CP Violation at LHCb

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On behalf of the LHCb collaboration

Outline

- **Introduction. CPV and the CKM unitarity triangle.**
- **CPV in the B meson system.**
- **CPV in the D meson system.**
- **CPV in baryon decays.**

Unless otherwise stated, all LHCb measurements reported here are performed with an integrated luminosity of **3fb**$^{-1}$ collected in Run I.

Introduction

Quark weak eigenstates related to mass eigenstates through the unitary V_{CKM} matrix

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \underbrace{\begin{pmatrix} \boxed{\begin{matrix} V_{ud} \\ V_{cd} \\ V_{td} \end{matrix}} & \begin{matrix} V_{us} \\ V_{cs} \\ V_{ts} \end{matrix} & \boxed{\begin{matrix} V_{ub} \\ V_{cb} \\ V_{tb} \end{matrix}} \end{pmatrix}}_{V_{\mathrm{CKM}}} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

$$\boldsymbol{V^\dagger V = V V^\dagger = 1}$$

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

Weak charge currents proportional to CKM matrix elements

$$\mathcal{L}_{\mathrm{int}}^{\mathrm{CC}} = -\frac{g}{\sqrt{2}} \begin{pmatrix} \bar{u}_L & \bar{c}_L & \bar{t}_L \end{pmatrix} \gamma^\mu W_\mu^\dagger \boldsymbol{V_{\mathrm{CKM}}} \begin{pmatrix} d_L \\ s_L \\ b_L \end{pmatrix} + \text{h.c.}$$

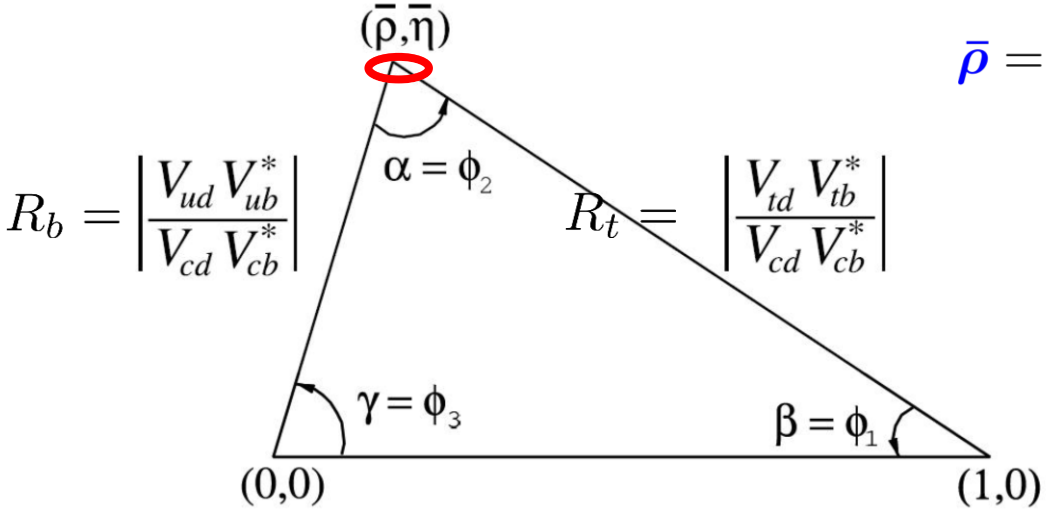
Wolfenstein parameterization using four real parameters: A, ρ, λ, η (**η ≠ 0 => CP Violation**)

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

$$\boldsymbol{\lambda} = \frac{|V_{us}|}{\sqrt{|V_{ud}|^2 + |V_{us}|^2}} \approx 0.22 \qquad \boldsymbol{A} = \frac{1}{\lambda}\left|\frac{V_{cb}}{V_{us}}\right| \qquad V_{ub}^* = A\lambda^3(\boldsymbol{\rho} + i\boldsymbol{\eta})$$

Unitarity triangle

Draw the relation $V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0$ as a triangle in the complex plane:

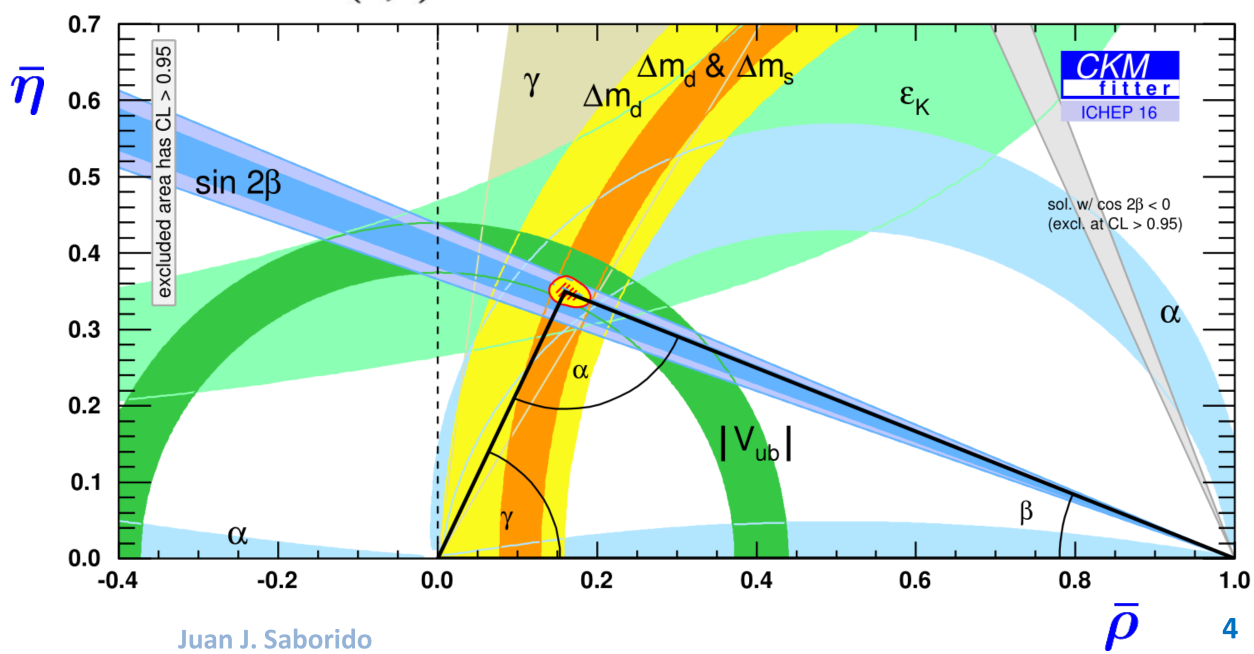


$$\bar\rho = \rho\left(1-\frac{1}{2}\lambda^2\right), \qquad \bar\eta = \eta\left(1-\frac{1}{2}\lambda^2\right)$$

$$\bar\rho + i\bar\eta = -\left(\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}\right)$$

Phase-convention independent

The measurement of all angles and sides of this triangle using a plethora of decay channels is a stringent test of the SM description of CP violation and quark transitions.



CP Violation

Direct CPV

$$\Gamma\left(B \to f\right) \neq \Gamma\left(\overline{B} \to \overline{f}\right)$$

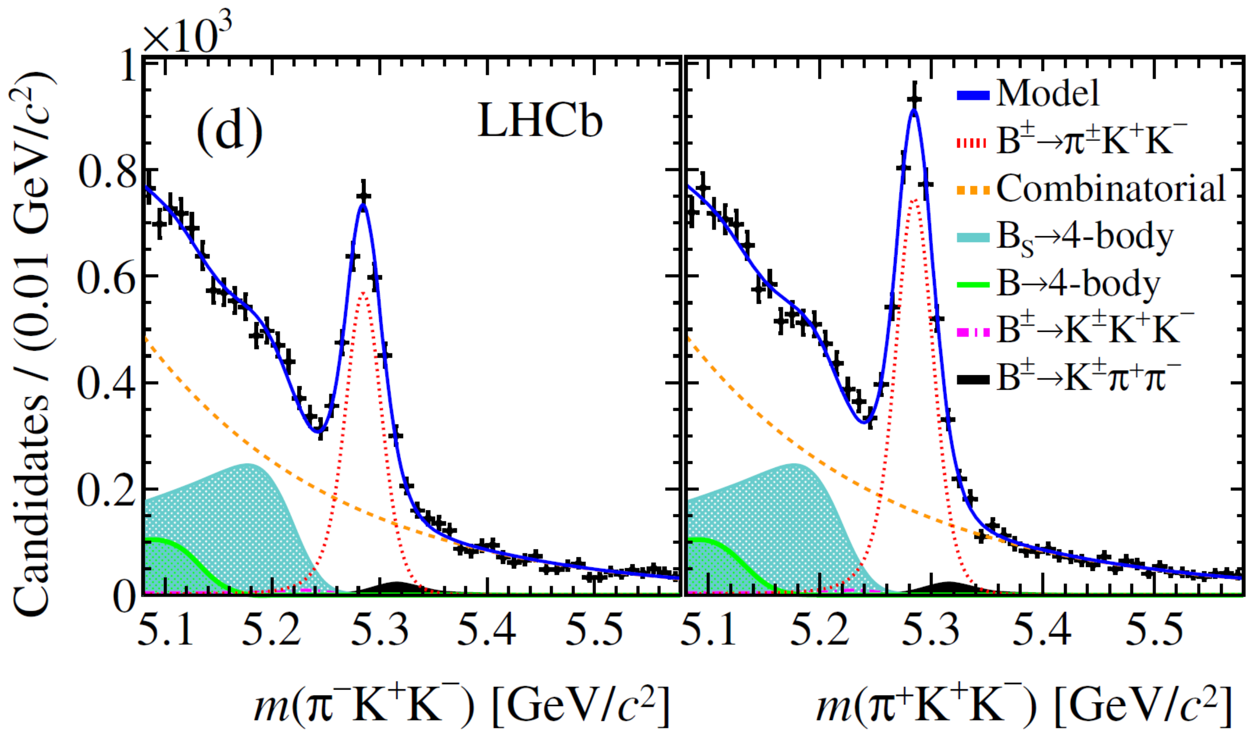
Best isolated in charged meson decays

$$\mathcal{A}_{\mathrm{CP}}^{\mathrm{dir}} = \frac{\Gamma(B^+ \to f^+) - \Gamma(B^- \to f^-)}{\Gamma(B^+ \to f^+) + \Gamma(B^- \to f^-)}$$

<u>**For example**</u>: $A_{CP}(B^{\pm} \to \pi^{\pm} K^+ K^-) = -0.123 \pm 0.022$

PRD 90, 112004 (2014)

$B^- \to \pi^- K^+ K^-$ $B^+ \to \pi^+ K^+ K^-$



CP Violation

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CPV in mixing

$$\Gamma\left(B \to \overline{B}\right) \neq \Gamma\left(\overline{B} \to B\right)$$

Best isolated in semi-leptonic decays of neutral mesons

$$\frac{\Gamma(\overline{B}^0(t) \to \ell^+\nu X) - \Gamma(B^0(t) \to \ell^-\overline{\nu} X)}{\Gamma(\overline{B}^0(t) \to \ell^+\nu X) + \Gamma(B^0(t) \to \ell^-\overline{\nu} X)}$$

CPV in mixing-decay

$$\Gamma\left(B \to f_{CP}\right) \neq \Gamma\left(\overline{B} \to f_{CP}\right)$$

f_{CP}, is a CP eigenstate

Direct CPV

$$\mathcal{A}(t) = \frac{\boldsymbol{S_f} \sin(\Delta m_{d(s)} t) - \boldsymbol{C_f} \cos(\Delta m_{d(s)} t)}{\cosh\left(\frac{\Delta\Gamma_{d(s)}}{2} t\right) - \boldsymbol{A_f^{\Delta\Gamma}} \sinh\left(\frac{\Delta\Gamma_{d(s)}}{2} t\right)}$$

Mixing-induced CPV

$\Delta\Gamma$ is negligible for B_d, so in that case $\mathcal{A}(t) \approx \boldsymbol{S_f} \sin(\Delta m_d t) - \boldsymbol{C_f} \cos(\Delta m_d t)$

$\sin(2\beta)$

$\beta \equiv \arg\left(-\frac{V_{cd}V_{cb}^*}{V_{td}V_{tb}^*}\right)$ is one of the angles of the CKM triangle (also called ϕ_1)

$B^0 \to J/\psi K_S^0$ Golden decay mode to measure **sin(2β)** through time-dependent CP Asy.

$$\mathcal{A}(t) \equiv \frac{\Gamma(\overline{B}^0(t) \to J/\psi K_S^0) - \Gamma(B^0(t) \to J/\psi K_S^0)}{\Gamma(\overline{B}^0(t) \to J/\psi K_S^0) + \Gamma(B^0(t) \to J/\psi K_S^0)} \approx S\sin(\Delta m t) - C\cos(\Delta m t)$$

Direct CP violation expected to be very small ($C \approx \mathbf{0}$), so $S \approx \mathbf{sin(2\beta)}$.

PRD 91 073007 (2015)

Other measurements that constrain the CKM triangle predict $\mathbf{\sin(2\beta) = 0.771^{+0.017}_{-0.041}}$

Small discrepancy with the average of direct measurements: $\mathbf{\sin(2\beta) = 0.691 \pm 0.017}$

HFAG arXiv:1612.07233

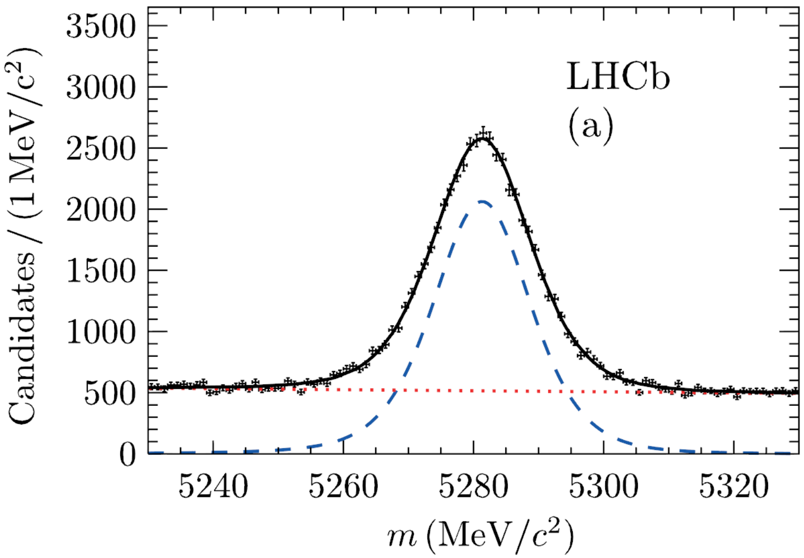
Better experimental precision and understanding of higher-order contributions needed to clarify the CKM picture.

$\sin(2\beta)$

PRL 115, 031601, (2015)

LHCb has become competitive with B-factories measurements.

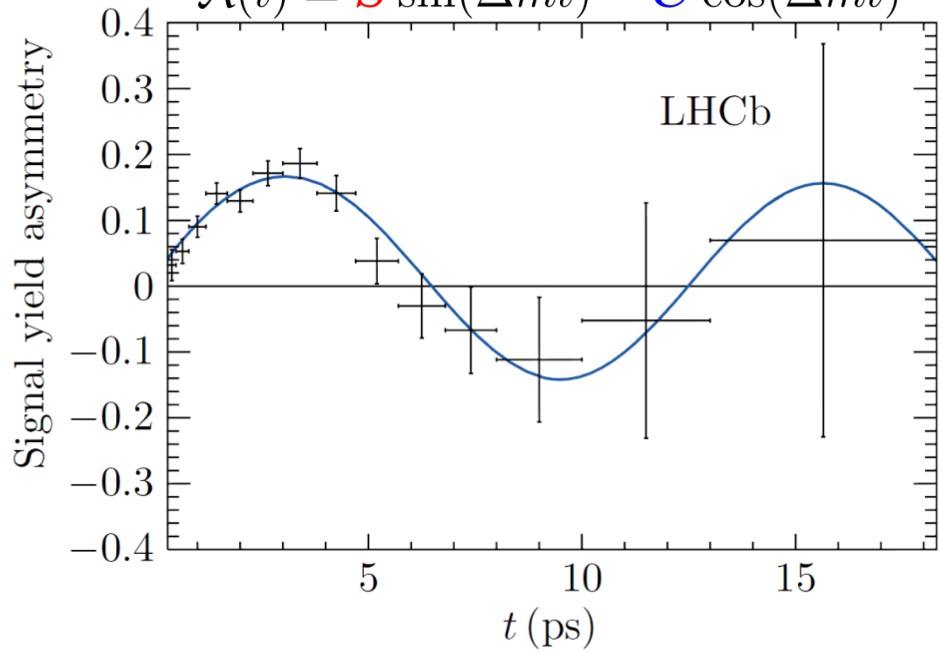
Stat. uncert.
BaBar ±0.036, Belle ±0.029

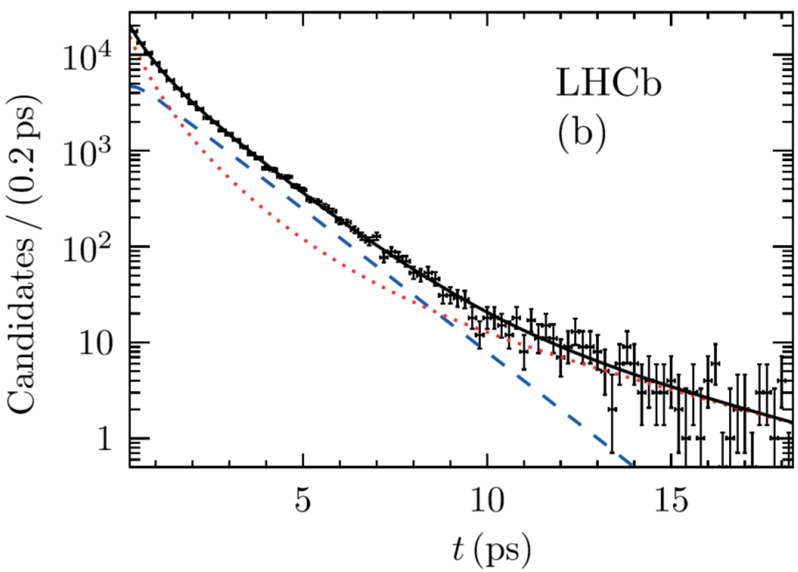


41560 ± 270 tagged $B^0 \to J/\psi\, K_S$ decays

Effective tagging efficiency: (3.02 ± 0.05) %

$\mathcal{A}(t) = S \sin(\Delta m t) - C \cos(\Delta m t)$

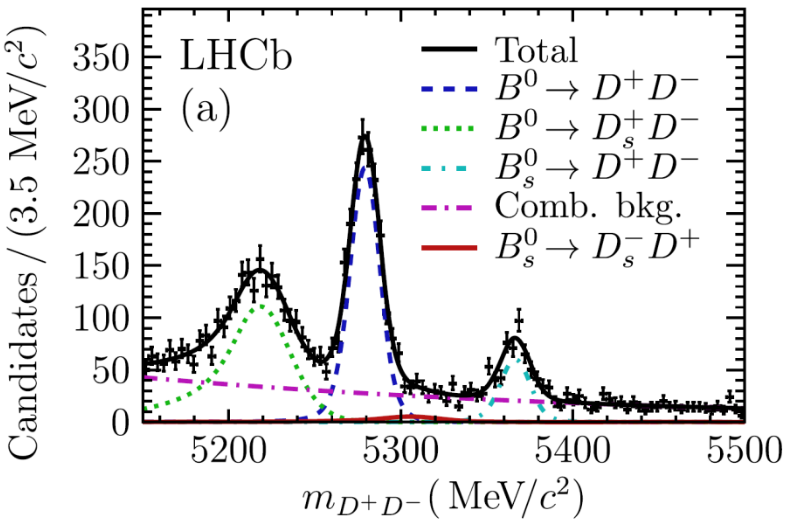


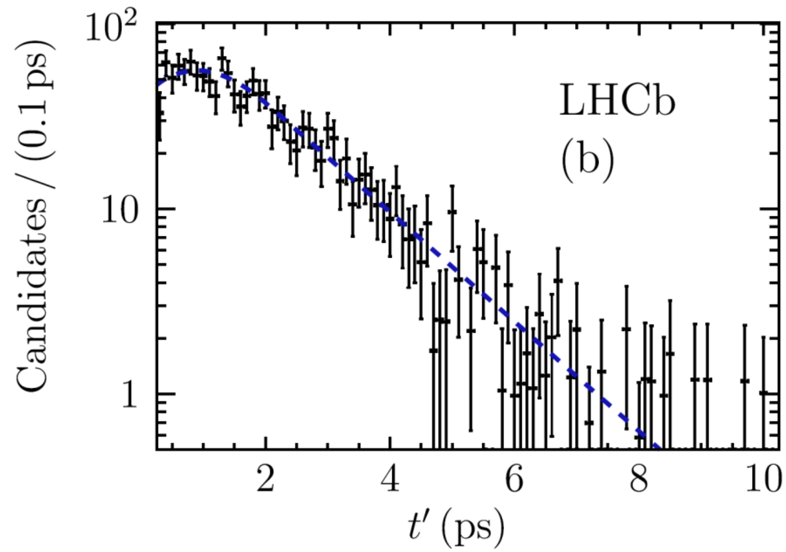


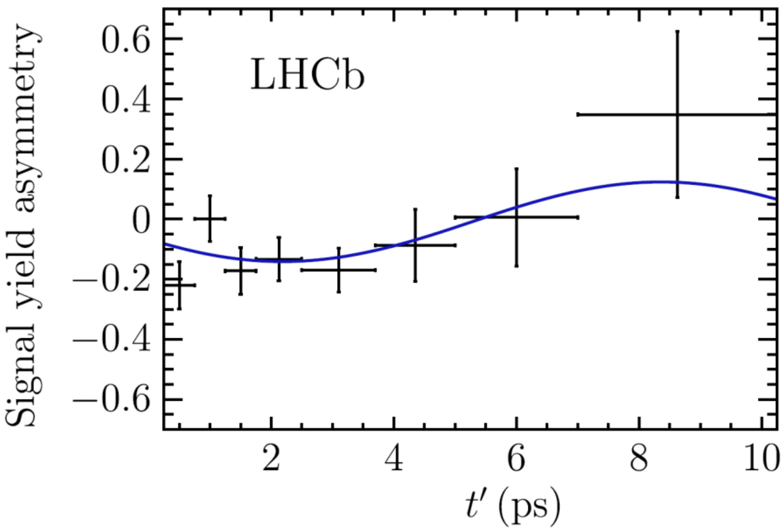
$$S = +0.731 \pm 0.035 \pm 0.020$$
$$C = -0.038 \pm 0.032 \pm 0.005$$

Time-dependent CPV in $B^0 \to D^+ D^-$ decays

PRL 117, 261801 (2016)







$$\frac{d\Gamma(t,d)}{dt} = \propto e^{-t/\tau}[1 - d\,S\sin(\Delta m t) + d\,C\cos(\Delta m t)]$$

(d is the B^0 flavour at production time)

$$\frac{S}{\sqrt{1-C^2}} = -\sin(\phi_d + \Delta\phi) \qquad \phi_d = 2\beta$$

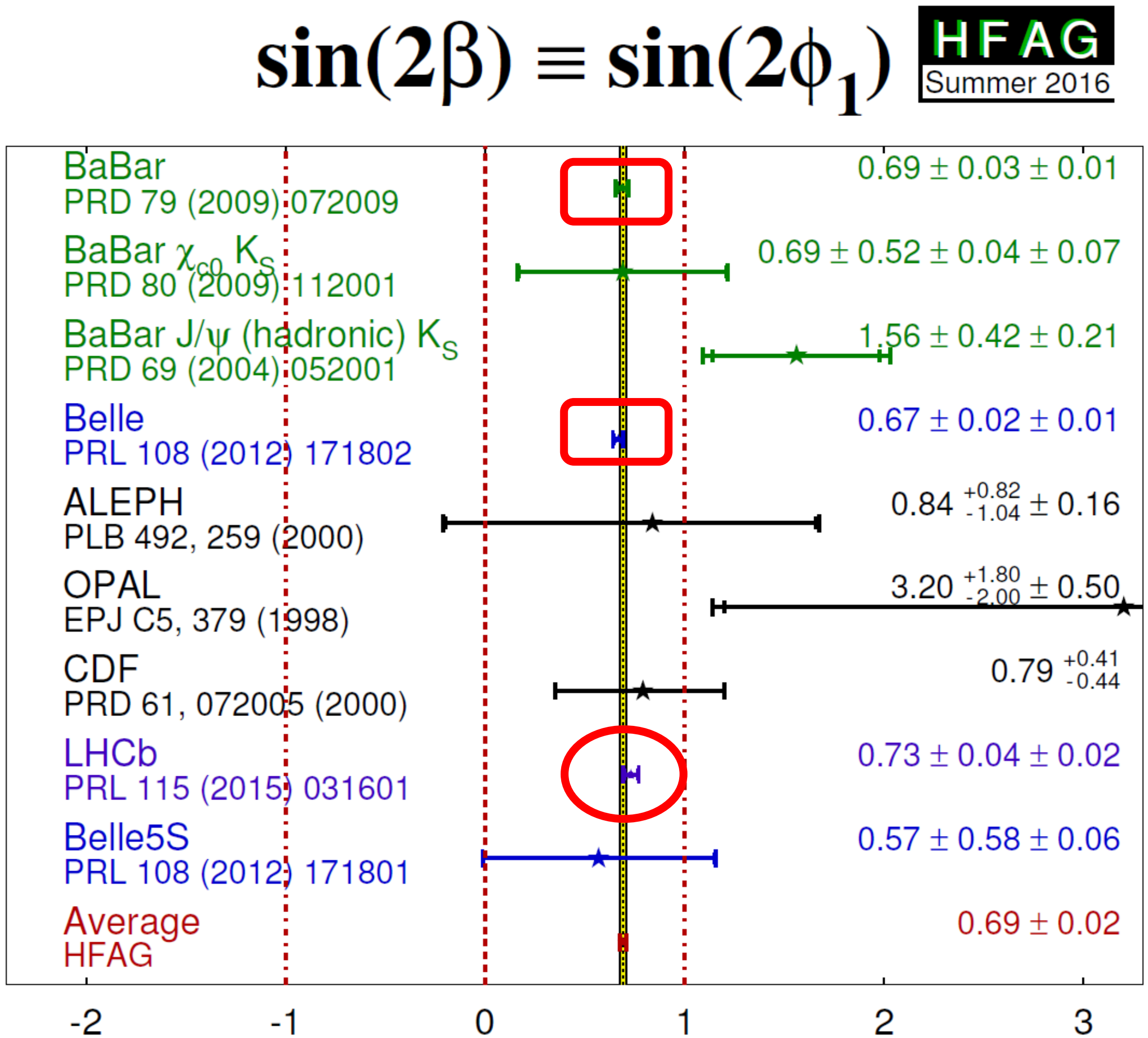
$$\boxed{S = -0.54^{+0.17}_{-0.16} \pm 0.05}$$

$$\boxed{C = +0.26^{+0.18}_{-0.17} \pm 0.05}$$

$$\boxed{\Delta\phi = -0.16^{+0.19}_{-0.21}}$$

Observed CPV at a level of $4.0\,\sigma$

$\sin(2\beta)$



World average $\sin 2\beta = 0.69 \pm 0.02$

The CKM unitarity angle γ

$\boxed{\gamma \equiv \arg\left(-\frac{V_{ud}V^*_{ub}}{V_{cd}V^*_{cb}}\right)}$ (also called ϕ_3) still the least-well known of the CKM unitarity angles (precision about 6º, compared to 3º and <1º for α and β).

Combination of all direct measurements yields $\gamma = \left(72.1^{+5.4}_{-5.8}\right)^\circ$

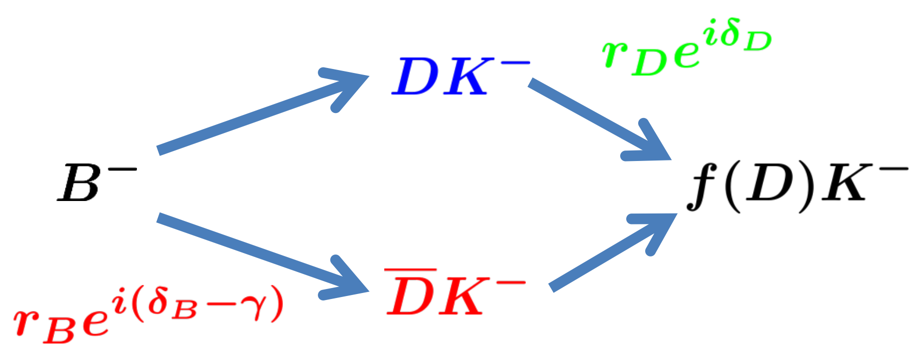
Latest LHCb-only combination: $\gamma = \left(72.2^{+6.8}_{-7.3}\right)^\circ$ JHEP 12 (2016) 087

Indirect constraints from the other CKM parameters $\gamma = \left(65.3^{+1.0}_{-2.5}\right)^\circ$ (CKM Fitter)

The comparison of **tree-level** measurements of γ to those from B decays involving **loop** transitions, $B_{d,s} \to hh'$, $(h = \{K, \pi\})$, may reveal signs of New Physics.

Methods to measure γ can be classified into time-independent and time-dependent.

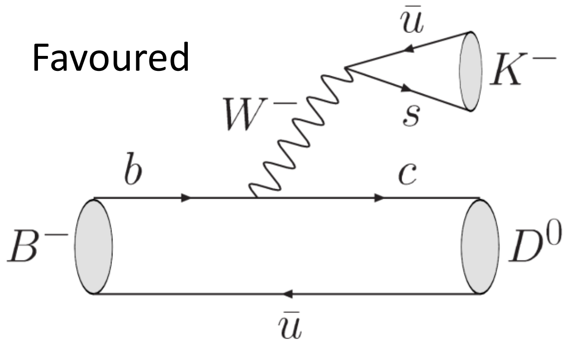
"Classic" **time-integrated** methods exploit the interference between tree-level $b \to u$ and $b \to c$ transitions.



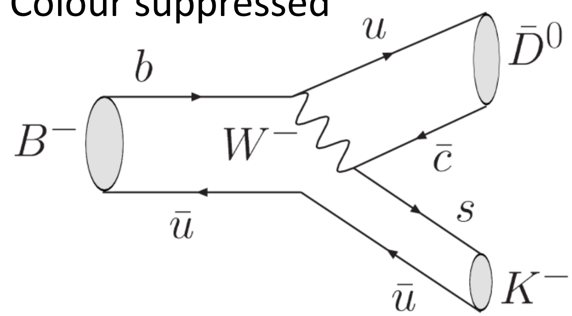
Need hadronic parameters $r_{B,D}$ and $\delta_{B,D}$ present in the ratio of suppressed to favoured ***B*** and ***D*** decays

The CKM unitarity angle γ

Favoured

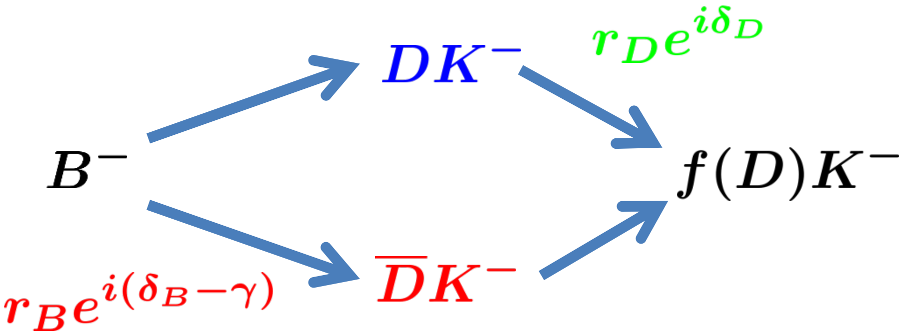


Colour suppressed



coherence factor

$$\Gamma(B^\pm \to [f]_D K^\pm) = r_D^2 + r_B^2 + 2\kappa r_D r_B \cos(\delta_B + \delta_D \pm \gamma)$$ (example of decay rate)



weak phase

$$\frac{A(B^- \to \overline{D}^0 K^-)}{A(B^- \to D^0 K^-)} = r_B e^{i(\delta_B - \gamma)}$$

CP conserving phases

$$\frac{A(D^0 \to K^+\pi^-)}{A(D^0 \to K^-\pi^+)} = r_D e^{i\delta_D}$$

Three main methods depending on the *D* final state:

GLW, $D \to$ CP-eigenstate $(\pi\pi, KK)$ **ADS**, $D \to$ quasi-flavour-specific state $(K\pi, K\pi\pi\pi)$

GGSZ, $D \to$ self-conjugated multibody final state $(K_S\pi\pi, K_S KK)$

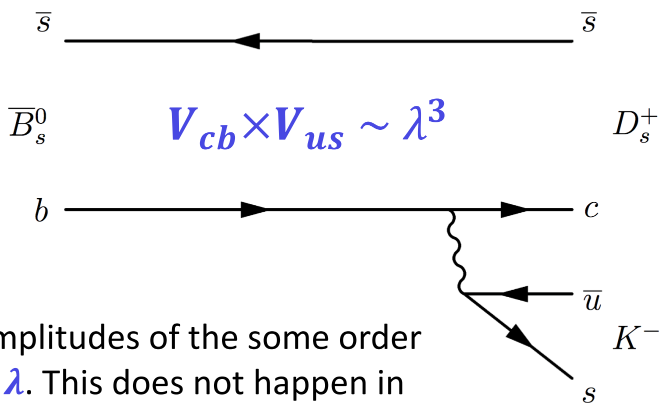
Time-dependent CPV asymmetries in $B_s^0 \to D_s^{\mp} K^{\pm}$ decays

LHCb-CONF-2016-015

(uptaded to full Run I data)

$B_s^0 \to D_s^{\mp} K^{\pm}$ decays are sensible to γ through CPV in the interference of mixing and decay.

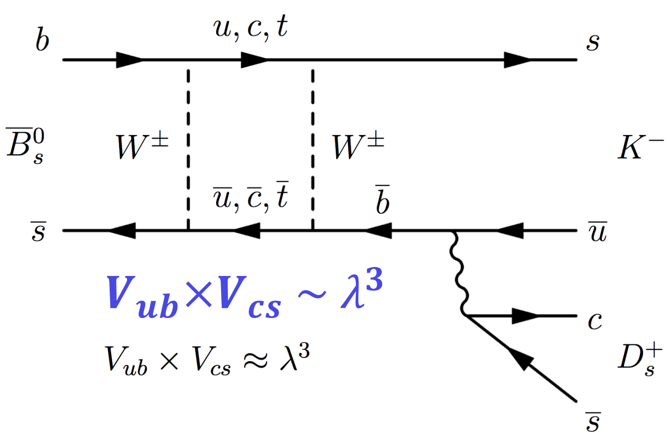
Non-negligible $\Delta\Gamma_s$. Access to additional CPV observ.

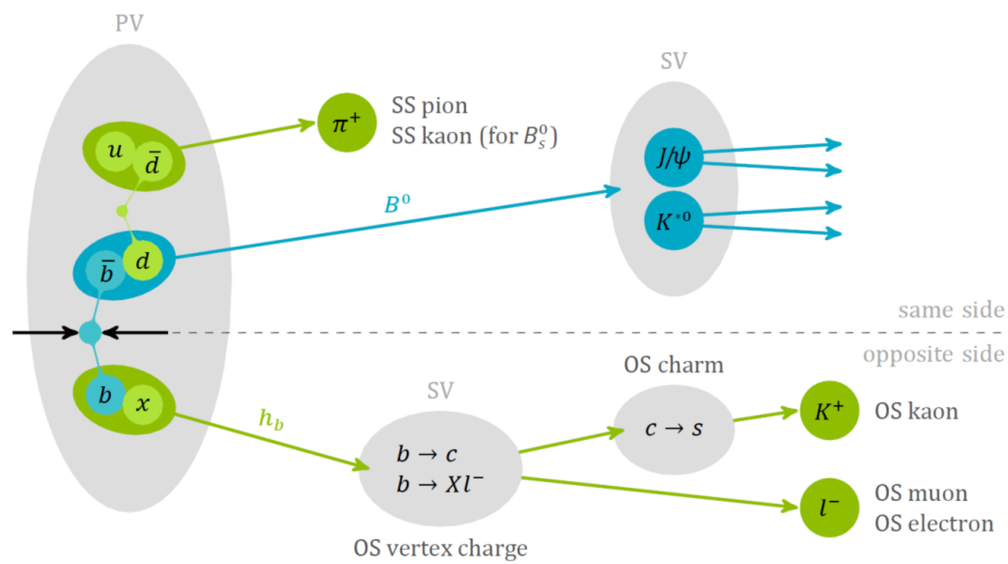


Measure the combination $\gamma - 2\beta_s \approx \gamma + \phi_s$ from the time evolution of the decay rates.

Use flavor-specific control channel $B_s^0 \to D_s^- \pi^+$ to determine time-dependent efficiencies and tagging performance.

Amplitudes of the some order in λ. This does not happen in $B^0 \to D^{(*)\mp}\pi^{\pm}$ decays





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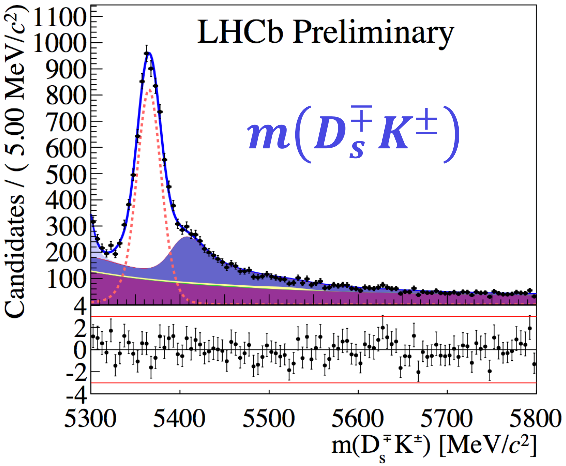
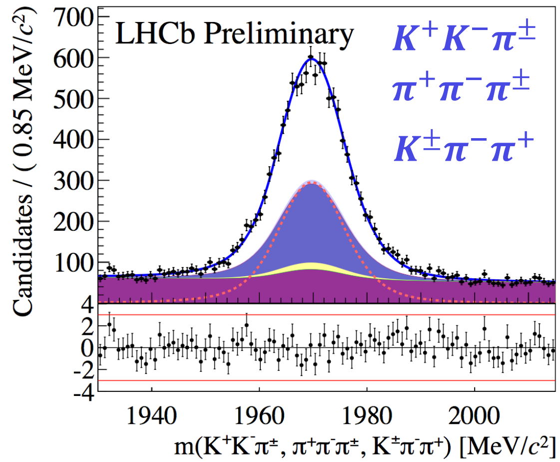
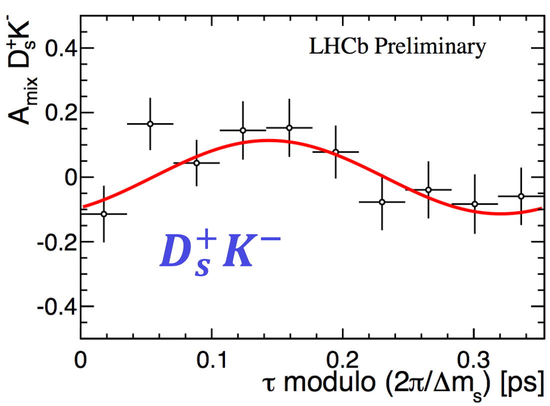
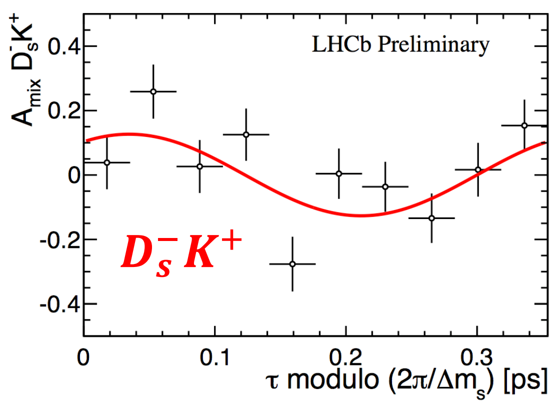
LHCb-CONF-2016-015

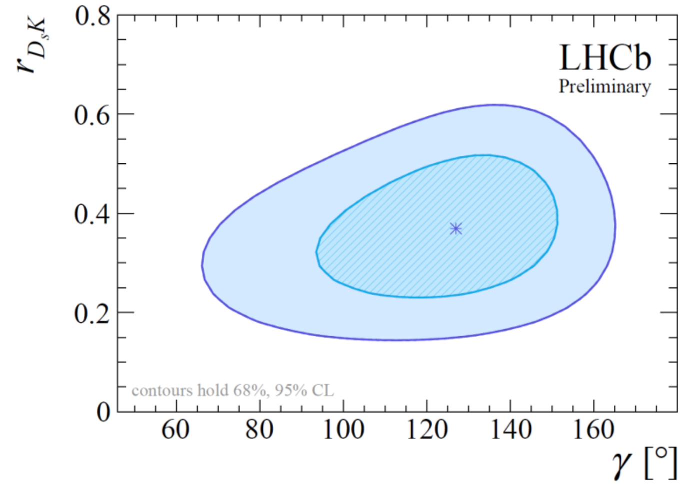




Parameter	Value
C_f	$0.735 \pm 0.142 \pm 0.048$
$A_f^{\Delta\Gamma}$	$0.395 \pm 0.277 \pm 0.122$
$A_{\bar{f}}^{\Delta\Gamma}$	$0.314 \pm 0.274 \pm 0.107$
S_f	$-0.518 \pm 0.202 \pm 0.073$
$S_{\bar{f}}$	$-0.496 \pm 0.197 \pm 0.071$







Get $\gamma - 2\beta_s$. Then use $-2\beta_s \approx \phi_s = -0.01 \pm 0.039$ (PRL 114, 04180, 2015) to obtain

$\gamma = (127^{+17}_{-22})^\circ$, $\delta = (358^{+15}_{-16})^\circ$, and $r_{D_sK} = 0.37^{+0.10}_{-0.09}$ with 68.3% CL.

(Intervals for the angles expressed modulo 180°)

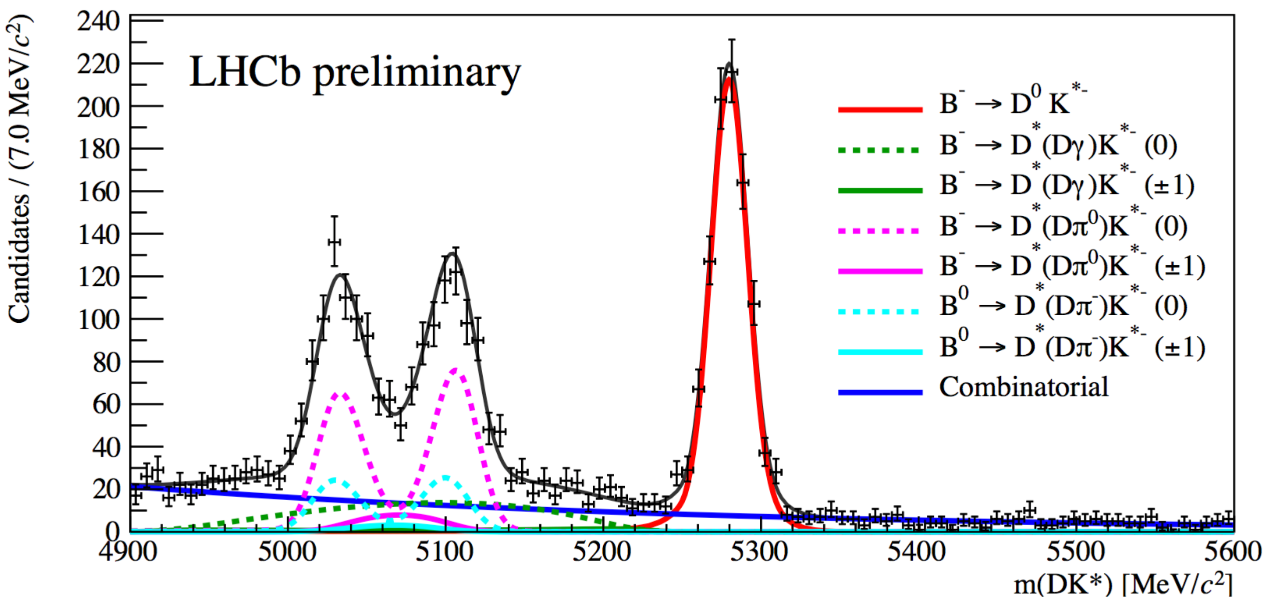
CPV in $B^{\pm} \to DK^{*\pm}$ decays

Recently, LHCb made the first measurement of the *CPV* observables in the decay $B^{\pm} \to DK^{*\pm}$. D stands for a superposition of D^0 and $\overline{D}^0$.

Analysis performed with $\mathbf{4\ fb^{-1}}$ of data: 3 fb^{-1} RUN I and 1.0 fb^{-1} Run II (full 2015 plus about half of 2016)

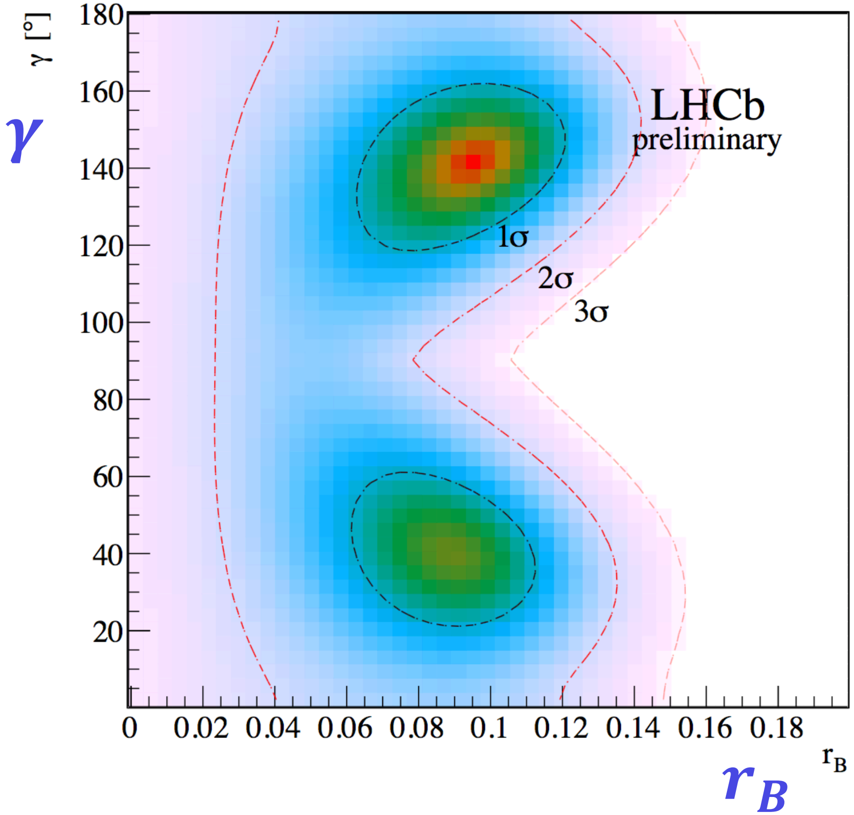
The D final states used are $K^-\pi^+, K^+K^-, \pi^+\pi^-$ and $K^+\pi^-$ (ADS/GLW) and the $K^{*\pm}$ is reconstructed in the $K^0_S\pi^{\pm}$ final state.

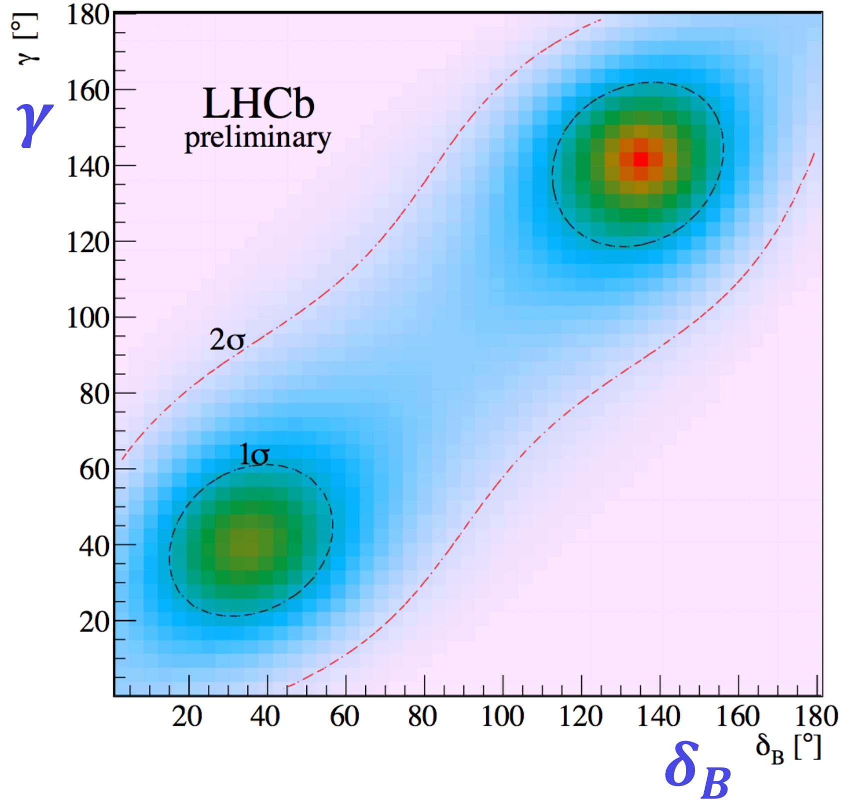
Seven *CPV* observables (3 CP asymmetries and 4 ratios of decay rates) determined via a simultaneous fit to the different D decay modes.



CPV in $B^{\pm} \to DK^{*\pm}$ decays

LHCb-CONF-2016-014





$$A_{CP+} = \frac{2\kappa r_B \sin\delta_B \sin\gamma}{1 + r_B^2 + 2\kappa r_B \cos\delta_B \cos\gamma}$$

$$R_{CP+} = 1 + r_B^2 + 2\kappa r_B \cos\delta_B \cos\gamma$$

$$R^{\pm} = \frac{r_B^2 + r_D^2 + 2\kappa r_B r_D \cos(\delta_B + \delta_D \pm \gamma)}{1 + r_B^2 r_D^2 + 2\kappa r_B r_D \cos(\delta_B - \delta_D \pm \gamma)}$$

r_B ratio between the **CS** and **CF** amplitudes of the B decay.

δ_B strong phase difference between the amplitudes.

Low sensitivity data, but consitent with the value $\gamma \sim 70°$

Combined measurement of γ

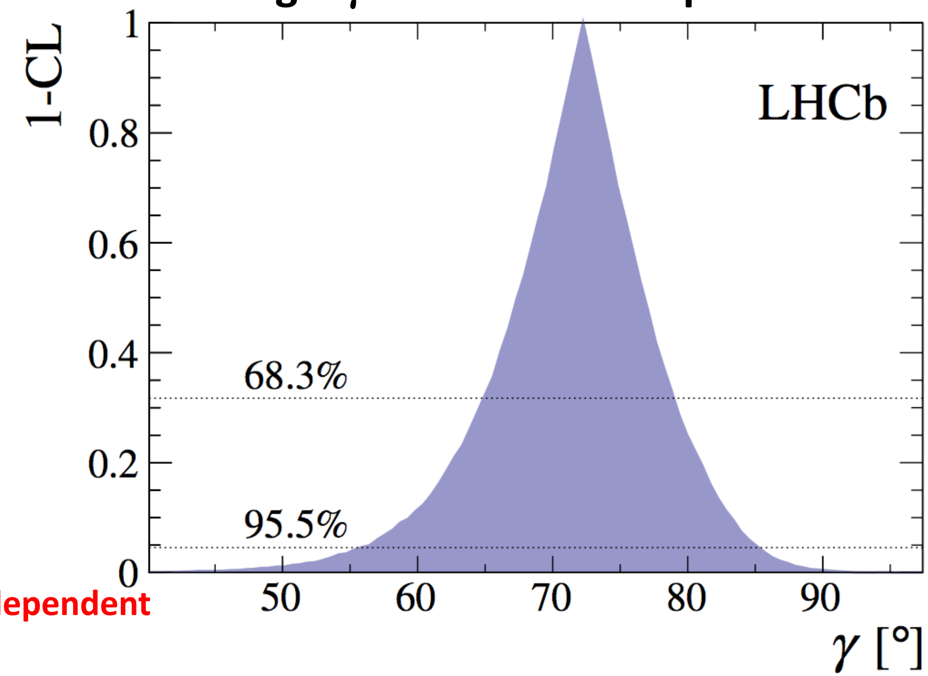
JHEP12 (2016) 087

Combining all direct measurements yields $\gamma = (72.1^{+5.4}_{-5.8})^\circ$ while the latest LHCb-only combination, JHEP 12 (2016) 087, gives $\gamma = (72.2^{+6.8}_{-7.3})^\circ$

B decay	D decay	Method
$B^+ \to Dh^+$	$D \to h^+h^-$	GLW/ADS
$B^+ \to Dh^+$	$D \to h^+\pi^-\pi^+\pi^-$	GLW/ADS
$B^+ \to Dh^+$	$D \to h^+h^-\pi^0$	GLW/ADS
$B^+ \to DK^+$	$D \to K^0_S h^+h^-$	GGSZ
$B^+ \to DK^+$	$D \to K^0_S K^-\pi^+$	GLS
$B^+ \to Dh^+\pi^-\pi^+$	$D \to h^+h^-$	GLW/ADS
$B^0 \to DK^{*0}$	$D \to K^+\pi^-$	ADS
$B^0 \to DK^+\pi^-$	$D \to h^+h^-$	GLW-Dalitz
$B^0 \to DK^{*0}$	$D \to K^0_S\pi^+\pi^-$	GGSZ
$B^0_s \to D^\mp_s K^\pm$	$D^+_s \to h^+h^-\pi^+$	TD

Time-dependent

Angle γ from tree-level processes



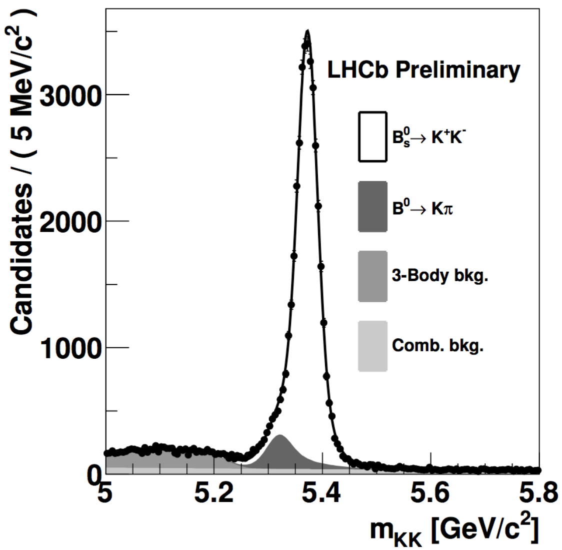
Indirect constraints from the other CKM parameters give $\gamma = (65.3^{+1.0}_{-2.5})^\circ$

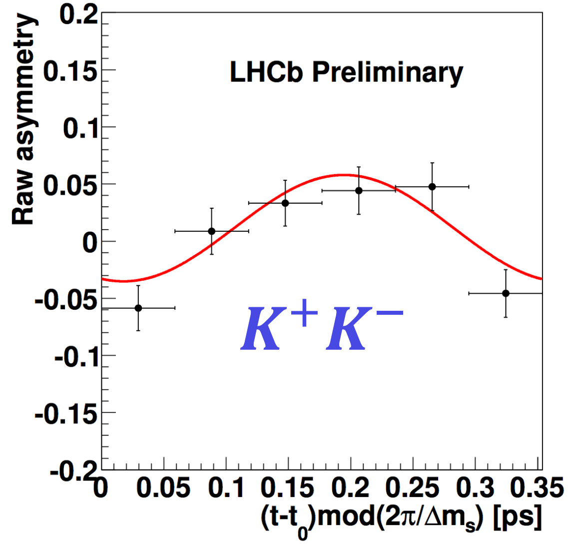
Precision to the level of 1° from direct measurements could reveal inconsistencies and hence possible New Physics.

Exploiting RUN II data would reduce the uncertainty on γ to about 4°.

Time-dependent CPV in $B_s^0 \to K^+K^-$ and $B^0 \to \pi^+\pi^-$

Decays related by U-spin symmetry → sensitivity to γ and $-2\beta_s$





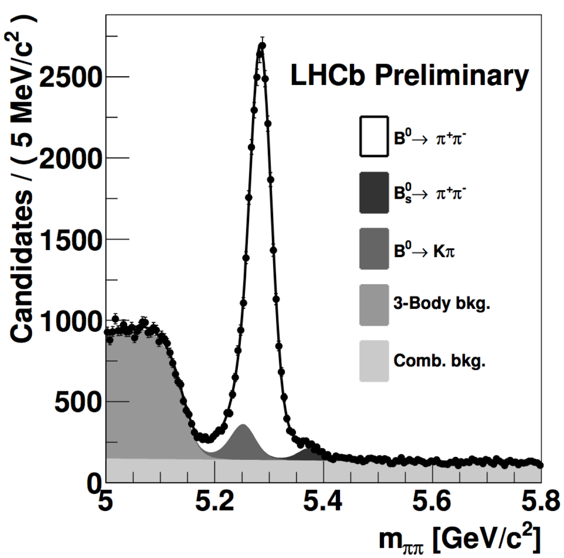
Use only OS flavour taggers calibrated with $B_{(d)} \to K\pi$ data

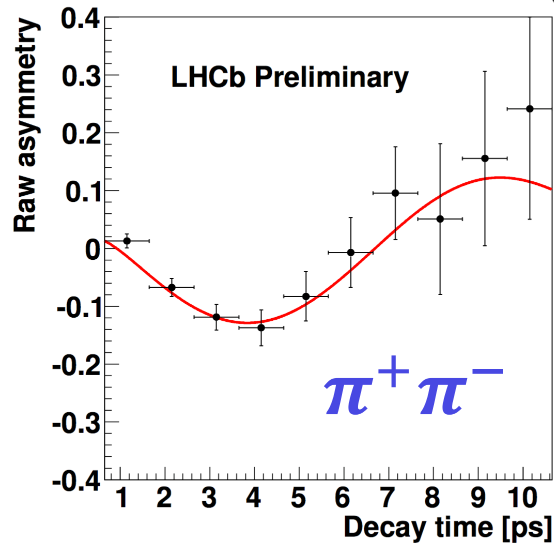
$$B_s^0 \to K^+K^-$$

$$C_{KK} = 0.24 \pm 0.06 \pm 0.02$$
$$S_{KK} = 0.22 \pm 0.06 \pm 0.02$$
$$A_{KK}^{\Delta\Gamma} = -0.75 \pm 0.07 \pm 0.11$$

LHCb-CONF-2016-018

$$\mathcal{A}(t) = \frac{\boldsymbol{S_f} \sin(\Delta m_{d(s)} t) - \boldsymbol{C_f} \cos(\Delta m_{d(s)} t)}{\cosh\left(\frac{\Delta\Gamma_{d(s)}}{2} t\right) + \boldsymbol{A_f^{\Delta\Gamma}} \sinh\left(\frac{\Delta\Gamma_{d(s)}}{2} t\right)}$$





$$B^0 \to \pi^+\pi^-$$

$$C_{\pi\pi} = -0.24 \pm 0.07 \pm 0.01$$
$$S_{\pi\pi} = -0.68 \pm 0.06 \pm 0.02$$

Most precise measurement of **CPV** in $B_s \to K^+K^-$. Future improvements including SS tagger and **Run 2** data.

CPV semileptonic asymmetry in B_s mixing

PRL 117, 061803 (2016)

CP-violating semileptonic asymmetry $\boldsymbol{a_{sl}^s}$ measured in $B_s^0 \to D_s^\pm(K^+K^-\pi^\pm)X\mu^\pm\nu$ decays.

Extends previous measurement which used only $B_s^0 \to D_s^\pm(\phi\pi^\pm)X\mu^\pm\nu$ decays.

$$a_{sl} = \frac{\Gamma(\bar{B} \to f) - \Gamma(B \to \bar{f})}{\Gamma(\bar{B} \to f) + \Gamma(B \to \bar{f})} = \frac{1 - |q/p|^4}{1 + |q/p|^4} \approx \frac{\Delta\Gamma}{\Delta M} \tan\phi_{12} \qquad \phi_{12} = \arg(-M_{12}/\Gamma_{12})$$

a_{sl} measures CPV in mixing, $\boldsymbol{f}$ is a flavour-specific final state

Lenz et al, JHEP 06 (2007) 072.

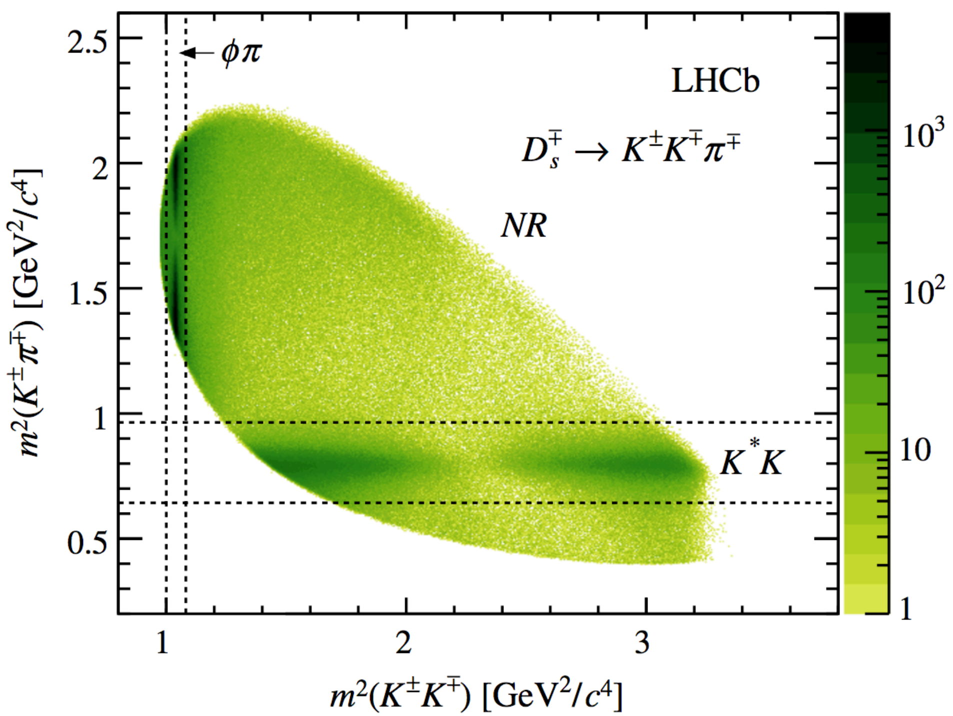
Φ_{12} very small in the SM, $a_{sl}^s = (2.22 \pm 0.27)\times 10^{-5}$, $a_{sl}^d = (-4.7 \pm 0.6)\times 10^{-4}$

Measure time-integrated asymmetry.

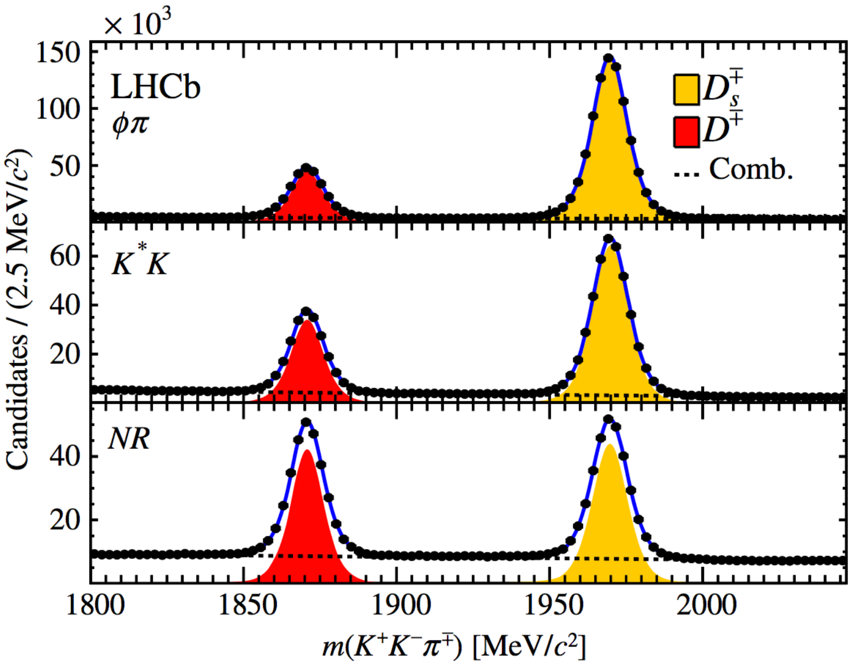
$$A_{\mathrm{raw}} = \frac{N(D_s^-\mu^+) - N(D_s^+\mu^-)}{N(D_s^-\mu^+) + N(D_s^+\mu^-)}$$

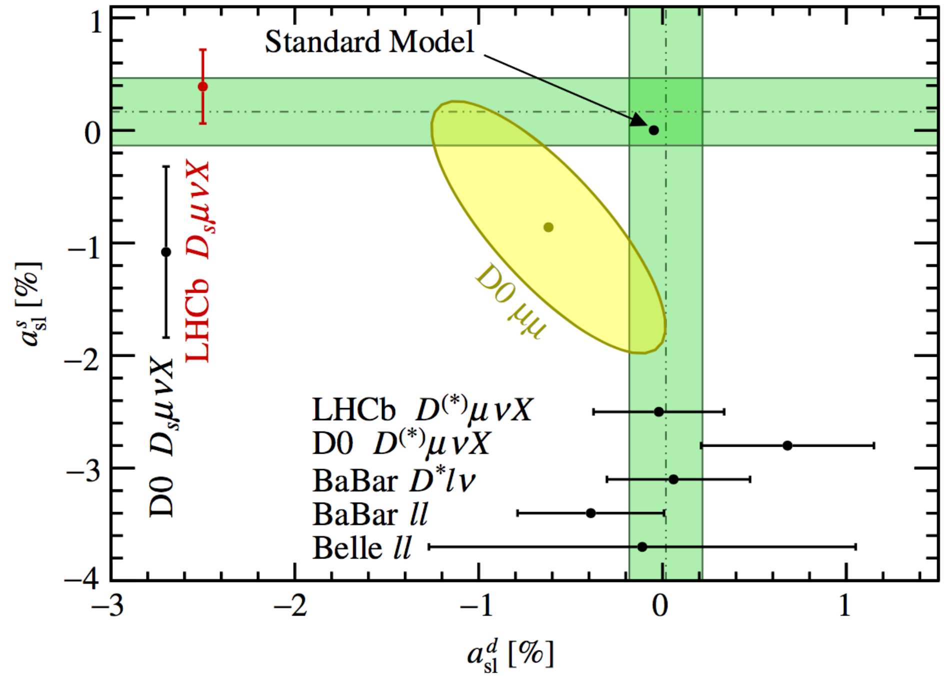
$$a_{sl}^s = \frac{2}{1 - f_{bkg}}\left(A_{\mathrm{raw}} - A_{\mathrm{det}} - f_{\mathrm{bkg}}A_{\mathrm{bkg}}\right)$$

$\boldsymbol{A_{\mathrm{det}}}$ is measured from data using calibration samples



Measurement of the CP asymmetry in B_s mixing





PRL 117, 061803 (2016)

$$a^s_{sl} = (0.39 \pm 0.26 \pm 0.20)\%$$

Most precise measurement to date

Simple average of pure a_{sl} measurements

$$a^d_{sl} = (0.02 \pm 0.20)\%$$

$$a^s_{sl} = (0.17 \pm 0.30)\%$$

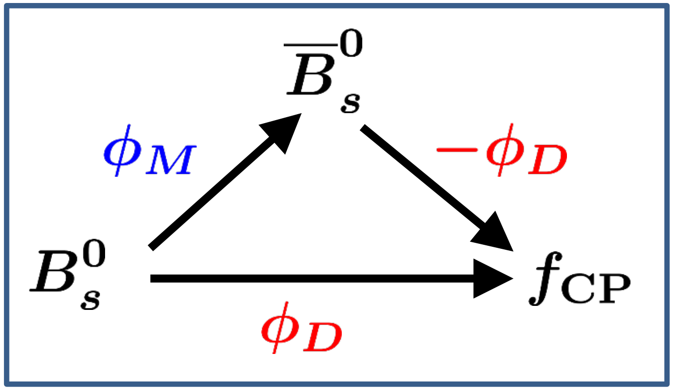
Consistent with SM prediction

The CP violation phase ϕ_s

The interference between two "decay paths" of a B_s meson to a CP eigenstate gives rise to a (final-state dependent) weak phase $\phi_s = \phi_M - 2\phi_D$

$$A_{CP}(t) = \frac{\Gamma(B_s^0 \to f) - \Gamma(\bar{B}_s^0 \to f)}{\Gamma(B_s^0 \to f) + \Gamma(\bar{B}_s^0 \to f)}$$

$$= -\eta_f \sin(\phi_s)\sin(\Delta m_s t)$$



$\phi_D \approx 0$

in the SM

NP might add larges phases to the SM prediction: $\phi_s = \phi_s^{\mathrm{SM}} + \phi_s^{\mathrm{NP}}$

For $b \to c\bar{c}s \; (B_s^0 \to J/\psi K^+K^-)$ indirect determination in the SM via global fits gives (neglecting penguin contributions):

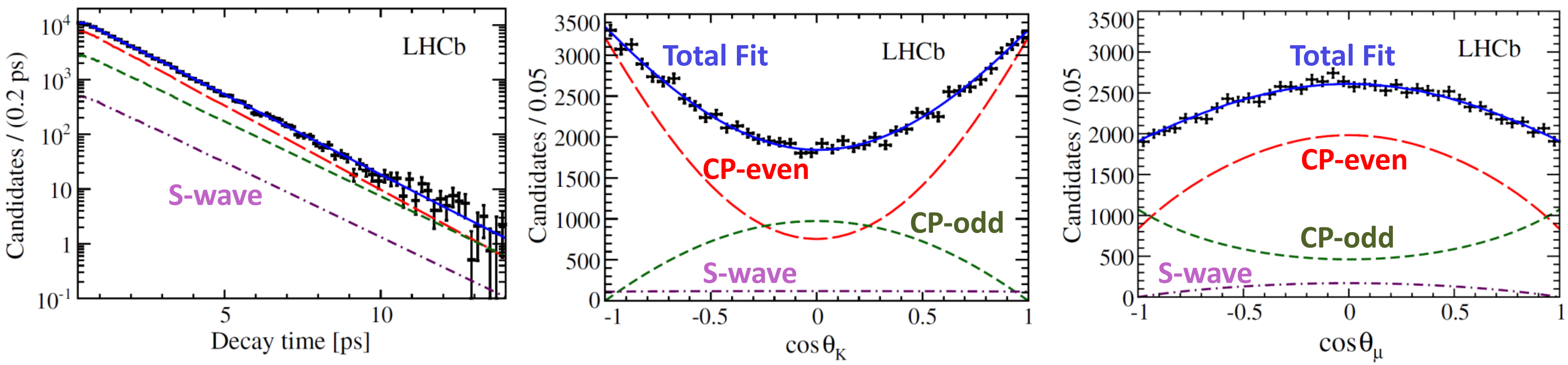
$$\phi_S^{\mathrm{SM}} = -2\arg\left(\frac{-V_{ts}V_{tb}^*}{V_{cs}V_{cb}^*}\right) = -0.0376^{+0.0008}_{-0.0007} \text{ rad}$$ **CKMfitter**

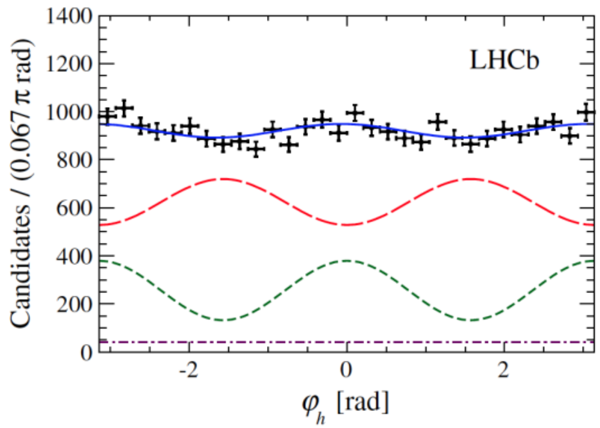
Corrections from loop diagrams have been shown to be small by LHCb: PLB 742 (2015) 38, JHEP 11 (2015) 082

A precise determination of ϕ_s is as a sensitive test of NP in the B_s sector.

ϕ_s from $B_s^0 \to J/\psi K^+K^-$

- Final state with CP-even and CP-odd components .K^+K^- system dominated by ϕ reson.
- Fit invariant mass, decay time and angular distributions of flavour-tagged events.
- 3fb^{-1} of data at √s=7 TeV and 8 TeV. (96000 events). Tagging power (3.73 ± 0.15)%





$$
\begin{aligned}
\phi_s &= -0.058 \pm 0.049 \pm 0.006 \quad \text{rad} \\
\Gamma_s &= 0.6603 \pm 0.0027 \pm 0.0015 \quad \text{ps}^{-1} \\
\Delta\Gamma_s &= 0.0805 \pm 0.0091 \pm 0.0032 \quad \text{ps}^{-1}
\end{aligned}
$$

Single most precise measurements

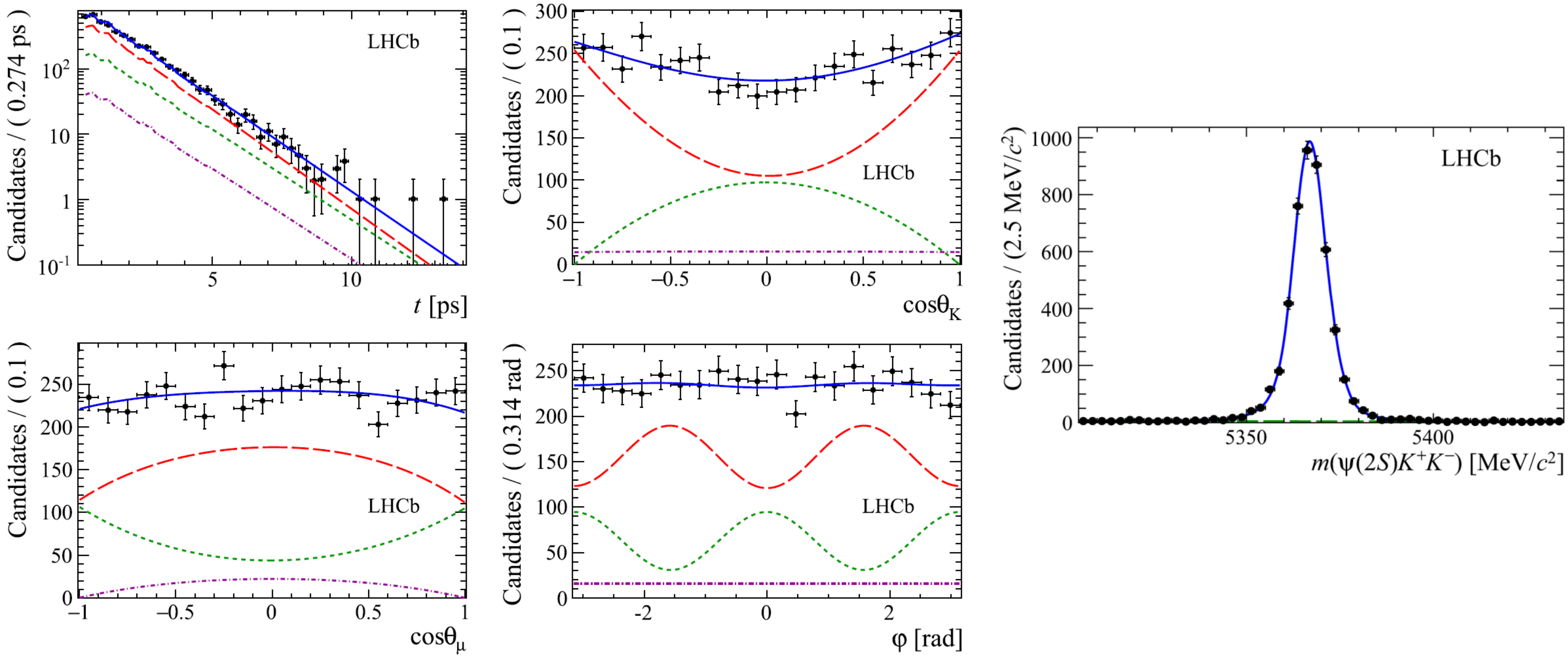
Combined analysis with $B_s^0 \to J/\psi\, \pi^+\pi^-$,
$\phi_s = -0.010 \pm 0.039$ rad.

Angles expressed in the helicity basis (see backup).

PRL 114, 041801 (2015)

First study of ϕ_s in $B_s \to \psi(2S)\,\phi$ decays

PLB 762 (2016) 253–262



First measurement ϕ_s and $\Delta\Gamma_s$ in a decay containing the $\psi(2S)$ resonance.

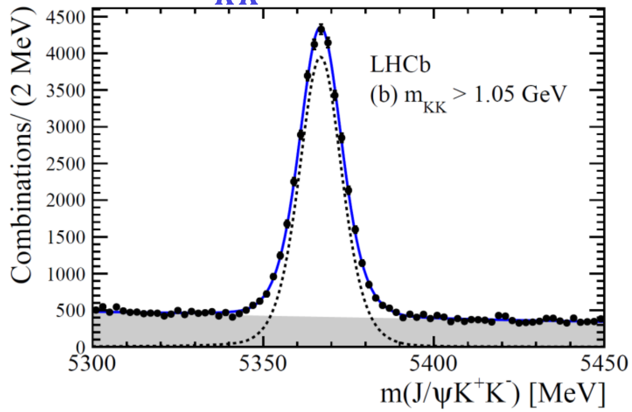
$$\phi_s = 0.23^{+0.29}_{-0.28} \pm 0.02 \ \ \text{rad}$$

$$\Delta\Gamma_s = 0.066^{+0.041}_{-0.044} \pm 0.007 \ \ \text{ps}^{-1}$$

New LHCb measurement of ϕ_s

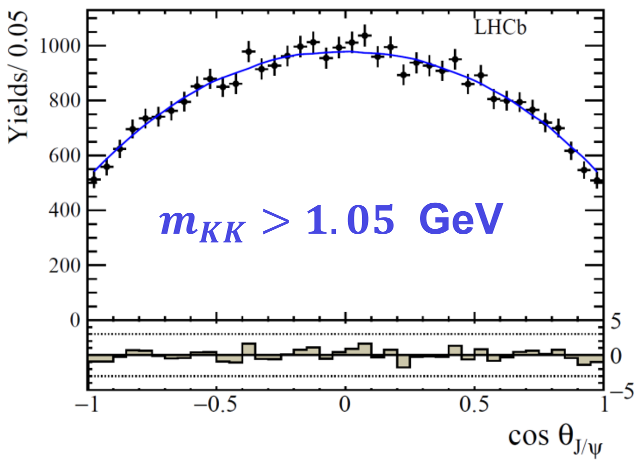
arXive:1704.08217
LHCb-PAPER-2017-008

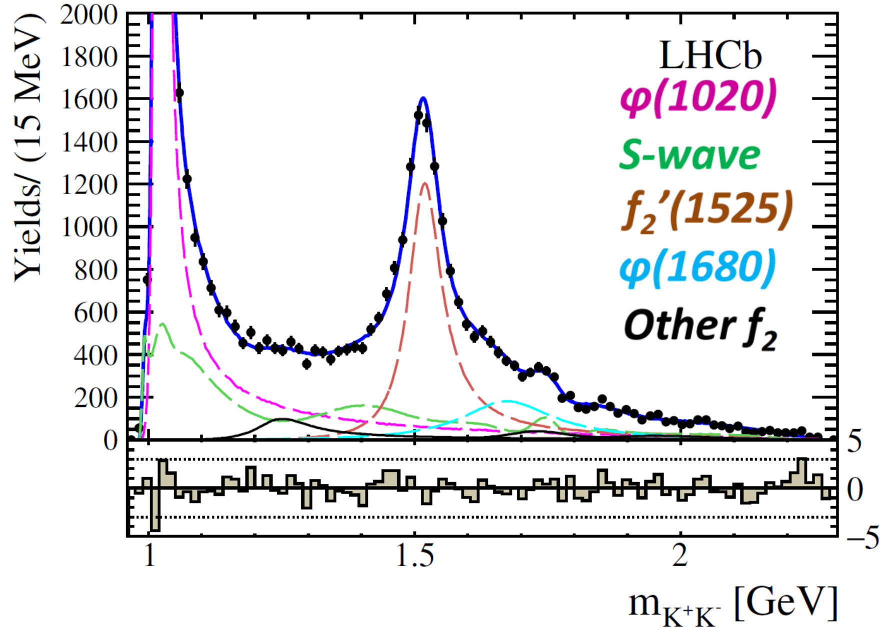
$m_{KK} > 1.05$ GeV



Flavour-tagged, time-dependent amplitude analysis of $B_s \to J/\psi\ K^+K^-$ with m_{KK} above the $\phi(1020)$ region using the Run I data.

Use $B_d \to J/\psi\ K^+K^-$ as a control channel



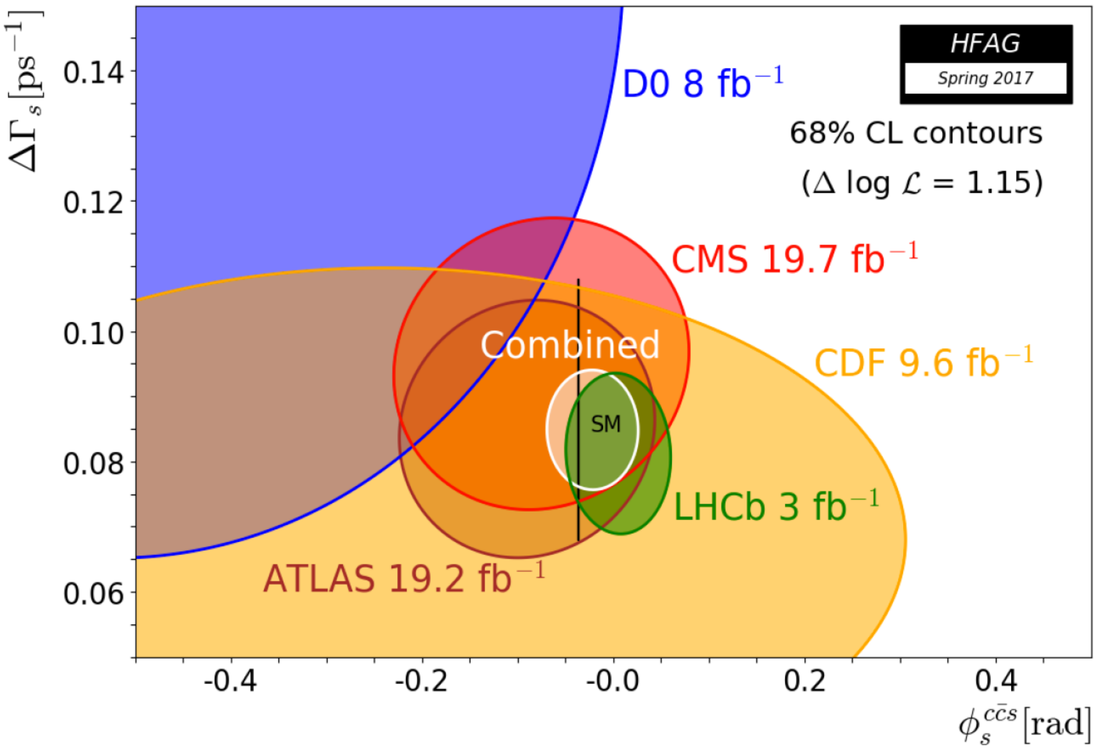


For $m_{KK} > 1.05$ GeV we measure $\phi_s = 0.119 \pm 0.107 \pm 0.034$ rad.

Combination with previous LHCb measurements using $B_s \to J/\psi\ K^+K^-$ and $B_s \to J/\psi\ \pi^+\pi^-$ yields

$$\boxed{\phi_s = 0.001 \pm 0.037 \text{ rad}}$$

Combined measurement of ϕ_s



$$\phi_s^{\text{HFAG WA}} = -0.030 \pm 0.033$$

$$\Delta\Gamma_s = 0.084 \pm 0.007$$

HFAG, arXive:1612.07233

World average dominated by LHCb combination. Includes results from $B_s \to J/\psi\, K^+K^-$, $B_s \to J/\psi\, \pi^+\pi^-$, $B_s \to \psi(2S)\, \phi$, $B_s^0 \to D_s^+ D_s^-$.

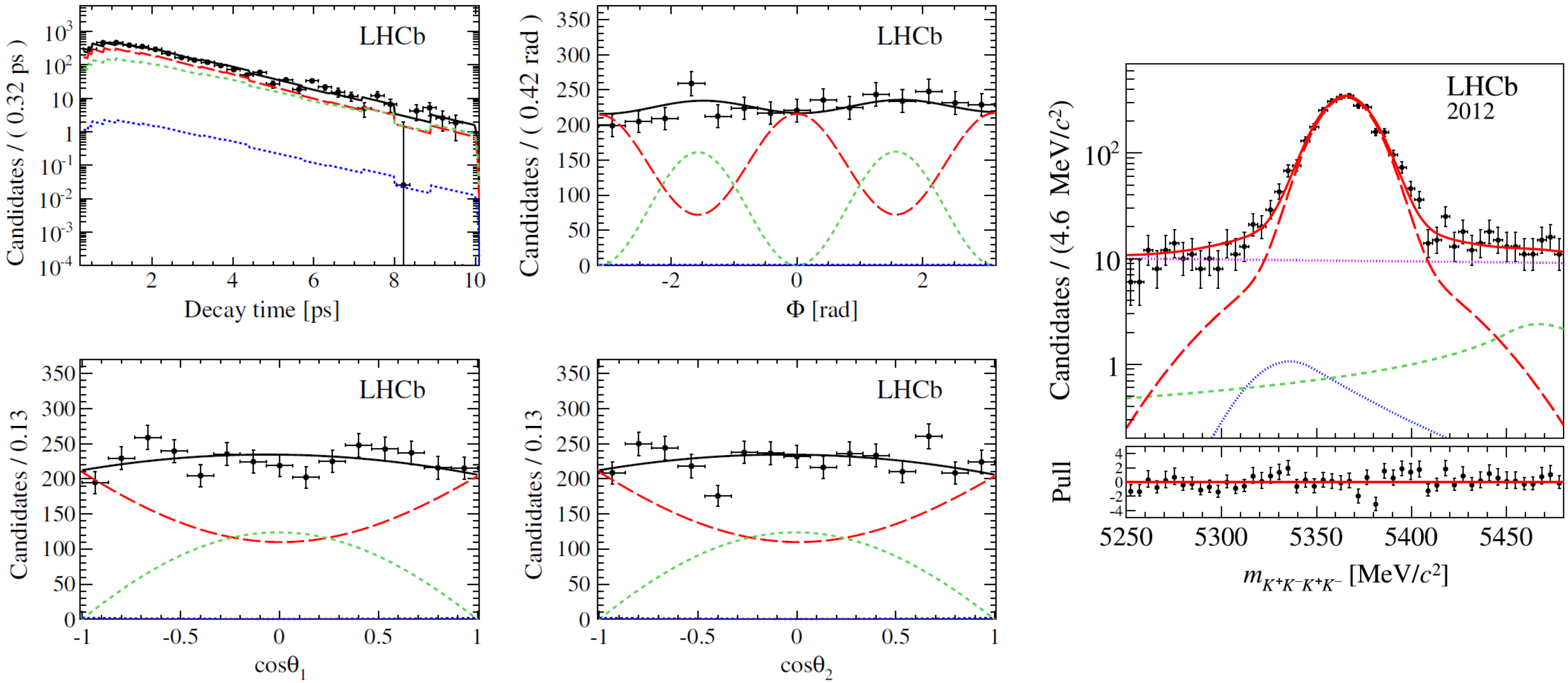
This average does not include recent LHCb measurements and a new LHCb combination which gives (see previous slide)

$$\boldsymbol{\phi_s = 0.001 \pm 0.037}\ \textbf{rad}$$

Other measurements of "ϕ_s"

Measurement of $\phi_s^{s\bar{s}}$ in $B_s^0 \to \phi\phi$ decays ($\bar{b} \to s\bar{s}s$ transition).

($B_s^0 \to J/\psi\,\phi$ is a $\bar{b} \to c\bar{c}s$ transition)



PRD 90, 052011 (2014)

$$\phi_s^{s\bar{s}} = -0.17 \pm 0.15 \pm 0.03 \text{ rad}$$

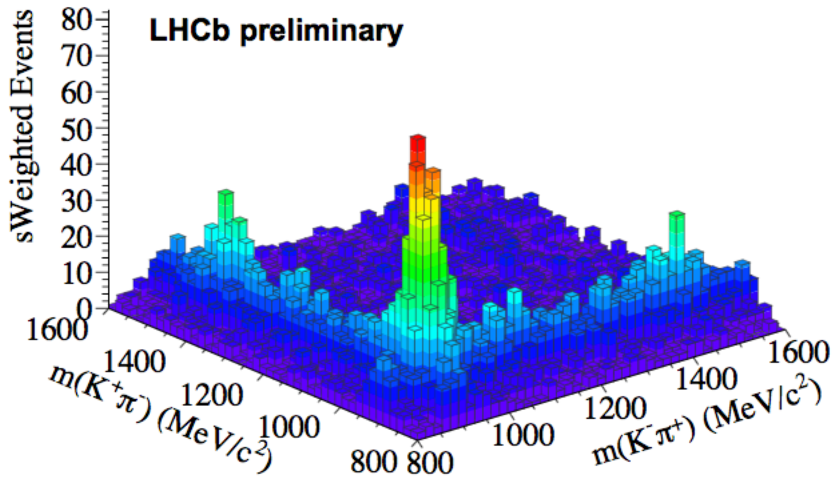
Measurement of $\phi_s^{d\bar{d}}$ in $B_s^0 \to (K^+\pi^-)(K^-\pi^+)$ decays

In preparation Slide from LHCb-TALK-2016-402. Julián García Pardiñas. CKM-2016 Mumbai

Dominant $K\pi$ components:

- **Scalar comp.**: $K_0^*(1430)^0$ + Non Res.
- **Vector comp.**: $K^*(892)^0$
- **Tensor comp.**: $K_2^*(1430)^0$

This leads to 3×3 = **9 decay channels** with **19 polarisation amplitudes**.



Channel	Decay	Polarisation states
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$\parallel$, VV$\perp$
Channel #7	$B_s^0 \to K^*(892)^0\bar{K}_2^*(1430)^0$	VT0, VT$\parallel$, VT$\perp$
Channel #8	$B_s^0 \to K_2^*(1430)^0\bar{K}^*(892)^0$	TV0, TV$\parallel$, TV$\perp$
Channel #9	$B_s^0 \to K_2^*(1430)^0\bar{K}_2^*(1430)^0$	TT0, TT$\parallel$1, TT$\perp$1, TT$\parallel$2, TT$\perp$2

Measurement of $\phi_s^{d\bar{d}}$ in $B_s^0 \to (K^+\pi^-)(K^-\pi^+)$ decays

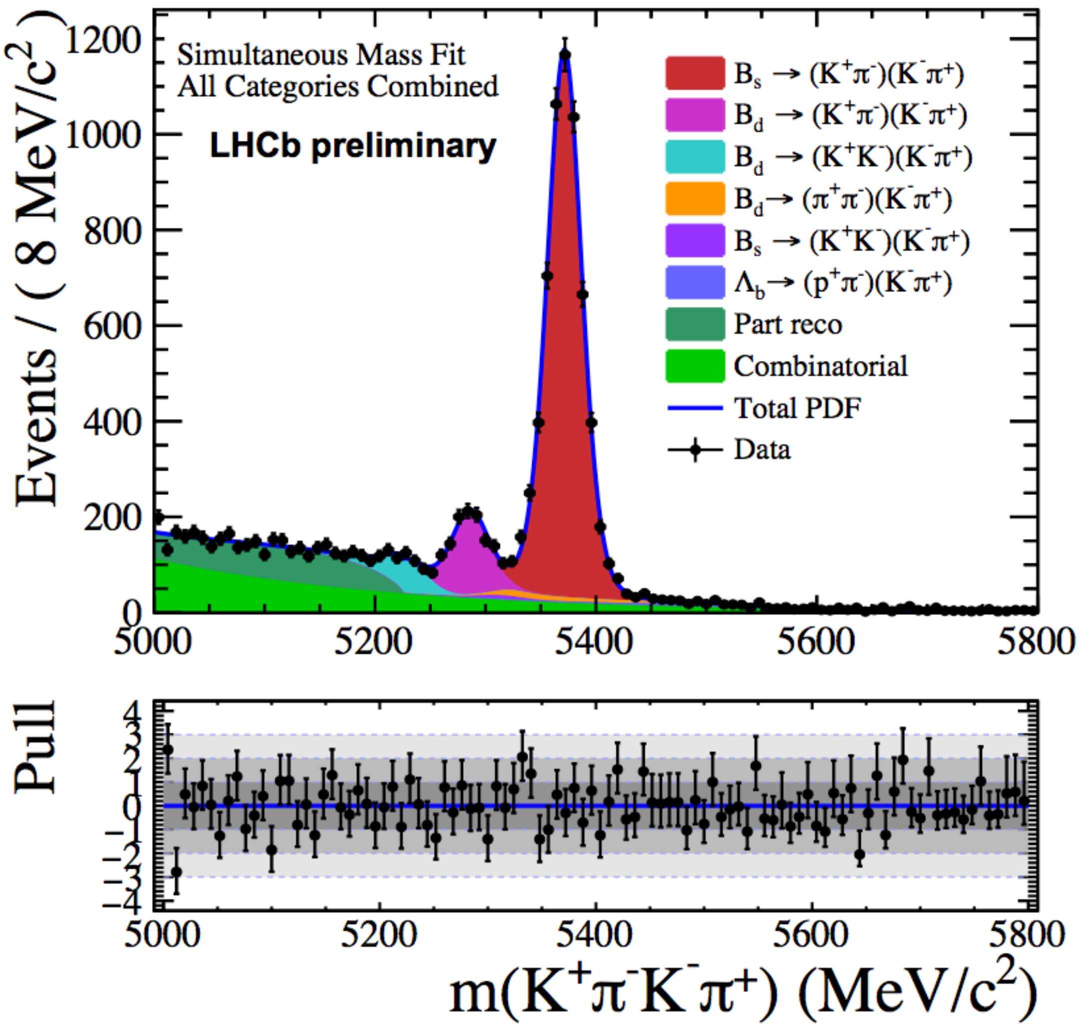
Slide from LHCb-TALK-2016-402. Julián García Pardiñas. CKM-2016 Mumbai

Model components:

- $B_s^0 \to (K^+\pi^-)(K^-\pi^+)$ (signal, all channels)
- $B^0 \to (K^+\pi^-)(K^-\pi^+)$
- Reflection bkgs.
- Partially reconstructed bkg.
- Combinatorial bkg.

Simultaneous fit in year (2011/2012) and hardware trigger (independent on signal or not) categories.

More than 6000 signal events are found (LHCb preliminary).



SM prediction $\phi_s^{d\bar{d}} = \phi_M - 2\phi_D \approx 0$

Expected statistical precision on $\phi_s^{d\bar{d}}$ **better than 0.2 rad**

$|V_{ub}|$ from $\Lambda_b^0 \to p\,\mu^-\,\bar{\nu}_\mu$

$\int \mathcal{L} = 2\ \mathrm{fb}^{-1}$

Nature Phys. 11 (2015) 743

Long standing discrepancy (**3σ**) between inclusive and exclusive measurements of V_{ub}

Measure $|V_{ub}| = (3.27 \pm 0.23) \times 10^{-3}$ through the following ratio (first ever to use a baryonic decay). 2 fb^{-1}.

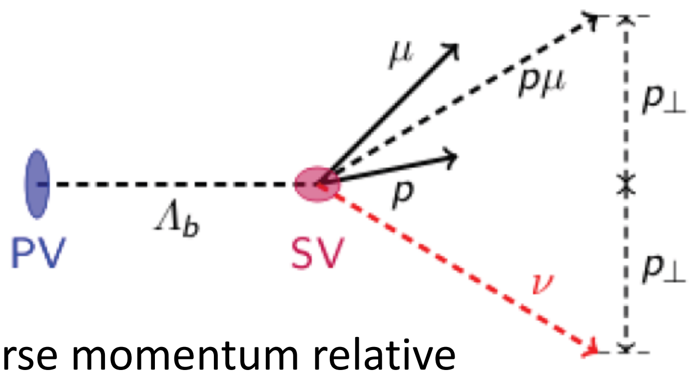
$$\frac{|V_{ub}|^2}{|V_{cb}|^2} = \frac{\mathcal{B}(\Lambda_b^0 \to p\mu^-\bar{\nu}_\mu)}{\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+\mu^-\bar{\nu}_\mu)} R_{\mathrm{FF}}$$

R_{FF} ratio of relevant form factors, from lattice QCD.

$$\Lambda_c^+ \to pK^-\pi^+$$

Experimental method → reconstruct a "corrected" mass:

$$m_{\mathrm{corr}} = \sqrt{m_{h\mu}^2 + p_\perp^2} + p_\perp \qquad h = p, \text{ or } \quad h = \Lambda_c^+$$



$m_{h\mu}$ is the "visible" mass of the $h\mu$ pair, and $p_\perp$ its transverse momentum relative to the Λ_b^0 flight direction.

Extract signal from a 1D fit to m_{corr}

$|V_{ub}|$ from $\Lambda_b^0 \to p\,\mu^-\,\bar{\nu}_\mu$

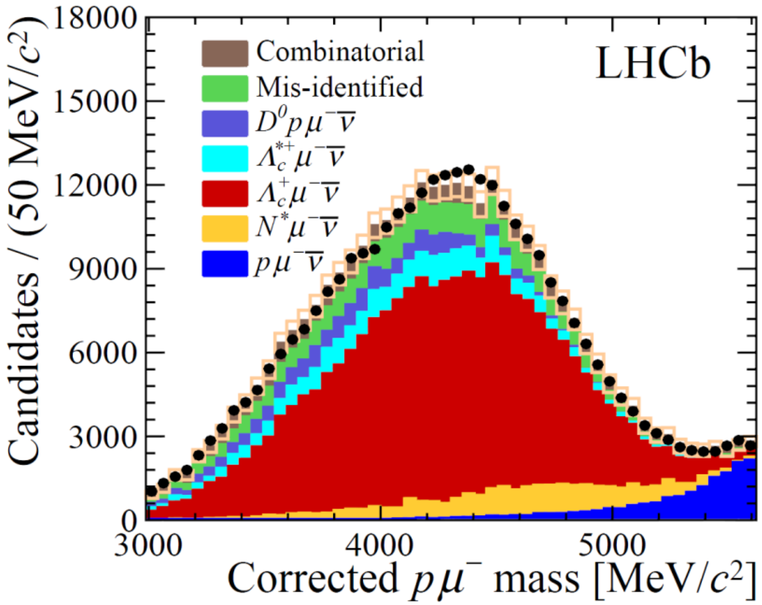
$\int \mathcal{L} = 2\ \mathrm{fb}^{-1}$

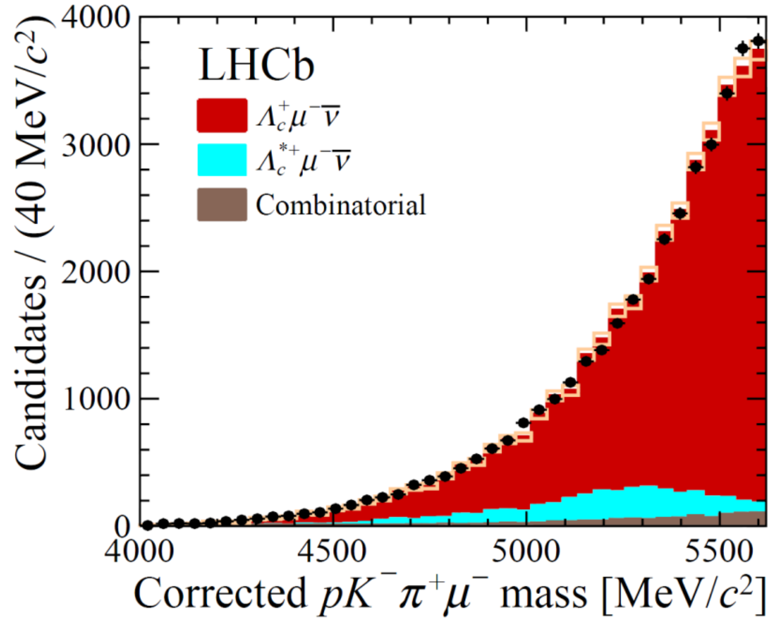
Nature Phys. 11 (2015) 743

Using the Λ_b mass and flight direction, $q^2 = m^2_{\mu\nu} = (p_{\Lambda_b} - p_{\mathrm{p}})^2$ can be estimated.

To avoid large LQCD corrections from R_{FF}, require
$$q^2 > 15\ \mathrm{GeV}^2/c^2 \text{ for } p\mu\bar{\nu}$$
$$q^2 > 7\ \mathrm{GeV}^2/c^2 \text{ for } \Lambda_c\mu\bar{\nu}$$

Use isolation algorithms to remove background with extra charged tracks.





$$N(\Lambda_b^0 \to p\mu^-\bar{\nu}_\mu) = 17687 \pm 733$$

$$N(\Lambda_b^0 \to \Lambda_c^+\mu^-\bar{\nu}_\mu) = 34255 \pm 571$$

$|V_{ub}|$ from $\Lambda_b^0 \to p\,\mu^-\,\bar{\nu}_\mu$

Nature Phys. 11 (2015) 743

$$\frac{\mathcal{B}(\Lambda_b^0 \to p\mu\bar{\nu})_{q^2>15\ \mathrm{GeV}}}{\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+\mu\bar{\nu})_{q^2>7\ \mathrm{GeV}}} = (1.00 \pm 0.04\,(\mathrm{stat}) \pm 0.08\,(\mathrm{syst})) \times 10^{-3}$$

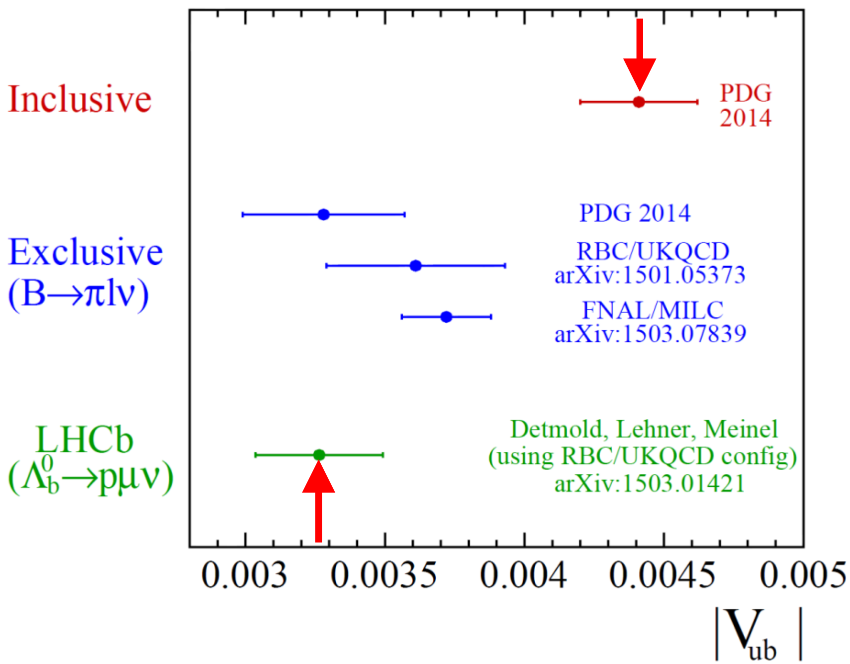
$$\frac{|V_{ub}|}{|V_{cb}|} = 0.083 \pm 0.004\,(\mathrm{exp}) \pm 0.004\,(\mathrm{lattice})$$

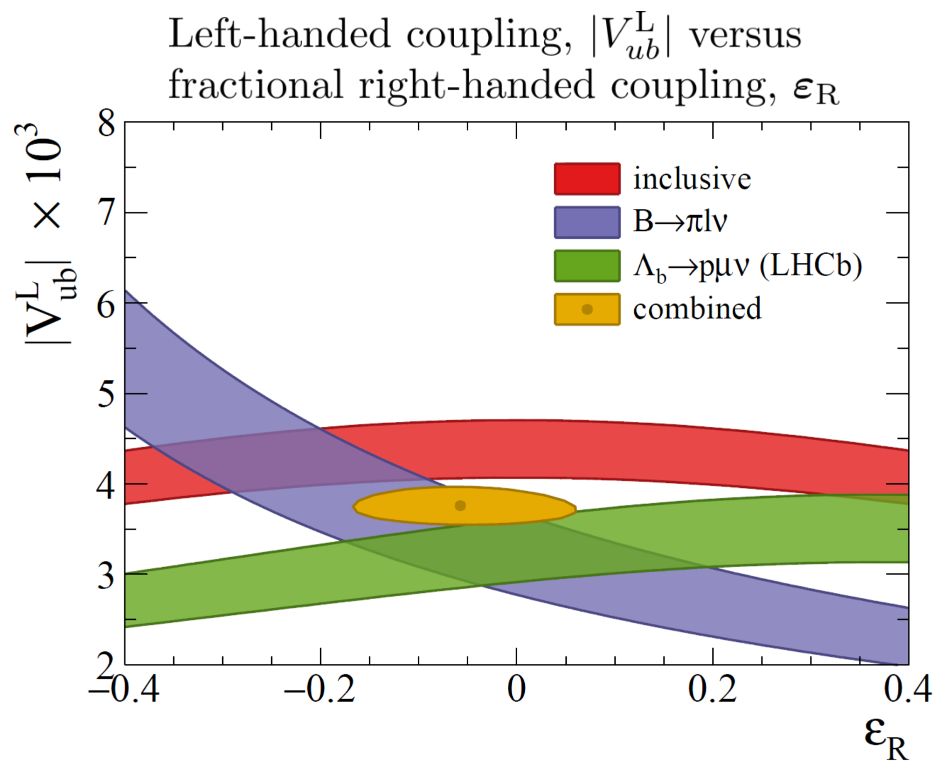
Using $|V_{cb}|$ world average

$$\boxed{|V_{ub}| = (3.27 \pm 0.23) \times 10^{-3}}$$

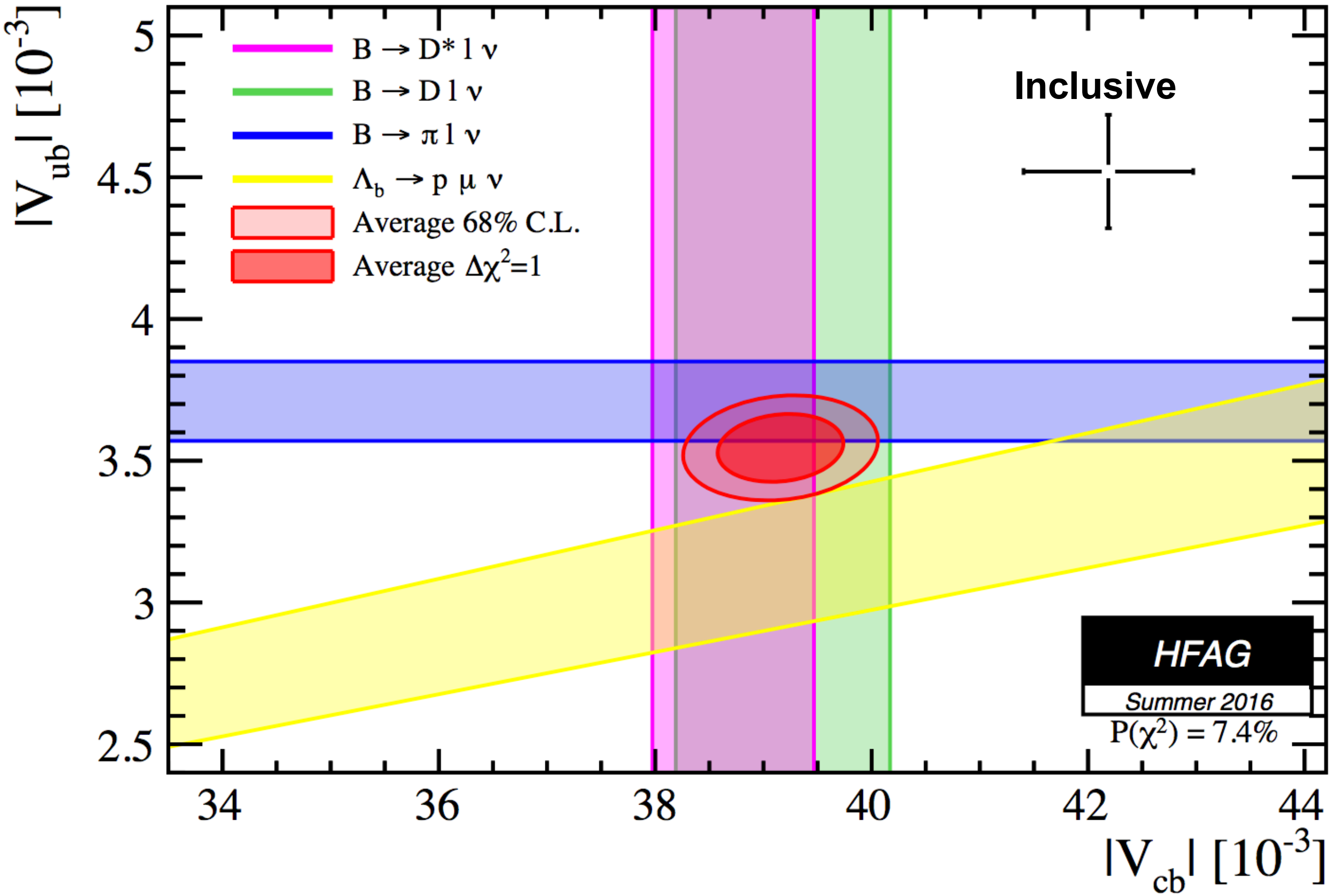
at 3.5 σ from inclusive measur.

Rules out models with large contributions from right-handed currents





$|V_{ub}| - |V_{cb}|$ plane



$|V_{ub}| = (3.55 \pm 0.12)\times 10^{-3}$

$|V_{cb}| = (39.16 \pm 0.58)\times 10^{-3}$

HFAG average, arXive:1612.07233.

(inclusive data not included)

$|V_{ub}|$ prospects

Measurement using $\Lambda_b^0 \to p\,\mu^-\,\bar{\nu}_\mu$ decays is currently systematic limited.

- Expect improvements from LQCD predictions on form factors.
- Use also $B_s^0 \to K^-\,\mu^+\,\nu_\mu$ to measure $|V_{ub}|$. Branching fraction lower than in Λ_b, though.
- Smaller uncertainty in the form factor.
- Normalisation mode branching fraction $B_s^0 \to D_s^-\,\mu^+\,\nu_\mu$ has smaller uncertainties.

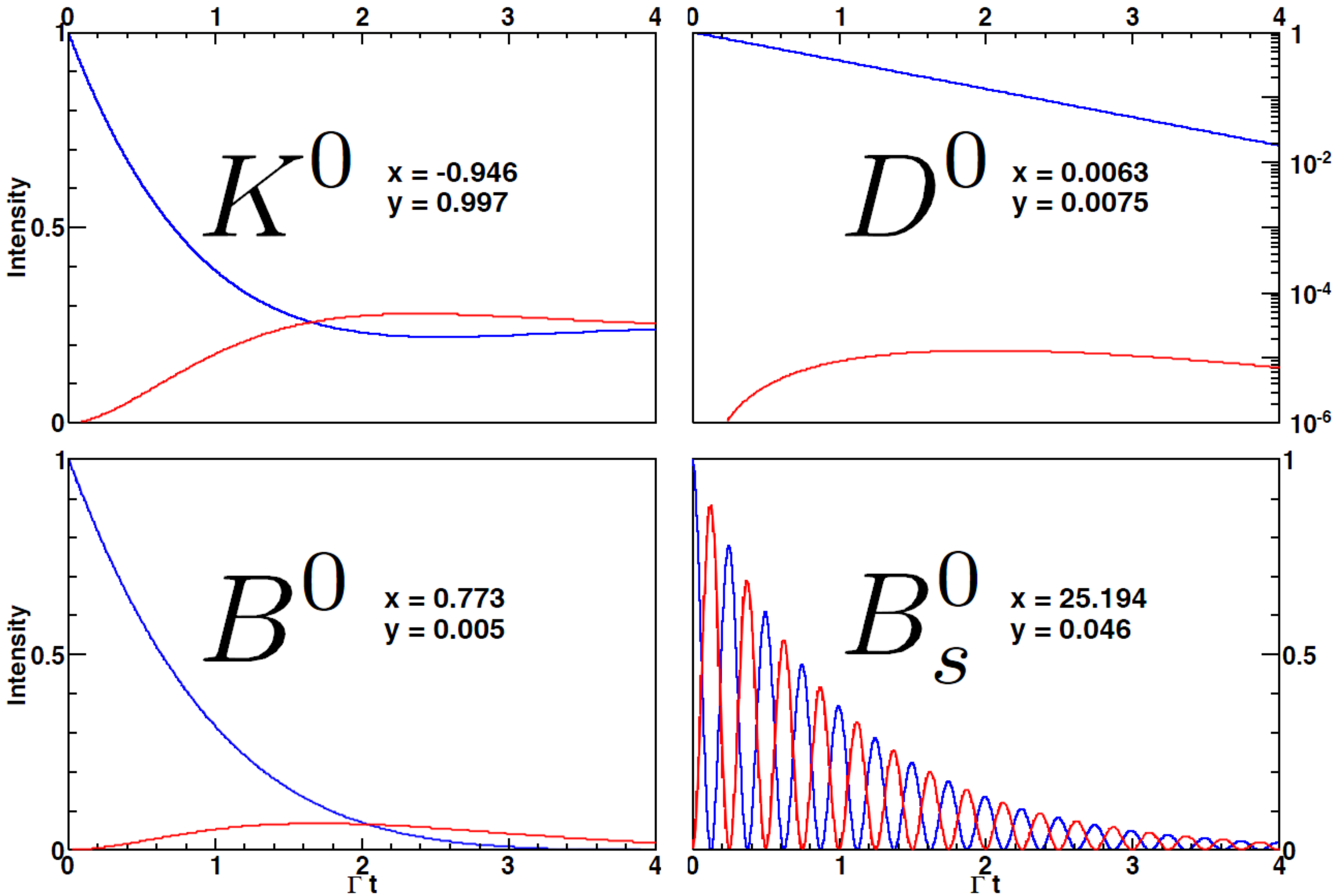
Neutral Meson Mixing

$$P\big(M(0) \to M(t)\big) \qquad P\big(M(0) \to \overline{M}(t)\big)$$

Plots from arXiv:1209.5806

$$x = \frac{\Delta m}{\Gamma}$$

$$y = \frac{\Delta\Gamma}{2\Gamma}$$



B^0 oscillation frequency

Eur. Phys. J. C76 (2016) 412

Use two decay modes, $B^0 \to D^{(*)-}\mu^+\nu_\mu X$, to make world-leading Δm_d determination.

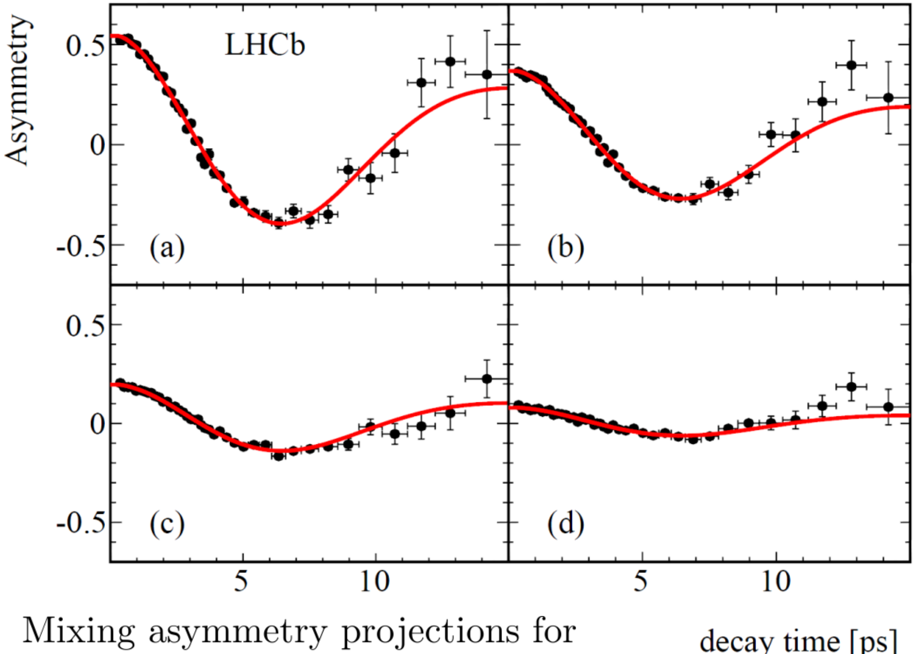
Δm_d is related to $(V_{tb}V_{td}^*)^2$

Assume $\Delta\Gamma_d \approx 0$ and neglect CPV in mixing

$$N^{\text{unmix}}(t) \equiv N(B^0 \to D^{(*)-}\mu^+\nu_\mu X)(t) \propto e^{-\Gamma_d t}[1+\cos(\Delta m_d t)]$$

$$N^{\text{mix}}(t) \equiv N(B^0 \to \overline{B}^0 \to D^{(*)+}\mu^-\overline{\nu}_\mu X)(t) \propto e^{-\Gamma_d t}[1-\cos(\Delta m_d t)]$$

$$\boxed{A(t) = \frac{N^{\text{unmix}}(t) - N^{\text{mix}}(t)}{N^{\text{unmix}}(t) + N^{\text{mix}}(t)} = \cos(\Delta m_d t)}$$



Mixing asymmetry projections for $B^0 \to D^-\mu^+\nu_\mu X$ in four flavour tagging categories.

B^0 flavour at production time and decay time determined using flavour tagging algorithms (effective tagging efficiency close to 2.5%)

Most precise single measurement

$$\Delta m_d = (505.0 \pm 2.1 \pm 1.0)\ \text{ns}^{-1}$$

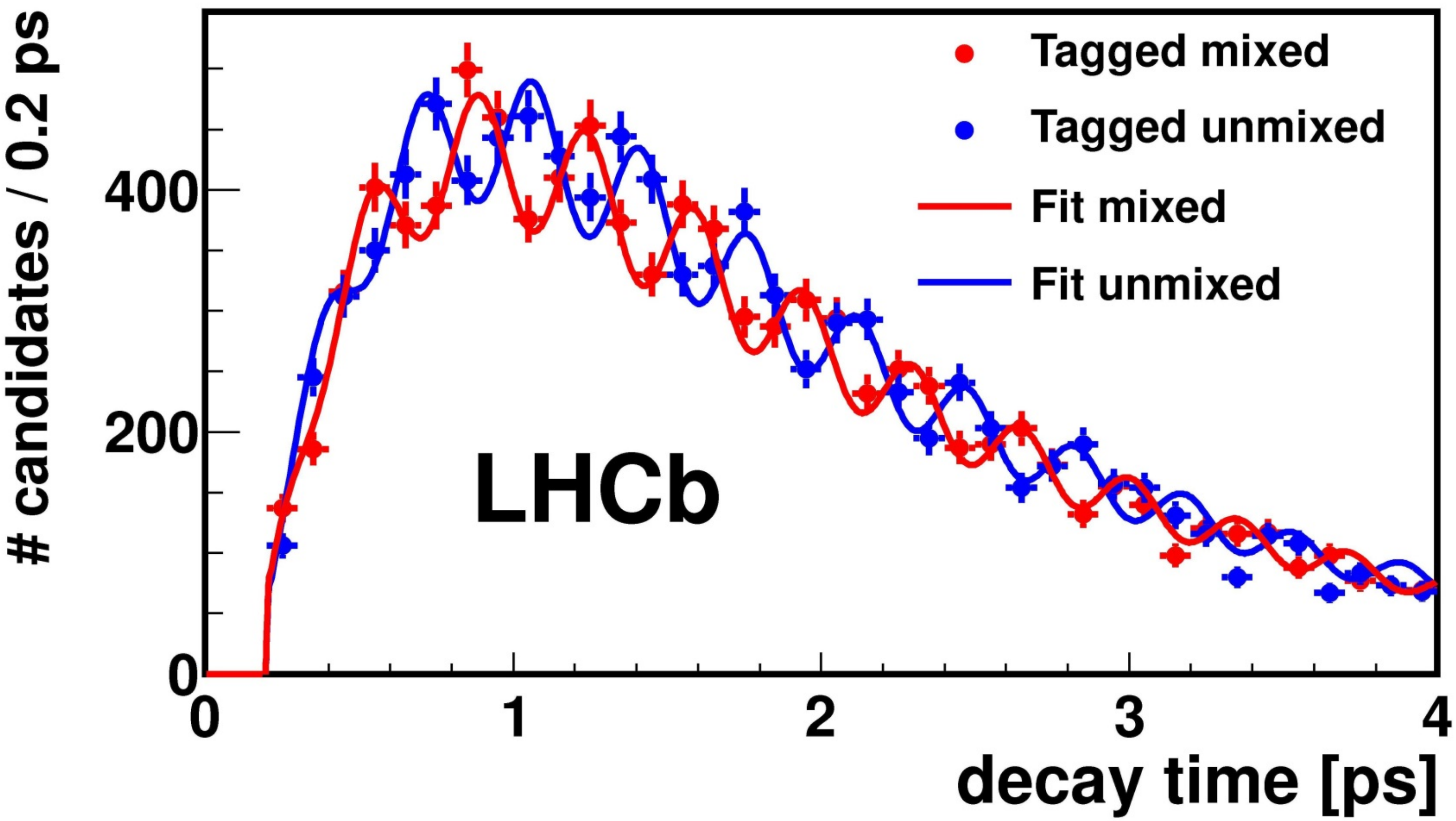
(stat) (syst)

World average $\Delta m_d = 506.5 \pm 1.9\ \text{ns}^{-1}$

HFAG, arXive:1612.07233

Measurement of Δm_s with the decay $B_s^0 \rightarrow D_s^- \pi^+$

New J. Phys. 15 (2013) 053021



$$\Delta m_s = 17.768 \pm 0.023 \pm 0.006 \ \ \mathrm{ps}^{-1}$$

Charm

Charm

Charm mesons provide a large range of probes for mixing and CP violation studies.

CPV not yet observed in charm. Predicted to be very small in the SM.

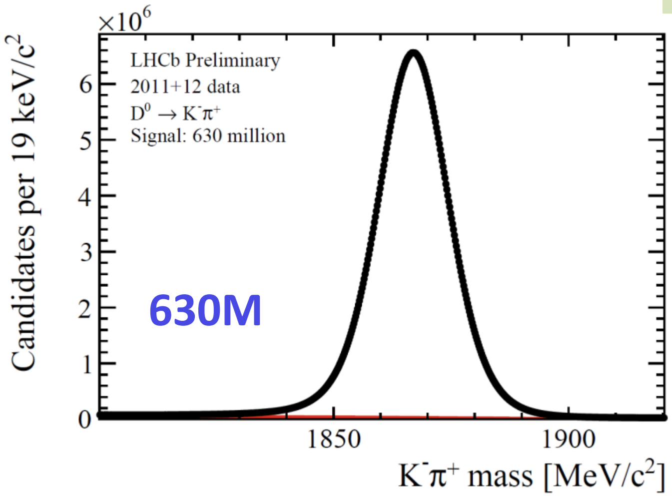
$$CPV \sim \mathcal{O}(V_{ub}V_{cb}^*/V_{us}V_{cs}^*) \sim 10^{-3}$$

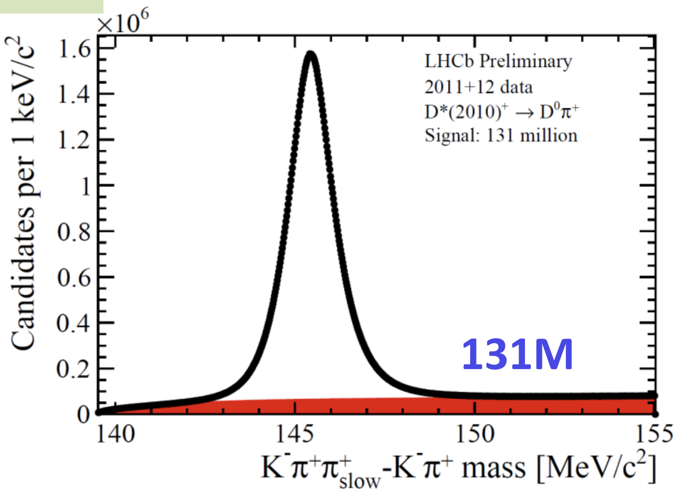
Very large samples of D decays available at LHCb. Suitable to approach SM predictions.

$D^0 \rightarrow K^- \pi^+$

LHCb-CONF-2016-005

$D^{*+} \rightarrow D^0 \pi^+$
$D^0 \rightarrow K^- \pi^+$





About $5{\times}10^{12}$ D^0 and $2{\times}10^{12}$ D^{*+} mesons in **Run I**. A factor of 30 larger than samples collected in past experiments

Charm

D^0 mixing well established. Happens at a very slow rate: $x, y \; < 10^{-2}$

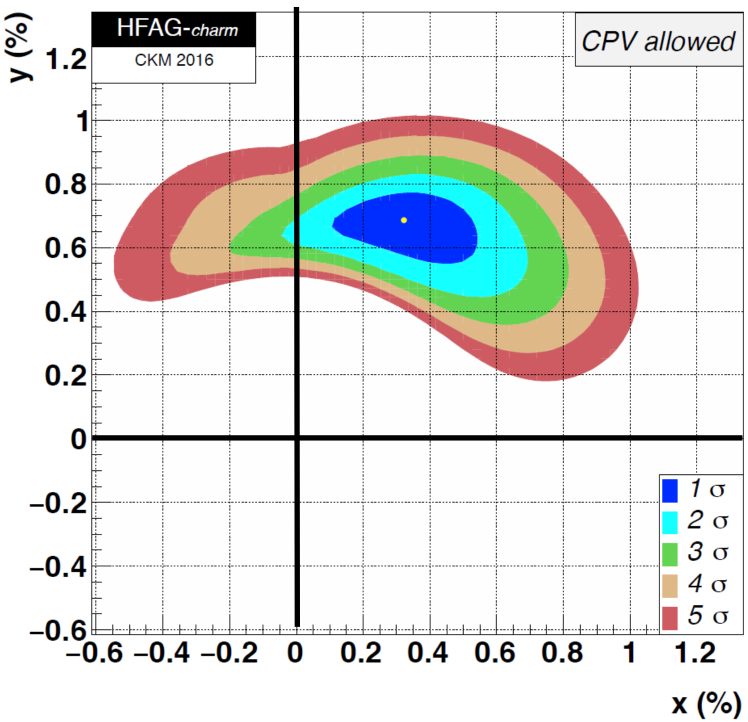
$$|D_{1,2}\rangle = q\,|D^0\rangle \pm |\bar{D}^0\rangle, \qquad |q|^2 + |p|^2 = 1, \qquad \phi = \arg(q/p)$$

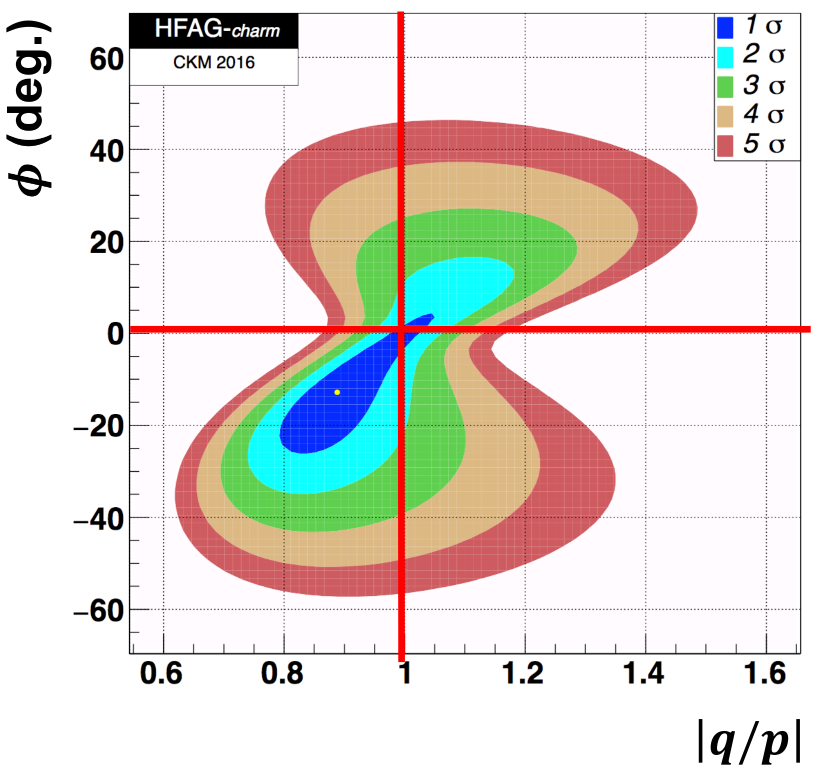
$$x = 2(m_2 - m_1)/(\Gamma_1 + \Gamma_2), \qquad y = (\Gamma_2 - \Gamma_1)/(\Gamma_1 + \Gamma_2)$$

$$\tan\phi = \left(1 - \left|\frac{q}{p}\right|\right)\frac{x}{y}$$

(neglecting direct CPV)

Dimensionless parameters describing D mixing.





Mixing and CPV in $D^0 \to K^{\pm}\pi^{\mp}$ decays

[PRD 95, 052004 (2017)](#)

Dimensionless parameters describing D mixing

$$x = 2(m_2 - m_1)/(\Gamma_1 + \Gamma_2), \qquad y = (\Gamma_2 - \Gamma_1)/(\Gamma_1 + \Gamma_2)$$

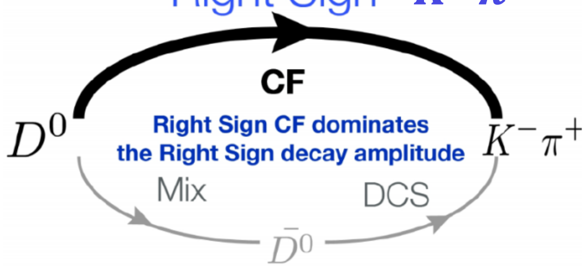
$$x' = x\cos\delta_{K\pi} + y\sin\delta_{K\pi}, \qquad y' = y\cos\delta_{K\pi} - x\sin\delta_{K\pi}$$

$\delta_{K\pi}$ relative strong phase between the DCS and CF amplitudes

CPV and mixing parameters measured using the time-dependent ratio of WS-to-RS decay rates

$$R(t)^{\pm} = R_D^{\pm} + \overbrace{\sqrt{R_D^{\pm}}\,y'^{\pm}\left(\frac{t}{\tau}\right)}^{\text{interference}} + \overbrace{\frac{(x'^{\pm})^2 + (y'^{\pm})^2}{4}\left(\frac{t}{\tau}\right)^2}^{\text{mixing}}$$

Right Sign $K^-\pi^+$

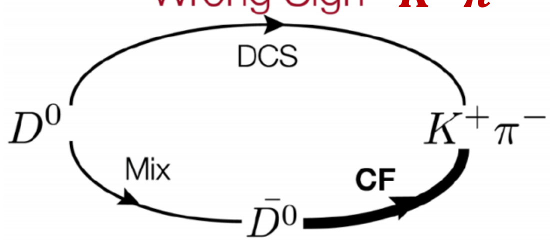


$$R_D^+ = |\mathcal{A}_{\bar f}/\mathcal{A}_f|^2 \qquad R_D^- = |\overline{\mathcal{A}}_f/\overline{\mathcal{A}}_{\bar f}|^2$$

Ratios of DCS to CF amplitudes

$$\mathcal{A}_{\bar f} \text{ for } D^0 \to K^+\pi^- \qquad \overline{\mathcal{A}}_f \text{ for } \overline{D}^0 \to K^-\pi^+$$

Wrong Sign $K^+\pi^-$



$R(t)^+$ and $R(t)^-$ for initially produced D and $\overline{D}$

Measure $R_D^{\pm}$, $(x'^{\pm})^2$ and $y'^{\pm}$ from fits to RS and WS samples

$$R_D^+ \neq R_D^- \implies \text{direct CPV}$$

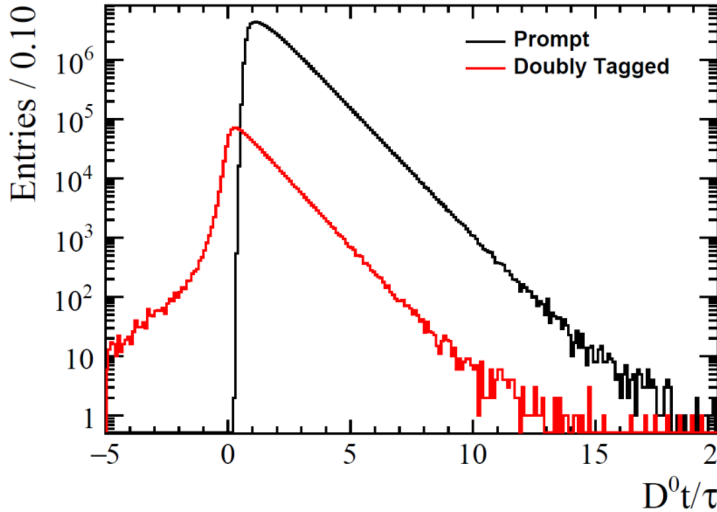
$$x'^+ \neq x'^-,\ y'^+ \neq y'^- \implies \text{CPV in mixing}$$

Mixing and CPV in $D^0 \to K^{\pm}\pi^{\mp}$ decays

PRD 95, 052004 (2017)

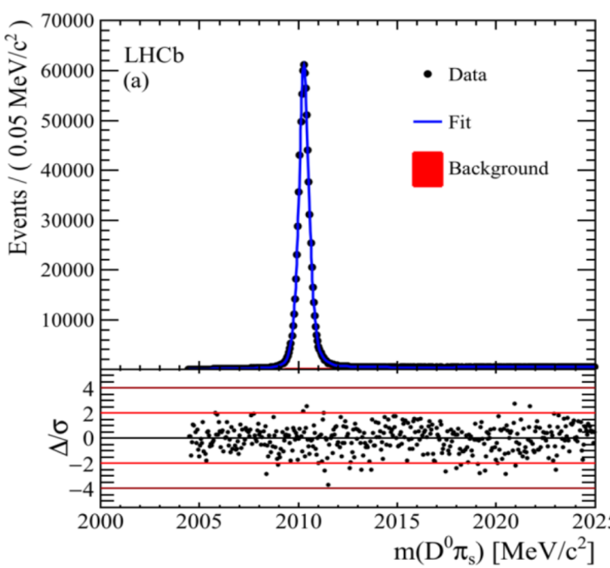
Use very pure **doubly-tagged** charm sample.
Unbiased with respect to the D^0 decay time.

$$\overline{B} \to D^{*+}\mu^- X$$
$$D^{*+} \to D^0\pi_s^+$$
$$D^0 \to K^{\pm}\pi^{\mp}$$



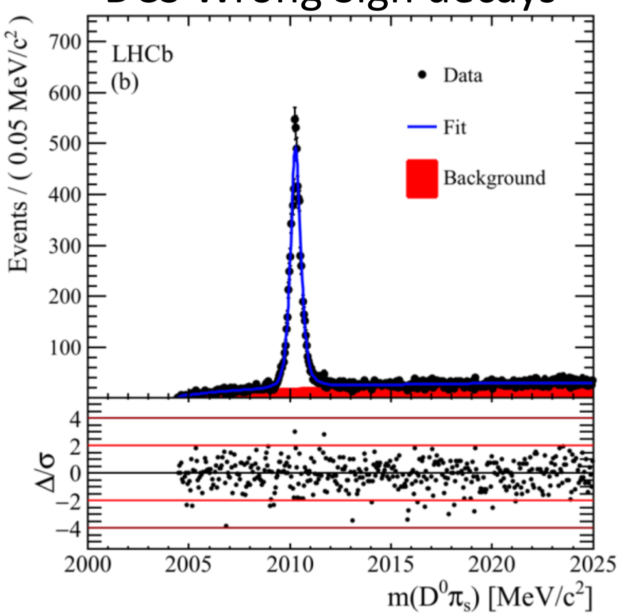
CF Right Sign decays

1.73×10^6 D^{*+} decays



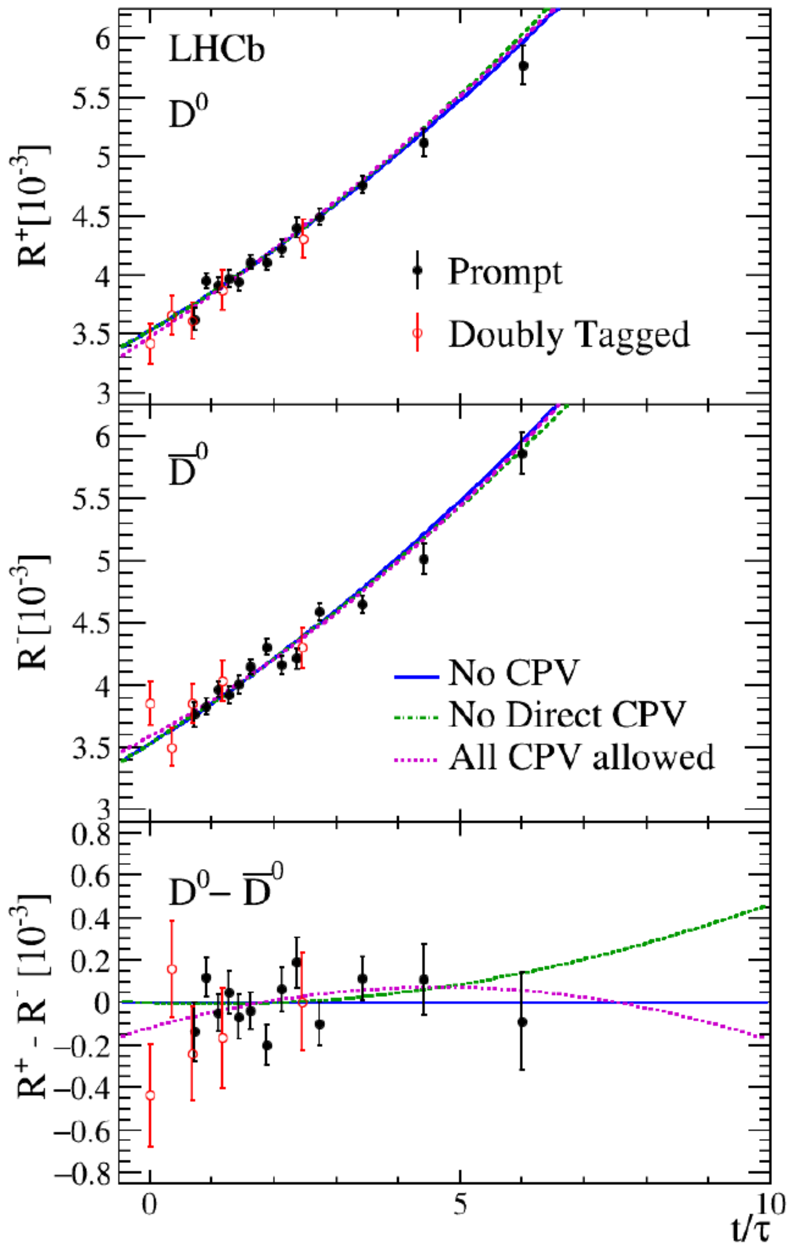
DCS Wrong Sign decays

6.68×10^3 D^{*+} decays



Mixing and CPV in $D^0 \to K^{\pm}\pi^{\mp}$ decays

PRD 95, 052004 (2017)



- Extract $R^{\pm}$ from RS and WS yields in bins of decay time.
- Red points DT analysis. Black points previous prompt charm analysis.
- Simultaneous fit to DT and prompt samples improves precision by 10-20% with respect to previous measurement.
- **Data consistent with CP symmetry**.

$$R_D^+ = (3.474 \pm 0.081)\times 10^{-3}$$
$$R_D^- = (3.591 \pm 0.081)\times 10^{-3}$$

$$(x'^+)^2 = (0.11 \pm 0.65)\times 10^{-4}$$
$$(x'^-)^2 = (0.61 \pm 0.61)\times 10^{-4}$$

$$y'^+ = (5.97 \pm 1.25)\times 10^{-3}$$
$$y'^- = (4.50 \pm 1.21)\times 10^{-3}$$

$$A_{CP}(f;t) \equiv \frac{\Gamma(D^0(t) \to f) - \Gamma(\bar{D}^0(t) \to f)}{\Gamma(D^0(t) \to f) + \Gamma(\bar{D}^0(t) \to f)} \qquad \boldsymbol{f = K^+K^-, \quad \pi^+\pi^-}$$

Due to the slow mixing rate, the **time-dependent** CP asymmetry can be approximated to be the sum of two terms:

$$A_{CP}(f;t) \approx a_{CP}^{\text{dir}}(f) + \frac{t}{\tau_D} a_{CP}^{\text{ind}} \quad \begin{cases} a_{CP}^{\text{dir}}(f) \equiv A_{CP}(f; t=0) = \dfrac{\Gamma(D^0 \to f) - \Gamma(\bar{D}^0 \to f)}{\Gamma(D^0 \to f) + \Gamma(\bar{D}^0 \to f)} \\ a_{CP}^{ind} = \dfrac{\eta_{CP}}{2}\left[y\left(\left|\dfrac{q}{p}\right| - \left|\dfrac{p}{q}\right|\right)\cos\phi - x\left(\left|\dfrac{q}{p}\right| + \left|\dfrac{p}{q}\right|\right)\sin\phi\right] \end{cases}$$

The **time-integrated** asymmetry over the measured D^0 decay time distribution is

$$A_{CP}(f) = a_{CP}^{\text{dir}}(f) + a_{CP}^{\text{ind}}(f)\int_0^\infty \frac{t}{\tau_D} D(t)\,\mathrm{d}t = a_{CP}^{\text{dir}}(f) + \frac{\langle t \rangle}{\tau_D} a_{CP}^{\text{ind}}(f)$$

$D(t)$ is the observed distribution of proper decay time

Time-integrated CP asymmetry in $D^0 \to K^- K^+$ decays

PLB 767 (2017) 177-187

Tag $D^0, \overline{D}^0$ from $D^{*+} \to D^0 \pi^+$

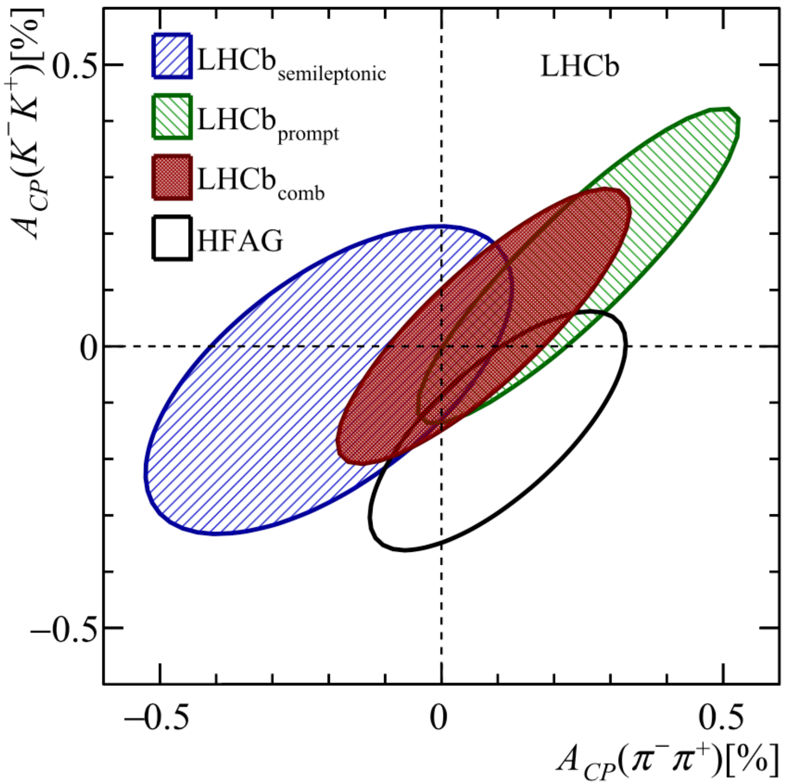
$$A_{CP}(D^0 \to K^- K^+) =$$
$$+\ A_{\rm raw}(D^0 \to K^- K^+)$$
$$-\ A_{\rm raw}(D^0 \to K^- \pi^+)$$
$$+\ A_{\rm raw}(D^+ \to K^- \pi^+ \pi^+)$$
$$-\ A_{\rm raw}(D^+ \to \overline{K}^0 \pi^+) + A_{\rm D}(\overline{K}^0)$$

CPV in CF calibration channels assumed negligible

$$A_{CP}(K^- K^+) = (0.14 \pm 0.15 \pm 0.10)\%$$

A combination with previous LHCb results yields

$$A_{CP}(K^- K^+) = (0.04 \pm 0.12 \pm 0.10)\%$$
$$A_{CP}(\pi^- \pi^+) = (0.07 \pm 0.14 \pm 0.11)\%$$



These are the most precise measurements from a single experiment. The result for $A_{CP}(K^- K^+)$ is the most precise determination of a time-integrated CP asymmetry in the charm sector to date.

No evidence of CP asymmetry.

CP asymmetry in $D^0 \to K^- K^+$ and $D^0 \to \pi^- \pi^+$ decays

Direct CP violation can be isolated through the difference between time integrated CP asymmetries in K^+K^- and $\pi^+\pi^-$ modes.

$$\Delta A_{CP} \equiv A_{CP}(K^-K^+) - A_{CP}(\pi^-\pi^+)$$
$$\approx \Delta a_{CP}^{\mathrm{dir}} \left(1 + \frac{\overline{\langle t \rangle}}{\tau} y_{CP}\right) + \frac{\Delta \langle t \rangle}{\tau} a_{CP}^{\mathrm{ind}}$$

To a good approximation, a_{CP}^{ind} is independent of the decay mode.

$\langle t(f) \rangle$ is the mean decay time of $D^0 \to f$ decays in the reconstructed sample.

y_{CP} is the deviation from unity of the ratio of the effective lifetimes of decays to flavour specific and CP-even final states.

Tag D^0 ($\overline{D}^0$) from $D^{*+} \to D^0\pi^+$ ($D^{*-} \to \overline{D}^0\pi^-$) decays and measure $\Delta A_{\mathrm{CP}} = A_{\mathrm{CP}}(K^+K^-) - A_{\mathrm{CP}}(\pi^+\pi^-)$

PRL 116, 191601, 2016

Run I data

$$\Delta A_{\mathrm{CP}} = (-0.10 \pm 0.08 \pm 0.03)\%$$

Muon tag from $\overline{B} \to D^0\mu^- X$ decays

JHEP 07 (2014) 041

$$\Delta A_{CP} = (+0.14 \pm 0.16 \pm 0.08)\%$$

LHCb dominates the world average

CP asymmetry in $D^0 \to K^-K^+$ and $D^0 \to \pi^-\pi^+$ decays

PRL 116, 191601, 2016

World's most precise measurement of a time-integrated CP asymmetry in the charm sector.

$$\Delta A_{CP} = (-0.10 \pm 0.08 \pm 0.03)\%$$

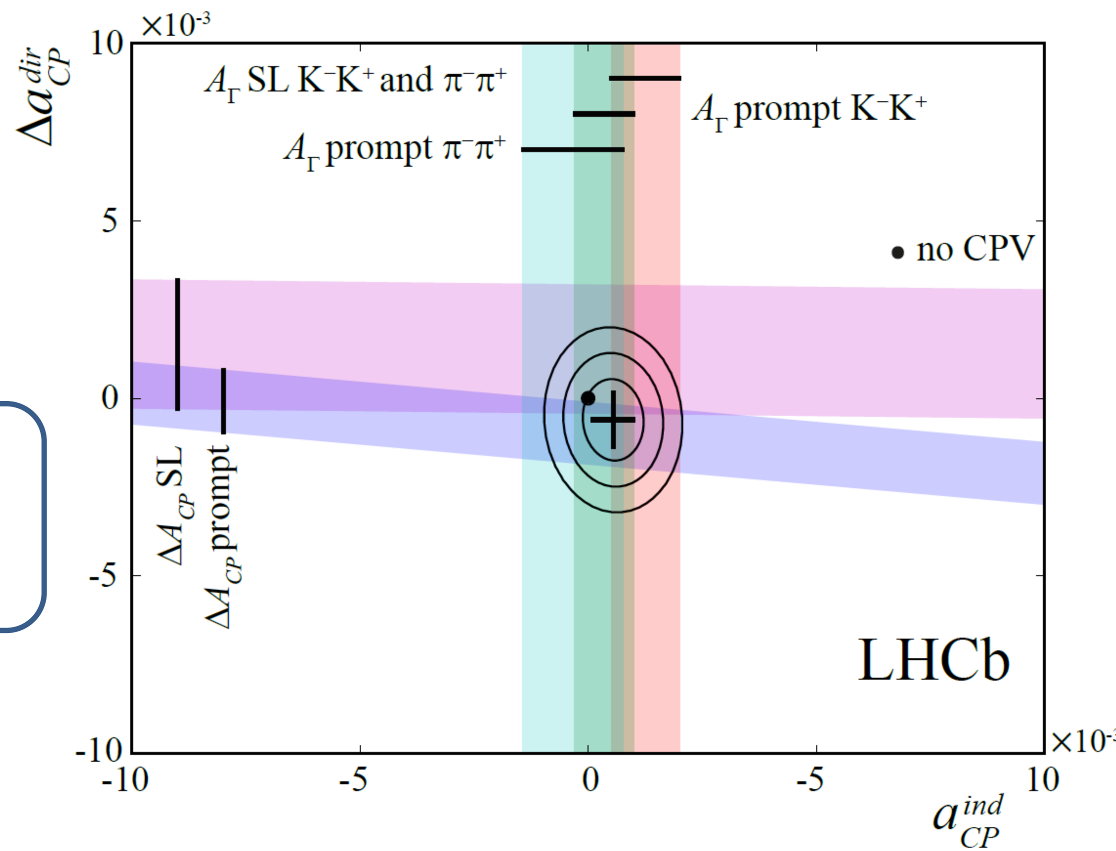
Consistent with no Direct CP violation

Combination of LHCb measurements

JHEP 07 (2014) 041, JHEP 04 (2012) 129
JHEP 04 (2015) 043, PRL 116 (2016) 191601

$$a_{CP}^{\text{ind}} = (+0.58 \pm 0.44)\times 10^{-3}$$
$$\Delta a_{CP}^{\text{dir}} = (-0.61 \pm 0.76)\times 10^{-3}$$

Direct versus Indirect A_{CP}



A_Γ from $D^0 \to K^+K^-$ and $D^0 \to \pi^+\pi^-$

arXiv:1702.06490
LHCb-PAPER-2016-063

Measure **time-dependent** CP asymmetries in effective decay widths. Time-integrated CP asymmetries and mixing parameters are known to be small, therefore:

(1) $$A_{CP}(t) \equiv \frac{\Gamma(D^0(t)\to f) - \Gamma(\overline{D}^0(t)\to f)}{\Gamma(D^0(t)\to f) + \Gamma(\overline{D}^0(t)\to f)} \approx a^f_{\rm dir} - A_\Gamma \frac{t}{\tau_D}$$

(2) $$A_\Gamma = \frac{\hat{\Gamma}_{D^0\to f} - \hat{\Gamma}_{\overline{D}^0\to f}}{\hat{\Gamma}_{D^0\to f} + \hat{\Gamma}_{\overline{D}^0\to f}} \qquad \hat{\Gamma}_{D^0\to f} = \frac{\int_0^\infty \Gamma(D^0(t)\to f)\,{\rm d}t}{\int_0^\infty t\,\Gamma(D^0(t)\to f)\,{\rm d}t}$$

To first order $a^f_{\rm dir} = 0$, and A_Γ is independent of the final state f. In the absence of CPV in mixing, $A_\Gamma = -x\sin\phi \approx -a^{\rm ind}_{CP}$.

Method based on Eq. **(1)** provides more precise results for A_Γ than that based on Eq. **(2)**. Quote only those.

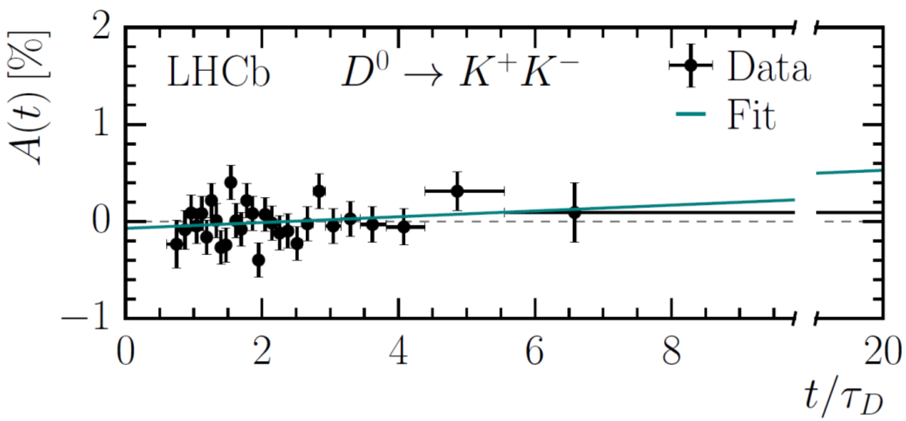
Measure $\boldsymbol{A_{CP}(t)}$ and make a linear fit to $\boldsymbol{A_{CP}(t) = a^f_{\rm dir} - A_\Gamma \frac{t}{\tau_D}}$.

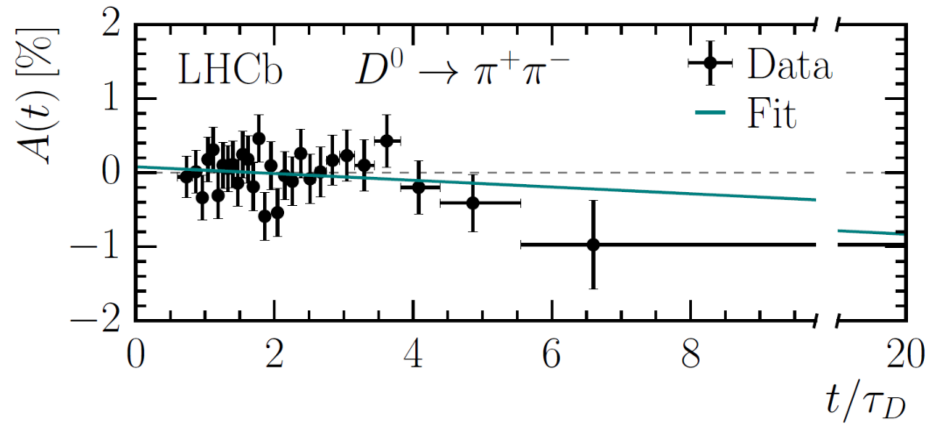
Determine residual asymmetries by exploiting the large control sample of $D^0 \to K^-\pi^+$ decays, where a negligible CP asymmetry is expected.

A_Γ from $D^0 \to K^+K^-$ and $D^0 \to K^+K^-$

arXiv:1702.06490
LHCb-PAPER-2016-063

Linear fit to $A_{CP}(t) \approx a_{\rm dir}^{f} - A_\Gamma \frac{t}{\tau_D}$





$$A_\Gamma(K^+K^-) = (-0.30 \pm 0.32 \pm 0.10) \times 10^{-3}$$
$$A_\Gamma(\pi^+\pi^-) = (-0.46 \pm 0.58 \pm 0.12) \times 10^{-3}$$

Consistent with no CPV

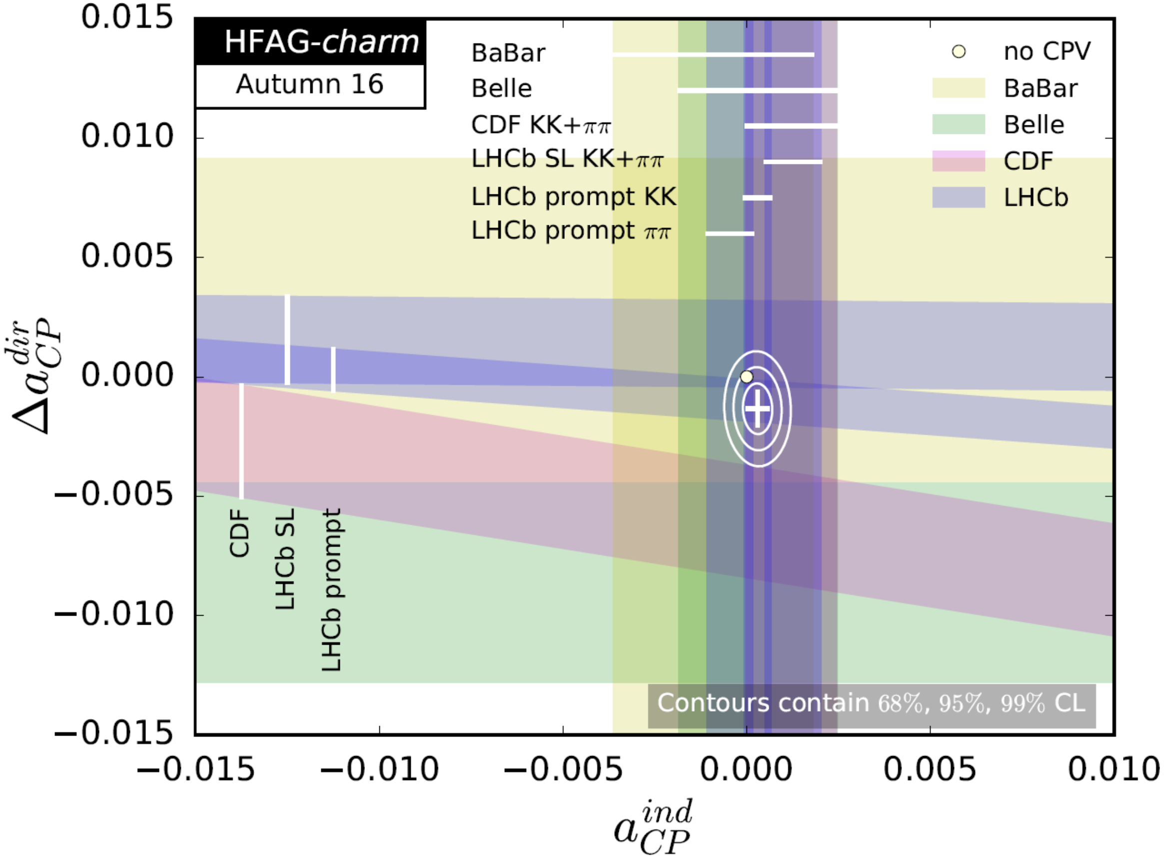
$\bar{B}^0 \to D^0\mu^-\bar{\nu}_\mu X$ $\quad B^- \to D^0\mu^-\bar{\nu}_\mu X$

Calculate average A_Γ and combine with the muon tagged sample JHEP 04 (2015) 043

$$A_\Gamma = a_{CP}^{\rm ind} = (-0.29 \pm 0.28)\times 10^{-3}$$

LHCb Run I combination.
Most precise measurement

Present situation of CPV in $D^0 \to h^+ h^-$ decays



$$-A_\Gamma = a_{CP}^{\mathrm{ind}} = (0.30 \pm 0.26)\times 10^{-3}$$

HFAG 2016, arXive:1612.07233

$$\Delta a_{CP}^{\mathrm{dir}} = (-1.34 \pm 0.70)\times 10^{-3}$$

$$-A_\Gamma = a_{CP}^{\mathrm{ind}} = (0.29 \pm 0.28)\times 10^{-3}$$

arXiv:1702.06490
LHCb-PAPER-2016-063

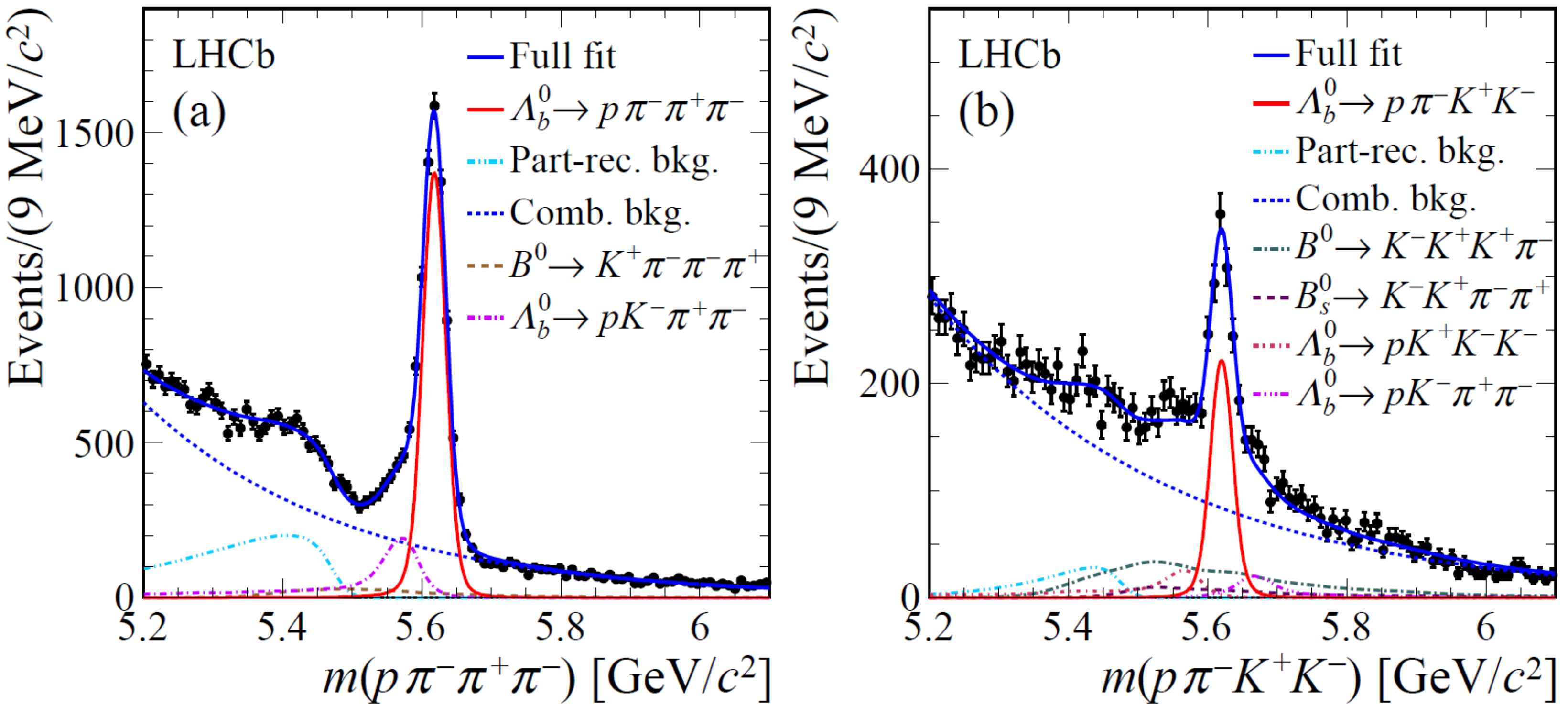
CP Violation in baryon decays

CPV in baryon decays

Nature Phys. 4021 (2017)

Decays $\Lambda_b^0 \to p\,\pi^-\pi^+\pi^-$ and $\Lambda_b^0 \to p\,\pi^-K^+K^-$ observed by the first time.

$N_{\text{sig}}(p\,\pi^-K^+K^-) = 6646 \pm 105$ $N_{\text{sig}}(p\,\pi^-\pi^+\pi^-) = 1030 \pm 56$

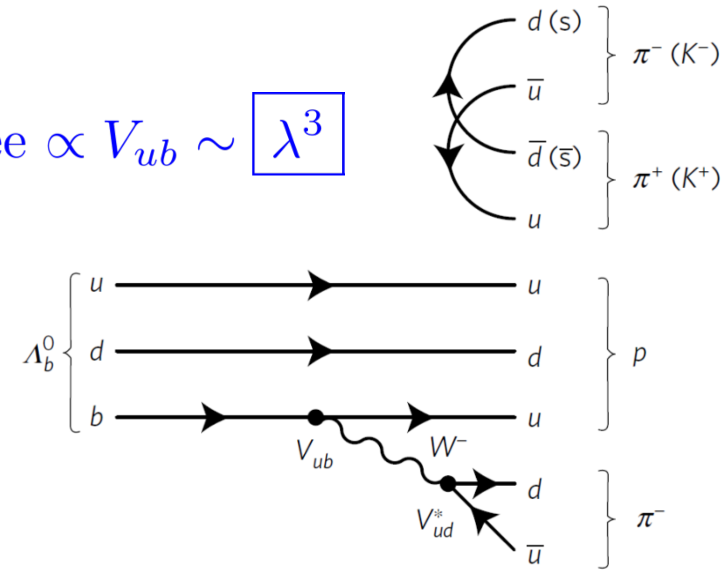


CPV in baryon decays

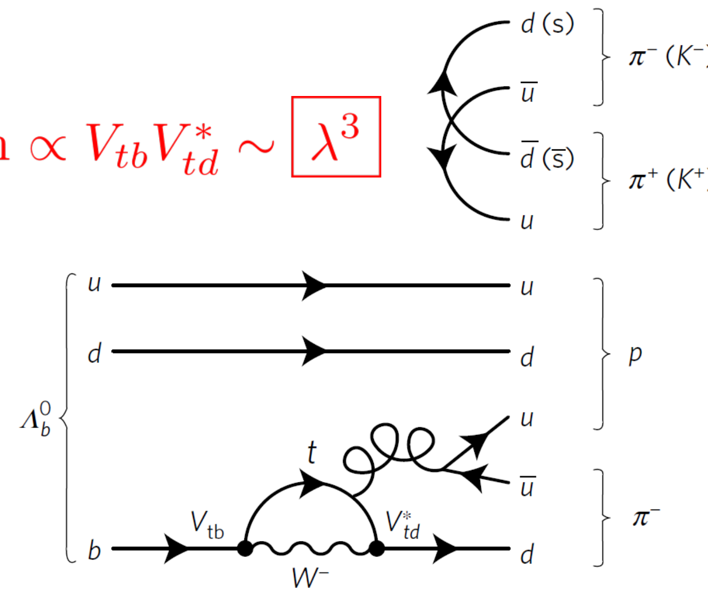
Nature Phys. 4021 (2017)

$\boldsymbol{\Lambda_b^0 \to p\,\pi^-\pi^+\pi^-}$ and $\boldsymbol{\Lambda_b^0 \to p\,\pi^- K^+ K^-}$ mainly governed by two amplitudes, tree and penguin, of similar magnitude.

$\text{Tree} \propto V_{ub} \sim \boxed{\lambda^3}$



$\text{Penguin} \propto V_{tb}V^*_{td} \sim \boxed{\lambda^3}$



In the SM, significant CPV could arise from the large weak relative phase α between CKM elements

$$\alpha = \arg\left(\frac{V_{tb}V_{td^*}}{V_{ub}V^*_{ud}}\right)$$

Search for CP-violating asymmetries in the decay angle distributions of $\boldsymbol{\Lambda_b^0}$ baryons.

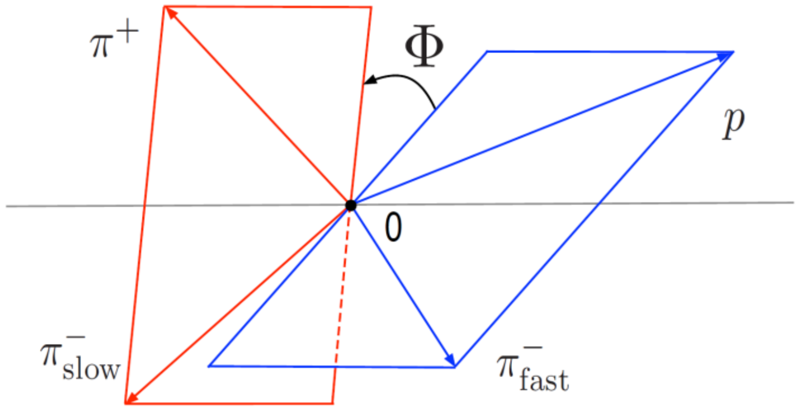
CPV in baryon decays

Nature Phys. 4021 (2017)

Scalar triple products in the Λ_b^0 rest frame.

$$C_{\widehat{T}} = \vec{p}_p \cdot (\vec{p}_{h_1^-} \times \vec{p}_{h_2^+}) \propto \sin\Phi, \quad \text{for} \quad \Lambda_b^0$$
$$\overline{C}_{\widehat{T}} = \vec{p}_{\bar{p}} \cdot (\vec{p}_{h_1^+} \times \vec{p}_{h_2^-}) \propto \sin\overline{\Phi}, \quad \text{for} \quad \overline{\Lambda}_b^0$$

$h_1 = h_2 = \pi$ for $\Lambda_b \to p\pi^-\pi^+\pi^-$
$h_1 = \pi,\, h_2 = K$ for $\Lambda_b \to p\pi^- K^+ K^-$



***P*-odd and $\widehat{T}$-odd** asymmetries for Λ_b^0 and $\overline{\Lambda}_b^0$. The unitary operator $\widehat{T}$ reverses both the momentum and spin three-vectors.

$$A_{\widehat{T}}(C_{\widehat{T}}) = \frac{N(C_{\widehat{T}} > 0) - N(C_{\widehat{T}} < 0)}{N(C_{\widehat{T}} > 0) + N(C_{\widehat{T}} < 0)} \qquad \overline{A}_{\widehat{T}}(\overline{C}_{\widehat{T}}) = \frac{\overline{N}(-\overline{C}_{\widehat{T}} > 0) - \overline{N}(-\overline{C}_{\widehat{T}} < 0)}{\overline{N}(-\overline{C}_{\widehat{T}} > 0) + \overline{N}(-\overline{C}_{\widehat{T}} < 0)}$$

P-violating observable

$$\boxed{a_P^{\widehat{T}\text{-odd}} = \frac{1}{2}\left(A_{\widehat{T}} + \overline{A}_{\widehat{T}}\right)}$$

CP-violating observable

$$\boxed{a_{CP}^{\widehat{T}\text{-odd}} = \frac{1}{2}\left(A_{\widehat{T}} - \overline{A}_{\widehat{T}}\right)}$$

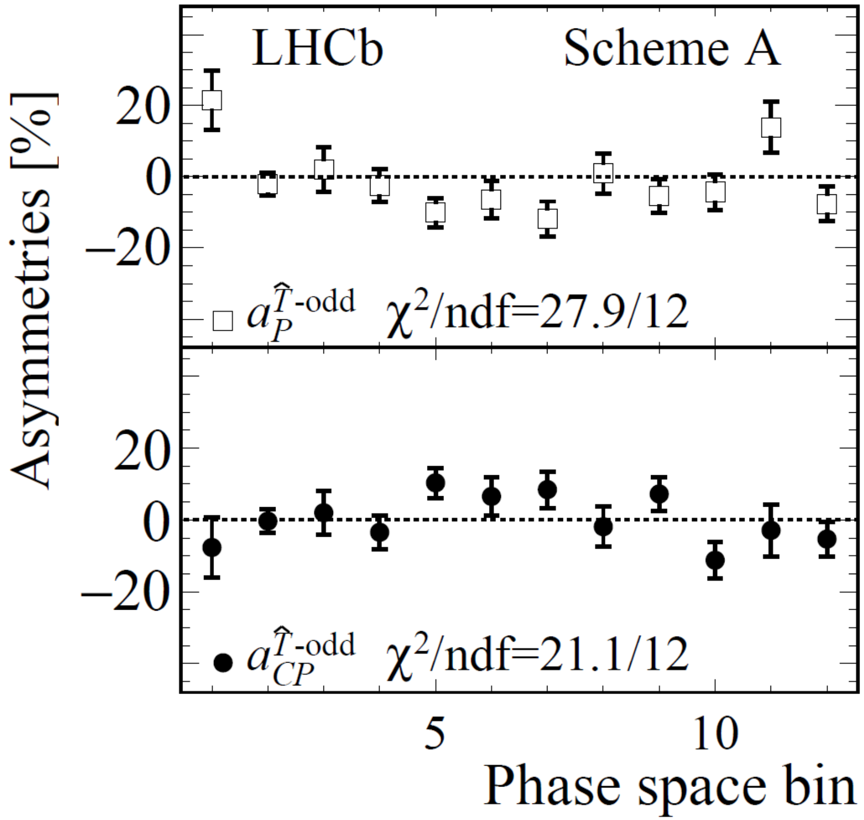
By construction, these observables are largely insensitive to production asymmetries and detector-induced charge asymmetries.

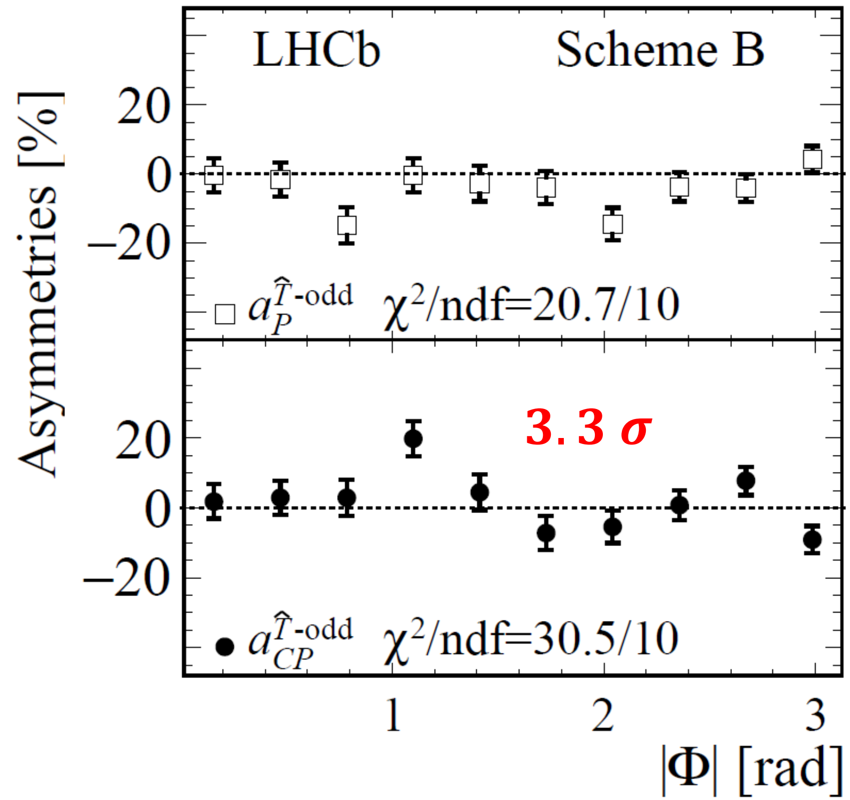
CPV in baryon decays

Nature Phys. 4021 (2017)

$\Lambda_b^0 \to p\,\pi^-\pi^+\pi^-$

Asymmetries in the entire phase space consistent with no CPV, but evidence for **CPV at 3.3 σ** found in localized regions of phase-space.





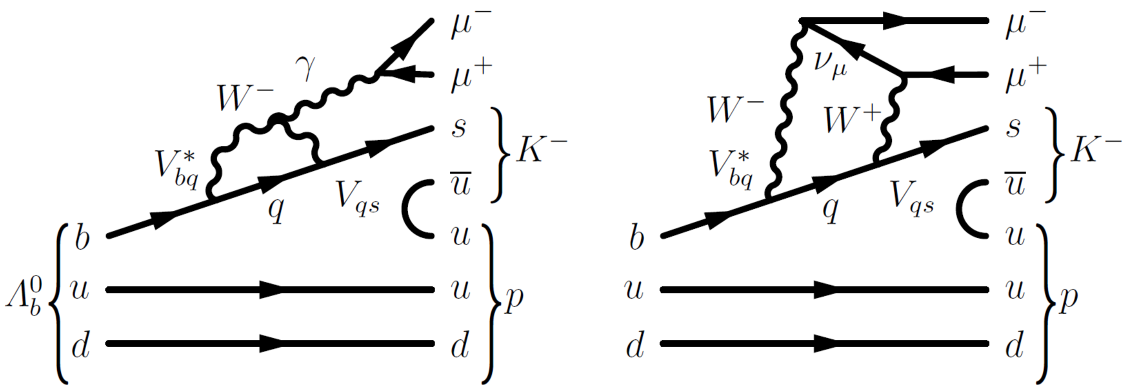
$\Lambda_b^0 \to p\,\pi^- K^+ K^-$

Global and local measurements consistent with CP symmetry.

CPV in baryon decays

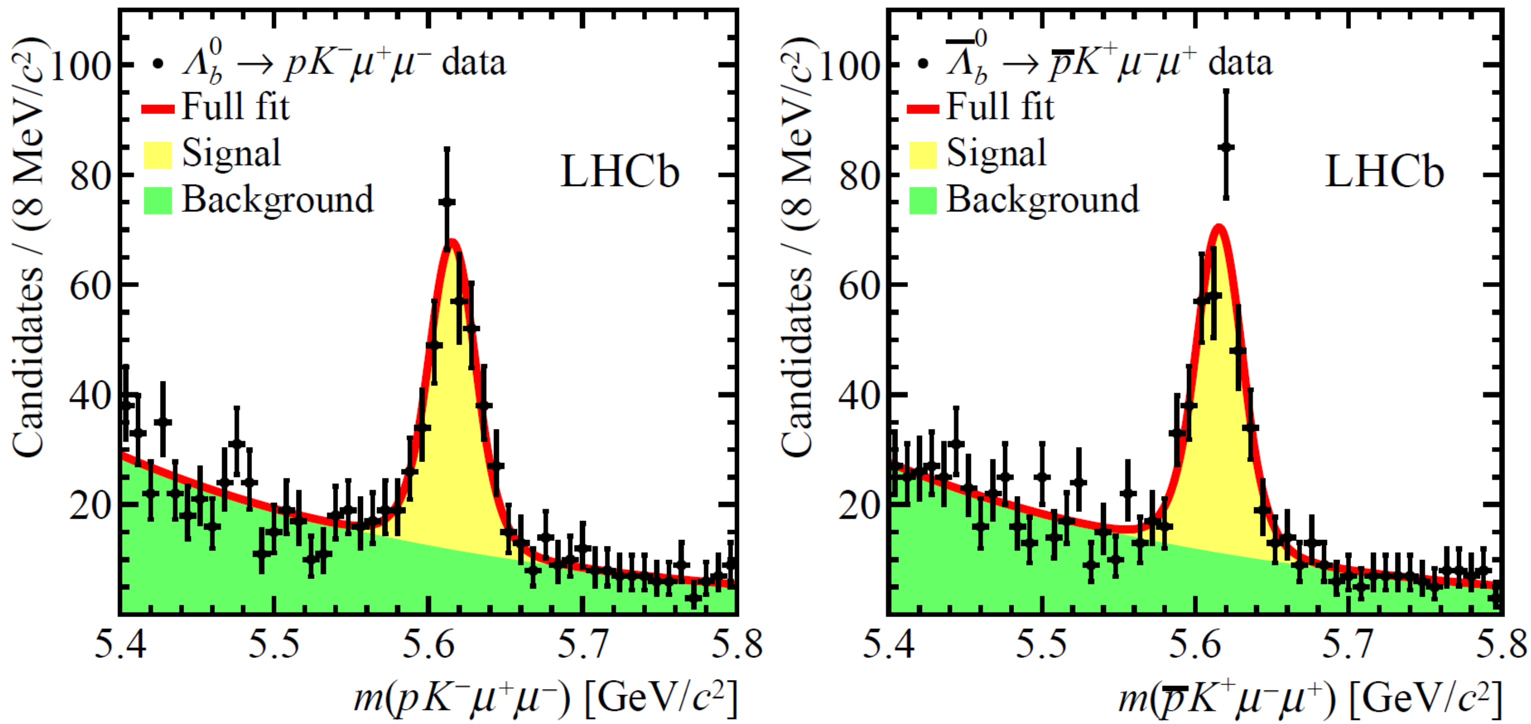
arXiv:1703.00256
LHCb-PAPER-2016-059

$\Lambda_b^0 \to p\,K^- \mu^+ \mu^-$



FCNC process. Small CPV predicted by the SM. Very sensitive to possible contributions of new heavy particles in the loop amplitudes and/or phases.

First observation of $\Lambda_b^0 \to p\,K^- \mu^+ \mu^-$ decays

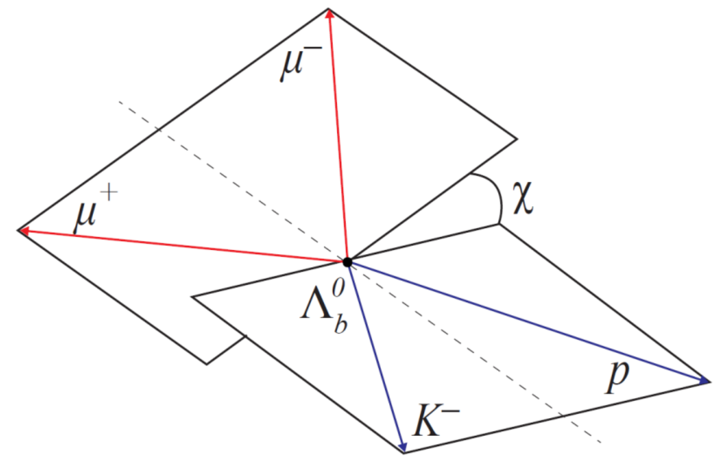


CPV in baryon decays

arXiv:1703.00256
LHCb-PAPER-2016-059

$\hat{T}$– odd triple products to build $a_{CP}^{\hat{T}\text{-odd}}$

$$C_{\hat{T}} = \vec{p}_{\mu^+} \cdot (\vec{p}_p \times \vec{p}_{K^-}) \;\propto\; \sin\chi, \quad \text{for } \Lambda_b^0$$
$$\overline{C}_{\hat{T}} = \vec{p}_{\mu^-} \cdot (\vec{p}_{\bar{p}} \times \vec{p}_{K^+}) \;\propto\; \sin\overline{\chi}, \quad \text{for } \overline{\Lambda}_b^0$$



$$\boxed{a_{CP}^{\hat{T}\text{-odd}} = (1.2 \pm 5.0 \pm 0.7)\times 10^{-2}}$$

$$\mathcal{A}_{\text{raw}} = \frac{N(\Lambda_b^0 \to pK^-\mu^+\mu^-) - N(\overline{\Lambda}_b^0 \to \bar{p}K^+\mu^-\mu^+)}{N(\Lambda_b^0 \to pK^-\mu^+\mu^-) + N(\overline{\Lambda}_b^0 \to \bar{p}K^+\mu^-\mu^+)}$$

$$\mathcal{A}_{\text{raw}} \approx \mathcal{A}_{CP}(\Lambda_b^0 \to pK^-\mu^+\mu^-) + \mathcal{A}_{\text{prod}}(\Lambda_b^0) - \mathcal{A}_{\text{reco}}(K^+) + \mathcal{A}_{\text{reco}}(p)$$

(CP-odd and $\hat{T}$-even)

$$\Delta\mathcal{A}_{CP} = \mathcal{A}_{CP}(\Lambda_b^0 \to pK^-\mu^+\mu^-) - \mathcal{A}_{CP}(\Lambda_b^0 \to pK^-\, J/\psi)$$

$$\Delta\mathcal{A}_{CP} \approx \mathcal{A}_{\text{raw}}(\Lambda_b^0 \to pK^-\mu^+\mu^-) - \mathcal{A}_{\text{raw}}(\Lambda_b^0 \to pK^-\, J/\psi)$$

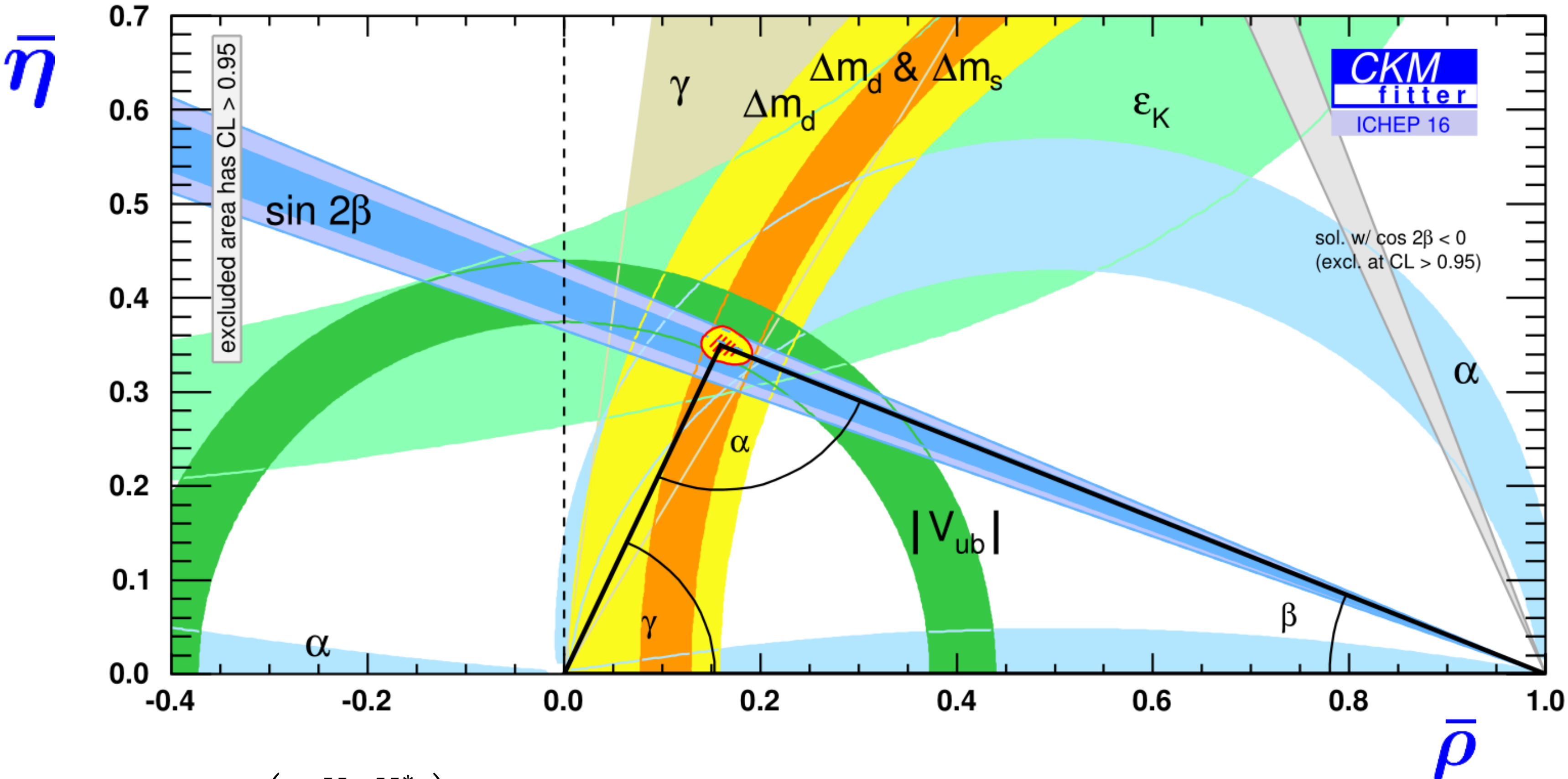
$$\boxed{\Delta\mathcal{A}_{CP} = (-3.5 \pm 5.0 \pm 0.2)\times 10^{-2}}$$

consistent with no CPV

Concluding remarks

- Until now, all measurements of CPV observables performed with RUN I data are compatible with SM predictions.
- We know, nevertheless, that the SM must "break" at some point.
- Interference measurements have repeatedly proven to be excellent and highly sensitive probes to explore mass scales well above the direct production scale.
- Flavour Physics has a lot to do with measurements of interfering amplitudes, although the LHCb physics program is much wider: EW precision measurements, direct searches, fixed target, heavy ions…
- After RUN II, LHCb plans to upgrade the detector and collect ~50 fb^{-1}, and is further interested to extend the physics program with a phase-2 upgrade.

Unitarity triangle



$$\alpha = \phi_2 = \arg\left(-\frac{V_{td}V_{tb}^*}{V_{ud}V_{ub}^*}\right)$$

$$\beta = \phi_1 = \arg\left(-\frac{V_{cd}V_{cb}^*}{V_{td}V_{tb}^*}\right)$$

$$\gamma = \phi_3 = \arg\left(-\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}\right)$$

$$\boxed{\boldsymbol{\alpha + \beta + \gamma = \left(183^{+7}_{-8}\right)^\circ}}$$

PDG, Chin. Phys. C, **40**, 100001 (2016)

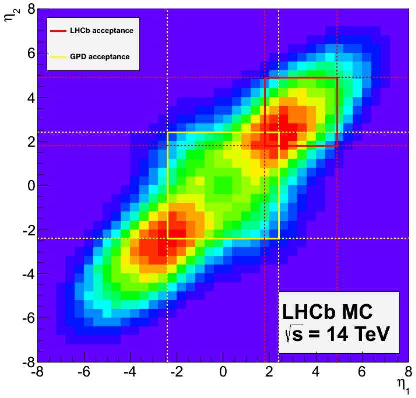
Thanks for your attention

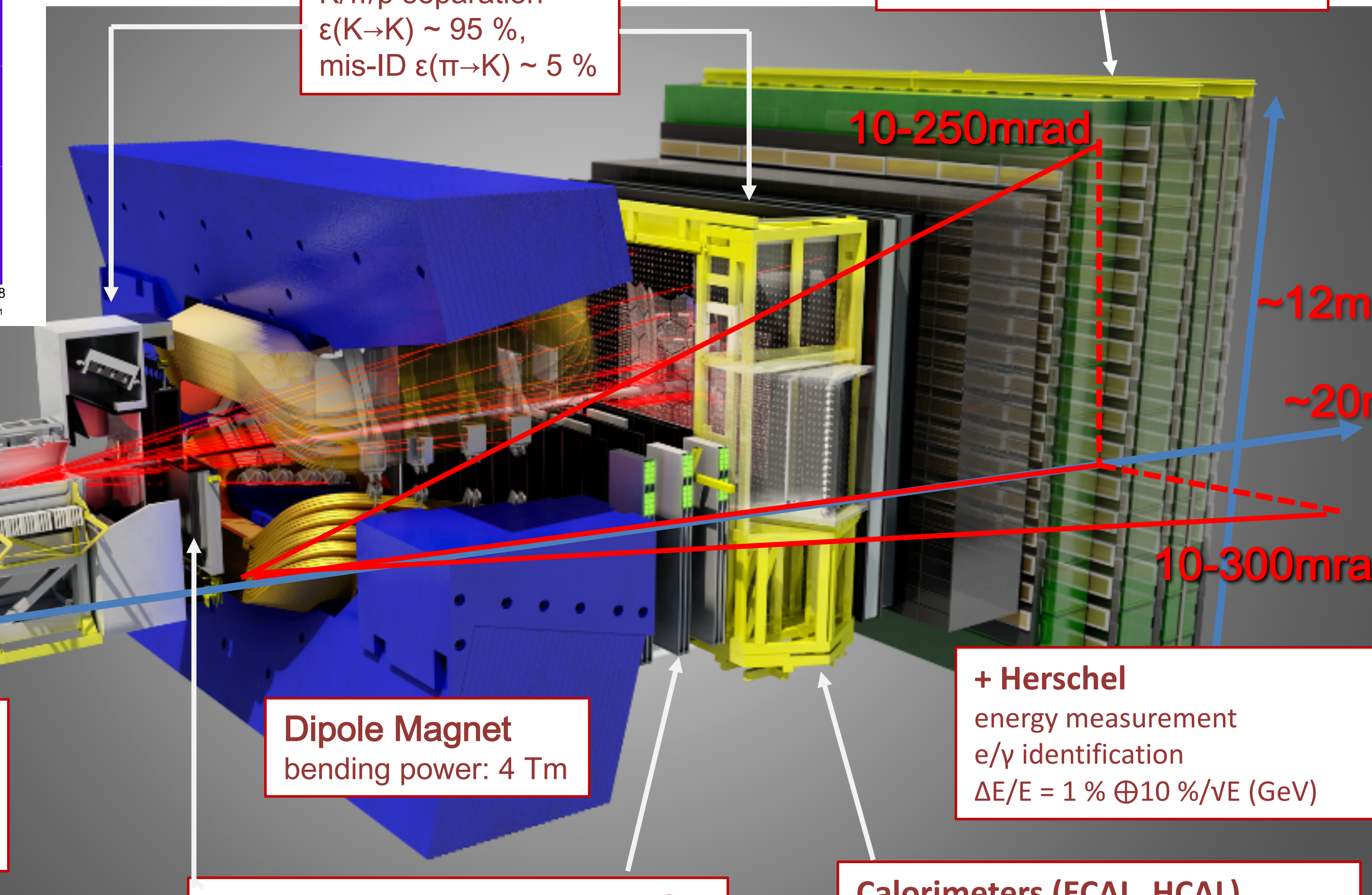
Backup

The LHCb detector

JINST 3 (2008) S08005

$b\bar{b}$ acceptance





RICH detectors
K/π/p separation
ε(K→K) ~ 95 %,
mis-ID ε(π→K) ~ 5 %

Muon system
μ identification ε(μ→μ) ~ 97 %,
mis-ID ε(π→μ) ~ 1-3 %

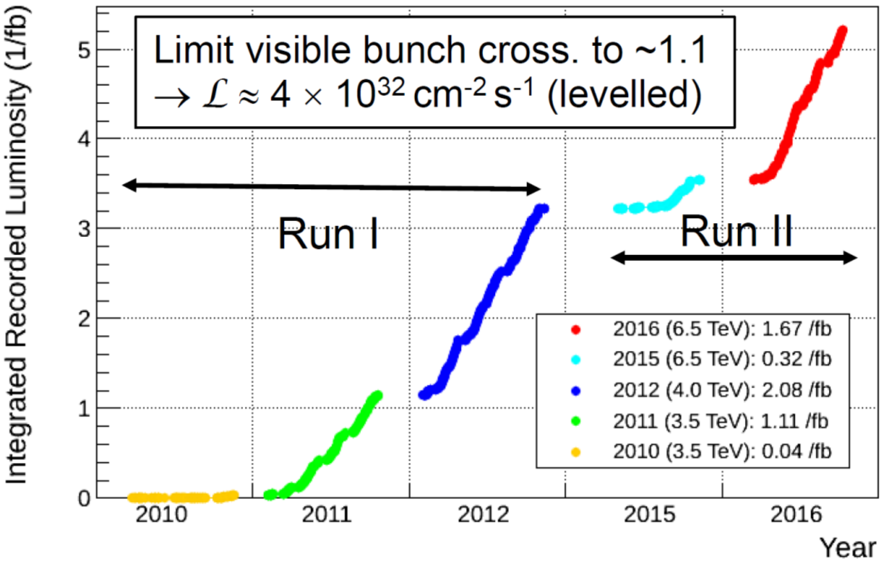
Vertex Detector
reconstruct vertices
decay time resolution: 45 fs
IP resolution: 20 μm

Dipole Magnet
bending power: 4 Tm

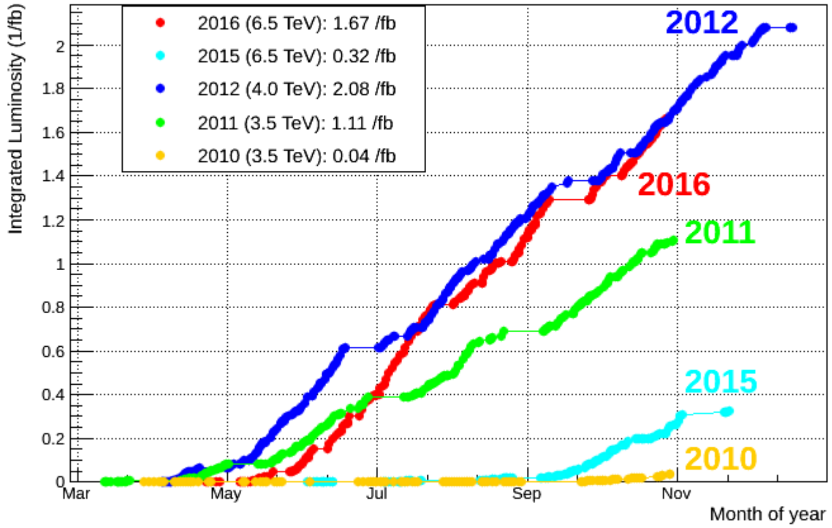
Tracking system: IT, TT and OT
momentum resolution
$\Delta p/p$ = 0.4%–0.8%
(5 GeV/c – 100 GeV/c)

Calorimeters (ECAL, HCAL)
energy measurement
e/γ identification
$\Delta E/E = 1\,\% \oplus 10\,\%/\sqrt{E}$ (GeV)

+ Herschel
energy measurement
e/γ identification
$\Delta E/E = 1\,\% \oplus 10\,\%/\sqrt{E}$ (GeV)

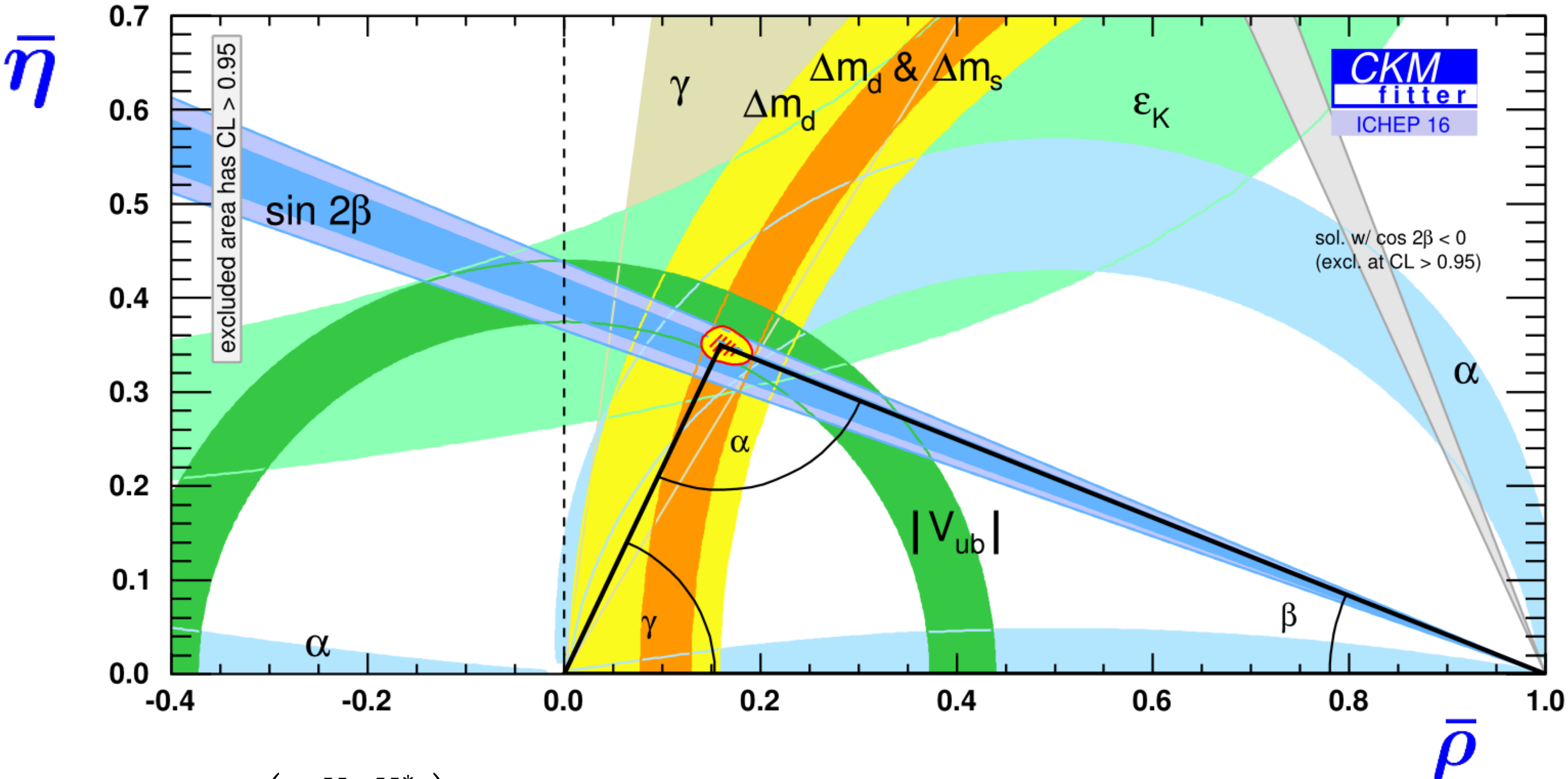


Limit visible bunch cross. to ~1.1
$\rightarrow \mathcal{L} \approx 4 \times 10^{32}\,\mathrm{cm^{-2}\,s^{-1}}$ (levelled)
Run I
Run II
2016 (6.5 TeV): 1.67 /fb
2015 (6.5 TeV): 0.32 /fb
2012 (4.0 TeV): 2.08 /fb
2011 (3.5 TeV): 1.11 /fb
2010 (3.5 TeV): 0.04 /fb
Integrated Recorded Luminosity (1/fb)
Year
2010
2011
2012
2015
2016



2016 (6.5 TeV): 1.67 /fb
2015 (6.5 TeV): 0.32 /fb
2012 (4.0 TeV): 2.08 /fb
2011 (3.5 TeV): 1.11 /fb
2010 (3.5 TeV): 0.04 /fb
2012
2016
2011
2015
2010
Integrated Luminosity (1/fb)
Month of year
Mar
May
Jul
Sep
Nov

Unitarity triangle



$$\alpha = \phi_2 = \arg\left(-\frac{V_{td}V_{tb}^*}{V_{ud}V_{ub}^*}\right)$$

$$\beta = \phi_1 = \arg\left(-\frac{V_{cd}V_{cb}^*}{V_{td}V_{tb}^*}\right)$$

$$\gamma = \phi_3 = \arg\left(-\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}\right)$$

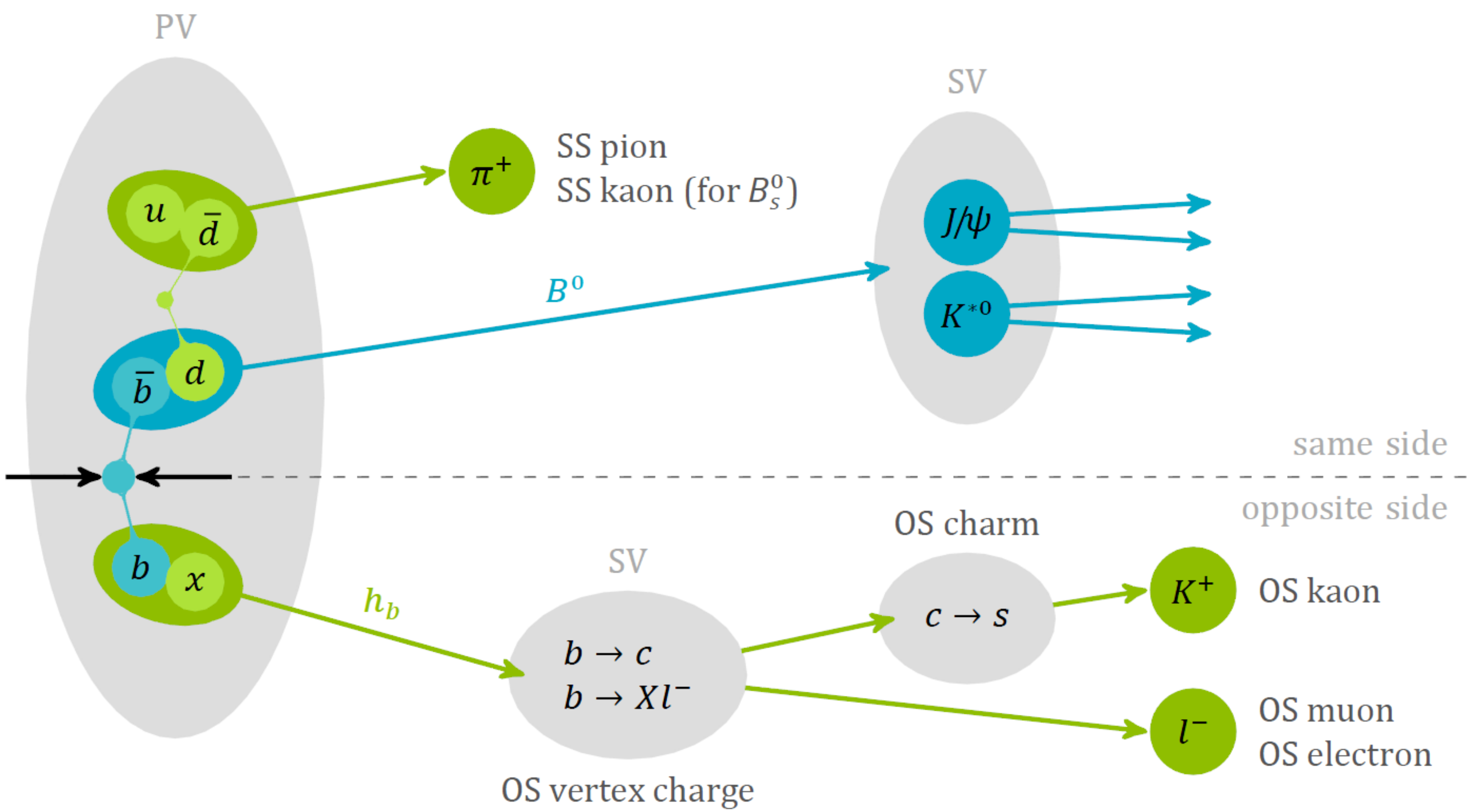
$$\boxed{\boldsymbol{\alpha + \beta + \gamma = \left(183^{+7}_{-8}\right)^\circ}}$$

PDG, Chin. Phys. C, **40**, 100001 (2016)

Flavour tagging in LHCb

Charm decays: tag initial flavour using $D^{*+} \to D^0 \boldsymbol{\pi}^+$ or $B^- \to D^0 \boldsymbol{\mu}^- X$.
The bachelor $\boldsymbol{\pi}^+$ or $\boldsymbol{\mu}^-$ unambiguosly tags the D^0 $\left(\overline{D}^0\right)$ flavour.

***B* decays:** a more complex process. In the $B^0 \to J/\psi\, K^{*0}$ analysis, for example:



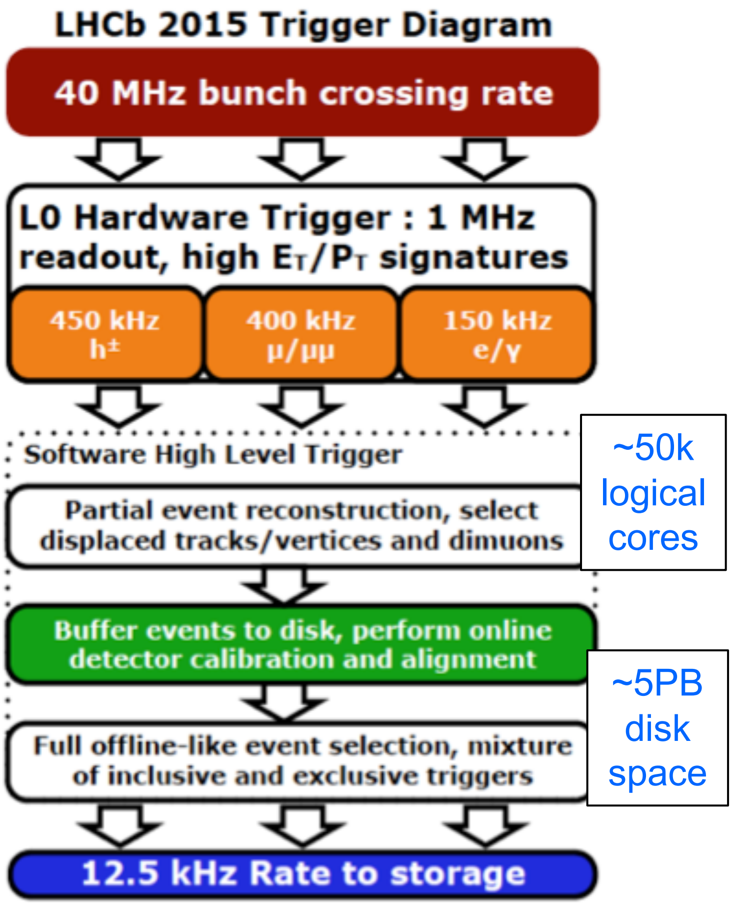
The tagging output is a tag decision and a tag (or mistag) probability.

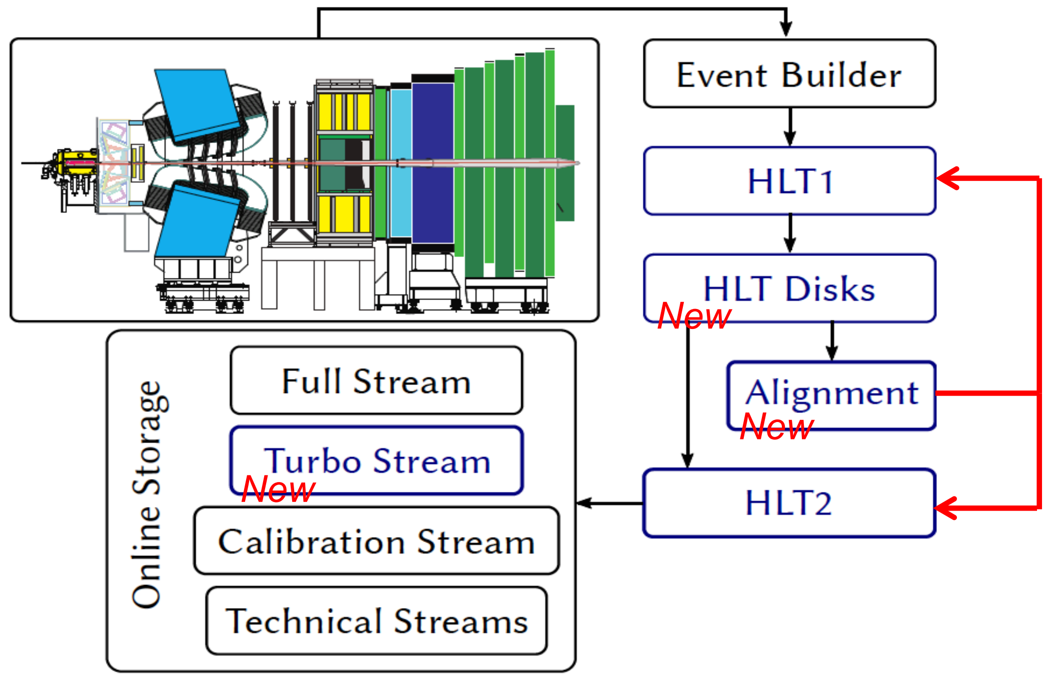
New software trigger architecture

Slide from F. Alessio

Real time calibration and alignment

New trigger system





Same online and offline reconstruction and PID!

- prompt alignment and calibration
- completely automatic and in real-time

Physics out of the trigger with Turbo Stream

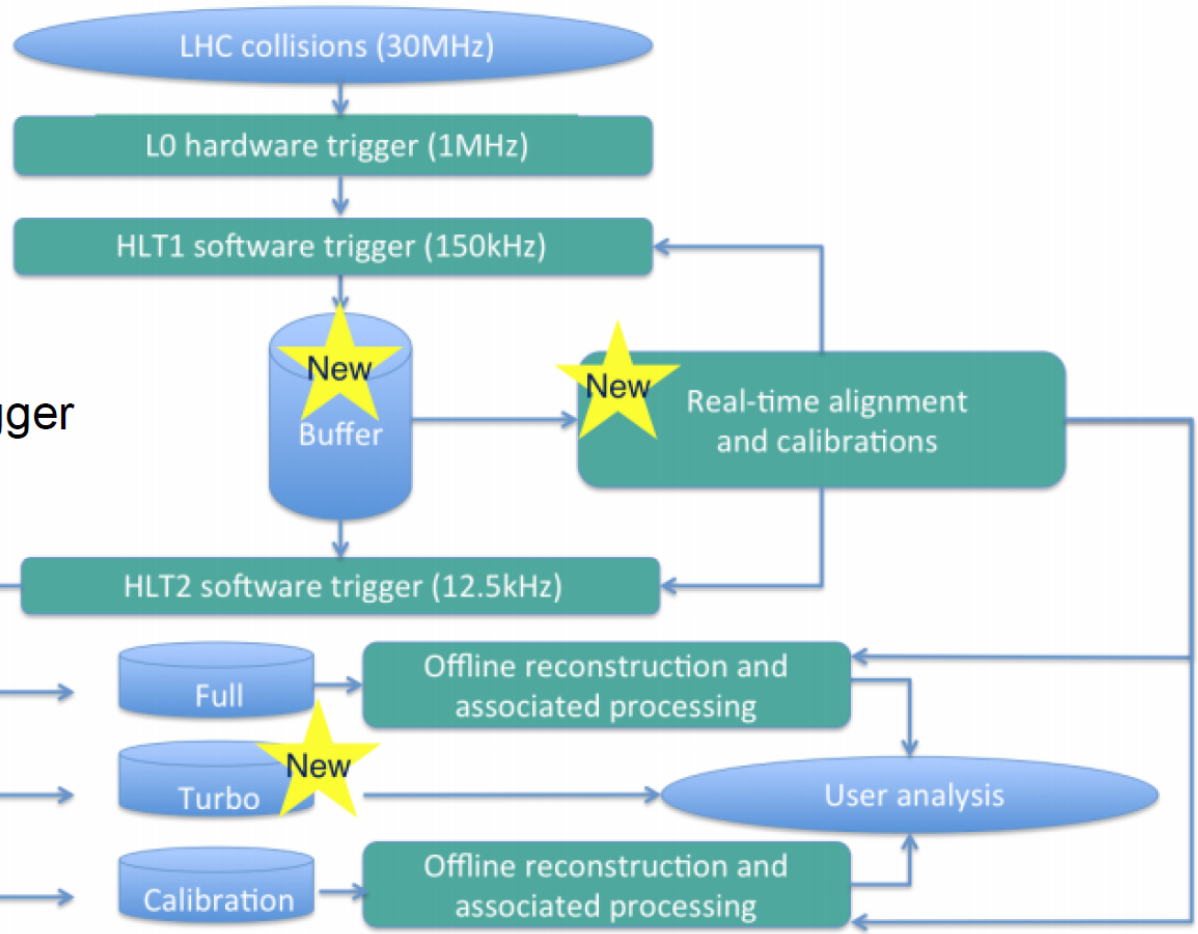
- Raw info discarded, candidates direclty available 24h after being recorded

New software trigger architecture

Slide from S. Borghi

- Buffer all events to disk before running 2nd software level trigger (HLT2)
- Perform calibration and alignment of the full tracking sub-detectors in real-time

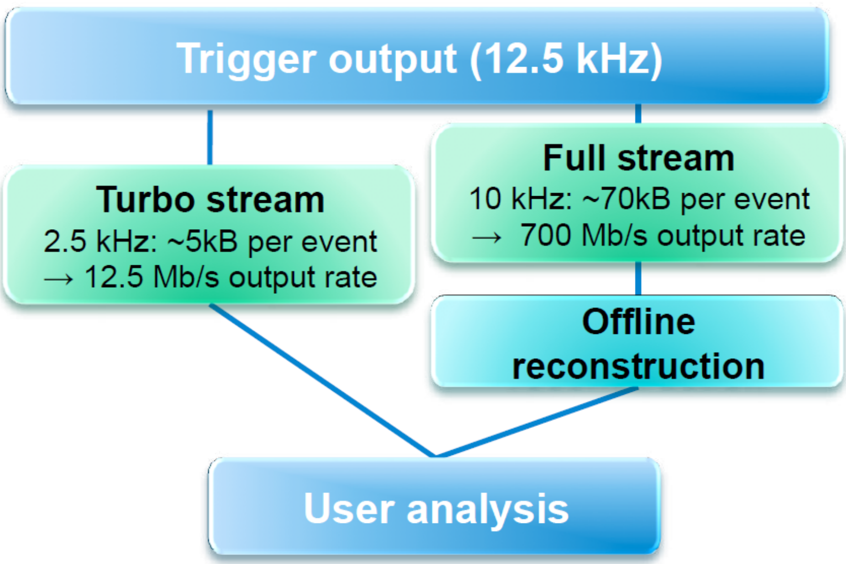
  ➔ same constants in the trigger and offline reconstruction
- Last trigger level runs the same offline reconstruction
- Some analyses performed directly on the trigger output
  - Storing only selected candidates to reduce event size



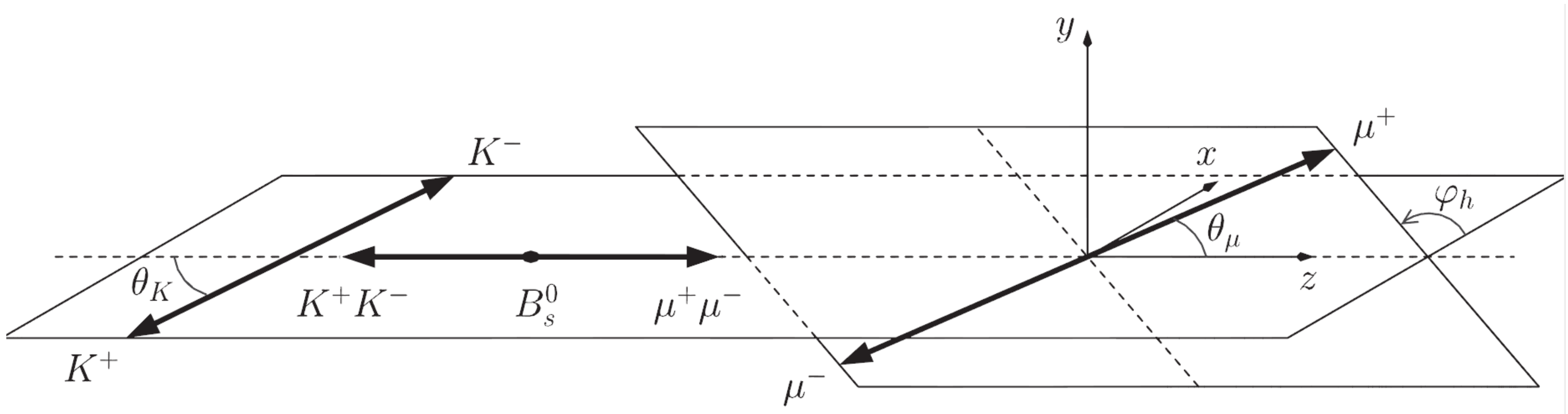
Turbo Stream

Slide from S. Borghi

- Some analyses performed directly on the trigger output
- Storing only selected candidates to reduce event size ➔ Save ~90% of space
- Analysis with large yields: possible to reduce the pre-scaling of all the channels that were trigger output rate constrained



Helicity basis angles



B^0 oscillation frequency

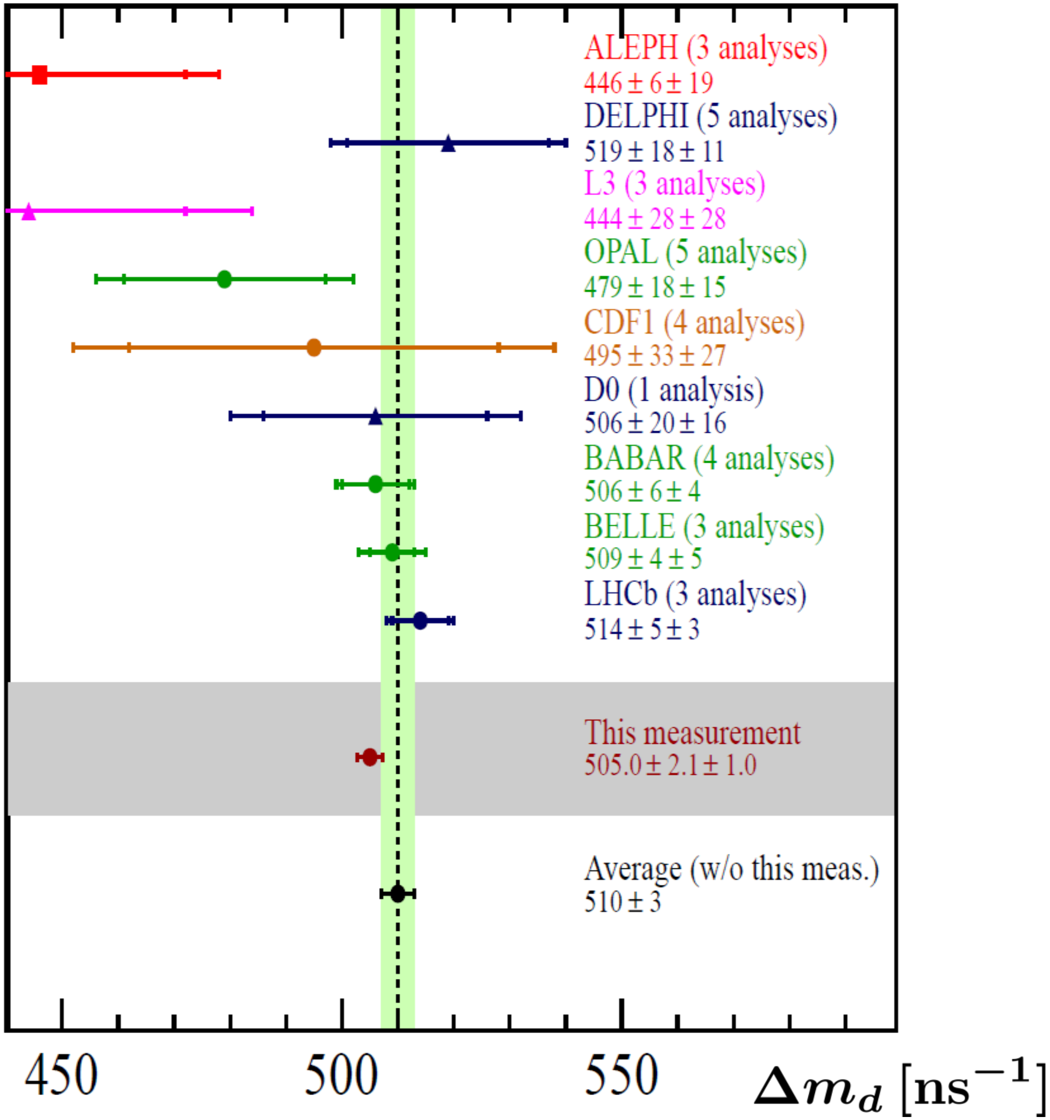
From PDG 2015

$$\Delta m_d = (0.510 \pm 0.003)\ \mathrm{ps}^{-1}$$
$$\Delta m_s = (17.757 \pm 0.021)\ \mathrm{ps}^{-1}$$

Theory prediction (Fermilab Lattice and MILC Collaborations) arXiv:1602.03560

$$\Delta m_d = 0.639(50)(36)(5)(13)\ \mathrm{ps}^{-1}$$
$$\Delta m_d/\Delta m_s = 0.0323(9)(9)(0)(3)$$

Δm_d and $\Delta m_d/\Delta m_s$ measurements are 2.1 σ and 2.9 σ from prediction.



CP asym. in $D^0 \to K^+K^-$ and $D^0 \to \pi^+\pi^-$ decays

PRL 116, 191601, 2016

$$A_{CP}(f;\, t) \equiv \frac{\Gamma(D^0(t) \to f) - \Gamma(\overline{D}^0(t) \to f)}{\Gamma(D^0(t) \to f) + \Gamma(\overline{D}^0(t) \to f)}$$

$$A_{CP}(f) \approx a_{CP}^{\rm dir}(f)\left(1 + \frac{\langle t(f)\rangle}{\tau}\, y_{CP}\right) + \frac{\langle t(f)\rangle}{\tau}\, a_{CP}^{\rm ind}$$

where $\langle t(f)\rangle$ denotes the mean decay time of $D^0 \to f$ decays in the reconstructed sample, $a_{CP}^{\rm dir}(f)$ as the direct CP asymmetry, τ the D^0 lifetime, $a_{CP}^{\rm ind}$ the indirect CP asymmetry and y_{CP} is the deviation from unity of the ratio of the effective lifetimes of decays to flavour specific and CP-even final states. To a good approximation, $a_{CP}^{\rm ind}$ is independent of the decay mode

$$\begin{aligned} \Delta A_{CP} &\equiv A_{CP}(K^-K^+) - A_{CP}(\pi^-\pi^+) \\ &\approx \Delta a_{CP}^{\rm dir}\left(1 + \frac{\overline{\langle t\rangle}}{\tau}\, y_{CP}\right) + \frac{\Delta\langle t\rangle}{\tau}\, a_{CP}^{\rm ind} \end{aligned}$$

where $\overline{\langle t\rangle}$ is the arithmetic average of $\langle t(K^-K^+)\rangle$ and $\langle t(\pi^-\pi^+)\rangle$

Mixing and CPV in $D^0 \to K^\pm\pi^\mp$ decays

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to (Γt). Allowing for all possible types of CPV, the time-dependent ratio of WS to RS decay rates, assuming $|x| \ll 1$ and $|y| \ll 1$, can be written as [5]

$$R(t)^\pm = R_D^\pm + \sqrt{R_D^\pm} y'^\pm \left(\frac{t}{\tau}\right) + \frac{(x'^\pm)^2 + (y'^\pm)^2}{4} \left(\frac{t}{\tau}\right)^2, \quad (4)$$

where the sign of the exponent in each term denotes whether the decay is tagged at production as D^0 $(+)$ or as $\overline{D}^0$ $(-)$. The terms x' and y' are x and y rotated by the strong phase difference δ, and $\tau = 1/\Gamma$.

The measured ratios of WS to RS decays differ from those of an ideal experiment due to matter interactions, detector response and experimental misidentifications. We use the formal approach of Ref. [1] to relate the signal ratios of Eq. (4) to a prediction of the experimentally observed ratios:

$$R(t)^\pm_{\mathrm{pred}} = R(t)^\pm (1 - \Delta_p^\pm)(\epsilon_r)^{\pm 1} + p_{\mathrm{other}}, \quad (5)$$

where the term $\epsilon_r \equiv \epsilon(K^+\pi^-)/\epsilon(K^-\pi^+)$ is the ratio of $K^\pm\pi^\mp$ detection efficiencies. The efficiencies related to the $\pi_s^\pm$ and $\mu^\mp$ candidates explicitly cancel in this ratio. The term $\Delta_p^\pm$ describes charge-specific peaking backgrounds produced by prompt charm mistakenly included in the DT sample, assumed to be zero after the "same-sign background subtraction" described in Sec. IV. The term p_{other} describes peaking backgrounds that contribute differently to RS and WS decays. All three of these terms are considered to be potentially time dependent.