Time-dependent and time-integrated CP violation in beauty at LHCb

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Today agenda

MOTIVATION

STATUS OF CKM ANGLES
$\gamma,\ \beta,\ \beta_s$

RESULTS PUBLISHED THIS YEAR

SUMMARY

First things, first

1 Baryogenesis tell us that there must be New Physics (NP) in CP violation (CPV).

2 CPV in the Standard Model (SM) comes from the CKM matrix, governing the quark mixing.

In Wolfenstein parametrization (incorporate experimental information), it can be written in terms of *A, λ, ρ* and *η* parameters.

$$V_{CKM} \approx \begin{pmatrix} 1-\frac{1}{2}\lambda^2-\frac{1}{2}\lambda^4 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\frac{1}{2}\lambda^2\ldots & A\lambda^2 \\ A\lambda^3(1-\bar{\rho}-i\bar{\eta}) & -A\lambda^2+\lambda^4(1-2(\rho-i\eta))\ldots & 1-\frac{1}{2}A^2\lambda^4 \end{pmatrix} + \mathcal{O}(\lambda^5)$$

$$V_{CKM} \approx \begin{pmatrix} |V_{ud}| & |V_{us}| & |V_{ub}|e^{-i\gamma} \\ -|V_{cd}| & |V_{cs}| & |V_{cb}| \\ |V_{td}|e^{-i\beta} & -|V_{ts}|e^{i\beta_s} & |V_{tb}| \end{pmatrix} + \mathcal{O}(\lambda^5)$$

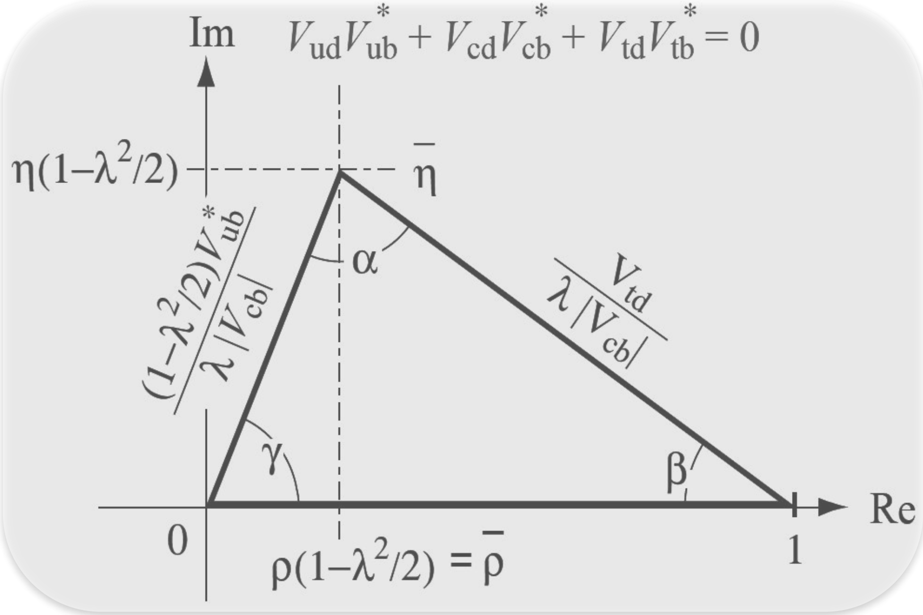
The Unitary Triangle (UT)

The CKM matrix that is unitary i.e. $\sum_k V_{ki} V^*_{kj} = \delta_{ij}$ (generate 6 eqs.)

$$V_{ud}V^*_{ub} + V_{cd}V^*_{cb} + V_{td}V^*_{tb} = 0\,, \quad V_{us}V^*_{ub} + V_{cs}V^*_{cb} + V_{ts}V^*_{tb} = 0\,, \quad \ldots$$

These equations requires the sum of 3 complex quantities to vanish and so can be **geometrically represented in the complex plane as UT**.

- The **area** of the UT is **related to the size of the CPV**.



$$\alpha = arg\left(\frac{-V^*_{tb}V_{td}}{V^*_{ub}V_{ud}}\right) \quad \beta = arg\left(\frac{-V^*_{cb}V_{cd}}{V^*_{tb}V_{td}}\right) \quad \gamma = arg\left(\frac{-V^*_{ub}V_{ud}}{V^*_{cb}V_{cd}}\right) \quad \beta_s = arg\left(\frac{-V_{ts}V^*_{tb}}{V_{cs}V^*_{cb}}\right)$$

The angles are **physical quantities** and can be **independently measured by CPV** in *B* decays.

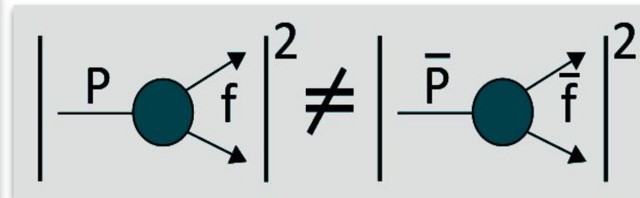
Types of CP violation

$A_f =< f \,|\, H \,|\, P >$
$\overline{A}_{\overline{f}} =< \overline{f} \,|\, H \,|\, \overline{P} >$
$\overline{A}_f =< f \,|\, H \,|\, \overline{P} >$

DECAY

Occurs when the decay rate of a B to final state f differs from the decay rate of an anti-B to the CP-conjugated final state anti-f. **[time integrated]**

$$\Gamma(P^0 \to f) \neq \Gamma(\bar{P}^0 \to \bar{f}) \quad \text{or} \quad \left|A_f/\overline{A}_{\overline{f}}\right| \neq 1$$



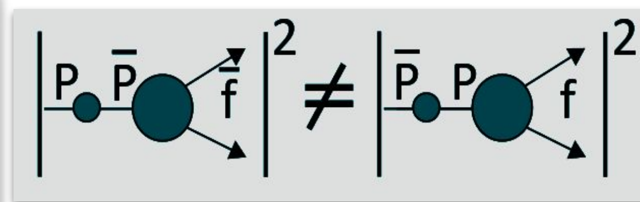
MIXING

Occurs in neutral mesons. Implies that the oscillation from meson to anti-meson is different from the oscillation from anti-meson to meson. **[time dependent]**

$$|P_1\rangle = p\,|P^0\rangle + q\,\left|\overline{P^0}\right\rangle$$

$$|P_2\rangle = p\,|P^0\rangle - q\,\left|\overline{P^0}\right\rangle$$

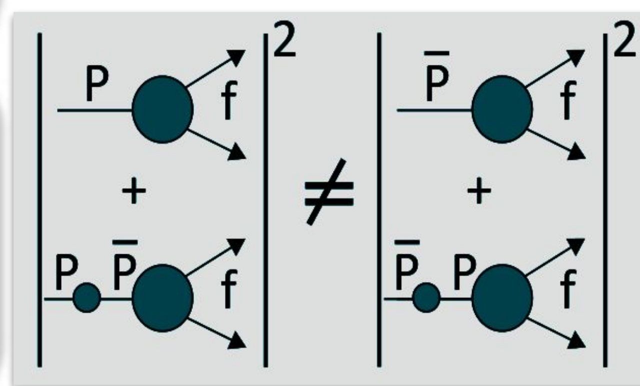
$$|q/p| \neq 1$$



INTERFERENCE

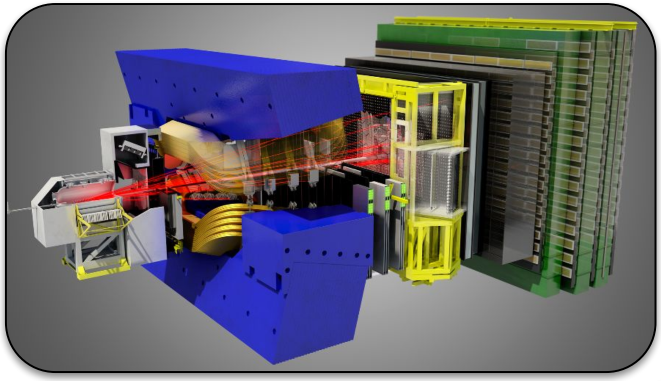
Occurs in neutral mesons. CPV in interference between a decay with and without mixing. **[time dependent]**

$$Im\left(\frac{q\,\overline{A}_f}{p\,A_f}\right) \neq 1$$



The LHCb detector

Int. J. Mod Phys. A30, 1530022 (2015)



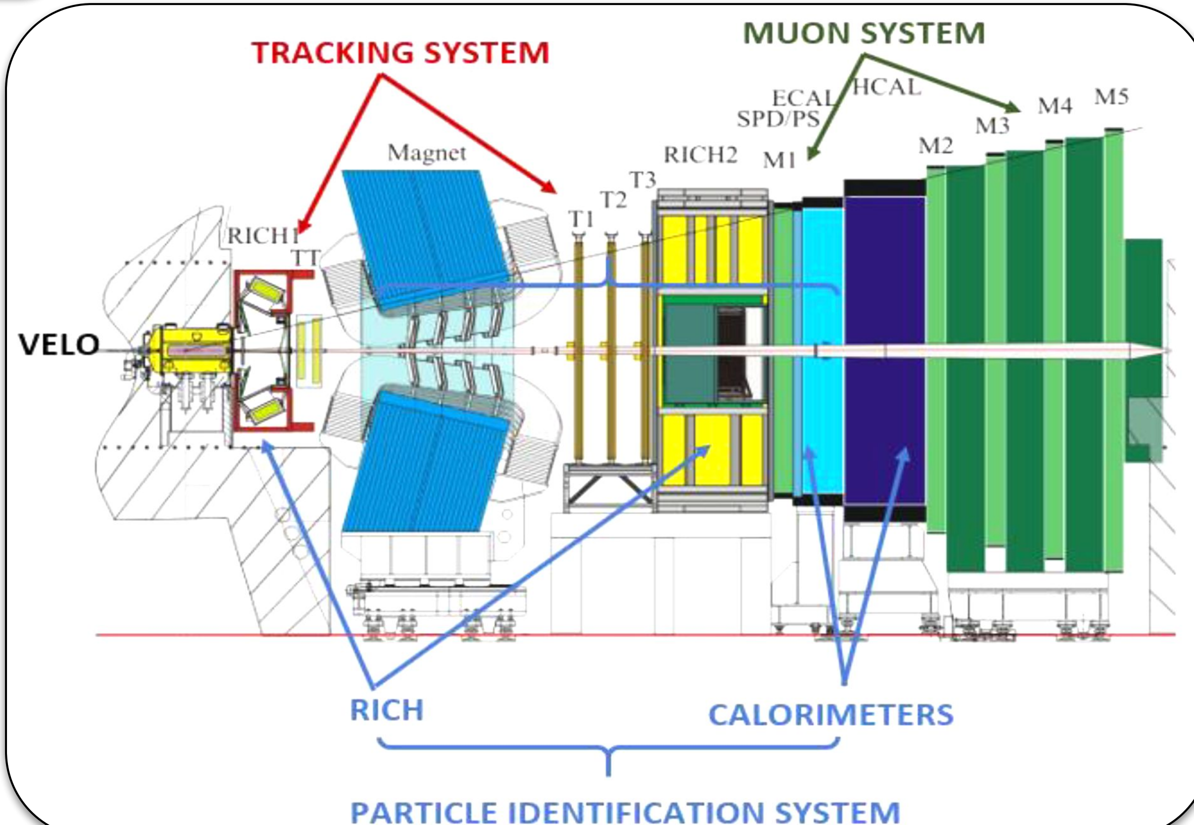
Dedicated to studying flavor physics at LHC.
Especially CPV and rare decays of *B* and *D* mesons.
Single-arm forward spectrometer.
Covering the pseudorapidity range ($2 < \eta < 5$).
Excellent track and vertex reconstructions.
Good PID separation, flexible trigger.

IP resolution: σ_{IP} = 20 μm

Momentum resolution:
$\Delta p/p$ = 0.5 - 0.8 %

Mass resolution:
$\sigma(m_{B\to hh}) \approx 22$ MeV

Decay-time resolution:
~45 fs



Today agenda

MOTIVATION

STATUS OF CKM ANGLES

$\gamma,\ \beta,\ \beta_s$

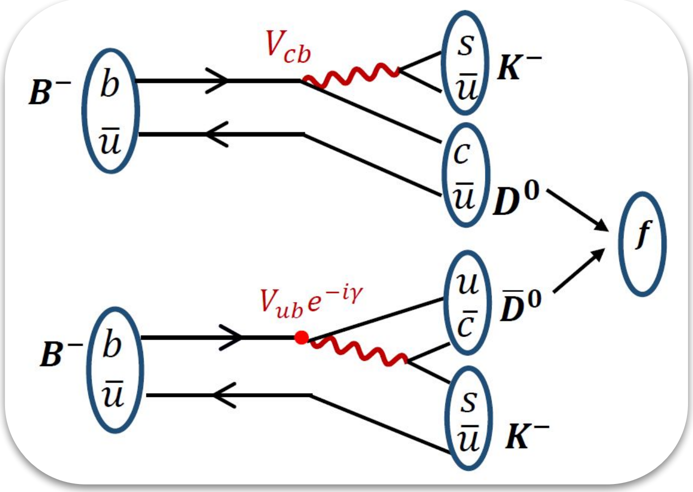
RESULTS PUBLISHED THIS YEAR

SUMMARY

The CKM angle γ

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

The value of γ can be determined by exploiting the interference between favored $b \to c$ (V_{cb}) and suppressed $b \to u$ (V_{ub}) transition amplitudes.



$$A_{CP} = \frac{\Gamma(B^- \to D^0 K^-) - \Gamma(B^+ \to D^0 K^+)}{\Gamma(B^- \to D^0 K^-) + \Gamma(B^+ \to D^0 K^+)} \propto \sin(\gamma)$$

$D^0 \leftrightarrow D^{\pm},\ D_s^{\pm},\ D^*$

$K^{\pm} \leftrightarrow K^{*0},\ K^{*+}$

Different experimental methods:

- GLW: D→ CP eigenstates: K^+K^-, $\pi^+\pi^-$, $K^+K^-\pi^0$, $\pi^+\pi^-\pi^0$
- ADS: D → CP non-eigenstates: $K^+\pi^-$, $K^+\pi^-\pi^+\pi^-$, $K_SK^+\pi^-$
- GGSZ: D→ 3 body self-conjugated: $K_S\pi^+\pi^-$, $K_SK^+K^-$

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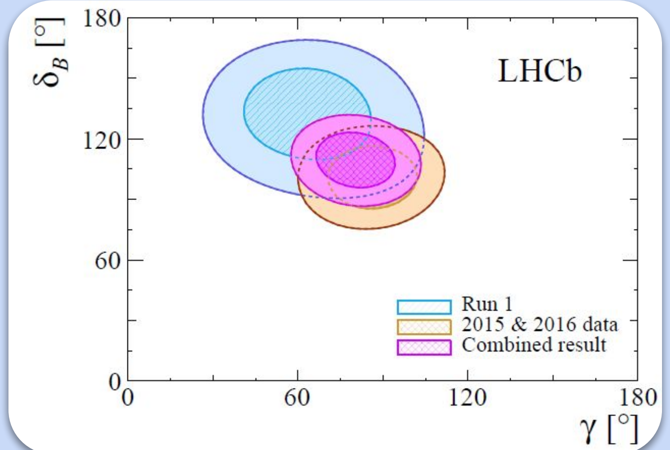
Model-independent GGSZ analysis of $B^{\pm} \to DK^{\pm}$.
Simultaneous measurements of $D \to K_S^0\pi^+\pi^-$ and $D \to K_S^0K^+K^-$.
Decay amplitude is a sum of suppressed and favored decay

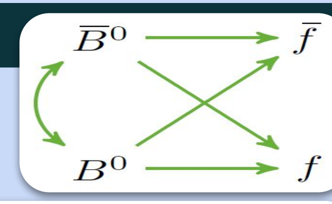
$$A_B(m_-^2, m_+^2) \propto A_D(m_-^2, m_+^2) + r_B e^{i(\delta_B - \gamma)} A_{\bar{D}}(m_-^2, m_+^2)$$

CPV observables: $x_{\pm} + iy_{\pm} = r_B e^{i(\delta_B \pm \gamma)}$

$$r_B = 0.087^{+0.013}_{-0.014}, \quad \delta_B = (101 \pm 11)^{\circ}, \quad \gamma = (87^{+11}_{-12})^{\circ}$$



JHEP 06 (2018) 084

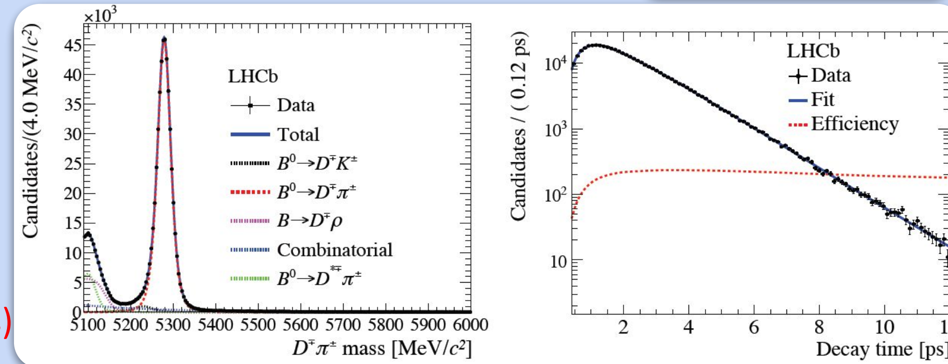


Time-dependent analysis of $B^0 \to D^{\mp}\pi^{\pm}$ ($D^{\mp} \to K^{\pm}\pi^{\mp}\pi^{\mp}$).

Method: decay-time fit to background -subtracted data, using FT, time acceptance and resolution obtained in a data-driven way.

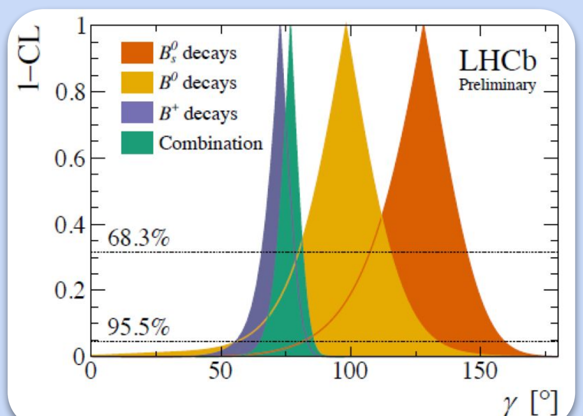
$$\text{Intervals (at 68\% CL)}: \begin{cases} |\sin(2\beta+\gamma)| \in [0.77, 1.0] \\ \gamma \in [5, 86]^\circ \cup [185, 266]^\circ \\ \delta \in [-41, 41]^\circ \cup [140, 220]^\circ \end{cases}$$

Largest flavour-tagged sample at LHCb! (~500K evts)



LHCb-CONF-2018-002

Everything consistent at the 2 sigma level currently.



B decay	D decay	Method
$B^+ \to DK^+$	$D \to h^+h^-$	GLW
$B^+ \to DK^+$	$D \to h^+h^-$	ADS
$B^+ \to DK^+$	$D \to h^+\pi^-\pi^+\pi^-$	GLW/ADS
$B^+ \to DK^+$	$D \to h^+h^-\pi^0$	GLW/ADS
$B^+ \to DK^+$	$D \to K_S^0h^+h^-$	GGSZ
$B^+ \to DK^+$	$D \to K_S^0h^+h^-$	GGSZ
$B^+ \to DK^+$	$D \to K_S^0K^+\pi^-$	GLS
$B^+ \to D^*K^+$	$D \to h^+h^-$	GLW
$B^+ \to DK^{*+}$	$D \to h^+h^-$	GLW/ADS
$B^+ \to DK^{*+}$	$D \to h^+\pi^-\pi^+\pi^-$	GLW/ADS
$B^+ \to DK^+\pi^+\pi^-$	$D \to h^+h^-$	GLW/ADS
$B^0 \to DK^{*0}$	$D \to K^+\pi^-$	ADS
$B^0 \to DK^+\pi^-$	$D \to h^+h^-$	GLW-Dalitz
$B^0 \to DK^{*0}$	$D \to K_S^0\pi^+\pi^-$	GGSZ
$B_s^0 \to D_s^{\mp}K^{\pm}$	$D_s^+ \to h^+h^-\pi^+$	TD
$B^0 \to D^{\mp}\pi^{\pm}$	$D^+ \to K^+\pi^-\pi^+$	TD

LHCb measurements

$$\gamma = (74.0^{+5.0}_{-5.8})^\circ \text{ at } 68.3\% \text{ C.L.}$$

Dominating the WA:

$$\gamma = (73.5^{+4.2}_{-5.1})^\circ$$

(HFLAV, winter 18)

Indirect constraints:

$$\gamma = (65.8 \pm 2.2)^\circ$$

(UTfit, summer 18, prel.)

The CKM angle β

$$\beta = arg\left(\frac{-V_{cb}^{*}V_{cd}}{V_{tb}^{*}V_{td}}\right)$$

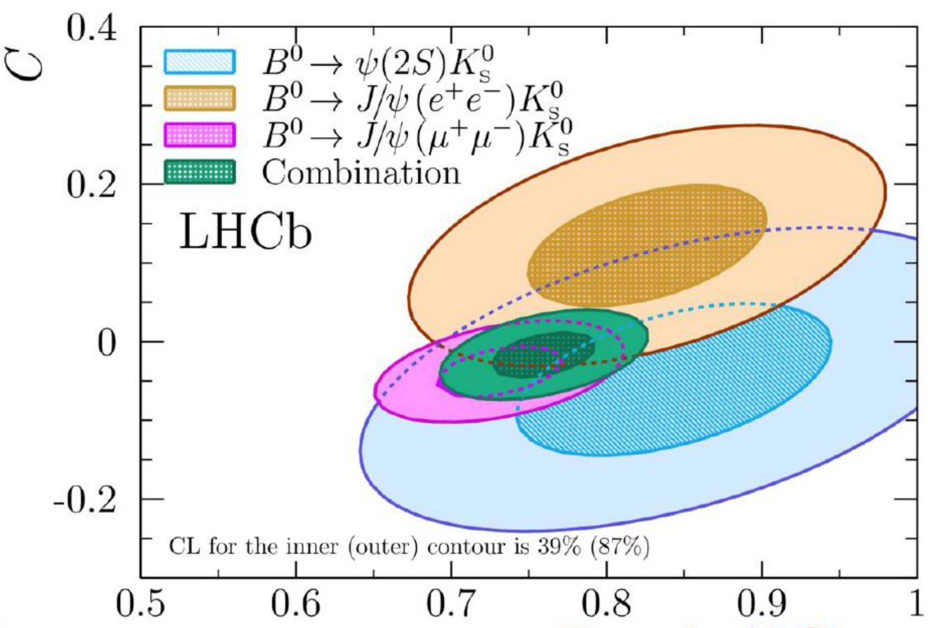
The β angle can be measured in the interference between B^0 mixing and decay.

The golden channel is: $B^0 \rightarrow J/\psi\, K_S$

- New Run 1 LHCb analysis of $B^0 \rightarrow J/\psi(ee)K_s$ and $B^0 \rightarrow \psi(2S)(\mu\mu)K_s$ [JHEP 11 (2017) 170].

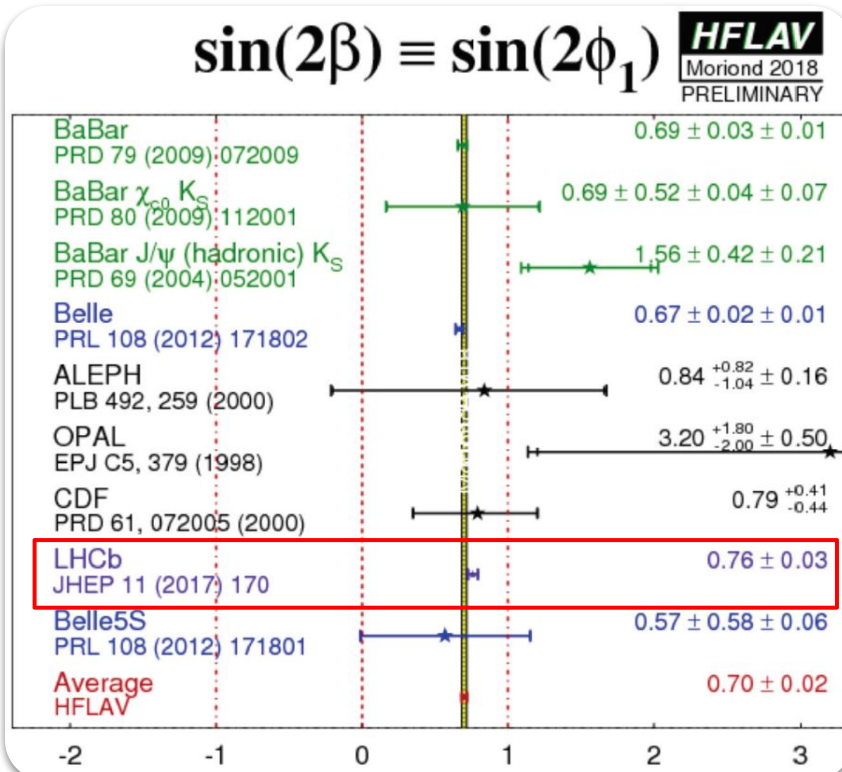
  LHCb combination:

  $C = -0.017 \pm 0.029, \qquad S = 0.760 \pm 0.034$



$S = \sin(2\beta)$

Using Run 1 data, LHCb reached the precision of Belle/BaBar.



The CKM angle β_s

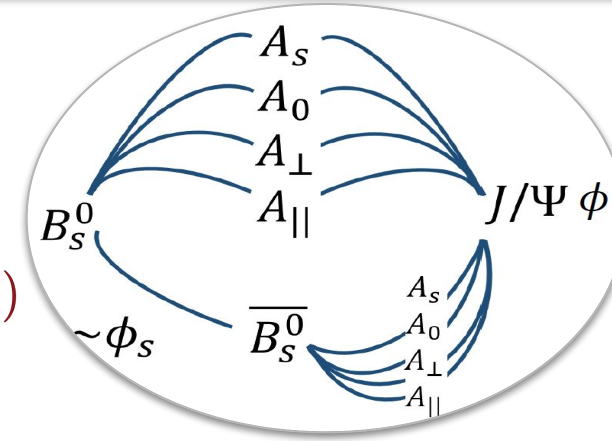
$$\beta_s = arg\left(\frac{-V_{ts}V_{tb}^*}{V_{cs}V_{cb}^*}\right)$$

The β_s angle can be measured in the interference between B_s^0 mixing and decay.

Tiny in SM ⇒ $\phi_S \sim mrad\,, \quad \phi_S = -2\beta_S$

Can be measured in the golden mode: $B_S^0 \to J/\psi\ \phi(1020)$

Angular analysis needed to disentangle the CP eigenstates.

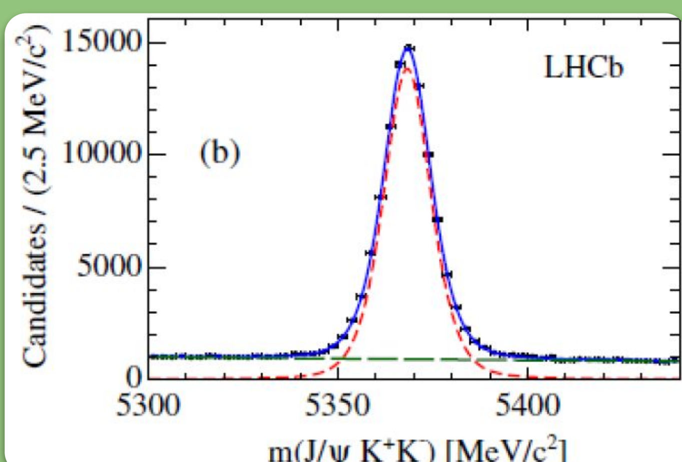


LHCb result: PRL 114, 041801 (2015)

Combined with other LHCb analyses

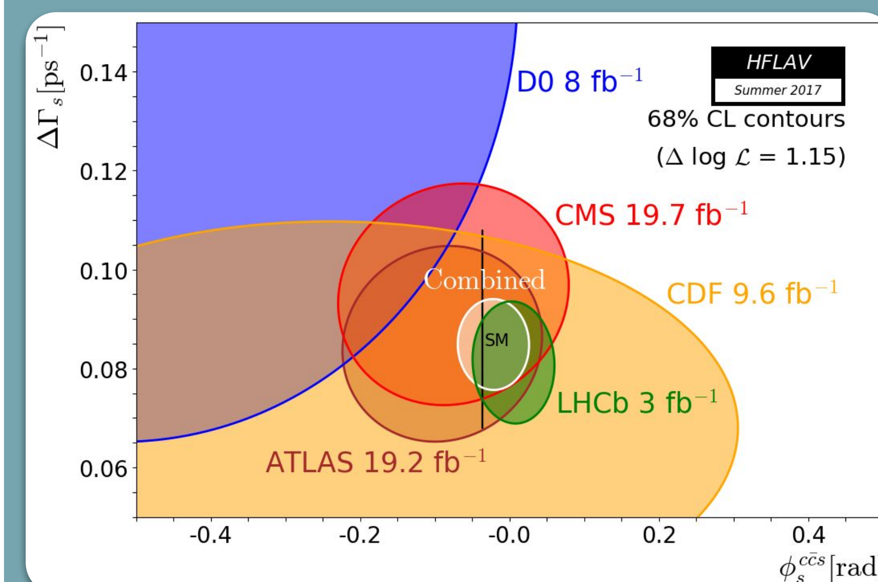
$$\phi_S = -10 \pm 39\, mrad$$

Consistent with the SM prediction.



Global fit: $\phi_s^{c\bar{c}s} = -21 \pm 31$ mrad [HFLAV]

Dominated by LHCb result PRL114,041801(2015)



Today agenda

- MOTIVATION
- STATUS OF CKM ANGLES $\gamma,\ \beta,\ \beta_s$
- RESULTS PUBLISHED THIS YEAR
- SUMMARY

CP violation in $B_s^0 \to \phi\phi$

LHCb-CONF-2018-001

Penguin dominated decay, sensitivity to NP not only in mixing but also in decay.

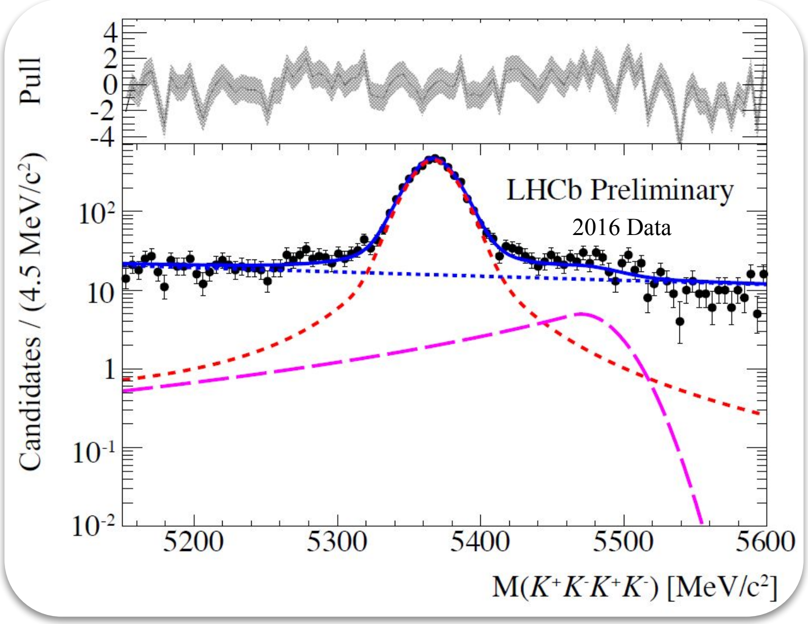
LHCb analysis measure time-dependent CPV, polarization fractions and triple-product asymmetries of ~5fb^{-1} data sample (~8500 $B_s^0 \to \phi\phi$).

$$U = cos\Phi \times sin\Phi \qquad A_U = \frac{N(U>0)-N(U<0)}{N(U>0)+N(U<0)}$$

$$V = \eta_\theta \times sin\Phi \qquad A_V = \frac{N(V>0)-N(V<0)}{N(V>0)+N(V<0)}$$

A_U and A_V are expected to be close to zero in the SM.

Method: decay-time-dependent angular fit to background-subtracted data, using FT, angular acceptance (from simulation), and time acceptance and resolution (data-driven).



$$\phi_s^{s\bar{s}s} = -0.07 \pm 0.13(\text{stat}) \pm 0.03(\text{syst})\ \text{rad},$$
$$|\lambda| = 1.02 \pm 0.05(\text{stat}) \pm 0.03(\text{syst})$$

$$A_U = 0.000 \pm 0.012(\text{stat}) \pm 0.004(\text{syst}),$$
$$A_V = -0.003 \pm 0.012(\text{stat}) \pm 0.004(\text{syst})$$

Compatible with no CPV and with the SM.

CPV in $B_s^0 \to (K^+\pi^-)(K^-\pi^+)$

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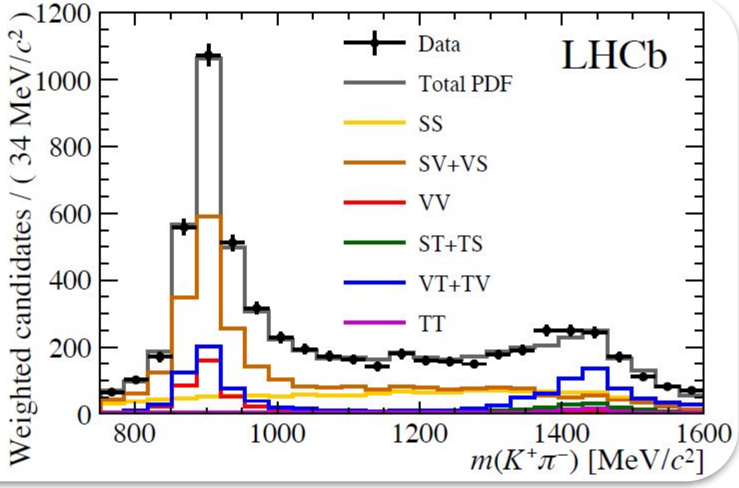
P→*VV* penguin dominated decay (~3fb^{-1} data sample)

Several decays studied together using a large M(Kπ) window.

Channel	Decay	Polarization amplitudes
Channel #1	$B_s^0 \to (K^+\pi^-)_0^*(K^-\pi^+)_0^*$	SS
Channel #2	$B_s^0 \to (K^+\pi^-)_0^*\bar{K}^*(892)^0$	SV
Channel #3	$B_s^0 \to K^*(892)^0(K^-\pi^+)_0^*$	VS
Channel #4	$B_s^0 \to (K^+\pi^-)_0^*\bar{K}_2^*(1430)^0$	ST
Channel #5	$B_s^0 \to K_2^*(1430)^0(K^-\pi^+)_0^*$	TS
Channel #6	$B_s^0 \to K^*(892)^0\bar{K}^*(892)^0$	VV0, VV∥, VV⊥
Channel #7	$B_s^0 \to K^*(892)^0\bar{K}_2^*(1430)^0$	VT0, VT∥, VT⊥
Channel #8	$B_s^0 \to K_2^*(1430)^0\bar{K}^*(892)^0$	TV0, TV∥, TV⊥
Channel #9	$B_s^0 \to K_2^*(1430)^0\bar{K}_2^*(1430)^0$	TT0, TT∥1, TT⊥1, TT∥2, TT⊥2



Method: Time-dependent angular and M(*Kπ*) fit to background-subtracted data, using FT, angular, mass and time acceptance and time resolution (from simulation).

$$\phi_s^{s\bar{d}\,d} = -0.010 \pm 0.13(\text{stat}) \pm 0.14(\text{syst})\ \text{rad}$$

$$|\lambda_{CP}| = 1.035 \pm 0.034(\text{stat}) \pm 0.089(\text{syst})$$

$$f_L = 0.208 \pm 0.032(\text{stat}) \pm 0.046(\text{syst})$$

Compatible with no CPV and with the SM.

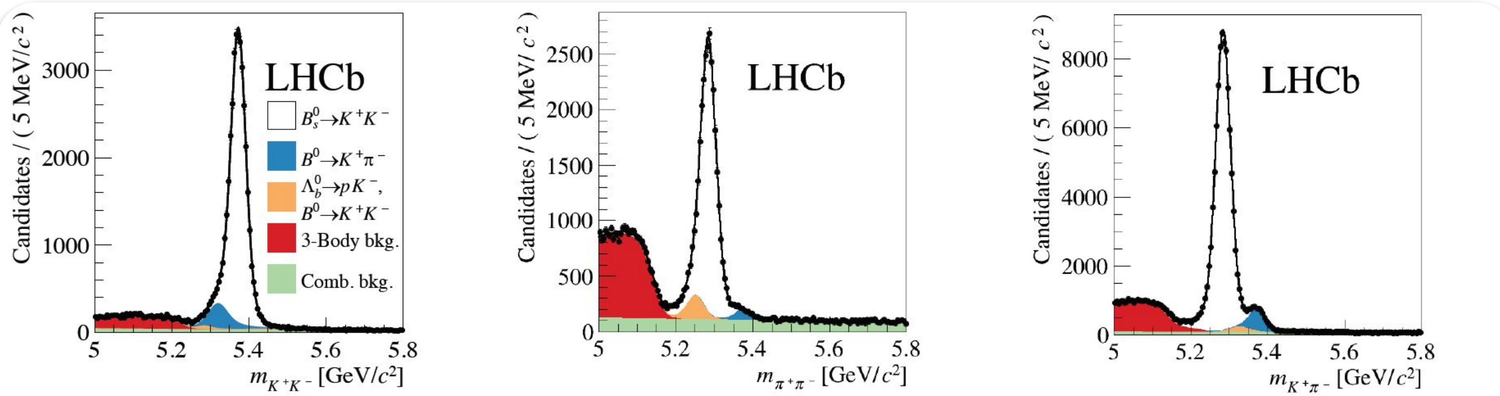
CPV in $B^0_{(s)} \to hh'$

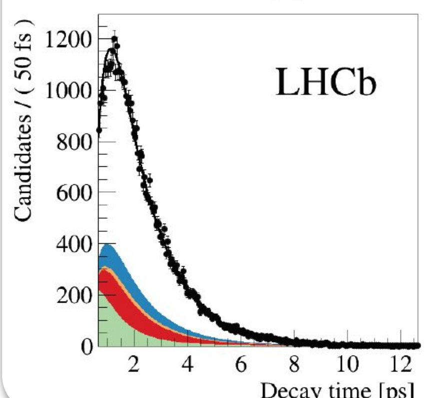
PRD 98, 032004 (2018)

New LHCb measurement using full Run 1 data:

- Measure time-dependent asymmetries in $B^0 \to \pi^+\pi^-$ and $B_s^0 \to K^+K^-$
- Measure time-integrated asymmetries in $B^0 \to K^+\pi^-$ and $B_s^0 \to \pi^+K^-$
- Updating previous results JHEP 10 (2013) 183 and PRL 110 (2013) 221601.

Method: fit with FT to the decay-time and M(hh') data distribution, simultaneously on *ππ*, *KK* and *Kπ*. Decay-time acceptance and resolution obtained in a data-driven way.





$$
\begin{aligned}
C_{\pi^+\pi^-} &= -0.34 \pm 0.06, \\
S_{\pi^+\pi^-} &= -0.63 \pm 0.05, \\
C_{K^+K^-} &= 0.20 \pm 0.06, \\
S_{K^+K^-} &= 0.18 \pm 0.06, \\
A^{\Delta\Gamma}_{K^+K^-} &= -0.79 \pm 0.07, \\
A_{CP}\left(B^0 \to K^+\pi^-\right) &= -0.084 \pm 0.004, \\
A_{CP}\left(B_s^0 \to \pi^+K^-\right) &= 0.213 \pm 0.015,
\end{aligned}
$$

Most precise measurements from a single experiment.

$(C_{K^+K^-}, S_{K^+K^-}, A^{\Delta\Gamma}_{K^+K^-})$ deviates **4.0 σ** from $(0, 0, -1)$

$\Longrightarrow$ Strongest evidence for time-dependent CP violation in the B_s^0 sector!

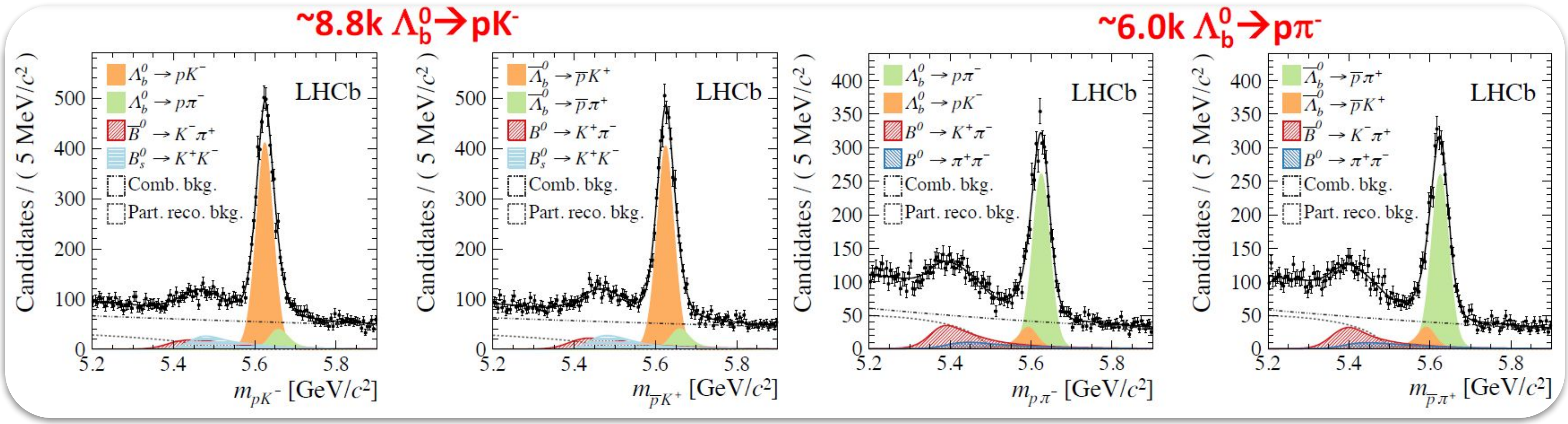
CPV in $\Lambda_b^0 \to ph$

arXiv:1807.06544

Previously, 1st evidence of CPV in a beauty baryon decay, $\Lambda_b^0 \to p\pi^-\pi^+\pi^-$ [Nature Physics 13, 391-396 (2017)]

Direct CPV in $\Lambda_b^0 \to pK^-$ and $\Lambda_b^0 \to p\pi^-$ had only been measured by CDF.

Method: fit to M(*hh'*), simultaneously on pπ and pK. Production and detection asymmetries are accounted for.



$$A_{CP}^{pK} = -0.020 \pm 0.013 \pm 0.019$$

$$A_{CP}^{p\pi} = -0.035 \pm 0.017 \pm 0.020$$

$$\Delta A_{CP} \equiv A_{CP}^{pK^-} - A_{CP}^{p\pi^-} = 0.014 \pm 0.021 \pm 0.013$$

Compatible with no CPV.

Main systematic uncertainty from production asymmetry.

CPV in $\Lambda_b^0 \to pK^- h^+ h^-$ and $\Xi_b^0 \to pK^- K^- \pi^+$

JHEP 08 (2018) 039

CPV based on triple-product asymmetries on

$$\Lambda_b^0 \to pK^- K^+ K^-,\ \Lambda_b^0 \to pK^- \pi^+ \pi^- \text{ and } \Xi_b^0 \to pK^- K^- \pi^+$$

Asymmetries are defined based on the operator **T** that reverses the spin and the momentum of the particles.

$$C_{\hat{T}} = \vec{p}_1 \cdot (\vec{p}_{h_1} \times \vec{p}_{h_2})$$

$$A_{\hat{T}} = \frac{N(C_{\hat{T}} > 0) - N(C_{\hat{T}} < 0)}{N(C_{\hat{T}} > 0) + N(C_{\hat{T}} < 0)},$$

$$\bar{A}_{\hat{T}} = \frac{\overline{N}(-\overline{C}_{\hat{T}} > 0) - \overline{N}(-\overline{C}_{\hat{T}} < 0)}{\overline{N}(-\overline{C}_{\hat{T}} > 0) + \overline{N}(-\overline{C}_{\hat{T}} < 0)}$$

The P-violating and CP-violating observables: $a_P^{\hat{T}-odd} = \frac{1}{2}(A_{\hat{T}} + \bar{A}_{\hat{T}}),\quad a_{CP}^{\hat{T}-odd} = \frac{1}{2}(A_{\hat{T}} - \bar{A}_{\hat{T}})$

	$\Lambda_b^0 \to pK^-\pi^+\pi^-$	$\Lambda_b^0 \to pK^-K^+K^-$	$\Xi_b^0 \to pK^-K^-\pi^+$
$a_P^{\widehat{T}\text{-odd}}$ (%)	$-0.60 \pm 0.84 \pm 0.31$	$-1.56 \pm 1.51 \pm 0.32$	$-3.04 \pm 5.19 \pm 0.36$
$a_{CP}^{\widehat{T}\text{-odd}}$ (%)	$-0.81 \pm 0.84 \pm 0.31$	$1.12 \pm 1.51 \pm 0.32$	$-3.58 \pm 5.19 \pm 0.36$

Significant deviation from zero in these observables would indicate P violation and CP violation.

No significant deviation from CP or P symmetry is found !

Summary

- Precision measurements of CPV offer a rich scenario to constrain potential New Physics models.
  - So far, no clear deviation from SM is found.
  - Some tension on measurement of the γ angle.
  - There still plenty of room for New Physics in CPV.

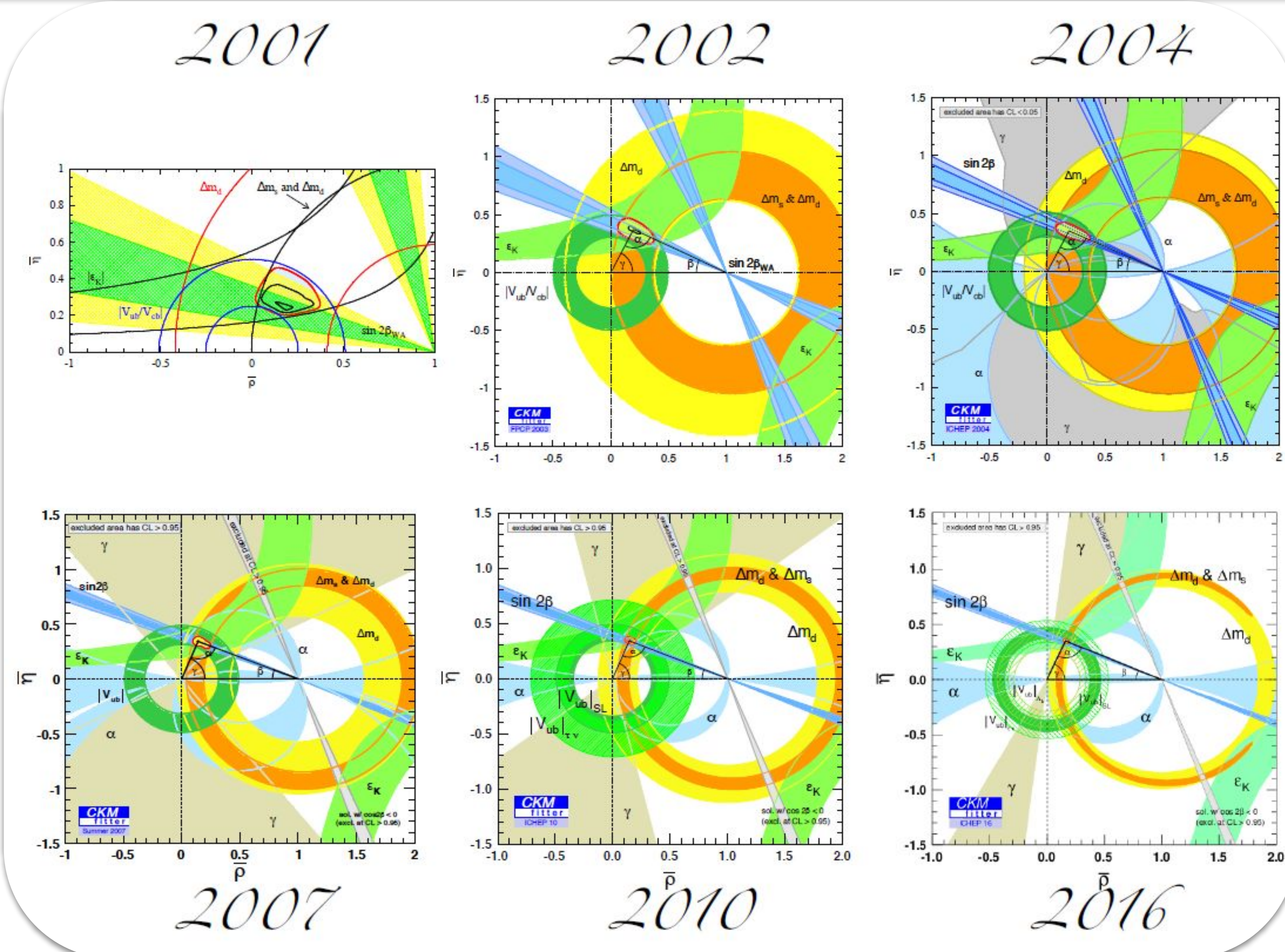
Currently [9 fb^{-1}]		Phase I - Upgrade [+ 50 fb^{-1}]	
Run 1 [3fb^{-1}] (2010 - 2012)	Run 2 [+6 fb^{-1}]* (2015 - 2018)	Run 3 (2021-2023)	Run 4 (2026-2029)

*Data Run 2 ($\sqrt{s}$ = 13 TeV), has a higher B meson production cross-section and a more efficient trigger.

- Run 2 precision for γ and β: $\Delta\gamma$ ~4°, $\Delta\beta$~0.6°
- Good prospect for measurements in Run 3!

Stay tuned!

Can we find NP in CPV in flavour-changing processes in the quark sector? Great progress



Thanks