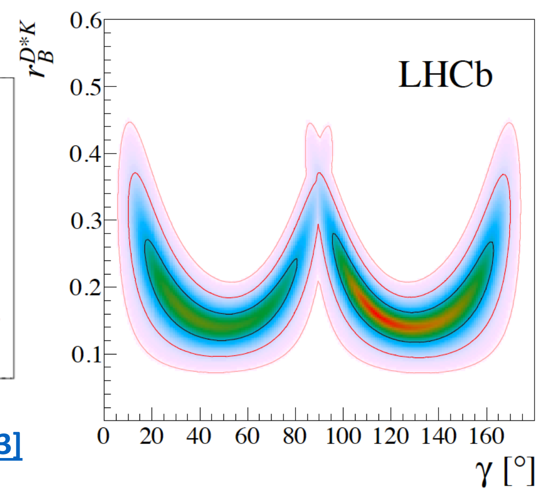


[HFLAV: arXiv:1612.07233]

- $B^{-} \to D^{*}h^{-}$: largely improve world-average & determine γ



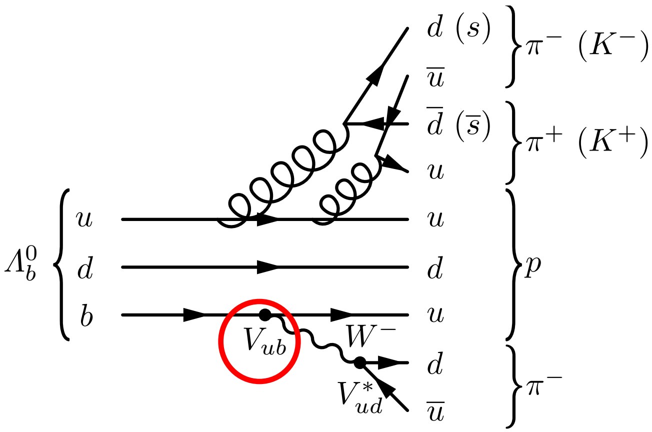


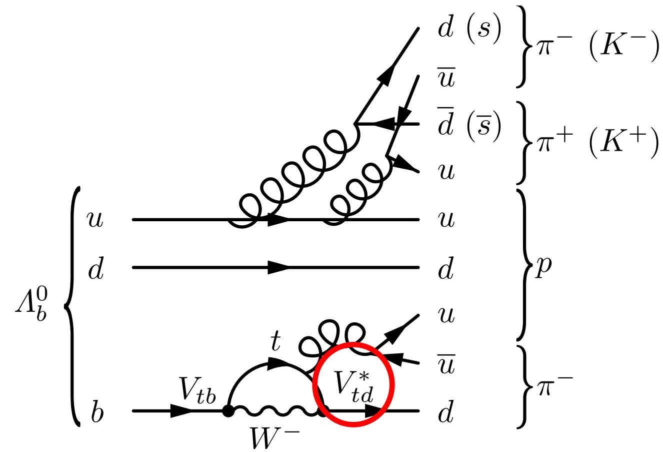


[HFLAV: arXiv:1612.07233]

CPV in $\Lambda_b^0 \to p\pi^-\pi^+\pi^-/K^+K^-$ [arXiv: 1609.05216]

- No CPV observed in baryon sector yet
- CPV in $\Lambda_b^0 \to p\pi^-\pi^+\pi^-/K^+K^-$ can arise from interference of:



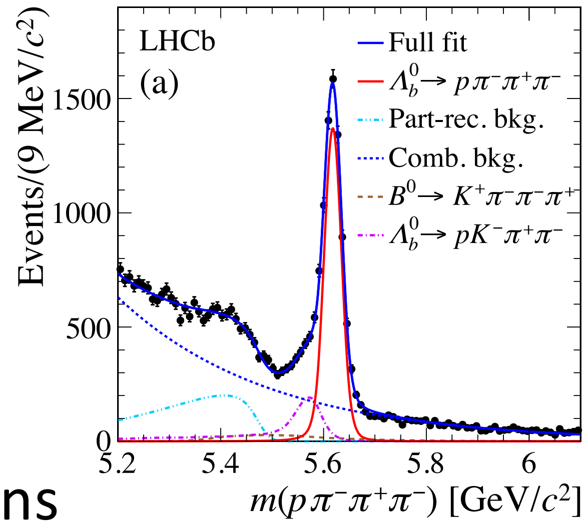


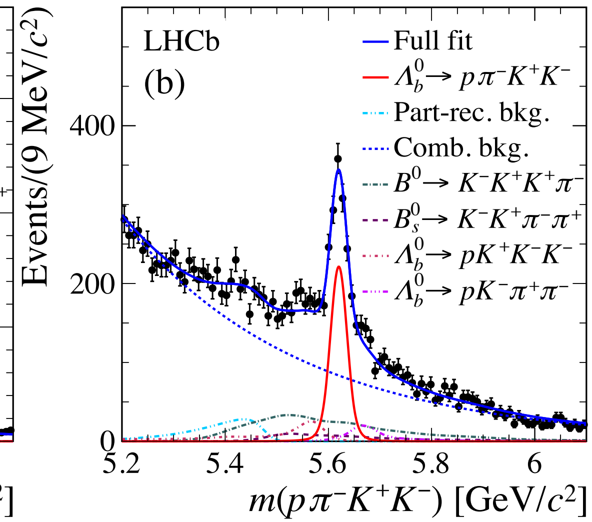
- Construct variable $\begin{cases} \Lambda_b^0: C = \vec{p}_p \cdot (\vec{p}_{h_1^-} \times \vec{p}_{h_2^+}) \\ \bar{\Lambda}_b^0: \bar{C} = \vec{p}_{\bar{p}} \cdot (\vec{p}_{h_1^+} \times \vec{p}_{h_2^-}) \end{cases}$
- P-odd asymmetries $\begin{cases} A(C) = \dfrac{N(C>0) - N(C<0)}{N(C>0) + N(C<0)} \\ \bar{A}(\bar{C}) = \dfrac{\bar{N}(-\bar{C}>0) - \bar{N}(-\bar{C}<0)}{\bar{N}(-\bar{C}>0) + \bar{N}(-\bar{C}<0)} \end{cases}$
- P- and CP-violating (if $\neq 0$) observables: $a_P^{\text{odd}} = \frac{1}{2}(A + \bar{A})$, $a_{CP}^{\text{odd}} = \frac{1}{2}(A - \bar{A})$

CPV in $\Lambda_b^0 \to p\pi^-\pi^+\pi^-/K^+K^-$ (cont.)

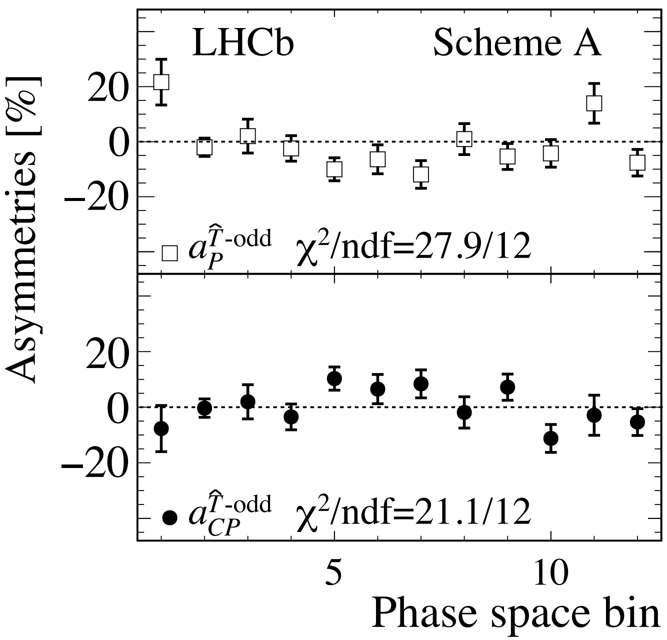
- First observation of $\Lambda_b^0 \to p\pi^-\pi^+\pi^-/K^+K^-$!

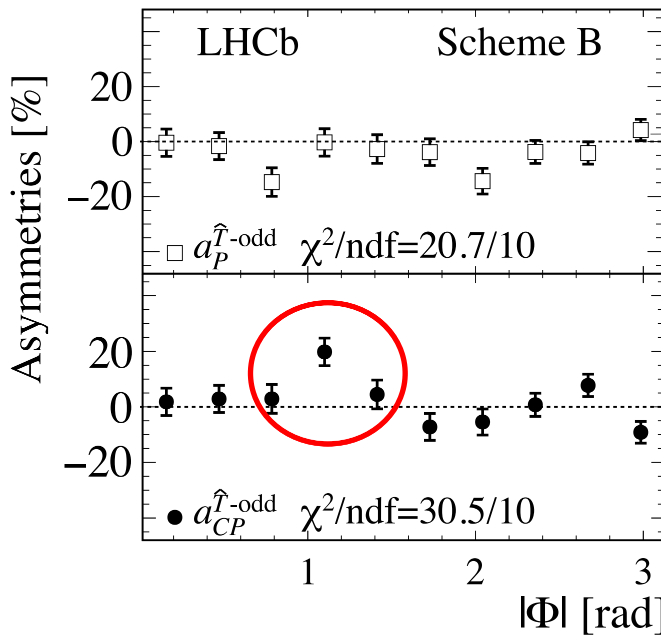
[arXiv: 1609.05216]

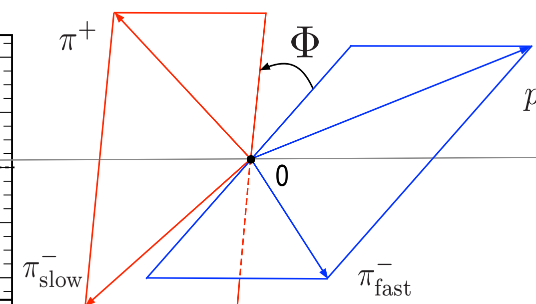




- Asymmetries measured in different phase space regions







CPV evidence in $\Lambda_b^0 \to p\pi^-\pi^+\pi^-$ at 3.3σ!

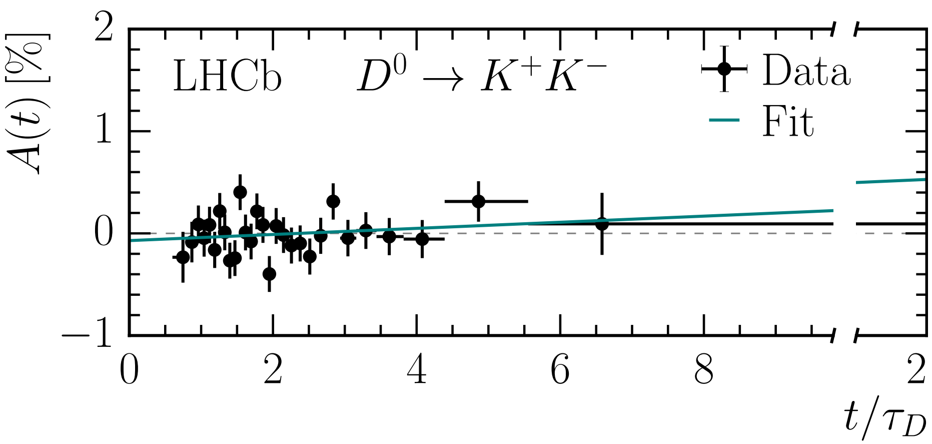
CPV in $D^0 \to K^+K^- \& D^0 \to \pi^+\pi^-$

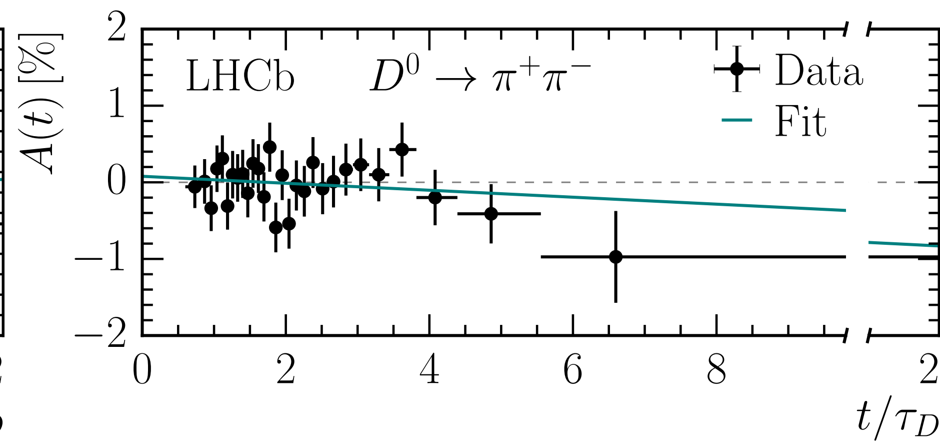
[PRL 118,261803 (2017)]

- CPV in charm practically absent in SM; ideal place to look for NP
- Aim to measure $A_\Gamma \equiv \dfrac{\hat{\Gamma}_{D^0\to f} - \hat{\Gamma}_{\bar{D}^0\to f}}{\hat{\Gamma}_{D^0\to f} + \hat{\Gamma}_{\bar{D}^0\to f}}$ via time-dependent CP asymmetry

$$A_{CP}(t) \equiv \frac{\Gamma(D^0(t)\to f) - \Gamma(\bar{D}^0(t)\to f)}{\Gamma(D^0(t)\to f) + \Gamma(\bar{D}^0(t)\to f)} \simeq a^f_{\rm dir} - A_\Gamma \frac{t}{\tau_D}$$

- Flavor tagged using the pion from $D^{*+} \to D^0\pi^+ (D^{*-} \to \bar{D}^0\pi^-)$





$$A_\Gamma(K^+K^-) = (-0.30 \pm 0.32 \pm 0.10)\times 10^{-3}$$
$$A_\Gamma(\pi^+\pi^-) = (0.46 \pm 0.58 \pm 0.12)\times 10^{-3}$$

No evidence for CPV!

Summary

- LHCb is actively exploring CPV
  - ✓Heavily contribute to $\beta_{(s)}, \gamma$ measurements and other parameters not included here
  - ✓First evidence of CPV in baryon sector
  - ✓No evidence of CPV in charm
- More to come!
  - ✓Fully exploit RunI data
  - ✓Precision to be improved with RunII and future upgrade data

Eg. $\gamma = (73.5^{+4.3}_{-5.0})^\circ \rightarrow \sim 0.9^\circ$ for phase-2 upgrade with $50\ \mathrm{fb}^{-1}$ data

[EPJC 73 (2013) 2373]

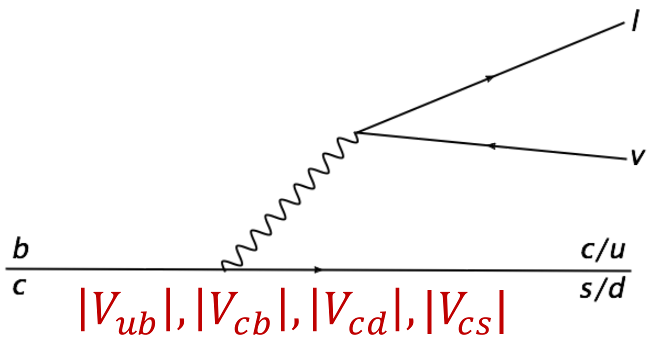
Back up

CPV in b and c sectors

➢ CKM matrix elements related to heavy flavors are less known

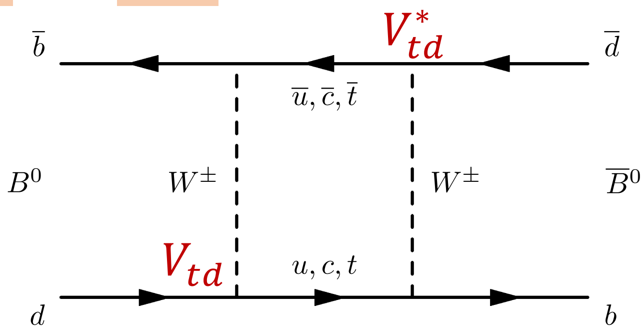
$\|V_{ud}\| = 0.97417$ ($\pm0.02\%$)	$\|V_{us}\| = 0.2248$ ($\pm0.3\%$)	$\|V_{ub}\| = 0.00409$ ($\pm9.5\%$) ★
$\|V_{cd}\| = 0.220$ ($\pm2.3\%$)	$\|V_{cs}\| = 0.995$ ($\pm1.6\%$)	$\|V_{cb}\| = 0.0405$ ($\pm3.7\%$)
$\|V_{td}\| = 0.0082$ ($\pm7.3\%$) ★	$\|V_{ts}\| = 0.0400$ ($\pm6.8\%$) ★	$\|V_{tb}\| = 1.009$ ($\pm3.1\%$)

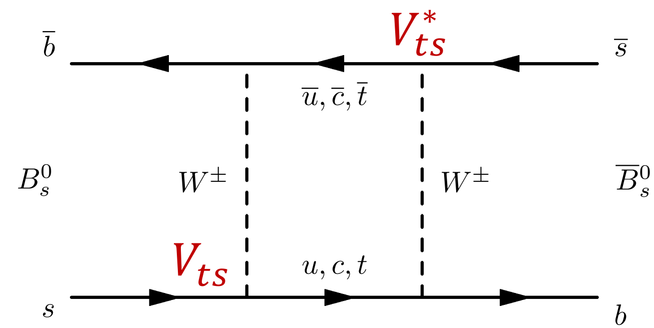
[PDG2017]



✓ $|V_{ub}|$, $|V_{cd}|$, $|V_{cs}|$ and $|V_{cb}|$ can be probed in B and D meson decays;

✓ $|V_{td}|$ and $|V_{ts}|$ are involved in B-$\bar{B}$ oscillations and loop-mediated B decays





✓ ★ Phases of V_{ub}, V_{td} and V_{ts} can be determined using B decays

➢ Various new physics models predict contributions to CP asymmetries in the b and c sectors, with different pictures

γ measurements

$$
\begin{aligned}
\Gamma_{\mp} &\propto r_B^2 + r_D^2 + 2r_B r_D \cos\left(\delta_B + \delta_D \mp \gamma\right), \\
\Gamma &\propto r_B^2 + r_D^2 + 2r_B r_D \cos\left(\delta_B + \delta_D\right)\cos\left(\gamma\right), \\
A &= \frac{2r_B r_D \sin\left(\delta_B + \delta_D\right)\sin\left(\gamma\right)}{r_B^2 + r_D^2 + 2r_B r_D \cos\left(\delta_B + \delta_D\right)\cos\left(\gamma\right)},
\end{aligned}
$$

$$
r_B = \left|\frac{A\left(B^- \to \overline{D}^0 K^-\right)}{A\left(B^- \to D^0 K^-\right)}\right| = \left|\frac{A\left(B^+ \to D^0 K^+\right)}{A\left(B^+ \to \overline{D}^0 K^+\right)}\right| \qquad r_D = \left|\frac{A\left(D^0 \to f\right)}{A\left(\overline{D}^0 \to f\right)}\right|
$$

GLW analysis	
$R_{CP\pm}$	$1 + r_B^2 \pm 2r_B \cos\left(\delta_B\right)\cos\left(\gamma\right)$
$A_{CP\pm}$	$\pm 2r_B \sin\left(\delta_B\right)\sin\left(\gamma\right)/R_{CP\pm}$
ADS analysis	
R_{ADS}	$r_B^2 + r_D^2 + 2r_B r_D \cos\left(\delta_B + \delta_D\right)\cos\left(\gamma\right)$
A_{ADS}	$2r_B r_D \sin\left(\delta_B + \delta_D\right)\sin\left(\gamma\right)/R_{\mathrm{ADS}}$
GGSZ Dalitz analysis ($D \to K_S^0\pi^+\pi^-$)	
$x_\pm$	$r_B \cos(\delta_B \pm \gamma)$
$y_\pm$	$r_B \sin(\delta_B \pm \gamma)$
Dalitz analysis ($D \to \pi^+\pi^-\pi^0$)	
$\rho^\pm$	$\lvert z_\pm - x_0\rvert$
$\theta^\pm$	$\tan^{-1}(\mathrm{Im}(z_\pm)/(\mathrm{Re}(z_\pm) - x_0))$

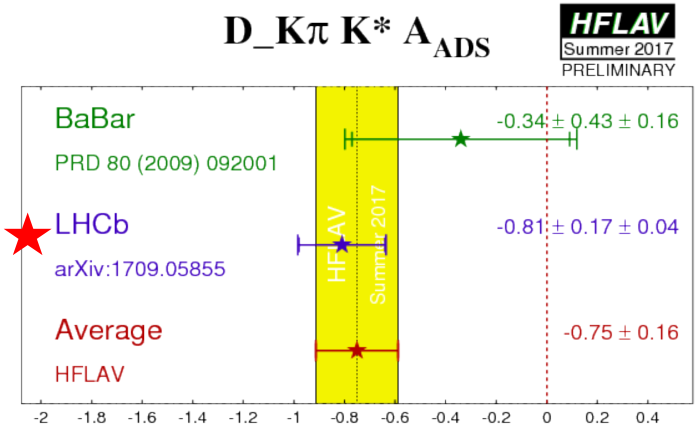
- GLW: f is CP eigenstate
- ADS: Large CPV effects in the interference
- GGSZ&Dalitz: multi-body decay
- Parameters can be shared for the same B decay mode

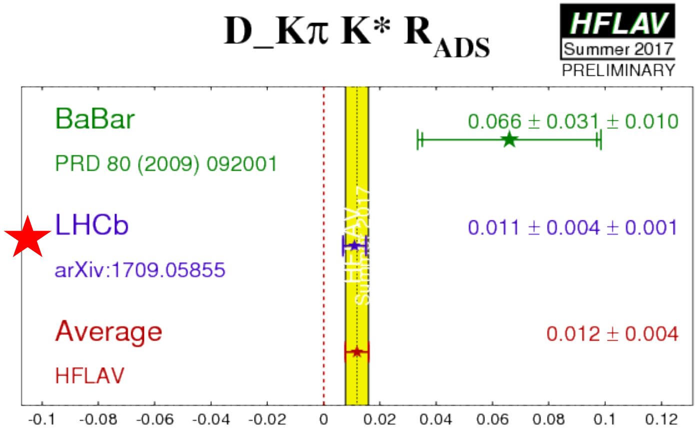
[HFLAV: arXiv:1612.07233]

γ from $B^{\pm} \to D K^{*\pm}$ [arXiv: 1709.05855]

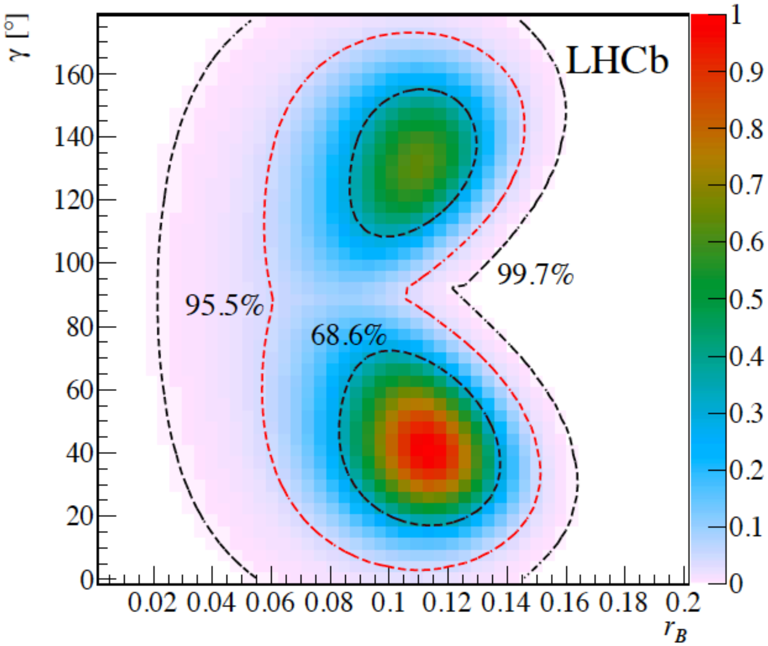
- Using 1.0, 2.0 and 1.8 fb^{-1} data at $\sqrt{s} = 7, 8$ and 13 TeV
- $D \to K^-\pi^+, K^-K^+, \pi^-\pi^+, (K^-/\pi^-)\pi^+\pi^-\pi^+$; $K^{*\pm} \to K_S^0\pi^{\pm}$
- Behavior of intermediate resonances of D four-body decays known

$\Rightarrow$CP asymmetries in two-body modes more precise than Babar



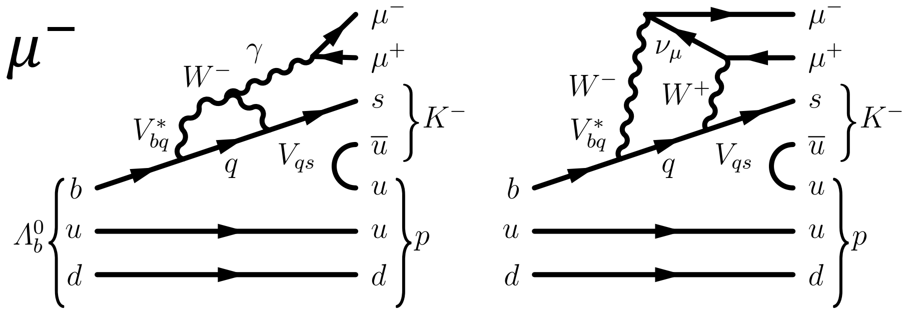


✓ γ determined using all modes:

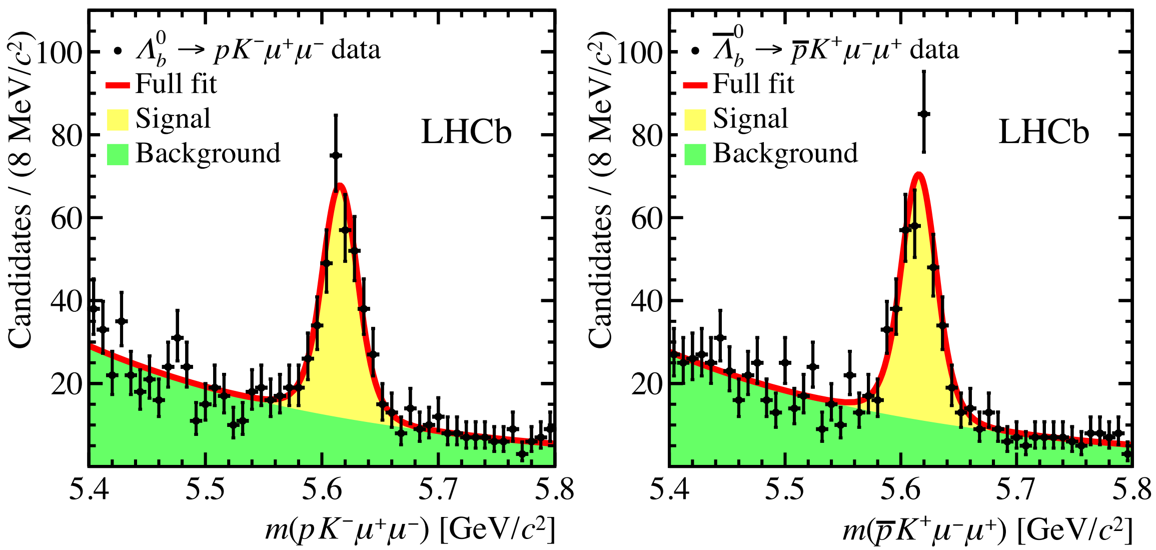


CPV in $\Lambda_b^0 \to pK^-\mu^+\mu^-$ [JHEP 06 (2017) 108]

- A rare FCNC process with $b \to s\mu^+\mu^-$



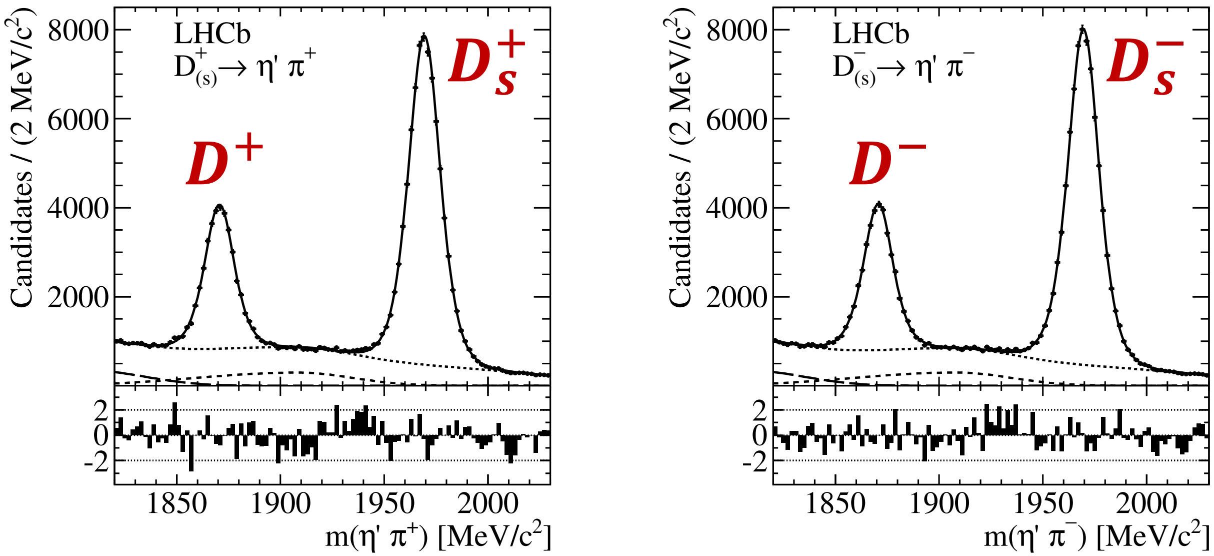
- CPV limited in SM; sensitive to CPV from beyond SM
- Observables: $\Delta\mathcal{A}_{CP} \equiv \mathcal{A}_{CP}(\Lambda_b^0 \to pK^-\mu^+\mu^-) - \mathcal{A}_{CP}(\Lambda_b^0 \to pK^-J/\psi)$ & a_{CP}^{odd}
  - ✓ Sensitive to different types of CPV effects from new physics
- First observation of the decay; consistent with no CPV



CPV in $D^\pm \to \eta'\pi^\pm$ & $D_s^\pm \to \eta'\pi^\pm$ [PLB 771 (2017) 21-30]

- Using $D^\pm \to K_S^0\pi^\pm$ and $D_s^\pm \to \phi\pi^\pm$ as control channels so that production and detection asymmetries cancel

$$\begin{aligned}\Delta\mathcal{A}_{CP}(D^\pm \to \eta'\pi^\pm) &\equiv \mathcal{A}_{CP}(D^\pm \to \eta'\pi^\pm) - \mathcal{A}_{CP}(D^\pm \to K_S^0\pi^\pm)\\ &= \mathcal{A}_{\rm raw}(D^\pm \to \eta'\pi^\pm) - \mathcal{A}_{\rm raw}(D^\pm \to K_S^0\pi^\pm) + \mathcal{A}(\overline{K}^0 - K^0),\\ \Delta\mathcal{A}_{CP}(D_s^\pm \to \eta'\pi^\pm) &\equiv \mathcal{A}_{CP}(D_s^\pm \to \eta'\pi^\pm) - \mathcal{A}_{CP}(D_s^\pm \to \phi\pi^\pm)\\ &= \mathcal{A}_{\rm raw}(D_s^\pm \to \eta'\pi^\pm) - \mathcal{A}_{\rm raw}(D_s^\pm \to \phi\pi^\pm).\end{aligned}$$



$$\mathcal{A}_{CP}(D^\pm \to \eta'\pi^\pm) = (-0.61 \pm 0.72 \pm 0.53 \pm 0.12)\%$$

$$\mathcal{A}_{CP}(D_s^\pm \to \eta'\pi^\pm) = (-0.82 \pm 0.36 \pm 0.22 \pm 0.27)\%$$

- ✓ Most precise measurement
- ✓ No evidence for CPV