CP Violation and CKM Matrix Measurements

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on behalf of the LHCb Collaboration

FFK19, Tihany, 9-14 June 2019

- CP Violation in Standard Model
- How to measure CKM elements and CPV?
- Key experimental inputs from LHCb

Motivation: Big questions to answer

- **Origin of matter-antimatter asymmetry in Universe?**
- CP Violation necessary to explain baryogenesis
- Measured CPV ~10^9 times too small to give:

$$(n_{Baryon} - n_{Anti\text{-}Baryon})/n_\gamma = 6\times10^{-10}$$

- Physics beyond Standard Model must exist
  to generate *missing* CP asymmetry

- **New Physics to make Standard Model complete/elegant?**
- New Particles from high-mass scale may affect flavour observables
  ⇨ we can *detect* them indirectly

Introduction to CP (a)symmetry

- Laws of Nature not symmetric
- P-transformation:
  space reversal,
  swaps up-down, left-right
- C-transformation:
  swaps particle-antiparticle
- Weak interactions violate:

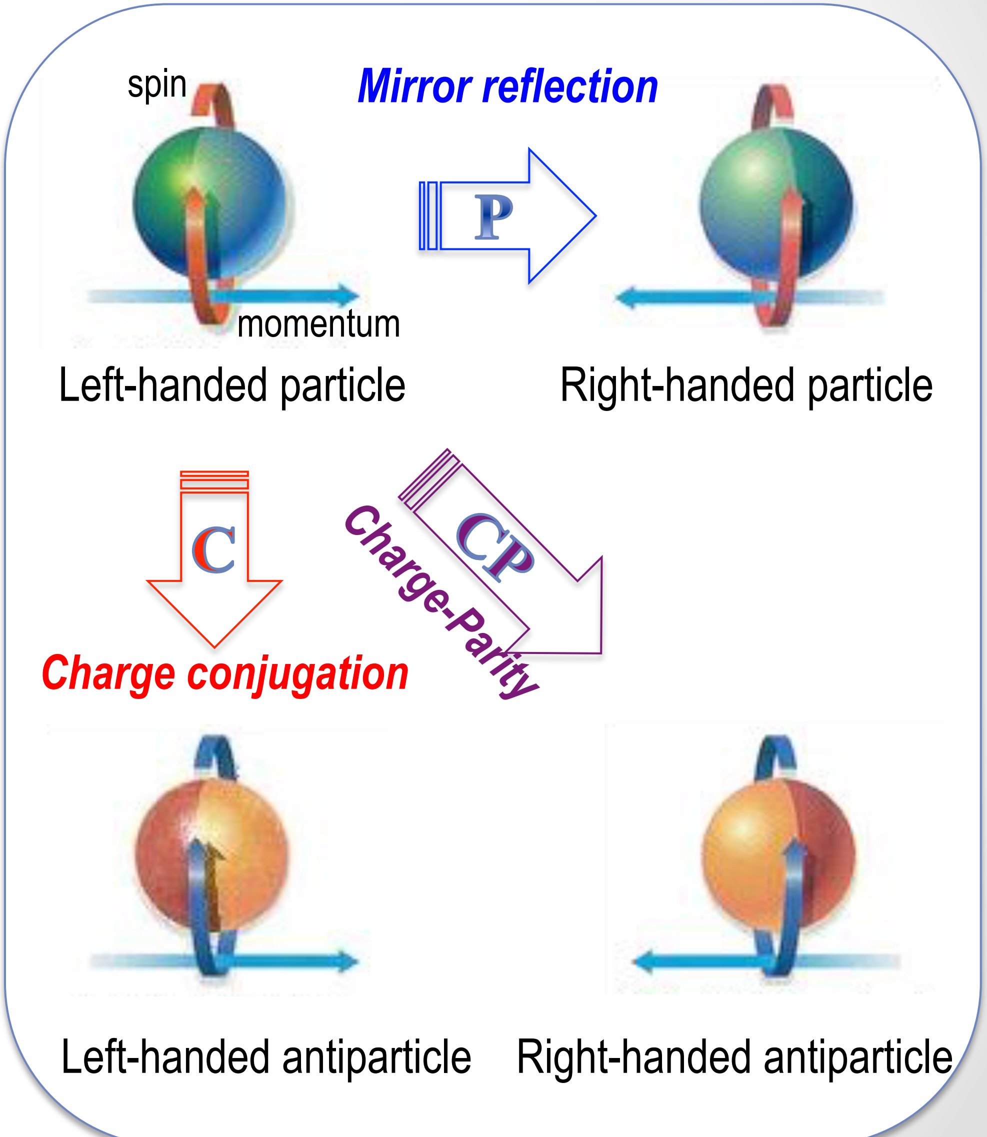
P- & C-symmetry, fully

ν_L ~~ν_R~~ ~~$\bar{\nu}_L$~~ $\bar{\nu}_R$

combined CP-parity, slightly

$K^0_L \rightarrow \pi^+\pi^-$ $O(10^{-3})$

$\Gamma(B^0 \rightarrow K^+\pi^-) > \Gamma(\bar{B}^0 \rightarrow K^-\pi^{-+})$ $O(10^{-2})$



CKM matrix: origin of CP Violation

- $[\text{quark}]_{\text{flavour}} = V_{CKM}\,[\text{quark}]_{\text{mass}}$

  weakly interacting — strongly produced

  ⇨ mixing of quarks of different generations through weak force

$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} = \begin{pmatrix} 1-\frac{1}{2}\lambda^2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\frac{1}{2}\lambda^2 & A\lambda^2 \\ A\lambda^3[1-\rho-i\eta] & -A\lambda^2 & 1 \end{pmatrix} + O(\lambda^4)$$

Wolfenstein parameterization; expansion in **λ~0.2**

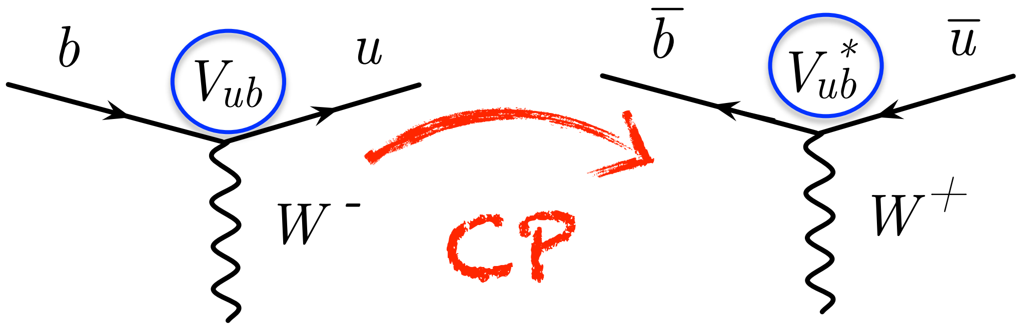
- Single complex phase in the CKM matrix

  ⇨ CP Violation

  [Kobayashi-Maskawa mechanism, Nobel Prize in 2008]

Why complex CKM matrix elements give CPV?

- CKM elements in practice:
  effective couplings between quarks in charged weak currents



Amplitude $\sim|V_{ub}|\exp(-i\gamma)$ $\sim|V_{ub}|\exp(+i\gamma)$

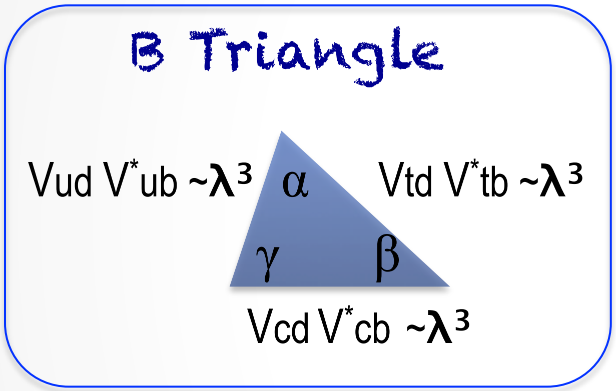
Different amplitudes, different rates ⇨ CP asymmetry

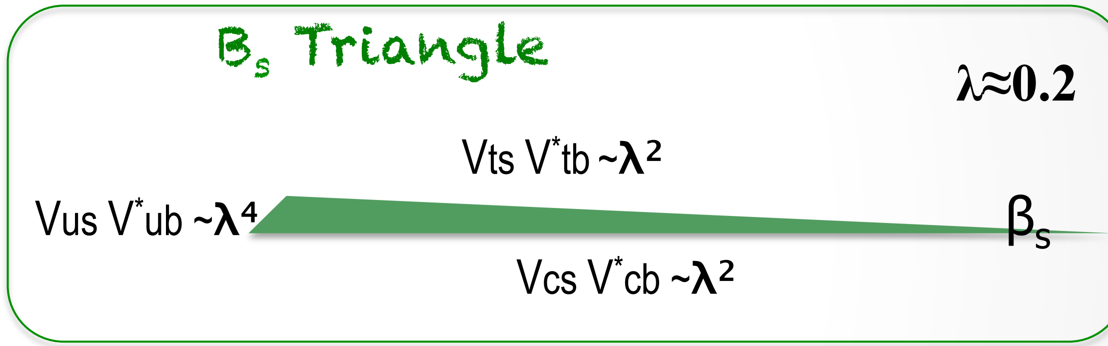
- Measure quark transitions by measuring decays of particles
  ⇨ access to CKM matrix elements

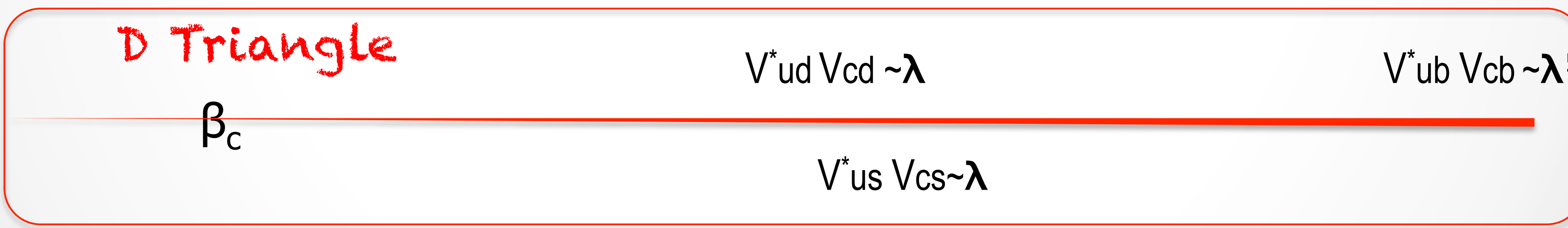
What Unitarity Triangles tell us?

- CKM matrix is unitary in the SM $V^{+}_{CKM} V_{CKM} = V_{CKM} V^{+}_{CKM} = 1$

⇨ If the CKM matrix complex ⇨ CPV ⇨ Unitarity Triangles



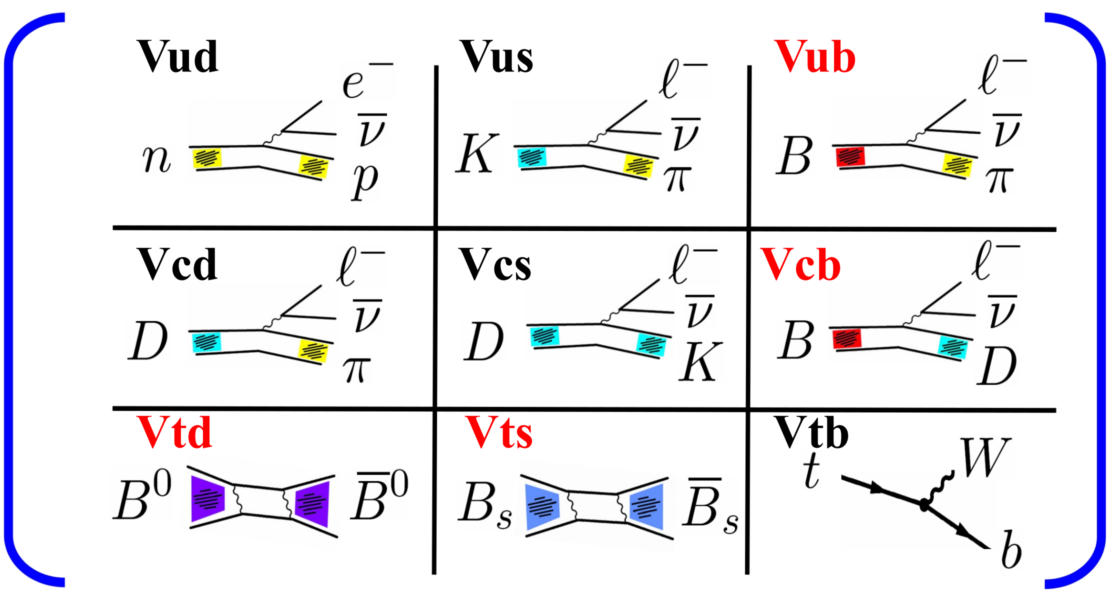




- Triangle openness indicates how large CPV expected
- Measure CPV in various processes ⇨ measure angles of the triangles

How do we measure the CKM parameters?

- CKM matrix elements from rates of semileptonic decays and $B^0_{(s)}$-$\bar{B}^0_{(s)}$ oscillation frequencies [$\Delta m_{d(s)}$]

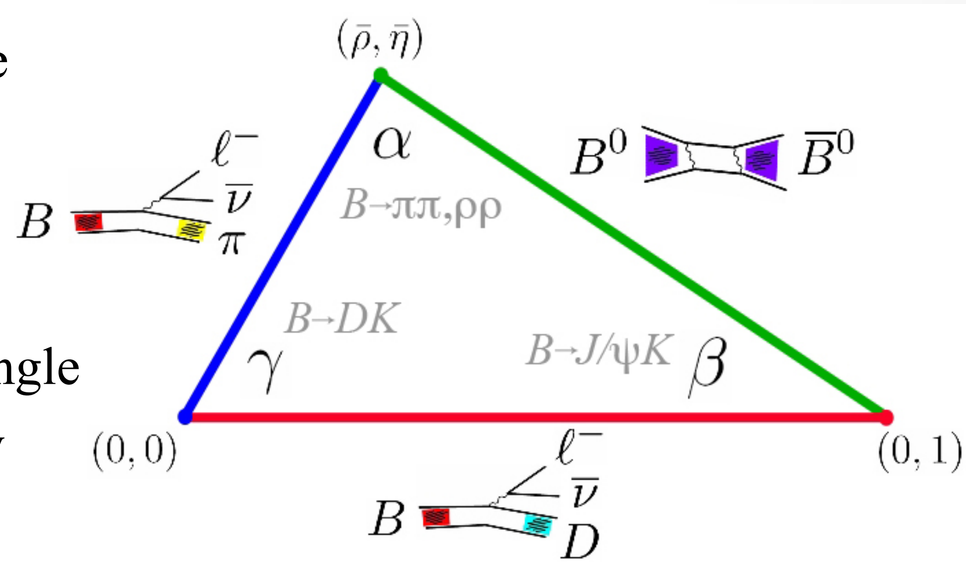


- Angles of the Unitarity Triangle from CP violation

- Measure sides and angles

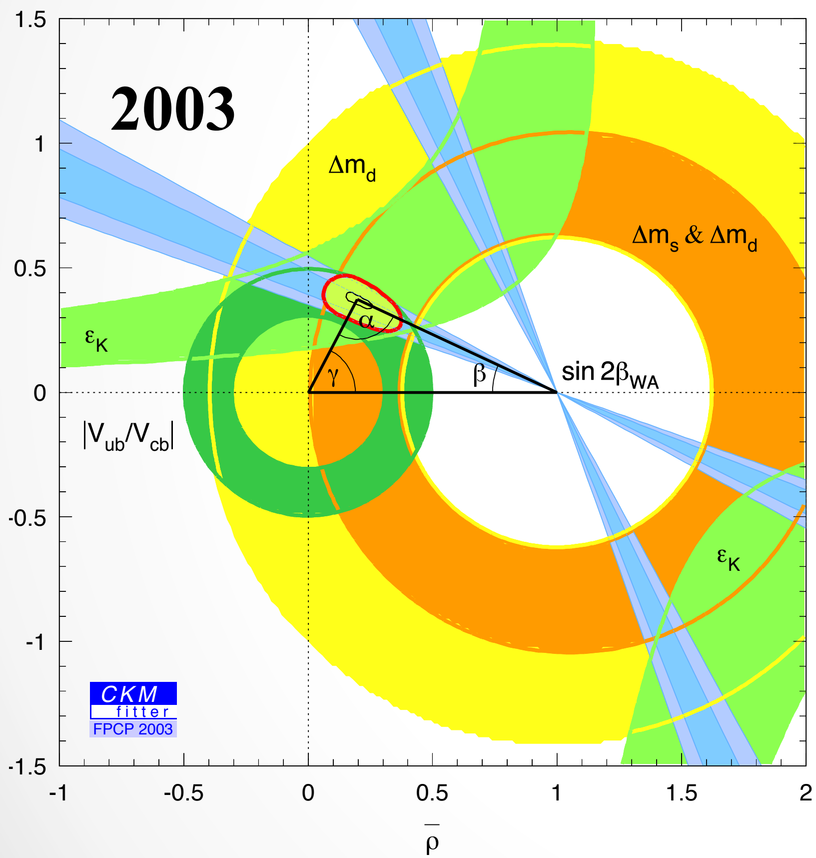
⇨ overconstrain the Unitarity Triangle

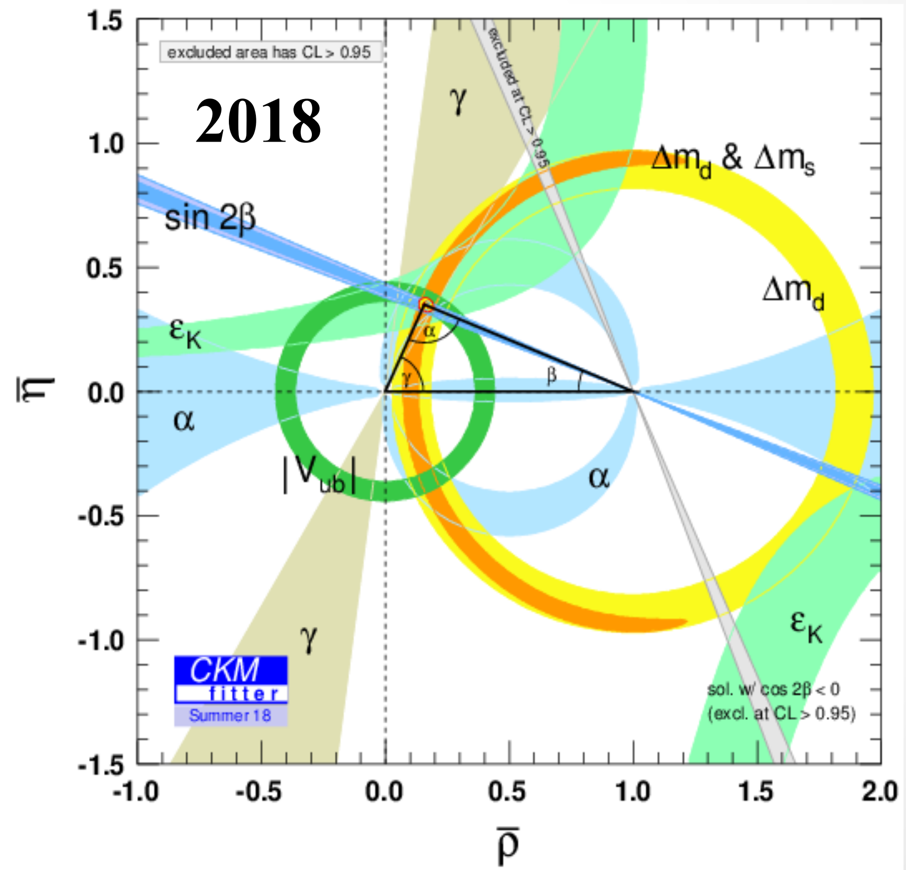
⇨ test Standard Model consistency



The Unitarity Triangle: how precision evolved

- 2001: 1st results from B-Factory experiments (Belle, BaBar)
- 2011: 1st results from LHCb



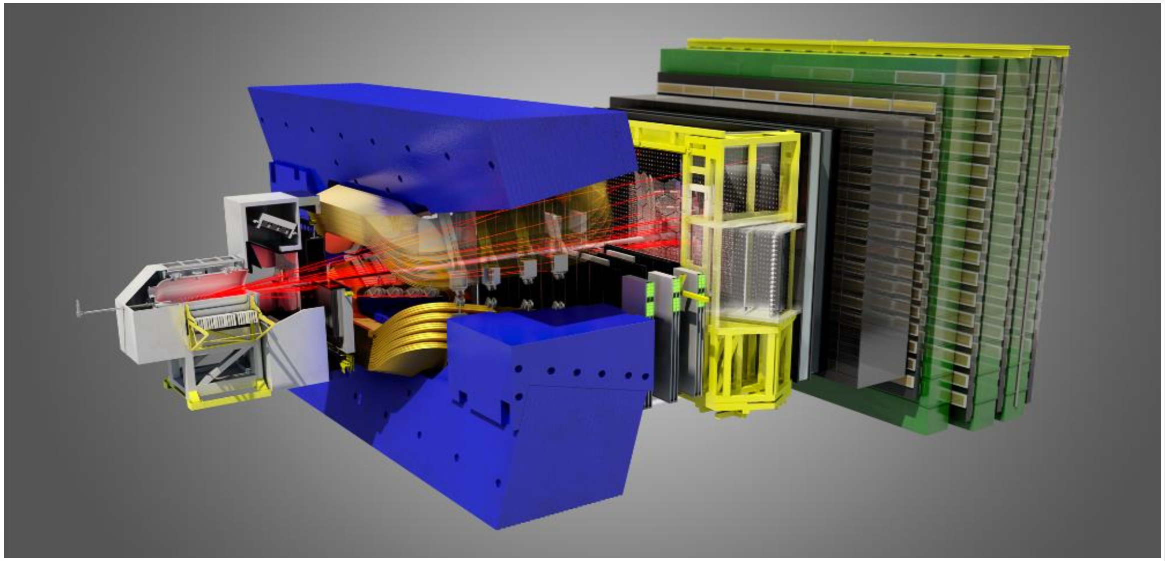


- Unitarity Triangle consistent with a triangle ⇨ SM seems fine [within errors]

LHCb: major player in flavour physics

- Large cross-sections: $\sigma(pp \to b\bar{b}) \sim 0.3$mb, $\sigma(pp \to c\bar{c}) \sim 6$mb
  ⇨ huge samples of charm and beauty hadrons
- All beauty-hadron species produced: B, B_s, B_c, Λ_b, …
- Very good track reconstruction & particle ID
- Excellent decay-time resolution: ~50fs

LHCb detector: single-arm forward spectrometer



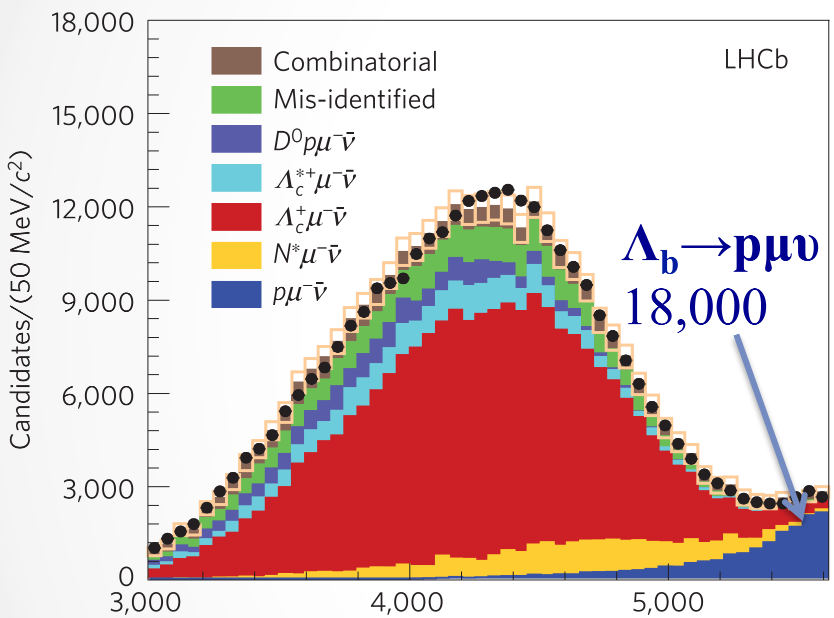
- LHCb data samples

Run1 (2011-2012)
3/fb at 7-8TeV
Run2 (2015-2018)
6/fb at 13 TeV

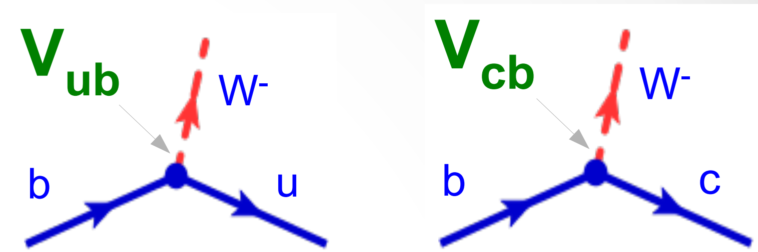
Nature Phys. 11 743-747 (2015)

$|V_{ub}|/|V_{cb}|$ using decays of beauty baryon Λ_b

- Complementary to results from B
- Using Λ_b helps to solve tensions



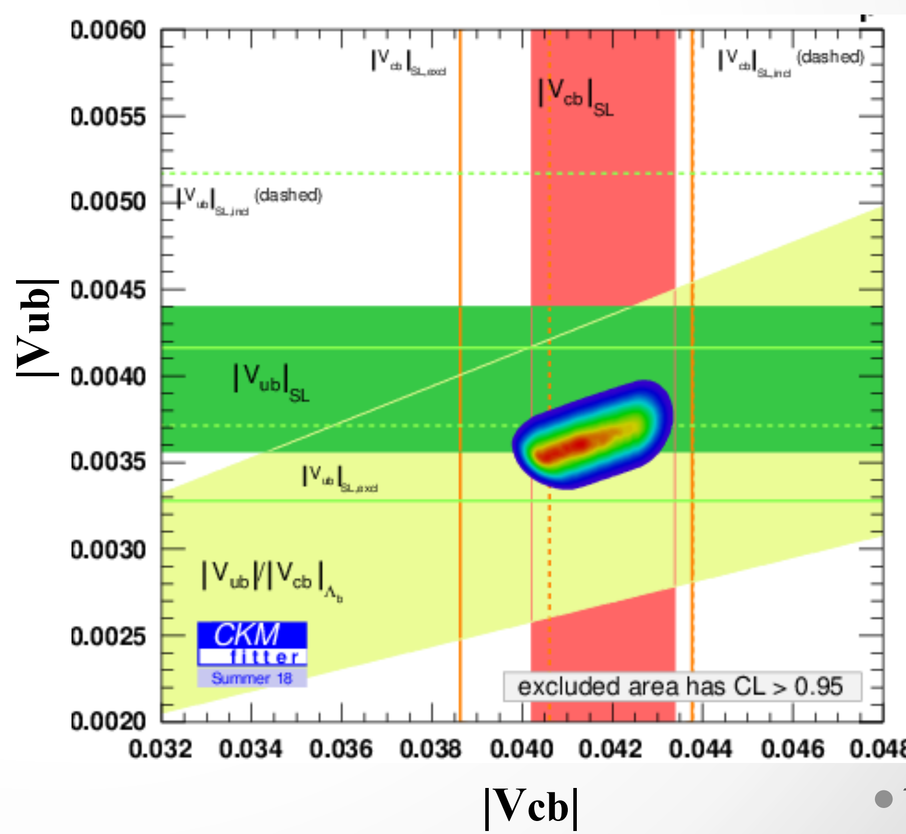
$$M_{\rm corr} = \sqrt{M^2(p\mu) + p_\perp^2} + p_\perp \quad [\text{MeV}]$$



$B \to \pi l\upsilon$ $\Lambda_b \to pl\upsilon$ $B \to Dl\upsilon$ $\Lambda_b \to \Lambda_c l\upsilon$

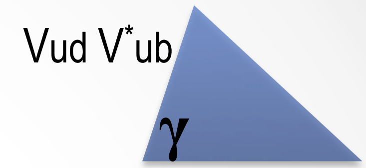
- Normalised with $\Lambda_b \to \Lambda_c \mu\upsilon$

$$\frac{|Vub|}{|Vcb|} = (8.3 \pm 0.4 \pm 0.4)\%$$

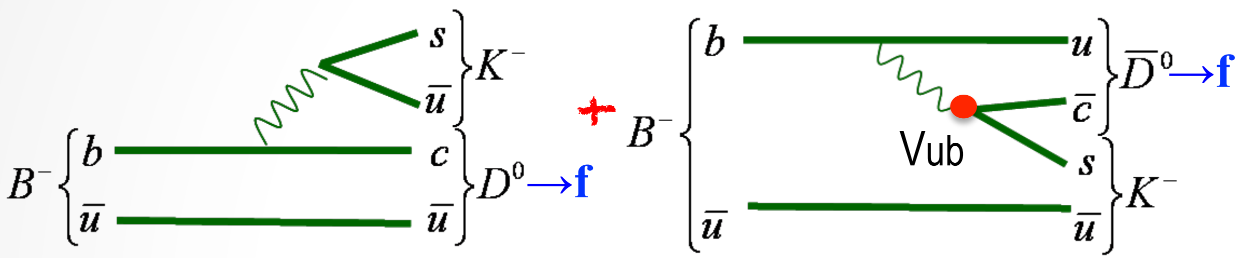


LHCB-CONF-2018-002 (Combination)

γ angle from $B^{\pm} \to DK^{\pm}$



- Clean test of the Standard Model
- Interference of favoured $b \to c$ & suppressed $b \to u$

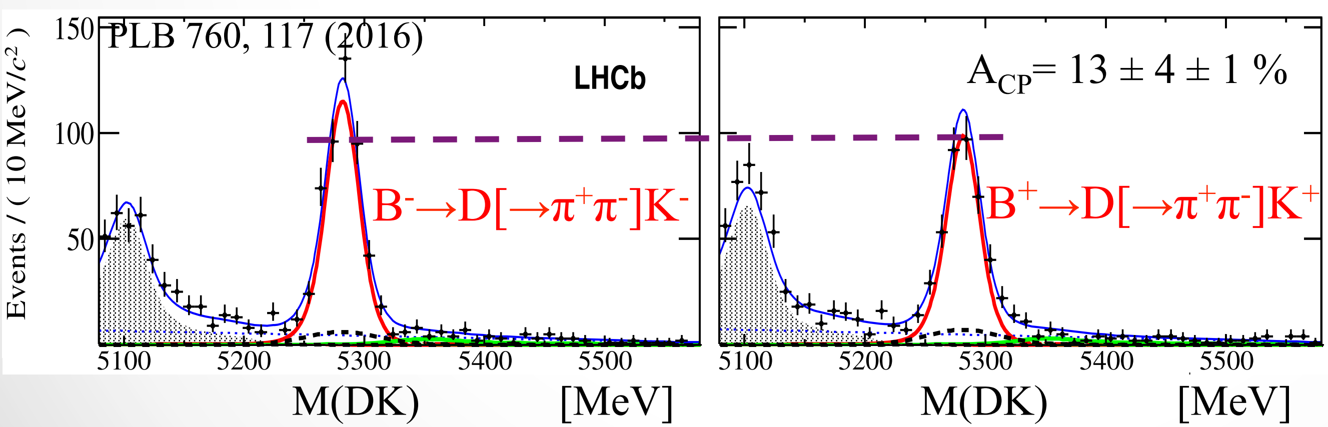


$$A(B^-) \sim A_{D\to f} + r_B e^{i(\delta_B - \gamma)} A_{\overline{D}\to f}$$

$$r_B e^{i\delta_B} = \frac{A\left(B^- \to \overline{D}K^-\right)}{A\left(B^- \to DK^-\right)}$$

r_B, δ_B: hadronic parameters

- Key observable: asymmetry between B^+ and B^- yields



Combinations:
LHCb: $\gamma = 74^{+5}_{-6}$°
Belle: $\gamma = 73 \pm 14$°
BaBar: $\gamma = 70 \pm 18$°

SM: $\gamma = 66 \pm 2$°
(UTfit)

- Many decays used e.g. $D \to K^+K^-$, $\pi^+\pi^-$, $K_S\pi^+\pi^-$, $K^+\pi^-\pi^+\pi^-$

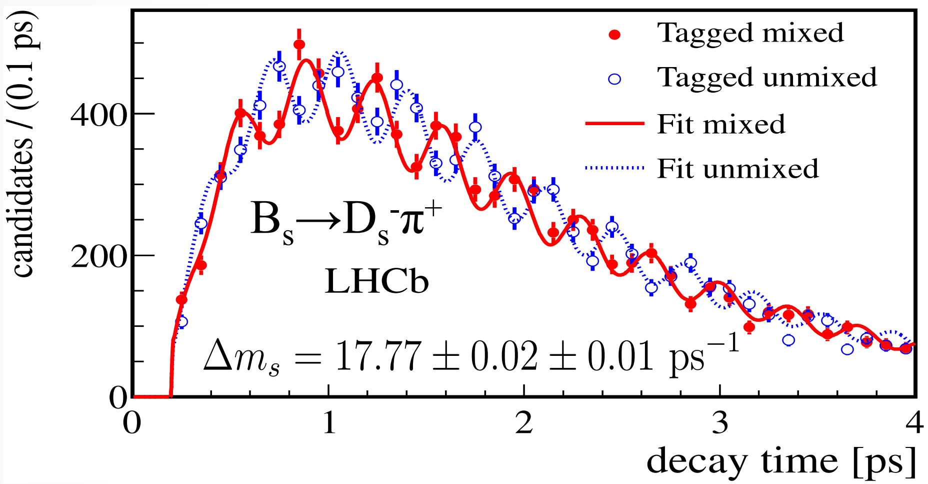
β_s angle from $B_s^0 \to J/\psi\varphi$ decays

$V_{ts}V^*_{tb}$

β_s

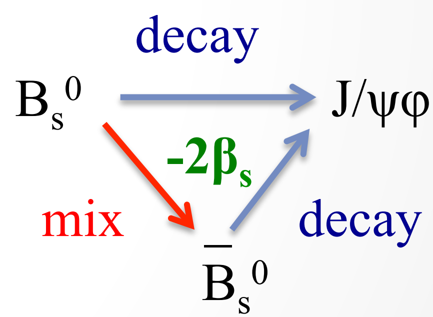
- Out of reach of Belle. Golden mode at LHCb
- B_s mesons quickly oscillate (mix) $B_s^0 \to \bar{B}_s^0 \to B_s^0$

New J.Phys15 053021 (2013)



$$\Delta m_s = m(B_{s,H}) - m(B_{s,L})$$

$$\Delta\Gamma_s = \Gamma(B_{s,H}) - \Gamma(B_{s,L})$$



- Different oscillations of $B_s^0 \to \bar{B}_s^0$ and $\bar{B}_s^0 \to B_s^0$?
- Asymmetry of decay-time distributions for B_s^0 and $\bar{B}_s^0$

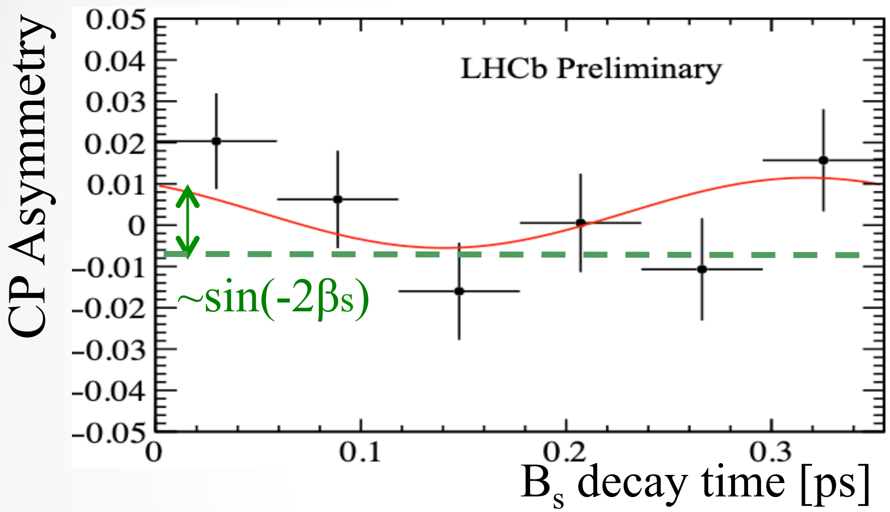
$$A_{CP}(t) = \frac{\Gamma(B_s^0 \to J/\psi\phi) - \Gamma(\overline{B}_s^0 \to J/\psi\phi)}{\Gamma(B_s^0 \to J/\psi\phi) + \Gamma(\overline{B}_s^0 \to J/\psi\phi)} \sim \sin(-2\beta_s)\sin(\Delta m_s t) + \cosh(\Delta\Gamma_s t)$$

- In Standard Model: $-2\beta_s = -37 \pm 1$ mrad

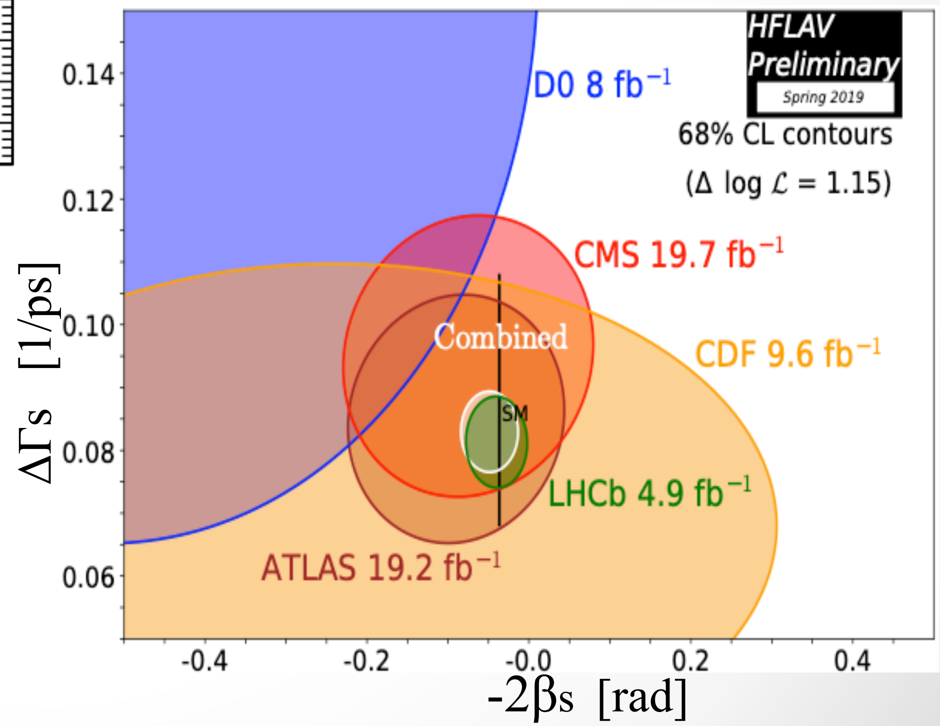
PRL 114, 041801 (2015)
LHCB-PAPER-2019-013

β_s angle from $B_s^0 \to J/\psi\varphi$ decays

- New from LHCb with 2015-2016 data (2/fb)



$$-2\beta_s = -83 \pm 41 \pm 6 \text{ mrad}$$
$$\Delta\Gamma_s = 0.077 \pm 0.008 \pm 0.003 \text{ ps}^{-1}$$



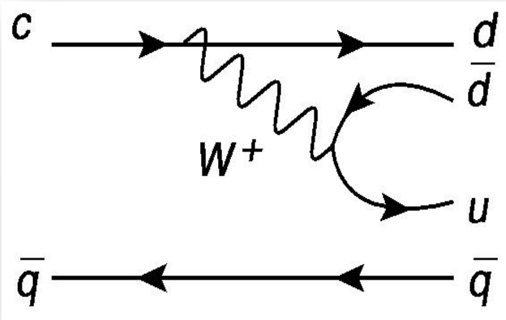
- Dominant input from LHCb
- Consistent with Standard Model

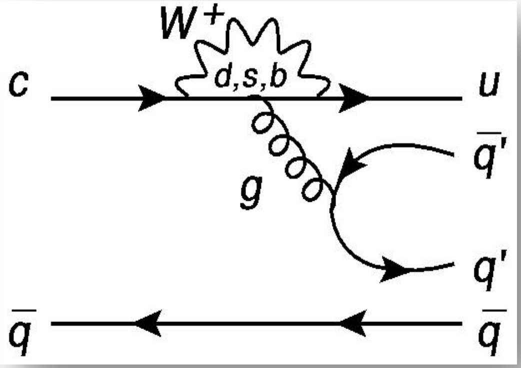
CP Violation in charm decays

- CP asymmetries in charm very small in Standard Model: **$\leq 10^{-3} \div 10^{-2}$**

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

- CPV requires two amplitudes with different weak & strong phases
  ⇨ can occur in charm decays with Tree + Penguin amplitudes





- Penguin amplitude in charm is tiny [no top quark in the loop]
- CP Violation in charm not observed till recently

Most precise
Very important

A_{CP} in two-body charm decays: all null so far

	LHCb (Run1)	Belle	BaBar	BESIII
Mode	A_{CP} [%]			
$D^0 \to K^+K^-$	+0.04 ± 0.12 ± 0.10	-0.32 ± 0.21 ± 0.09	+0.00 ± 0.34 ± 0.13	
$D^0 \to \pi^+\pi^-$	+0.07 ± 0.14 ± 0.11	+0.55 ± 0.36 ± 0.09	-0.24 ± 0.52 ± 0.22	
$D^0 \to K_sK_s$	-2.9 ± 5.2 ± 2.2	+0.00 ± 1.53 ± 0.17		
$D^0 \to \pi^0\pi^0$		-0.03 ± 0.64 ± 0.10		
$D^0 \to K_s\eta$		+0.54 ± 0.51 ± 0.16		
$D^0 \to K_s\eta'$		+0.98 ± 0.67 ± 0.14		
$D^+ \to \pi^+\pi^0$		+2.31 ± 1.24 ± 0.23		
$D^+ \to K_sK^+$	+0.03 ± 0.17 ± 0.14	+0.08 ± 0.28 ± 0.14	+0.46 ± 0.36 ± 0.25	-1.5 ± 2.8 ± 1.6
$D^+ \to \varphi\pi^+$	-0.04 ± 0.14 ± 0.14	+0.51 ± 0.28 ± 0.05		
$D^+ \to \eta\pi^+$		+1.74 ± 1.13 ± 0.19		
$D^+ \to \eta'\pi^+$	-0.61 ± 0.72 ± 0.55 ± 0.12	-0.12 ± 1.12 ± 0.17		
$D_s^+ \to K_s\pi^+$	+0.38 ± 0.46 ± 0.17	+5.45 ± 2.50 ± 0.33	+0.3 ± 2.0 ± 0.3	
$D_s^+ \to \eta'\pi^+$	-0.82 ± 0.36 ± 0.24 ± 0.27			

https://hflav-eos.web.cern.ch/hflav-eos/charm/

PRL122 211803 (2019)

Search via $\Delta A_{CP}=A_{CP}(D^0\to K^+K^-) - A_{CP}(D^0\to\pi^+\pi^-)$

- Simple & sensitive:
  nuisance production & detection asymmetries cancel out

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

$$A_{RAW}(K^+K^-) = \frac{N(D^0 \to K^+K^-) - N(\bar{D}^0 \to K^+K^-)}{N(D^0 \to K^+K^-) + N(\bar{D}^0 \to K^+K^-)}$$

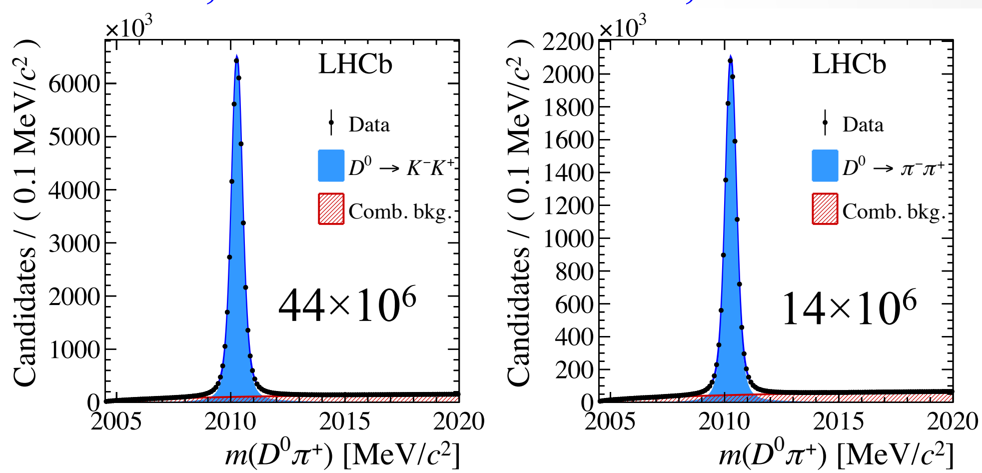
- Data 6/fb Run2 (2015-2018)

prompt charm $D^{*+}\to D^0\pi^+$
$D^{*-}\to \bar{D}^0\pi^-$

$$\Delta A_{CP} = (-18.2 \pm 3.2 \pm 0.9) \times 10^{-4}$$

Most precise!

$D^0, \bar{D}^0\to K^+K^-$ $D^0, \bar{D}^0\to \pi^+\pi^-$



- **LHCb Run1+Run2** **$\Delta A_{CP}=(-15.4 \pm 2.9)\times10^{-4}$** **5.3σ away from zero!**
- Agrees with SM prediction: $10^{-4} \div 10^{-3}$ **1st observation of CPV in charm!**
-

Summary

- CP Violation in the Standard Model:
  from single phase in the CKM matrix
- SM tests: investigate entire CKM structure

- **B decays**: precision of the Unitarity Triangle
- **B_s sector**: LHCb opened era of precision
- **D decays**: CPV finally observed!
  Last missing bit in the SM quark sector

- Experiment still consistent with the SM
- We are entering higher precision era:
  BelleII (2019-) and LHCb Upgrade (2021-)