CP Violation at LHCb

Discrete Symmetries in Particle, Nuclear and Atomic Physics
and implications for our Universe

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on behalf of the LHCb Collaboration

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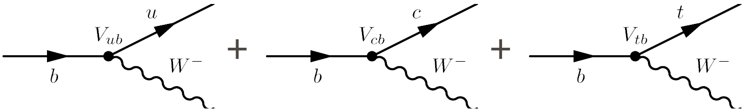
Rostock

Introduction

- Diagonalizing Yukawa matrices leads to **quark mass eigenstates** q, but skews **quark flavor eigenstates** q'

$$\mathcal{J}^{\mu}_{cc} \supset (\overline{u'}, \overline{c'}, \overline{t'})\, \gamma^{\mu} \frac{1-\gamma^5}{2} \begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} \longrightarrow (\overline{u}, \overline{c}, \overline{t})\, \gamma^{\mu} \frac{1-\gamma^5}{2} V_{\text{CKM}} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$



- This introduces the non-trivial transformation matrix V_{CKM} for quarks (CKM matrix)
- V_{CKM} is a **unitary** 3×3 matrix

The CKM Matrix

$$V_{\text{CKM}} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} = \underbrace{\begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - \mathrm{i}\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-\mathrm{i}\eta) & -A\lambda^2 & 1 \end{pmatrix}}_{\text{cf. Wolfenstein: Phys. Rev. Lett. 51 (1945), 21}} + \mathcal{O}(\lambda^3)$$

$$\lambda \approx .23, A \approx .81, \rho \approx .14, \eta \approx .35$$

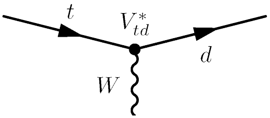
- → One non-trivial complex phase, encoded in matrix elements
  - → V_{ub} and V_{td} (up to $\mathcal{O}(\lambda^2)$)
  - → V_{cd}, V_{cs} and V_{ts} (up to $\mathcal{O}(\lambda^6)$)
- → CP violation (CPV) if and only if $\eta \neq 0$

CP violation (?)

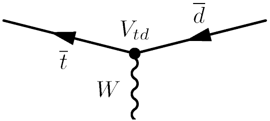
- If $\eta \neq 0$ some V_{ij} carry a complex phase (*weak* phase)
  - amplitude: $\mathcal{A}(t \to dW^+) \sim V_{td}^*$
  - amplitude: $\bar{\mathcal{A}}(\bar{t} \to \bar{d}W^-) \sim V_{td}$
  - CPV since $\mathcal{A} \neq \bar{\mathcal{A}}$ (?)

… not quite

- Amplitude $\mathcal{A}$ is not observable …
- … but branching fraction $\mathcal{B} \sim |\mathcal{A}|^2$
  - CPV needs at least two interfering decay modes with …
  - … one **CP odd** and one **CP even** phase



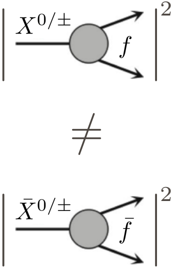
$t \to dW^+$



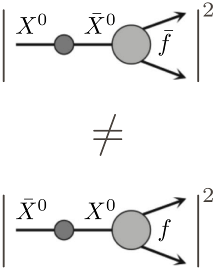
$\bar{t} \to \bar{d}W^-$

Types of CPV

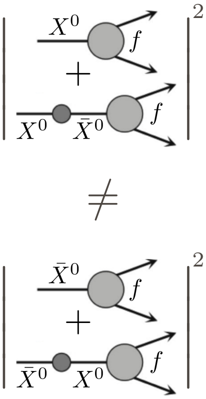
(1) Direct CPV



(2) CPV in mixing



(3) CPV in interference of mixing and decay



(Images: *CP Violation*, I. I. Bigi and A. I. Sanda)

- CP odd: from CKM matrix
- CP even:
  - (1): strong phase difference between both amplitudes (e.g. *tree* and *penguin*)
  - (2),(3): $\pi/2$ (**constant!**)

The CKM Matrix

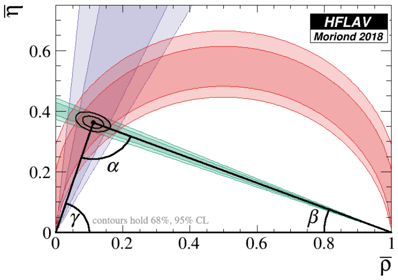
Another parametrization – Prog. Part. Nucl. Phys. 47 (2001)

$$V_{\text{CKM}} = \begin{pmatrix} |V_{ud}| & |V_{us}| & |V_{ub}|e^{-i\tilde{\gamma}} \\ -|V_{cd}|e^{+i\phi_4} & |V_{cs}|e^{-i\phi_6} & |V_{cb}| \\ |V_{td}|e^{-i\tilde{\beta}} & -|V_{ts}|e^{+i\phi_2} & |V_{tb}| \end{pmatrix}$$

$$\gamma \equiv \tilde{\gamma} - \phi_4, \qquad \phi_2 \approx \eta\lambda^2$$
$$\beta \equiv \tilde{\beta} + \phi_4, \qquad \phi_4 \approx \eta A^2\lambda^4$$
$$\alpha \equiv \pi - \beta - \gamma, \qquad \phi_6 \approx \eta A^4\lambda^6$$
$$\beta_s \equiv \phi_s \equiv \phi_2 + \phi_6$$

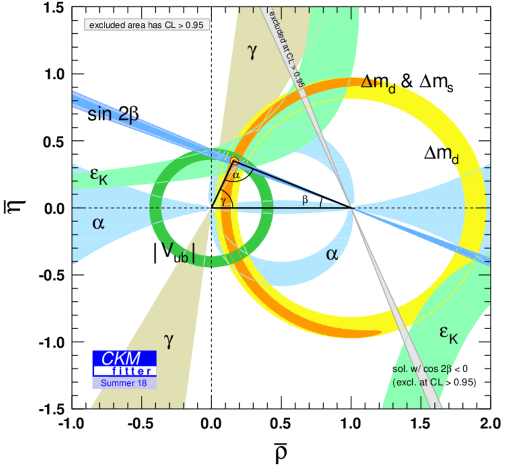
- From unitarity: 6 triangles
  - $V_{ud}V_{us}^* + V_{cd}V_{cs}^* + V_{td}V_{ts}^* = 0$
  - $V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0$
  - … 4 more
- Angles $\tilde{\alpha}$, $\tilde{\beta}$, $\tilde{\gamma}$ and $\phi_{2,4,6}$ **depend on phase convention** (i.e. not observable)
- Phases of products $V_{ij}V_{kl}V_{il}^*V_{kj}^*$ are **invariant** and **observable** (e.g. α, β, γ, …)

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

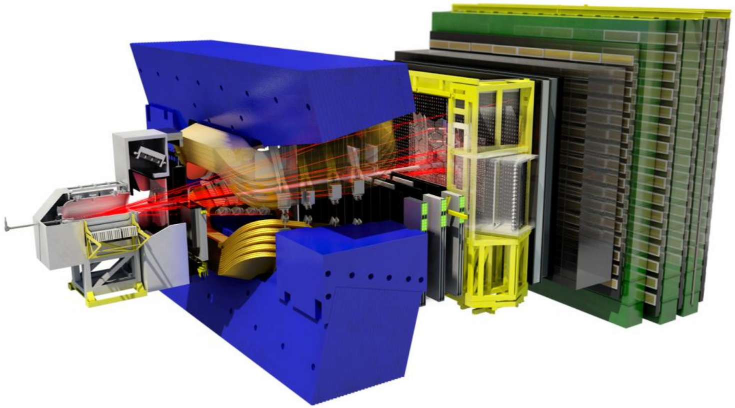


Probing the SM by Overconstraining

- **Motivation:**
  - We utterly fail explaining CPV on cosmological scale!
  - Is the CKM matrix the only source of CPV?
  - Is the SM incomplete / are there more particles?
- **Strategy:**
  - Overconstrain CKM triangles by measuring
    - sides – e.g. $|V_{td}V_{tb}^*|$
    - angles – e.g. $\gamma = \arg\left(-\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}\right)$
  - Is $\beta_s = \arg\left(-\frac{V_{ts}V_{tb}^*}{V_{cs}V_{cb}^*}\right)$ tiny? ($\mathcal{O}(\lambda^2)$)
  - Any deviation would point towards **new physics**, e.g. 4th quark family?



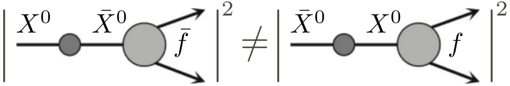
The LHCb Detector



more information: *The LHCb Detector at the LHC*, JINST 3 (2008), `S08005`

or visit: `http://lhcb-public.web.cern.ch/`

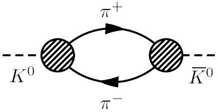
CPV in Mixing

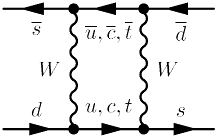


CPV in Mixing

Neutral mesons mix through weak interactions

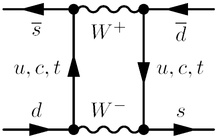
- CPV if $\mathcal{P}(X^0 \to \bar{X}^0) \neq \mathcal{P}(\bar{X}^0 \to X^0)$
- SM: CPV large for $K^0/\bar{K}^0$ (first discovery of CPV)
- SM: CPV small for $B^0_{(s)}/\bar{B}^0_{(s)}$





Example: CPV in mixing for $B^0_{(s)}/\bar{B}^0_{(s)}$ in semileptonic modes

- $B^0 \to D^{(*)-}\mu^+\nu_\mu X^\star$
- $B^0_s \to D^-_s\mu^+\nu_\mu X^{\star\star}$
- decays are theoretically clean
  - flavor specific
  - CP-conserving
  - tree-dominated



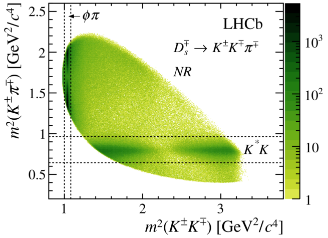
*Phys. Rev. Lett. 114 (2015), 041601, **Phys. Rev. Lett. 117 (2016), 061803

CPV in Mixing

Example: $B_s^0 \to D_s^- \mu^+ \nu_\mu X$

- CPV parametrization:
  - Semileptonic CP asymmetry (const. in time)

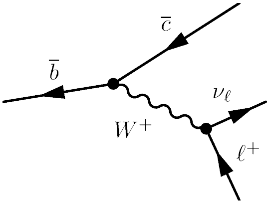
$$a_{\text{sl}}^s = \frac{\Gamma(\bar{B}_s^0 \to D_s^- \mu^+ | t) - \Gamma(B_s^0 \to D_s^+ \mu^- | t)}{\Gamma(\bar{B}_s^0 \to D_s^- \mu^+ | t) + \Gamma(B_s^0 \to D_s^+ \mu^- | t)}$$



Phys. Rev. Lett. 117 (2016), 061803

- Observables:
  - $\Gamma[D_s^- \mu^+, t] \equiv \Gamma(\bar{B}_s^0 \to D_s^- \mu^+ | t) + \Gamma(B_s^0 \to D_s^- \mu^+ | t)$
  - $\Gamma[D_s^+ \mu^-, t] \equiv \Gamma(B_s^0 \to D_s^+ \mu^- | t) + \Gamma(\bar{B}_s^0 \to D_s^+ \mu^- | t)$

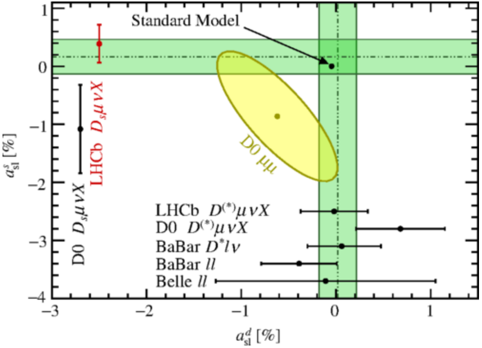
$$\frac{\Gamma[D_s^- \mu^+, t] - \Gamma[D_s^+ \mu^-, t]}{\Gamma[D_s^- \mu^+, t] + \Gamma[D_s^+ \mu^-, t]} = \frac{a_{\text{sl}}^s}{2} \underbrace{\left(1 - \frac{\cos \Delta m_s t}{\cosh \Delta\Gamma t/2}\right)}_{\approx 1 \text{ for fast oscillation}}$$



CPV in Mixing

$$A_{\text{raw}} \equiv \frac{\Gamma[D_s^- \mu^+, t] - \Gamma[D_s^+ \mu^-, t]}{\Gamma[D_s^- \mu^+, t] + \Gamma[D_s^+ \mu^-, t]} \approx \frac{a_{\text{sl}}^s}{2}$$

- Fast oscillation of B_s:
  - no dependency on production asymmetry between B_s and $\bar{B}_s$
  - measure A_{raw} time-integrated
  - include detection and background asymmetries
- Reconstruct $D_s^{\mp} \to K^+ K^- \pi^{\mp}$ in various subsamples of
  - magnet polarity
  - Dalitz regions
  - data taking periods



a_{sl}^d: Phys. Rev. Lett. 114 (2015), 041601

a_{sl}^s: Phys. Rev. Lett. 117 (2016), 061803

$$a_{\text{sl}}^s = (.39 \pm .26\,(\text{stat.}) \pm .20\,(\text{syst.}))\,\%$$

CPV in Mixing

$$A_{\text{raw}} \equiv \frac{\Gamma[D_s^- \mu^+, t] - \Gamma[D_s^+ \mu^-, t]}{\Gamma[D_s^- \mu^+, t] + \Gamma[D_s^+ \mu^-, t]} \approx \frac{a_{\text{sl}}^s}{2}$$

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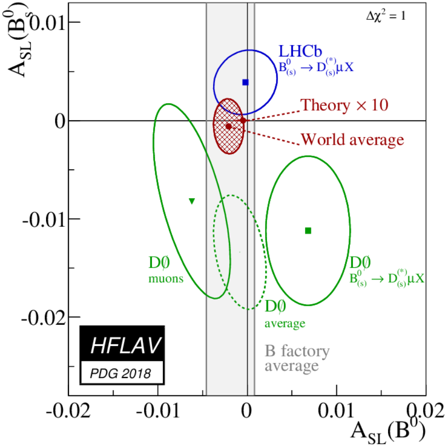
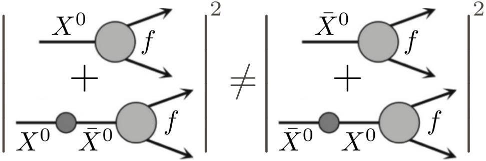
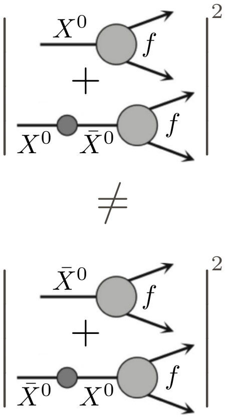


CPV in Mixing and Decay



Golden Channel: $B^0 \to J/\psi K_s$

- $B^0/\bar{B}^0$ decays to CP eigenstate $J/\psi K_s$
- Theoretically clean mode
  - leading transitions via tree
  - penguin strongly suppressed
  - no CPV from mixing expected
- sensitive to $\sin 2\beta$ (*Golden Channel*)

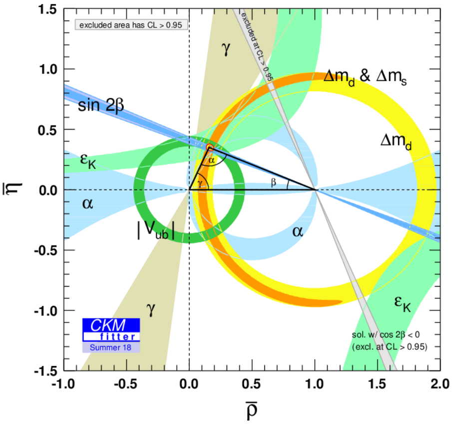


CPV in Mixing and Decay

- Reconstruct: $B^0 \to [c\bar{c}]K_s$
  - $[c\bar{c}] = J/\psi \to \mu\mu^{\star}$
  - $[c\bar{c}] = J/\psi \to ee, \psi(2S) \to \mu\mu^{\star\star}$
- Measure:
  - $\Gamma(t) \equiv \Gamma(B^0(t{=}0) \to [c\bar{c}]K_s|t)$
  - $\bar{\Gamma}(t) \equiv \Gamma(\bar{B}^0(t{=}0) \to [c\bar{c}]K_s|t)$
- CPV observable: $(\bar{\Gamma} - \Gamma)/(\bar{\Gamma} + \Gamma)(t)$

$$\approx -C\cos(\Delta m t) + S\sin(\Delta m t)$$

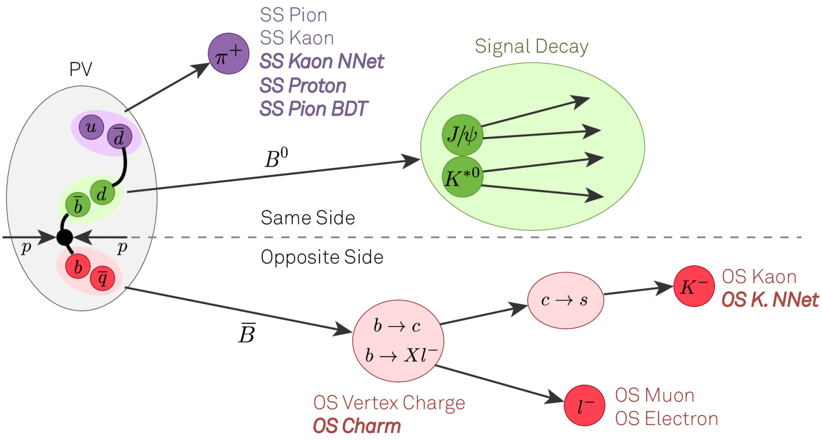
  - assuming negligible CPV in mixing
  - $C \approx 0$ ($\sim$ (no) direct CPV)
  - $S = \sin 2\beta$



*Phys. Rev. Lett. 115 (2015), 031601

**JHEP11 (2017), 170

Tagging at LHCb

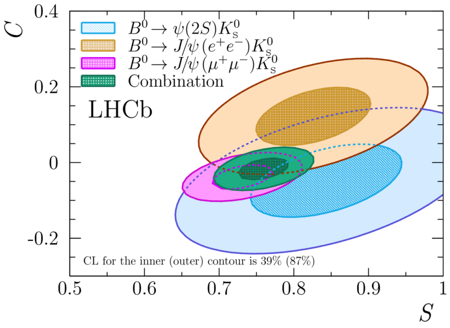


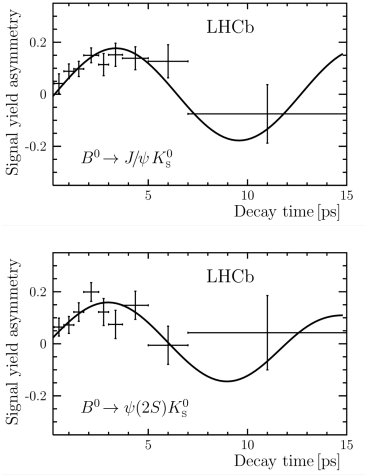
Time-dependent CP measurements need **flavor** of $B^0/\bar{B}^0$-system **at production time!**

CPV in Mixing and Decay

Combined results:

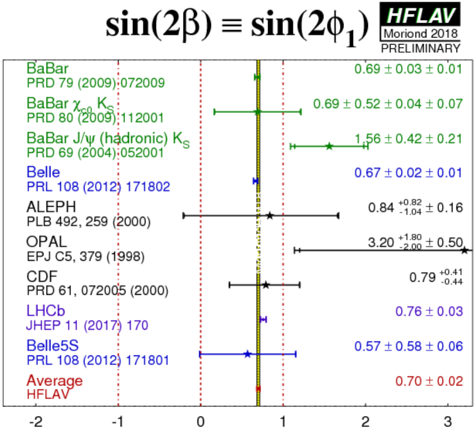
- → Direct CPV: $C(B^0 \to [c\bar{c}]K_s) = -.014(30)$
- → $\sin 2\beta = S(B^0 \to [c\bar{c}]K_s) = -.75(4)$





$\sin 2\beta$ has a two-fold ambiguity: $2\beta \leftrightarrow \pi - 2\beta$; cf. `arXiv:1804.06152` (2018): combined dataset of Babar and Belle excludes $\pi - 2\beta$ (@ $7.3\,\sigma$)

CPV in Mixing and Decay

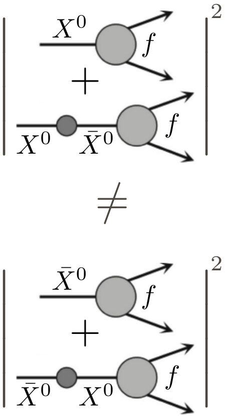


LHCb measurements are already competitive with B-factories!

Another Channel: $B^0_{(s)}/\bar{B}^0_{(s)} \to h^+h^-$

- $B^0_{(s)}/\bar{B}^0_{(s)}$ decays to CP eigenstates $\pi^+\pi^-$ or K^+K^-
- Theoretically nuisance: **tree** and **penguin** contributions
- CPV observable: $(\bar{\Gamma}-\Gamma)/(\bar{\Gamma}+\Gamma)(t)$

$$= \frac{-C_f \cos(\Delta m_{d,s} t) + S_f \sin(\Delta m_{d,s} t)}{\cosh(\Delta\Gamma_{d,s} t/2) + A_f^{\Delta\Gamma} \sinh(\Delta\Gamma_{d,s} t/2)}$$



CPV in interference of mixing and decay

$$A_{\mathrm{CP}}(t) = \frac{-C_f \cos(\Delta m_{d,s} t) + S_f \sin(\Delta m_{d,s} t)}{\cosh(\Delta\Gamma_{d,s} t/2) + A_f^{\Delta\Gamma} \sinh(\Delta\Gamma_{d,s} t/2)}$$

→ Parameters C_f, S_f and $A_f^{\Delta\Gamma}$ are completely defined by $\lambda_f \in \mathbb{C}$

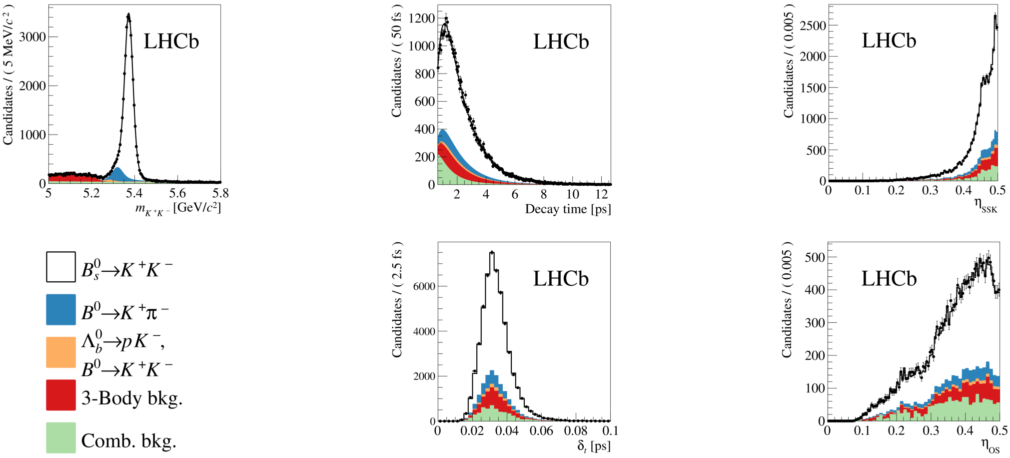
$$\lambda_f \equiv \underbrace{\frac{\langle \bar{X}^0 | X_L \rangle}{\langle X^0 | X_L \rangle}}_{q/p} \underbrace{\frac{\mathcal{A}(\bar{X}^0 \to f)}{\mathcal{A}(X^0 \to f)}}_{\mathcal{A}_f/\bar{\mathcal{A}}_f}$$

- → direct CPV if $|\mathcal{A}_f/\bar{\mathcal{A}}_f| \neq 1$
- → CPV in oscillation if $|q/p| \neq 1$
- → CPV from interference of mixing and decay if $\mathrm{Im}(\lambda_f) \neq 0$

$$\text{CPV} \Leftrightarrow \lambda_f \neq 1$$

CPV in Mixing and Decay

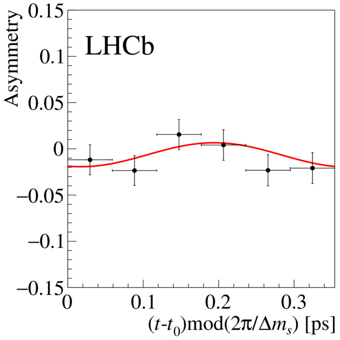
Fit simultaneously to unfold time-dependent CP asymmetries



Phys. Rev. D98 (2018), 032004

CPV in interference of mixing and decay

- Obtain $C_{KK}, S_{KK}, A^{\Delta\Gamma}_{KK}$ (and $A_{\text{CP}}(B^0_{(s)})$) from simultaneous fit to:
  - invariant mass
  - decay time + uncertainty
  - tagging decision + associated mistag probabilities
- unfold time-dependent asymmetries
- Check: $\lambda_{KK} = 1$
  $$\Leftrightarrow (C_{KK}, S_{KK}, A^{\Delta\Gamma}_{KK}) = (0, 0, -1)$$
  - Excluded by 4σ! (for B^0_s)



Same side tag for $B^0_s \to K^+K^-$

(Phys. Rev. D98 (2018), `032004`)

Strongest evidence for time-dependent CPV in B^0_s to date!

CPV in interference of mixing and decay

- Obtain $C_{KK}, S_{KK}, A^{\Delta\Gamma}_{KK}$ (and $A_{\text{CP}}(B^0_{(s)})$) from simultaneous fit to:
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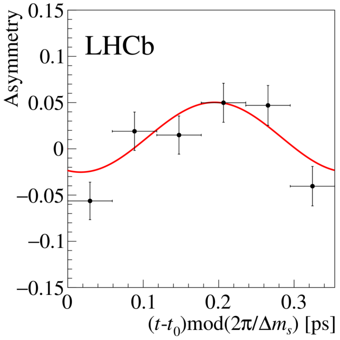


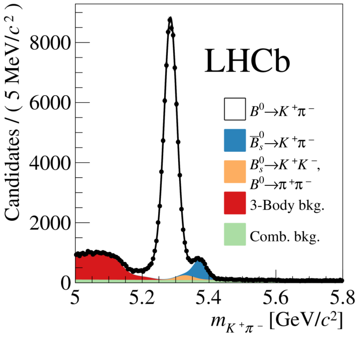
Opposite side tag for $B^0_s \to K^+K^-$

(Phys. Rev. D98 (2018), `032004`)

Strongest evidence for time-dependent CPV in B^0_s to date!

CPV in interference of mixing and decay

- Same machinery for $B^0 \to \pi^+\pi^-$
  - most precise measurements of $C_{\pi\pi}$ and $S_{\pi\pi}$ from a single experiment to date
  - combination of both measurements allow stringent constraints on γ and β_s
- Measurement of CP asymmetry $A_{\mathrm{CP}}^{B^0}$ and $A_{\mathrm{CP}}^{B_s^0}$
  - most precise measurements from a single experiment to date
  - improve constraints on BSM that contributes to loop diagrams



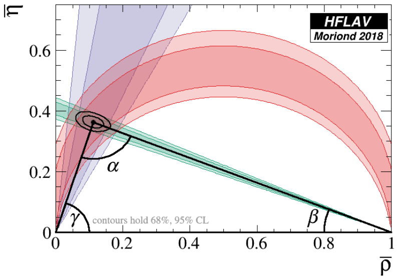
Phys. Rev. D98 (2018), 032004

CKM Angle γ

Why γ?

- γ (had been) the CKM angle with largest uncertainties amongst α, β, γ
- γ does **not depend on any top quark coupling!**
  - measurements are dominated by **tree** contributions!
  - smaller uncertainties in physical observables!
  - but: **direct CPV**, i.e. strong phases and suppression by lowest amplitude

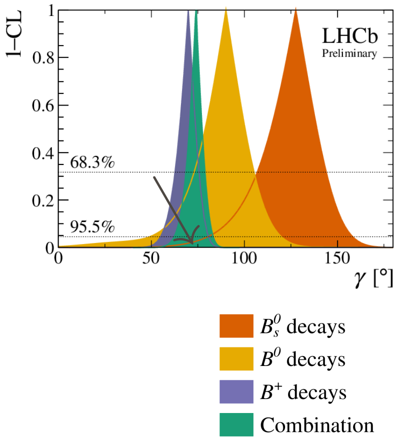
$$\gamma \equiv \arg\left(-\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}\right)$$



CKM Angle γ

LHCb Combination – LHCb-CONF-2018-002

- Time-integrated amplitude analyses (GLW, ADS, GLW+ADS, GGSZ, …)
  - $B^+ \to D^{(*)}K^+, DK^{(*)+}$
  - $B^0 \to DK^{*0}$
  - $B^0 \to DK^+\pi^-$
  - $B^+ \to DK^+\pi^+\pi^-$
- Time-dependent
  - $B_s^0 \to D_s^{\mp}K^{\pm}$
  - $B^0 \to D^{\mp}\pi^{\pm}$



Best Fit value: $\gamma_{\text{LHCb}} = (74.0^{+5.0}_{-5.8})^\circ$

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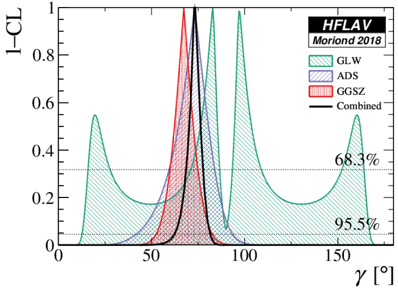
- → Most precise measurement from a single experiment (to date)
- → cf. full BaBar dataset: $\gamma_{\text{BaBar}} = (69^{+17}_{-16})^\circ$ (Phys. Rev. D87 (2013), 052015)



$\gamma_{\text{HFLAV}} = (73.5^{+4.2}_{-5.1})^\circ$

There is more!

There is more at LHCb

- There are more angles than β and γ and LHCb can measure these!
- LHCb also probes the baryon sector for CPV, e.g.
  - $\Lambda_b \to p\pi^-\pi^+\pi^-, p\pi^-K^+K^-$
  - $\Lambda_b \to p\pi^-, pK^-$
- Besides CPV: probing *lepton universality*, e.g.
  - $B^+ \to K^+\ell^+\ell^-$
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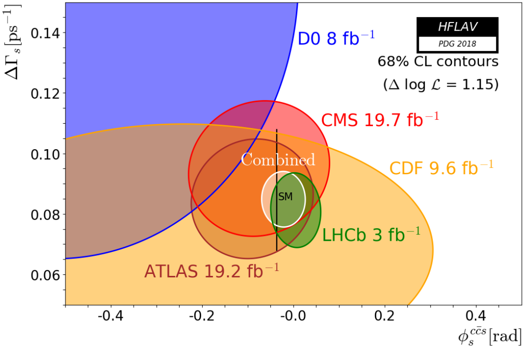
- …



Including four LHCb measurements (i.a. first evidence for $\Delta\Gamma_s > 0$!)

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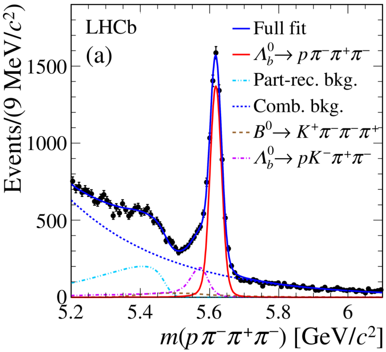

First evidence (3.3σ) for CPV in baryon sector

(Nature Physics 13 (2017), 391)

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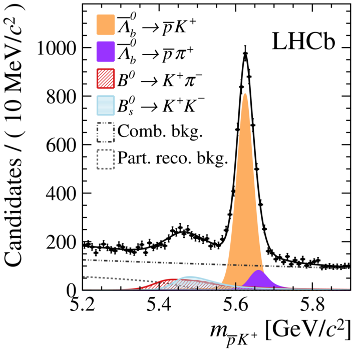

Most precise measurement to date, compatible with no direct CP violation in $\Lambda_b \to ph^-$ (arXiv:1807.06544, 2018)

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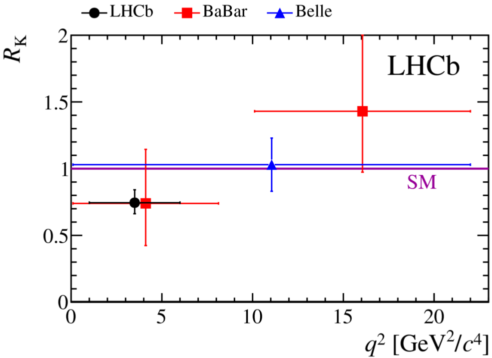

Most precise measurements of R_{K^0} to date (lepton universality), compatible with SM at 2.6σ (Phys. Rev. Lett. 113 (2014), 151601)

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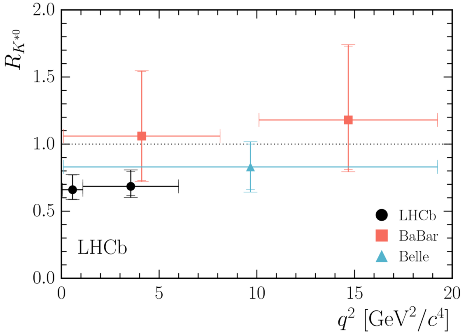

Most precise measurements of $R_{K^{*0}}$ to date (lepton universality), compatible with SM at $2.1 \ldots 2.3\sigma$ and $2.4 \ldots 2.5\sigma$ (JHEP 08 (2017), 055)

There is more at LHCb

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- LHCb also probes the baryon sector for CPV, e.g.
  - $\Lambda_b \to p\pi^-\pi^+\pi^-, p\pi^-K^+K^-$
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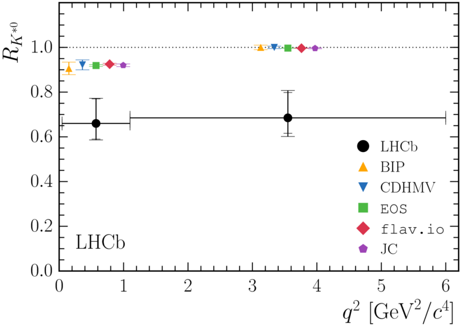

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- $\dots$

Universität Rostock

ECT*

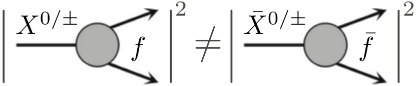
Bundesministerium für Bildung und Forschung

LHCb

Thank you for your attention!

Backup

Direct CP Violation

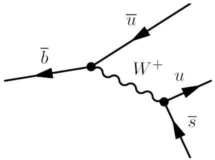


Example: Direct CP Violation

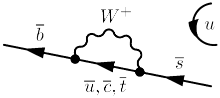
Decay $X \to Y$ via **two different channels** (*weak* phases $\phi_{1,2}$, *strong* phases $\delta_{1,2}$)

$$\mathcal{A}(X \to Y) = |\mathcal{A}_1| e^{+i\phi_1 + i\delta_1} + |\mathcal{A}_2| e^{+i\phi_2 + i\delta_2}$$
$$\bar{\mathcal{A}}(\bar{X} \to \bar{Y}) = |\mathcal{A}_1| e^{-i\phi_1 + i\delta_1} + |\mathcal{A}_2| e^{-i\phi_2 + i\delta_2}$$

$$\frac{|\bar{\mathcal{A}}|^2 - |\mathcal{A}|^2}{|\bar{\mathcal{A}}|^2 + |\mathcal{A}|^2} = \frac{2|\mathcal{A}_1||\mathcal{A}_2| \sin(\phi_1 - \phi_2) \sin(\delta_1 - \delta_2)}{|\mathcal{A}_1|^2 + |\mathcal{A}_2|^2 + 2|\mathcal{A}_1||\mathcal{A}_2| \cos(\phi_1 - \phi_2) \cos(\delta_1 - \delta_2)}$$



tree diagram: $\bar{b} \to \bar{u} u \bar{s}$

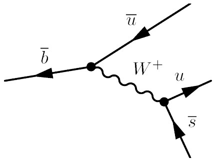


penguin diagram: $\bar{b} \to \bar{u} u \bar{s}$

Example: Direct CP Violation

Decay $X \to Y$ via **two different channels** (*weak* phases $\phi_{1,2}$, *strong* phases $\delta_{1,2}$)

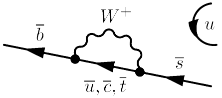
$$\frac{\Gamma(\bar{X} \to \bar{Y}) - \Gamma(X \to Y)}{\Gamma(\bar{X} \to \bar{Y}) + \Gamma(X \to Y)} = \frac{2|\mathcal{A}_1||\mathcal{A}_2| \sin(\phi_1 - \phi_2) \sin(\delta_1 - \delta_2)}{|\mathcal{A}_1|^2 + |\mathcal{A}_2|^2 + 2|\mathcal{A}_1||\mathcal{A}_2| \cos(\phi_1 - \phi_2) \cos(\delta_1 - \delta_2)}$$



tree diagram: $\bar{b} \to \bar{u} u \bar{s}$

→ Measurable numerical value of CPV depends on

- → difference between the weak phases: $|\phi_1 - \phi_2|$ (👍)
- → difference between the strong phases: $|\delta_1 - \delta_2|$ (👎)
- → product of amplitudes: $|\mathcal{A}_1 \mathcal{A}_2| / |\mathcal{A}_1 + \mathcal{A}_2|^2$ (👎)



penguin diagram: $\bar{b} \to \bar{u} u \bar{s}$

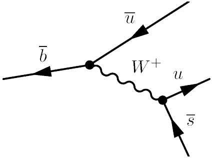
The Thing about Direct CPV

- **Key channels** (non-comprehensive and IMHO)
  - $\alpha : B^0 \to \rho\rho$ / $\pi\pi$ (CPV in **mixing + decay**, i.e. time-dependent)
  - $\beta : B^0 \to J/\psi\, K_s$ (CPV in **mixing + decay**, i.e. time-dependent)
  - $\beta_s : B_s^0 \to J/\psi\, \phi$ (CPV in **mixing + decay**, i.e. time-dependent)
  - $\gamma : B$'ish $\to D$'ish K'ish (*mostly* **direct** CPV, i.e. time-integrated)
- Why direct CPV for γ?
  - no need to tag initial flavor
  - bring amplitudes on same level by nifty composing suppressed and favored modes
  - experimental extraction of strong phases in similar decays

Example: $B^0 \to K^+\pi^-$

- → Interference between tree and penguin
- → CPV observable: **time-integrated** asymmetry

$$\frac{\Gamma(B^0 \to K^+\pi^-) - \Gamma(\bar{B}^0 \to K^-\pi^+)}{\Gamma(B^0 \to K^+\pi^-) + \Gamma(\bar{B}^0 \to K^-\pi^+)}$$



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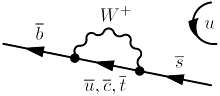


penguin diagram: $\bar{b} \to \bar{u}u\bar{s}$

Direct CP Violation

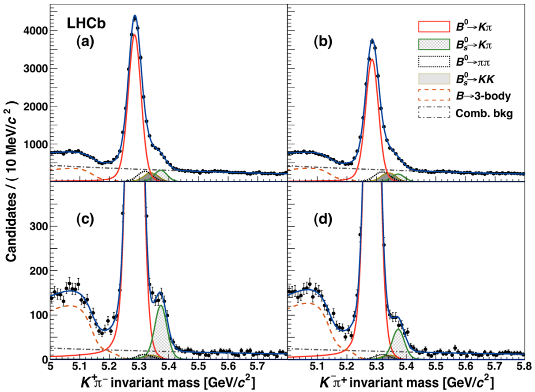
Early results in 2011

- improved determination:

$$A_{\text{CP}}(B^0 \to K^+\pi^-) = -.080 \pm .007\,(\text{stat}) \pm .003\,(\text{syst})$$

- first measurement:

$$A_{\text{CP}}(B_s^0 \to K^-\pi^+) = +.27 \pm .04\,(\text{stat}) \pm .01\,(\text{syst})$$



Phys. Rev. Lett. 110 (2013), 221601

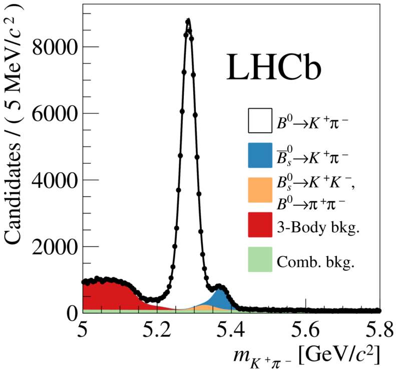
Direct CP Violation

Improved results in 2018

- $A_{\text{CP}}(B^0 \to K^+\pi^-) =$
  $-.084 \pm .004$ (stat) $\pm .003$ (syst)
- $A_{\text{CP}}(B_s^0 \to K^-\pi^+) =$
  $+.213 \pm .015$ (stat) $\pm .007$ (syst)

Remember: direct CPV $\sim \sin\Delta\phi_{\text{weak}} \times \sin\Delta\delta_{\text{strong}}$

- strong phase difference $\Delta\delta_{\text{strong}}$ not yet accessible from theory (with acceptable uncertainties)
- just two (boring) manifestations of CPV?



Phys. Rev. D98 (2018), 032004

Direct CP Violation

- SM + U-Spin symmetry (assumption) – Phys. Lett. B492 (2000), 297

$$|\mathcal{A}(B_s^0 \to K^-\pi^+)|^2 - |\mathcal{A}(\bar{B}_s^0 \to K^+\pi^-)|^2$$
$$= |\mathcal{A}(\bar{B}^0 \to K^-\pi^+)|^2 - |\mathcal{A}(B^0 \to K^+\pi^-)|^2$$

- or:

$$\Delta = \frac{A_{\mathrm{CP}}^{B^0}}{A_{\mathrm{CP}}^{B_s^0}} + \frac{\mathcal{B}(B_s^0 \to K^-\pi^+)}{\mathcal{B}(B^0 \to K^+\pi^-)} \frac{\tau(B^0)}{\tau(B_s^0)} = 0$$

- *…the equality follows from a "miracle" which occurs in the standard model and is not expected in common new physics models* – Phys. Lett. B621 (2005), 126-132

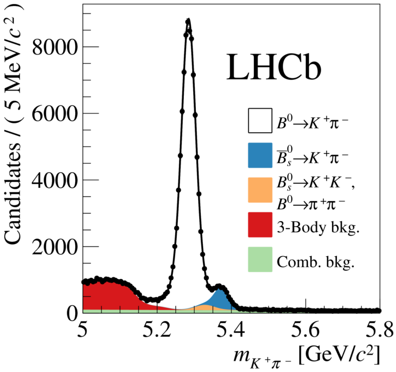
Direct CP Violation

→ Theory (assuming U-Spin symmetry):

$$\Delta = \frac{A_{\mathrm{CP}}^{B^0}}{A_{\mathrm{CP}}^{B_s^0}} + \underbrace{\frac{\mathcal{B}(B_s^0 \to K^-\pi^+)}{\mathcal{B}(B^0 \to K^+\pi^-)} \frac{\tau(B^0)}{\tau(B_s^0)}}_{\text{from literature}^\star} = 0$$

→ LHCb measurement:

$$\Delta = -.11 \pm .04\,(\text{meas.}) \pm .03\,(\text{lit.}^\star)$$



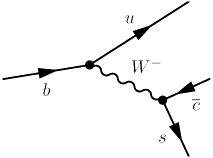
Phys. Rev. D98 (2018), `032004`

*HFLAV avg. `arXiv:1612.07233` & JHEP 04 (2013), `001`

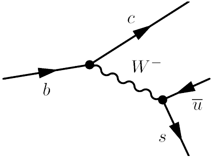
Example: GLW* method in $B^+ \to D^0 K^+$

*Phys. Lett. B253 (1991), 483 & Phys. Lett. B265 (1991), 172

- Reconstruct D^0 in CP-even states, such as K^+K^-
  - $B^+ \to D_{\text{CP-even}} K^+$
  - $B^- \to D_{\text{CP-even}} K^-$
- Reconstruct D^0 self-tagging: $D^0 \to K^-\ell^+\nu_\ell$, or $K^-\pi^+$
  - $B^+ \to D^0 K^+$ and c.c.
  - $B^+ \to \bar{D}^0 K^+$ and c.c.
- Combination of all 6 (4) modes allow clean extraction of γ (no theory input for strong phase necessary)
- Note: CPV is not in D^0, but needs entire decay chain!



tree: $b \to s\,[\bar{c}u]_{\bar{D}^0}$



tree: $b \to s\,[c\bar{u}]_{D^0}$

$\cos 2\beta > 0$

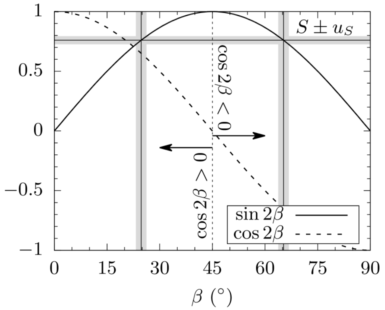
Combined dataset Babar & Belle

`arXiv:1804.06152`

- Time-dependent Dalitz analysis for $B^0 \to D^{(*)} h^0, D \to K_s \pi^+ \pi^-$
- $\Gamma(B^0(t{=}0) \to [K_s \pi^+ \pi^-]_{D^{(*)}} h^0 | t) = \ldots$

$$\mathrm{Im}(\mathcal{A}_{D^0} \mathcal{A}^*_{\bar{D}^0}) \cos 2\beta \; - \; \mathrm{Re}(\mathcal{A}_{D^0} \mathcal{A}^*_{\bar{D}^0}) \sin 2\beta$$

- Clean extraction of β (not just $\sin 2\beta$)



$S \pm u_S$ from JHEP11 (2017), 170