LHCb results on CP violation

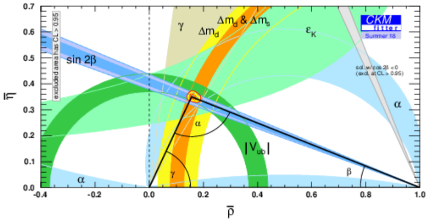
Agnieszka Dziurda[1]
on behalf of the LHCb collaboration

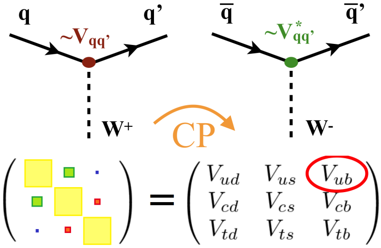
[1]IFJ PAN, Krakow

2nd Workshop on Hadronic Contributions to New Physics Searches

24.09.2019

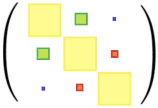
Motivation: CKM matrix





- Amplitudes of weak interactions depend on parameters in the CKM matrix.
- One goal in flavor physics is to thoroughly test whether these parameters really do describe both the magnitudes and phases of quark transitions associated with many decay processes
- Any discrepancy in the position of the apex of the Unitarity Triangle from the different measurements would indicate physics beyond Standard Model.
- O(20%) New Physics contributions to most loop-level processes (FCNC) are still allowed (arXiv:1309.2293 [hep-ph]).

CP violation

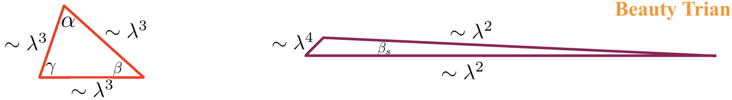
$V_{CKM} =$  $= \begin{pmatrix} 1-\frac{1}{2}\lambda^2-\frac{1}{8}\lambda^4 & \lambda & A\lambda^3(\rho-i\eta) \\ -\lambda[1+A^2\lambda^4(\rho+i\eta-\frac{1}{2})] & 1-\frac{1}{2}\lambda^2-\frac{1}{8}\lambda^4(1+4A^2) & A\lambda^2 \\ A\lambda^3[(1-\rho-i\eta)(1-\frac{1}{2}\lambda^2)] & -A\lambda^2[1+\lambda^2(\rho+i\eta-\frac{1}{2})] & 1-\frac{1}{2}A^2\lambda^4 \end{pmatrix}$

γ β β_s β_c

$A \approx 0.81 \quad \rho \approx 0.13 \quad \eta \approx 0.35 \quad \lambda \approx 0.22$

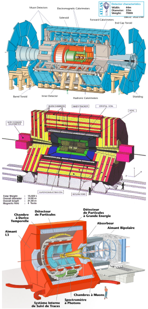
- Unitarity: $V_{CKM}V^{\dagger}_{CKM} = V^{\dagger}_{CKM}V_{CKM} = 1$
- Measure CPV in various processes $\rightarrow$ measure angles of the triangles.
- Triangle openness indicate how large the CP violation effects is expected.
  $\beta_c \sim 0.03^\circ$ (charm), $\beta_s \sim 1^\circ$ (beauty-strange), $\beta \sim 22^\circ$ (beauty).
- In this talk: γ, β, β_s, β_c.

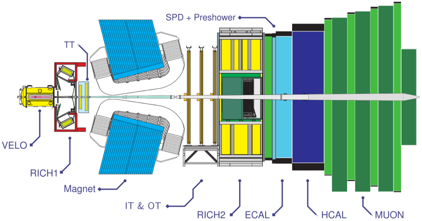
Beauty Triangles

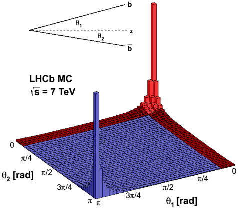


Charm Triangle

The LHCb experiment

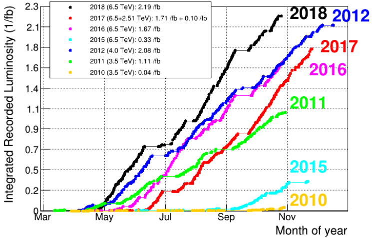






- LHCb is a general purpose detector at the LHC.
- In contrast to other detectors, the LHCb detector is a single-arm forward spectrometer with a pseudorapidity η in the range $2 < \eta < 5$.
- Outstanding physics results require excellent detector performance.

JINST 3 (2008) S08005
JINST 14 (2019) P04013
Int. J. Mod. Phys. A 30, 1530022 (2015)

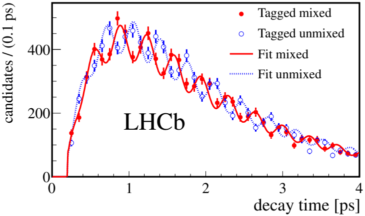


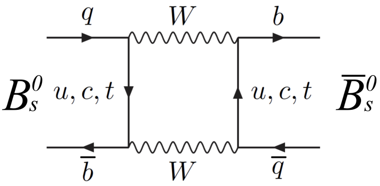
- Already $9fb^{-1}$ of data collected!
- Still prominent future in front of us.
- Most of analyses presented in this talk: Run1 + part of Run2 data.

LHC (pp)			HL-LHC (pp)		SuperKEKB (e^+e^-)
Run1	Run2	Run3	Run4	Run5	Belle II
3 fb^{-1}	6 fb^{-1}	23 fb^{-1}	50 fb^{-1}	300 fb^{-1}	50 ab^{-1}

Oscillation frequency in the B_s system

- LHCb is unique in using hadronic B_s decays:
  - γ: $B_s \to D_s K$
  - $\sin(2\beta_s)$: $B_s \to J/\psi\phi$, $B_s \to D_s D_s$
  - ...
- Fast $B_s^0 - \bar{B}_s^0$ oscillations (B_s^0 oscillates about 9 times before decaying).
- This requires excellent decay-time resolution: ~ 50 fs.
- Essential input parameter to all time-dependent measurements!

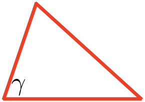




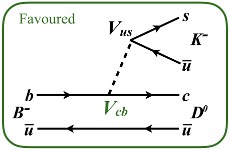
$$1/\text{fb (2011 data)}: \ \Delta m_s = 17.77 \pm 0.023 \pm 0.006 \ ps^{-1}.$$

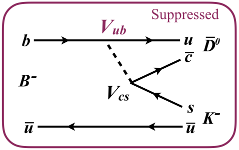
New J. Phys. 15 (2013) 053021

The CKM angle γ: introduction



- $\gamma \propto arg(-V_{ud}V_{ub}^*/V_{cd}V_{cb}^*)$ - before LHCb era, the least-well measured of the CKM angles.
- Standard candle of SM - tree-level processes from B decays [Phys. Rev. D 92, 033002 (2015)]
- Theoretically clean $\delta\gamma/\gamma \sim 10^{-7}$ [JHEP01(2014)051]
- Comparison with loop-level transitions from $B_{d,s} \to hh'$ $(h = K, \pi)$ (and others) provides test of SM.
- Can be measured in the interference between $b \to c$ (favoured) and $b \to u$ (suppressed) transitions, e.g.:





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

ratio of magnitudes

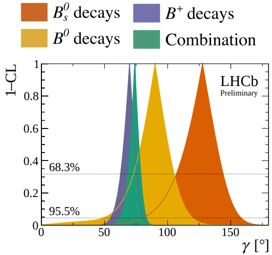
weak phase

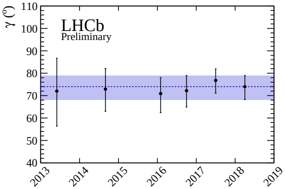
strong phase

- Strategy similar to previous combinations: frequentist treatment.
- LHCb combination: $\gamma = (74.0^{+5.0}_{-5.8})^\circ$

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

† Run 1 corresponds to an integrated luminosity of 3 fb^{-1} taken at centre-of-mass energies of 7 and 8 TeV . Run 2 corresponds to an integrated luminosity of 2 fb^{-1} taken at a centre-of-mass energy of 13 TeV .





- LHCb result dominates the world-avarage.
- Most precise determination of γ from a single experiment

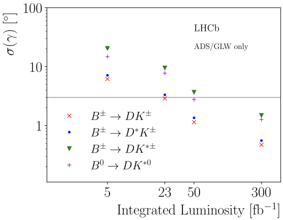
The CKM angle γ: prospects

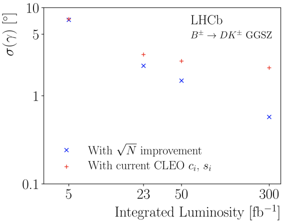
LHCB-PUB-2018-009

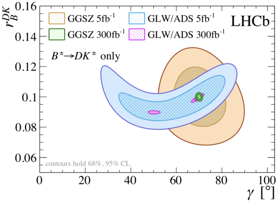
	Run2	Run3	Run 4	Run 5
σ_γ [°] overall	4	1.5	<1.0	$\sim$ 0.4
σ_γ [°] for $B_s \to D_s K$	10	4	2	1

Target precision

Belle 2 (in 2025): 1.5 degrees







ADS/GLW

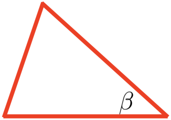
- $D \to hh'$ decays
- Dominant syst., due to knowledge of background contributions, expected to scale with statistics

GGSZ

- $D \to$ 3-body self-conjugated final state
- Depends on the strong phase inputs δ_D:
  - Current inputs taken from CLEO-c
  - Future BESIII and LHCb charm inputs are vital

The CKM angle β: introduction & status

- $\beta \propto arg(-V_{cd}V_{cb}^{*}/V_{td}V_{tb}^{*})$
- $\sin(2\beta)$ measured in time-dependent asymmetries.
- Golden mode: $B^0 \to J/\psi K_s^0$
- LHCb has a similar precision to the B-factories

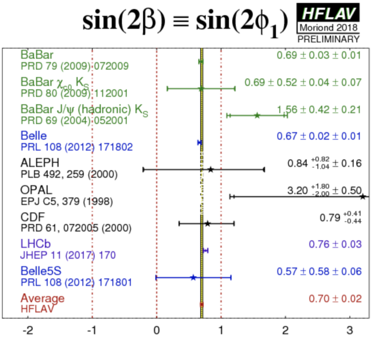


Experiments

- LHCb: S = 0.760 ± 0.034
  [JHEP 11(2017) 170]. (RUN 1 ONLY)
- Belle: S = 0.667 ± 0.023 ± 0.012
  [PRL 108(2012) 171802]
- Babar: S = 0.691 ± 0.031
  [PRD 79(2009) 072009]

World averages:

- HFLAV: $S \equiv -\eta_{CP}\sin(2\beta) = 0.699 \pm 0.017$
  [HFLAV 2018]
- CKMFitter: $S^{SM} \equiv \sin(2\beta) = 0.740^{+0.020}_{-0.025}$
  [CKMFitter]



Small tension of B-factories results with SM predictions to be clarified.

The CKM angle β: prospects

LHCB-PUB-2018-009

Predicted precision with $B^0 \to J/\psi K_s^0$

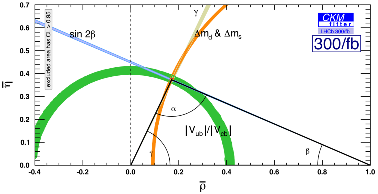
	LHCb (50/fb)	LHCb (300/fb)	Belle 2 (50/ab)
σ_β	0.006	0.003	0.005

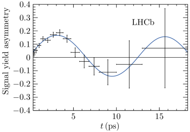
Systematics:

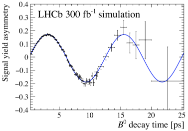
- scales with statistics (depends on the size of control modes).
- understanding $K^0 - \bar{K}^0$ CPV and nuclear cross-section asymmetry.
- Leading sources different between LHCb and Belle - complementary measurements

Penguin pollutions:

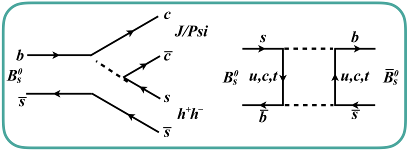
- controlled with $B \to J\psi\pi^0$ and $B_s \to J/\psi K_s^0$.
- $B_s \to J/\psi K_s^0$ - studied in LHCb [Phys. Rev. Lett. 115 (2015) 031601]
- $B \to J/\psi\pi^0$ - good precision in Belle 2



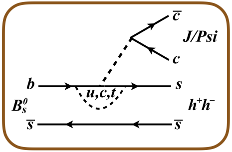




The CKM angle $\phi_s = (-2\beta_s)$: introduction



Dominant contributions



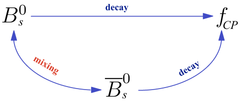
Higher order „penguin" contributions

possible New Physics
(might be difficult to distinguish
from penguins)

$$\phi_s = \phi_s^{SM} + \Delta\phi_s^{peng} + \Delta\phi_s^{NP}$$

- $\beta_s \propto arg(V_{ts}V_{tb}^*/V_{cs}V_{cb}^*)$
- Precisely predicted by the SM:
  $\phi_s \equiv$ -2β_s = -36.86$^{+0.96}_{-0.68}$ mrad [CKMFitter]
- Source of CP: interference between mixing and decay.
- Time-dependent asymmetry:

$$A_{CP} \equiv \frac{\Gamma(B_s^0 \to J\psi\phi) - \Gamma(\bar{B}_s^0 \to J\psi\phi)}{\Gamma(B_s^0 \to J\psi\phi) + \Gamma(\bar{B}_s^0 \to J\psi\phi)} \sim \sin(\phi_s)\sin(\Delta m_s t)$$



- Golden channel exploited by LHCb, ATLAS, CMS: $B_s \to J/\psi\phi$
- LHCb also measured many other channels.

The CKM angle $\phi_s = (-2\beta_s)$: status

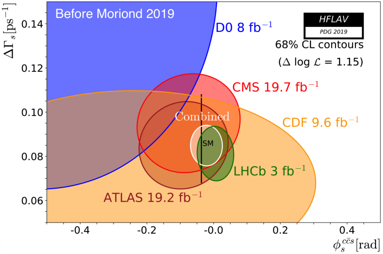
- Combination of all LHCb results including Run 2: $B_s \to J/\psi KK$ and $B_s \to J/\psi \pi\pi$
- Outcome:
  - ϕ_s consistent with SM,
  - ϕ_s 1.6σ away from 0 (no CPV in intereference).
  - $|\lambda|$ consistent with 1 - no direct CPV

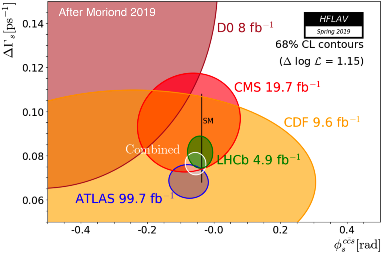
LHCb ([arXiv:1906.08356])

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

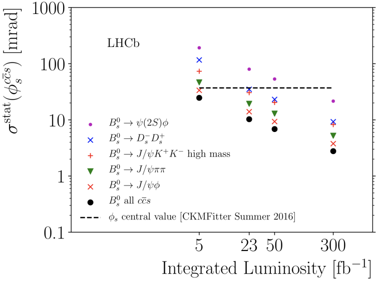
HFLAV

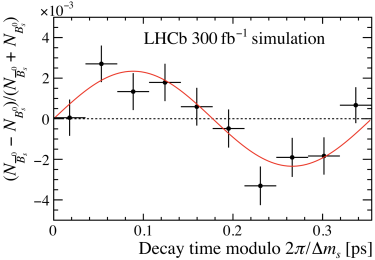
$$\phi_s = \text{-0.055} \pm 0.021 \text{ rad}$$
$$\Delta\Gamma_s = 0.0764^{+0.0034}_{-0.0033} \text{ ps}^{-1}$$





LHCB-PUB-2018-009





- $B_s \to D_s^- D_s^+$ will enter the game (trigger gains)
- Additional modes planned, example: $J/\psi \to ee$.
- Expected to be systatistically limited by Upgrade II.

300/fb: $\sigma_{\phi_s}^{stat} \sim 4$ mrad
only from $B_s^0 \to J/\psi KK$

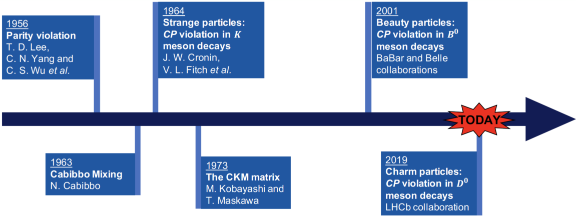
Important impact of Upgrade!

CPV in charm: introduction

- Standard Model prediction for CP asymmetry in the charm sector: $\leq 10^{-4} - 10^{-3}$
  - CKM/GIM suppression.
  - Large uncertainties due to low-energy strong interaction effects.
- Can occur for decays with tree-level and penguin diagrams
  - penguin amplitude tiny - no top quark in the loop.
- Asymmetry:

$$A_{CP} = \frac{\Gamma(D \to f) - \Gamma(\bar{D} \to f)}{\Gamma(D \to f) - \Gamma(\bar{D} \to f)}$$

- Remaining piece finally found [Phys. Rev. Lett. 122, 211803]:



PHYS. REV. LETT. 122 (2019) 211803

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

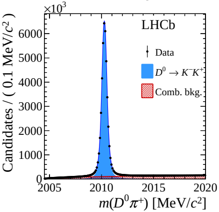
$$A = A_{CP} + A_D + A_P$$

CP asymmetry; detection asymmetry; production asymmetry

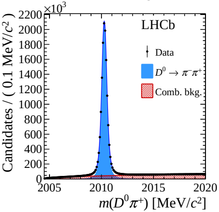
- Search for $\Delta A_{CP} = A(K^+K^-) - A(\pi^+\pi^-)$
- Statistics: $D^0, \bar{D}^0 \to K^+K^-$: $\sim 50 \times 10^6$, $D^0, \bar{D}^0 \to \pi^+\pi^-$: $\sim 20 \times 10^6$ candidates.

- Two different methods to tag the initial D^0 flavour:
  - Prompt (π tagged): coming from primary vertex, i.e. $D^{*+} \to D^0\pi^+_{soft}$
  - Semileptonic (μ tagged) : coming from B-decays, i.e. $B \to D^0\mu^- X$

Prompt



Prompt



Run 2 results:

$$\Delta A_{CP}^{\pi-tag} = (-18.2 \pm 3.2 \pm 0.9) \times 10^{-4}$$
$$\Delta A_{CP}^{\mu-tag} = (-9 \pm 8 \pm 5) \times 10^{-4}$$

Combined Run 1-2 result:

$$\Delta A_{CP} = (-15.4 \pm 2.9) \times 10^{-4} \; (5.3\sigma!)$$

CPV in charm: prospects

- Many interesting charm analyses this year!
  - Measurement of the mass difference between neutral charm-meson eigenstates from $D^0 \to K_s^0 \pi^+ \pi^-$ [PHYS. REV. LETT. 122 (2019) 231802]
  - Search for time-dependent CP violation $D^0 \to K^+ K^-$, $D^0 \to \pi^+ \pi^-$ [LHCb-CONF-2019-001]

The current world-average precision:

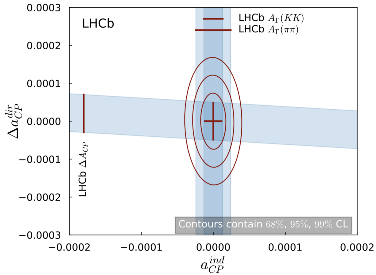
- indirect: $\pm$ 2.6 $\times 10^{-4}$
- direct: $\pm$ 18 $\times 10^{-4}$

larger than the full scale of the plot!

Still many interesting results to come!

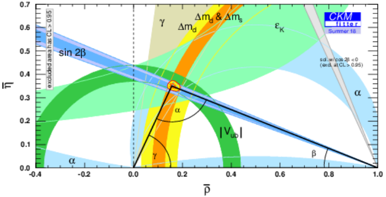
LHCB-PUB-2018-009

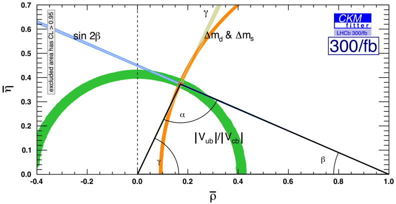
Sample ($\mathcal{L}$)	Tag	Yield $D^0 \to K^- K^+$	Yield $D^0 \to \pi^- \pi^+$	$\sigma(\Delta A_{CP})$ [%]	$\sigma(A_{CP}(hh))$ [%]
Run 1–2 (9 fb^{-1})	Prompt	52M	17M	0.03	0.07
Run 1–3 (23 fb^{-1})	Prompt	280M	94M	0.013	0.03
Run 1–4 (50 fb^{-1})	Prompt	1G	305M	0.007	0.015
Run 1–5 (300 fb^{-1})	Prompt	4.9G	1.6G	0.003	0.007



Conclusion

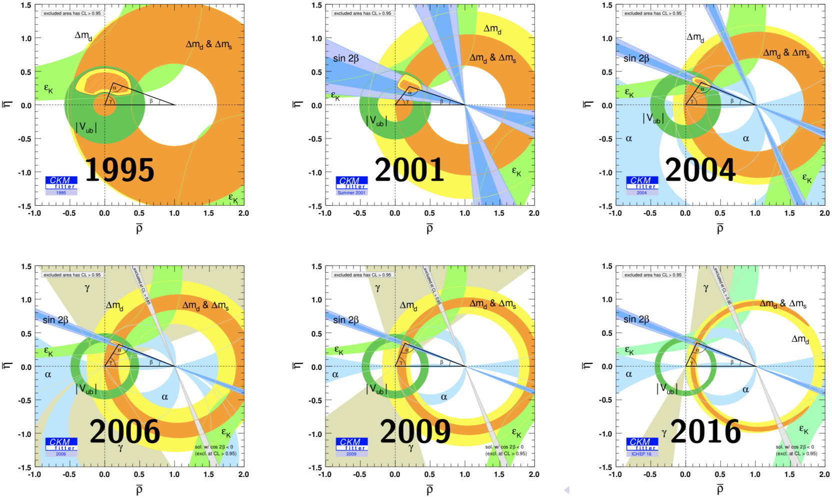
- LHCb plays a crucial role in the CPV measurements:
    - **B decays:** precision of the Unitarity Triangle
    - B_s **decays:** LHCb opened era of precision
    - **D decays:** CPV finally found!
- CPV results still consistent with the Standard Model
- More to come:
    - LHCb Upgrade,
    - Belle 2
- Stay tuned!





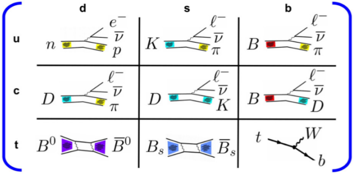
Thank You!

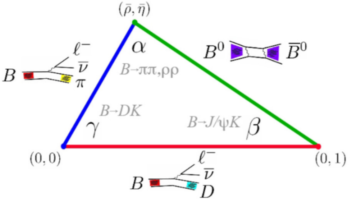
CKM



Luiz Vale Silva, CKM workshop 2018

CKM

V = 

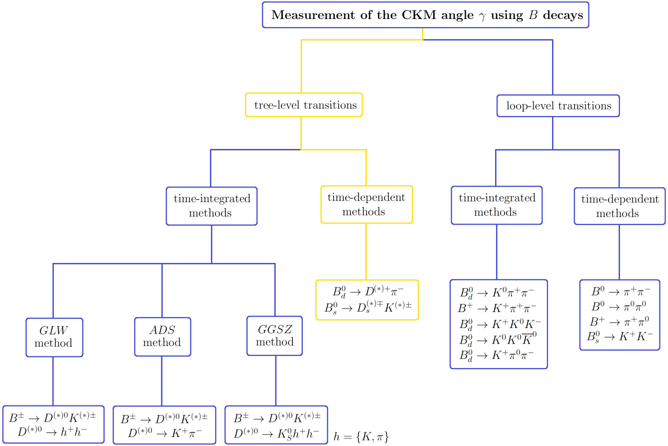


Observables with **very different properties** are available:

- *Tree*: e.g., $|V_{ub}|$
- *Loop*: e.g., Δm_d, Δm_s, ϵ_K, $\sin(2\beta)$
- *$\mathcal{CP}$-conserving*: e.g., $|V_{ub}|$, Δm_d, Δm_s
- *$\mathcal{CP}$-violating*: e.g., γ, ϵ_K, $\sin(2\beta)$

Luiz Vale Silva, CKM workshop 2018

The CKM angle γ



Time-dependent equations

$$\frac{\Gamma_{\overline{B}^0_{(s)}\to f}(t) - \Gamma_{B^0_{(s)}\to f}(t)}{\Gamma_{\overline{B}^0_{(s)}\to f}(t) + \Gamma_{B^0_{(s)}\to f}(t)} = \frac{S_f \sin(\Delta m_{d(s)} t) - C_f \cos(\Delta m_{d(s)} t)}{\cosh(\frac{\Delta\Gamma_{d(s)} t}{2}) + A_f^{\Delta\Gamma_{d(s)}} \sinh(\frac{\Delta\Gamma_{d(s)} t}{2})}\,.$$

$$A_f^{\Delta\Gamma} \equiv -\frac{2\,\Re(\lambda_f)}{1+|\lambda_f|^2}\,, \quad C_f \equiv \frac{1-|\lambda_f|^2}{1+|\lambda_f|^2}\,, \quad S_f \equiv \frac{2\,\Im(\lambda_f)}{1+|\lambda_f|^2}\,.$$

$$\lambda_f = \frac{q}{p}\frac{\bar{A}_f}{A_f}\,.$$

The CKM angle ϕ_s

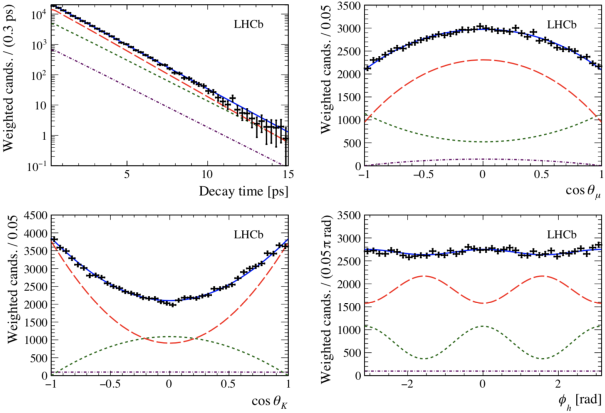


Figure 11: Decay-time and helicity-angle distributions for background subtracted $B_s^0 \to J/\psi K^+K^-$ decays (data points) with the one-dimensional projections of the PDF at the maximum-likelihood point. The solid blue line shows the total signal contribution, which contains (long-dashed red) *CP*-even, (short-dashed green) *CP*-odd and (dotted-dashed purple) S-wave contributions. Data and fit projections for the different samples considered (data-taking year, trigger and tagging categories, $m(K^+K^-)$ bins) are combined.

The CKM angle β

Source	ϕ_s [rad]	$\lvert\lambda\rvert$	$\Gamma_s - \Gamma_d$ [ps^{-1}]	$\Delta\Gamma_s$ [ps^{-1}]
Mass: width parametrisation	-	-	-	0.0002
Mass: decay-time & angles dependence	0.004	0.0037	0.0007	0.0022
Multiple candidates	0.0011	0.0011	0.0003	0.0001
Fit bias	0.0010	-	-	0.0003
C_{SP} factors	0.0010	0.0010	-	0.0001
Time resolution: model applicability	-	-	-	-
Time resolution: t bias	0.0032	0.0010	0.0002	0.0003
Time resolution: wrong PV	-	-	-	-
Angular efficiency: simulated sample size	0.0011	0.0018	-	-
Angular efficiency: weighting	0.0022	0.0043	0.0001	0.0002
Angular efficiency: clone candidates	0.0005	0.0014	0.0002	0.0001
Angular efficiency: t & σ_t dependence	0.0012	0.0007	0.0002	0.0010
Decay-time efficiency: statistical	-	-	0.0012	0.0008
Decay-time efficiency: kinematic weighting	-	-	0.0002	-
Decay-time efficiency: PDF weighting	-	-	0.0001	0.0001
Decay-time efficiency: $\Delta\Gamma_s = 0$ simulation	-	-	0.0003	0.0005
Length scale	-	-	-	-
Quadratic sum of syst.	0.0061	0.0064	0.0015	0.0026

Charm systematics

$$A_{CP}(f) \approx a_{CP}^{\text{dir}}(f) - \frac{\langle t(f) \rangle}{\tau(D^0)} A_\Gamma(f),$$

$$\begin{aligned}\Delta A_{CP} &\equiv A_{CP}(K^-K^+) - A_{CP}(\pi^-\pi^+) \\ &\approx \Delta a_{CP}^{\text{dir}} - \frac{\Delta\langle t \rangle}{\tau(D^0)} A_\Gamma,\end{aligned}$$

$$A_{\text{raw}}^{\pi\text{-tagged}}(f) \equiv \frac{N\left(D^{*+} \to D^0(f)\pi^+\right) - N\left(D^{*-} \to \overline{D}^0(f)\pi^-\right)}{N\left(D^{*+} \to D^0(f)\pi^+\right) + N\left(D^{*-} \to \overline{D}^0(f)\pi^-\right)},$$

$$A_{\text{raw}}^{\mu\text{-tagged}}(f) \equiv \frac{N(\overline{B} \to D^0(f)\,\mu^-\bar{\nu}_\mu X) - N(B \to \overline{D}^0(f)\,\mu^+\nu_\mu X)}{N(\overline{B} \to D^0(f)\,\mu^-\bar{\nu}_\mu X) + N(B \to \overline{D}^0(f)\,\mu^+\nu_\mu X)},$$

Charm systematics

Source	π-tagged	μ-tagged
Fit model	0.6	2
Mistag	–	4
Weighting	0.2	1
Secondary decays	0.3	–
Peaking background	0.5	–
B fractions	–	1
B reco. efficiency	–	2
Total	0.9	5

Data collection