CP VIOLATION RESULTS FROM LHCb

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In the SM quarks
can change flavour

Unitarity $V_{\text{CKM}} \cdot V_{\text{CKM}}^\dagger = I$ imposes
several conditions which give rise to
“unitarity” triangles

$$V_{\text{CKM}} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

E.g. Unitarity condition from 2nd and 3rd columns:

$$V_{us}V_{ub}^* + V_{cs}V_{cb}^* + V_{ts}V_{tb}^* = 0$$

The CKM fit: a lot of room for NP

- The SM works so remarkably well that we have to make more and more precise measurements
- O(20%) NP contributions to most loop-level processes (FCNC) are still allowed
 - See e.g. J. Charles at al [arXiv:1309.2293](https://arxiv.org/abs/1309.2293) [hep-ph]
- Interesting comparison of tree-level vs higher-order observables. In the latter, unknown particles could contribute.

The LHCb detector

- Single arm spectrometer designed for high precision flavour physics measurements
- Pseudorapidity range $\eta \in [2,5]$

LHCb Detector Performance
Int. J. Mod. Phys. A30 (2015)1530022

LUMINOSITY AND PROSPECTS FOR THE FUTURE

The full pp LHCb data set is about 9fb^{-1}

THANKS
LHC!!

2015: 0.3fb^{-1}
2016: 1.6fb^{-1}
2017: 1.7fb^{-1}
2018: 2.1fb^{-1}

Large number of beauty and charm hadrons:

$$\sigma_{b\bar{b}}(7\text{ TeV}) = 72.0 \pm 0.3 \pm 6.8\text{ }\mu\text{b}$$

$$\sigma_{b\bar{b}}(13\text{ TeV}) = 154.3 \pm 1.5 \pm 14.3\text{ }\mu\text{b}$$

$$\sigma_{c\bar{c}}(13\text{ TeV}) \cong 2.4\text{ mb}$$

[PRL 118 (2017) 052002]

[JHEP 03 (2016) 159]

Upgrade I of the LHCb detector ongoing

Status of γ

- $\gamma = -\arg(V_{ud}V_{ub}^*/V_{cd}V_{cb}^*)$ is still the least well-known angle of the Unitarity Triangle
- TI measurements of γ from B decays mediated only by tree-level transitions provide a standard candle for the SM (assuming no new physics in tree-level decays [Phys. Rev. D 92, 033002 (2015)] $\Rightarrow$ Theoretically clean $[\delta\gamma/\gamma] \lesssim \mathcal{O}(10^{-7})$ [JHEP 1401 (2014) 051])
- This can be compared with γ values from B decays involving loop-level transitions, such as $B_{d,s}^0 \rightarrow hh'$ decays ($h = K, \pi$), to get signs of NP

$\rightarrow$ If the assumption is dropped, Upgrade 2 will allow to search for NP.

- Can be measured in the interference between $b \rightarrow c$ (favoured) and $b \rightarrow u$ (suppressed) transitions, e.g.:

$$\frac{A_{sup}}{A_{fav}} = r_B^{Dh} e^{i(\delta_B^{Dh} \pm \gamma)}$$

Ratio of magnitudes

Strong phase difference

Small signal yields (BR 10^{-7}), small interference effects (10%). Combining a plethora of independent decay modes is the key to achieve the ultimate precision.

State of art of γ

- Strategy similar to previous combinations: frequentist treatment.
- This combination includes new and updated measurements.

B decay	D decay	Method	Ref.	Dataset [†]	Status since last combination [3]
$B^+ \rightarrow DK^+$	$D \rightarrow h^+ h^-$	GLW	[14]	Run 1 & 2	Minor update
$B^+ \rightarrow DK^+$	$D \rightarrow h^+ h^-$	ADS	[15]	Run 1	As before
$B^+ \rightarrow DK^+$	$D \rightarrow h^+ \pi^- \pi^+ \pi^-$	GLW/ADS	[15]	Run 1	As before
$B^+ \rightarrow DK^+$	$D \rightarrow h^+ h^- \pi^0$	GLW/ADS	[16]	Run 1	As before
$B^+ \rightarrow DK^+$	$D \rightarrow K_S^0 h^+ h^-$	GGSZ	[17]	Run 1	As before
$B^+ \rightarrow DK^+$	$D \rightarrow K_S^0 h^+ h^-$	GGSZ	[18]	Run 2	New
$B^+ \rightarrow DK^+$	$D \rightarrow K_S^0 K^+ \pi^-$	GLS	[19]	Run 1	As before
$B^+ \rightarrow D^* K^+$	$D \rightarrow h^+ h^-$	GLW	[14]	Run 1 & 2	Minor update
$B^+ \rightarrow DK^{*+}$	$D \rightarrow h^+ h^-$	GLW/ADS	[20]	Run 1 & 2	Updated results
$B^+ \rightarrow DK^{*+}$	$D \rightarrow h^+ \pi^- \pi^+ \pi^-$	GLW/ADS	[20]	Run 1 & 2	New
$B^+ \rightarrow DK^+ \pi^+ \pi^-$	$D \rightarrow h^+ h^-$	GLW/ADS	[21]	Run 1	As before
$B^0 \rightarrow DK^{*0}$	$D \rightarrow K^+ \pi^-$	ADS	[22]	Run 1	As before
$B^0 \rightarrow DK^+ \pi^-$	$D \rightarrow h^+ h^-$	GLW-Dalitz	[23]	Run 1	As before
$B^0 \rightarrow DK^{*0}$	$D \rightarrow K_S^0 \pi^+ \pi^-$	GGSZ	[24]	Run 1	As before
$B_s^0 \rightarrow D_s^\mp K^\pm$	$D_s^\pm \rightarrow h^+ h^- \pi^\pm$	TD	[25]	Run 1	Updated results
$B^0 \rightarrow D^\mp \pi^\pm$	$D^\pm \rightarrow K^+ \pi^- \pi^\pm$	TD	[26]	Run 1	New

LHCb combination

$$\gamma = (74.0_{-5.8}^{+5.0})^\circ$$

In agreement with world averages
Supersedes the previous LHCb measurement.

Most precise determination of γ from a single experiment to date.

Francesca Dordei - CP violation results from LHCb

Prospects for γ

- 4° with Run 2 data ($\sim 9 \text{ fb}^{-1}$)
- 1.5° by the end of Run 3 ($\sim 22 \text{ fb}^{-1}$)
- $< 1^\circ$ by the end of Run 4 ($\sim 50 \text{ fb}^{-1}$)
- $\sim 0.4^\circ$ in Phase 2 upgrade ($\sim 300 \text{ fb}^{-1}$)

[arXiv:1709.10308v5][CERN-LHCC-2017-003]

- Belle-II targets a precision of 1.5° at the end of data-taking (2025)

- D reconstructed in a 2 charged-track final state
- All ADS/GLW asymm. currently statistically limited
- Dominant syst., due to knowledge of background contributions, expected to scale with statistics

- D is reco in a 3-body self-conjugated final state
- Powerful input to the overall determination of γ
- Need good description of strong phase difference δ_D
 - Current inputs taken from CLEO-c (current syst $\sim 2^\circ$)
 - Future BESIII and LHCb charm inputs are vital

State of art of $\sin(2\beta)$

Golden channel $B^0 \rightarrow J/\psi K_S^0$, averages including all charmonium:

LHCb:

◦ $S = 0.760 \pm 0.034$ [JHEP 11(2017) 170]. (RUN 1 ONLY)

Belle:

◦ $S = 0.667 \pm 0.026$ [PRL 108(2012) 171802]

Babar:

◦ $S = 0.691 \pm 0.031$ [PRD 79(2009) 072009]

$$S \equiv -\eta_{CP} \sin(2\beta) = 0.699 \pm 0.017$$

[HFLAV 2018]

$$S^{SM} \equiv \sin(2\beta) = 0.748^{+0.030}_{-0.032}$$

[CKMfitter]

- LHCb has a similar precision to the B-factories
- Small tension of B-factories results with SM predictions to be clarified

Prospects for $\sin(2\beta)$

- @50/fb: $\sigma_{stat} = 0.006$ with $B^0 \rightarrow J/\psi K_S^0$
- @300/fb: $\sigma_{stat} = 0.003$ with $B^0 \rightarrow J/\psi K_S^0$

Belle II @50/ab: $\sigma_{stat} = 0.005$ with $B^0 \rightarrow J/\psi K_S^0$

Systematics:

- Mostly depends on size of control samples
→ scale with statistics
- Important to understand how to take into account $K^0 - \bar{K}^0$ CP violation and nuclear cross-section asymmetry.

Leading sources of systematic uncertainty are different between Belle II and LHCb

Penguins controlled using $B^0 \rightarrow J/\psi \pi^0$ and $B_s^0 \rightarrow J/\psi K_S^0$

- $B_s^0 \rightarrow J/\psi K_S^0$ studied by LHCb [Phys. Rev. Lett. 115 (2015) 031601]
- Belle II expects a good precision for $B^0 \rightarrow J/\psi \pi^0$
- Improving ECAL will allow also LHCb to contribute
- Upgrade II will also allow to study other SU(3) related modes

CP violation in B mixing and decay, φ_s

Dominant SM “tree” contribution

Higher order “penguin”
contributions from non-perturbative
hadronic effects

NP could be difficult to
distinguish from
penguins...

CP-violating phase arising from interference between mixing and decay.

- Precisely predicted by the SM: $\varphi_s^{SM} = -36.86_{-0.68}^{+0.96}$ mrad [CKMFitter]
- Golden channel exploited by LHCb, ATLAS, CMS: $B_s^0 \rightarrow J/\psi\phi$
- LHCb also measured many other channels
- World average (dominated by LHCb) consistent with predictions;
- Exp. uncertainty (31 mrad) almost a factor of 30 larger than uncert. of indirect determination when penguin pollution is ignored.

Overview of the results

Combination of all LHCb results
including Run 2 $B_s^0 \rightarrow J/\psi K K$ and $B_s^0 \rightarrow J/\psi \pi \pi$

[arXiv:1906.08356]

$$\begin{aligned}\varphi_s &= -0.041 \pm 0.025 \text{ rad} \\ |\lambda| &= 0.993 \pm 0.010 \\ \Gamma_s &= 0.6562 \pm 0.0021 \text{ ps}^{-1} \\ \Delta\Gamma_s &= 0.0816 \pm 0.0048 \text{ ps}^{-1}\end{aligned}$$

φ_s 0.1 σ away from SM
consistent with Standard Model

φ_s 1.6 σ away from 0
consistent with no CPV in interference

$|\lambda|$ consistent with 1
consistent with no direct CPV

$\Gamma_s - \Gamma_d$ consistent with HQE prediction
[JHEP12 (2017) 068]

The HFLAV combination is:

$$\begin{aligned}\varphi_s &= -0.055 \pm 0.021 \text{ rad} \\ \Delta\Gamma_s &= 0.0764_{-0.0033}^{+0.0034} \text{ ps}^{-1}\end{aligned}$$

[HFLAV]

Prospects for the future

[LHCB-PUB-2018-009]

- Include gain in trigger for $B_s^0 \rightarrow D_s^- D_s^+$ after Upgrade 1
- Same performances as in Run I
 - Assumed tagging power 4%
- Additional modes planned: $J/\psi \rightarrow ee$, $\eta' \rightarrow \rho^0 \gamma$ or , $\eta' \rightarrow \eta \pi \pi$ or $\gamma \gamma$ as cross cheks

300/fb: $\sigma^{\text{STAT}}(\varphi_s) \sim 4$ mrad from $B_s^0 \rightarrow J/\psi KK$ only

- φ_s expected to be statistically limited

Impact of Upgrade I and II very important for φ_s !

CP violation in charm

- Searching for CP violation (CPV) in charm decays is a stress test to the Standard Model:
 - Up-type quark: complementary to studies in K and B systems
- Small CP asymmetries expected (0.01%÷0.1%)
 - CKM/GIM suppression, large uncertainties due to low-energy strong interaction effects [Phys.Lett. B222 (1989) 501]
- CPV searched for since decades, this year finally observed with the ΔA_{CP} measurement [Phys. Rev. Lett. 122, 211803]!

Courtesy of A. Carbone

CP violation in charm

The raw asymmetry (A) in Cabibbo Suppressed $D^0 \rightarrow h^- h^+$ decays ($h = K$ or π) includes both physics and detector effects:

$$A = A(D \rightarrow f) = \frac{N(D \rightarrow f) - N(\bar{D} \rightarrow \bar{f})}{N(D \rightarrow f) + N(\bar{D} \rightarrow \bar{f})} = A_{CP} + \underbrace{A_D}_{\text{Detection asym. from } \pi^+ \text{soft or } \mu^+} + \underbrace{A_P}_{\text{Production asym. from } D^{*+} \text{ or } B \text{ decays}}$$

To eliminate these contributions:

$$\Delta A_{CP} = A(K^+ K^-) - A(\pi^+ \pi^-) = A_{CP}(K^+ K^-) - A_{CP}(\pi^+ \pi^-)$$

Two different methods to tag the initial D^0 flavor:

Prompt (π – tagged): coming from primary vertex, i.e. $D^{*+} \rightarrow D^0 \pi^+_{\text{soft}}$

Semileptonic (μ – tagged) : coming from B-decays, i.e. $B \rightarrow D^0 \mu^- X$

◦ Run-2 results:

$$\Delta A_{CP}^{\pi\text{-tagged}} = [-18.2 \pm 3.2 \text{ (stat.)} \pm 0.9 \text{ (syst.)}] \times 10^{-4}$$

$$\Delta A_{CP}^{\mu\text{-tagged}} = [-9 \pm 8 \text{ (stat.)} \pm 5 \text{ (syst.)}] \times 10^{-4}$$

◦ Combined with LHCb Run-1 yields:

CPV @ 5.3σ !

$$\Delta A_{CP} = (-15.4 \pm 2.9) \times 10^{-4}$$

Recent charm measurements and prospects for the future

- Search for CP violation in $D_s^+ \rightarrow K_s^0 \pi^+$, $D^+ \rightarrow K_s^0 K^+$ and $D^+ \rightarrow \phi \pi^+$ decays [[Phys. Rev. Lett.122 \(2019\) 191803](#)]
- Search for time-dependent CP violation in $D^0 \rightarrow K^+ K^-$ and $D^0 \rightarrow \pi^+ \pi^-$ [[LHCb-CONF-2019-001](#)]

$$A(f, t) = \frac{\Gamma(D \rightarrow f, t) - \Gamma(\bar{D} \rightarrow \bar{f}, t)}{\Gamma(D \rightarrow f, t) + \Gamma(\bar{D} \rightarrow \bar{f}, t)} \approx A_{CP}^{\text{decay}}(f) - A_{\Gamma} \frac{t}{\tau_{D^0}} \quad \text{where} \quad A_{\Gamma}(D^0 \rightarrow h^+ h^-) = -a_{CP}^{\text{indir}} = (0.9 \pm 2.1 \pm 0.7) \cdot 10^{-4}$$

Estimated constraints for LHCb Upgrade II on indirect and direct charm CP violation from the analysis of two-body CP eigenstates. The current world-average precision is larger than the fullscale of this plot!

Conclusions and remarks

- Interest in precision flavour measurements is stronger than ever
 ➡ If no direct evidence of NP pops out of the LHC, flavour physics can play a key role.
- CPV discovery in charm opens a new tool to investigate the SM
- All results in this sector in **good agreement with SM**, need to go to even **higher precision**: x2 statistics already available in Run 2.
- **Good prospects for precision measurements in the Upgrade phase of LHCb.**

"And if someone dares to yawn during your presentation, this pointer easily transforms from a laser to a taser!"

BACKUP

B flavour mixing

- Neutral B_s^0 mesons can oscillate between their particle and anti-particle states

The physical mass eigenstates (L,H) are admixtures of the weak eigenstates:

$$\begin{aligned} |B_L\rangle &= p |B_s^0\rangle + q |\bar{B}_s^0\rangle \\ |B_H\rangle &= p |B_s^0\rangle - q |\bar{B}_s^0\rangle \end{aligned}$$

- with mass difference $\Delta m = m_H - m_L$ and decay-width difference $\Delta\Gamma = \Gamma_L - \Gamma_H$
- flavor at production ($t=0$) could be different from flavour at decay time t

Different kinds of CP violation

- Must have two interfering amplitudes with different strong (δ) and weak (φ) phases
- For a B_s^0 decay to a CP eigenstate f , CP-violating effects depend on $\lambda_f = \frac{q}{p} \frac{\bar{A}_f}{A_f}$

Some thoughts on γ in Upgrade 2

- Since the bulk of the sensitivity to γ comes from the difference in rates of the $B - \bar{B}$ processes, a precise control of asymmetries in charged-particle identification and detection is crucial
→ these systematic uncertainties are considered to scale with integrated luminosity
- Upgrade of the calorimeter will greatly expand LHCb's capabilities for modes with neutrals in the final state.
- Upgrade 2 will also make it interesting to measure γ using baryonic decays
→ TORCH system particularly helpful in allowing for low-momentum separation of protons and kaons
- Addition of magnet-side stations may lead to important signal-yield improvements, particularly for high-multiplicity final states.
- Constrain $\beta_{(s)}$ without penguin contaminations → $\sim 2^\circ$ sensitivity on $\gamma - 2\beta_s$ from $B_s^0 \rightarrow D_s K$

Flavour tagging in the future

Almost everything will be new in Run3 (similar situation as in 2010)

- Upgrade challenge: increase in track multiplicity and pile-up (~ 6 for Upgrade-I and ~ 55 for Upgrade-II) that have negative effect on ω and ε_{tag} .
- FT performance directly linked to the ability to associate PV $\Leftrightarrow$ track. To improve/maintain tagging performance need:
 - **Hardware**: timing information (upgrade-II workshops)
 - **Software**: deep neural networks to learn correlations between all tracks and the signal B meson (inclusive taggers), need to reduce significantly persisted info.

Control of penguin pollution

- U-spin or SU(3) flavour symmetry to constrain size of penguin with $b \rightarrow c\bar{c}d$ (related by s-d spectator exchange)
- Penguin pollution and/or CP violation **could be different for each polarisation state**, $f \in (0, \perp, \parallel, S)$
 → no sign yet of dependence in $B_s^0 \rightarrow J/\psi KK$ (also in Run 2) so penguins are small
- $SU(3)_F$: $B_s^0 \rightarrow J/\psi K^{*0}$ and $B^0 \rightarrow J/\psi \rho^0$ are $b \rightarrow c\bar{c}d$ transitions.

$$\begin{aligned}\Delta\phi_{s,0}^{J/\psi\phi} &= 0.000_{-0.011}^{+0.009} \text{ (stat)} \quad {}_{-0.009}^{+0.004} \text{ (syst)} \text{ rad} \\ \Delta\phi_{s,\parallel}^{J/\psi\phi} &= 0.001_{-0.014}^{+0.010} \text{ (stat)} \pm 0.008 \text{ (syst)} \text{ rad} \\ \Delta\phi_{s,\perp}^{J/\psi\phi} &= 0.003_{-0.014}^{+0.010} \text{ (stat)} \pm 0.008 \text{ (syst)} \text{ rad}\end{aligned}$$

[JHEP 11 (2015) 082]

Precision of ~ 10 mrad

To be compared with the current precision of HFLAV of 21 mrad

Fundamental to **update these analyses**, expected sensitivity at 300/fb is 1.5 mrad (statistically limited)

+ adding $B_s^0 \rightarrow J/\psi\omega$ and $B^0 \rightarrow J/\psi\phi$ (E + PA diagrams only)