CP violation in b hadrons at LHCb

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Outline

- Interest on CP violation
- CPV in quark sector
- b hadron CP measurements in LHCb
- Summary

Note: most results shown are based on full Run 1 data. Few of them include 2015+2016 Run 2 data

Why do we need CP violation?

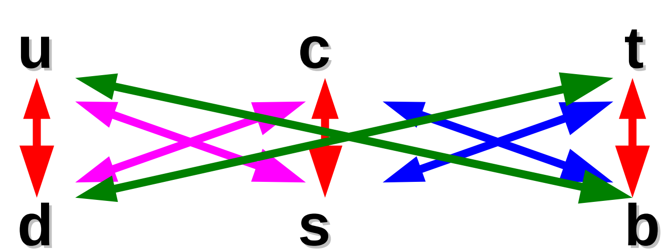
- Excess of matter over antimatter in the universe, $(n(\mathscr{B}) - n(\overline{\mathscr{B}}))/n(\gamma) \sim 10^{-10}$
- For this to happen, Sakharov converged to three conditions *JETP Lett. 91B, 24 (1967)*
  - (a) Need for baryon number violating interactions
  - (b) Need for CP violation to insure that a process in (a) does not have a CP conjugate with the same probability
  - (c) Universe out of thermal equilibrium: thermal equilibrium would turn any baryon asymmetry back into even numbers of baryons and antibaryons.

Note: CPV in Standard Model is far off the requirement

CPV in the quark sector

Weak eigenstates different from mass eigenstates:
Cabibbo Kobayashi Maskawa matrix

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



Clear hierarchy in the couplings: the further from diagonal, the weaker the element

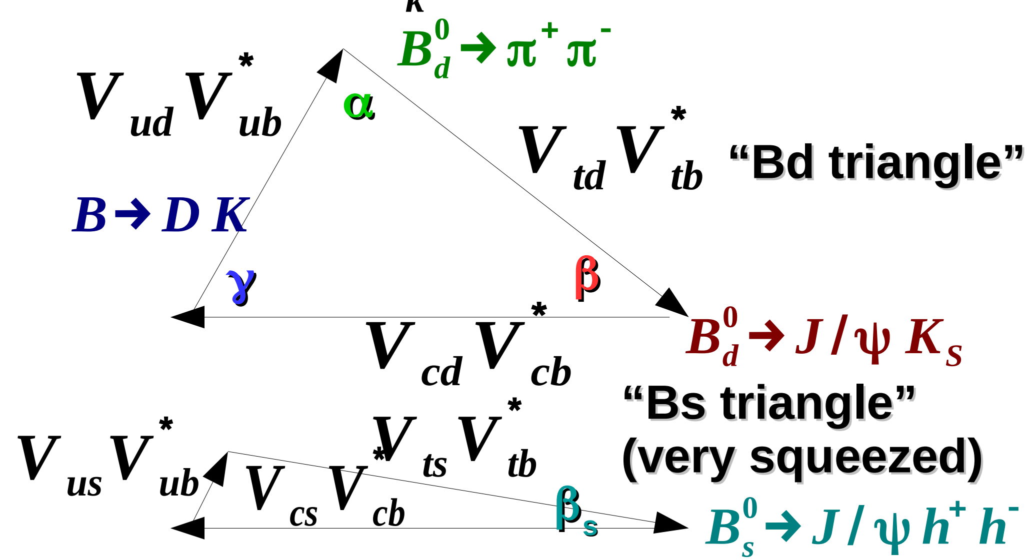
QFT shows that from N = 3 generations, 1 CP violating phase is possible
Unitarity of CKM matrix imposes in particular $\sum_k V_{ik} V^*_{jk} = 0$

Most convenient relation:

$$V_{ud} V^*_{ub} + V_{cd} V^*_{cb} + V_{td} V^*_{tb} = 0$$

Sides usually measured in semileptonic decays and oscillation frequency, angles in CP asymmetries

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



CP violation, decay vs oscillations

Amplitudes :

B → f $A_f = \langle f | H_{eff} | B \rangle$ **$\bar{B}$ → $\bar{f}$** $\overline{A}_{\bar{f}} = \langle \bar{f} | H_{eff} | \overline{B} \rangle$

B → $\bar{f}$ $A_{\bar{f}} = \langle \bar{f} | H_{eff} | B \rangle$ **$\bar{B}$ → f** $\overline{A}_f = \langle f | H_{eff} | \overline{B} \rangle$

1) CP violation in the decay A($\bar{B}$ → $\bar{f}$) ≠ A(B → f)
Charged B or flavor-specific final state + at least two contributions to the amplitude A with different weak and strong phases

2) CP violation in the mixing A($\bar{B}^0$ → B^0) ≠ A(B^0 → $\bar{B}^0$) : different measurement techniques. In LHCb, use of flavor-specific state and compare «wrong-sign » decays occuring because of the mixing.
A($\bar{B}^0$ → B^0 → f)≠A(B^0 → $\bar{B}^0$ → $\bar{f}$). Typically: f = X ℓ^- ν

3) Combination of decay and mixing : needs CP final state accessible by both $\bar{B}^0$ and B^0. Induced by interference of B^0 → $\bar{B}^0$ → f_{CP} and B^0 → f_{CP}. Needs the tagging of the flavor of B at the production !
Measurement of CKM angles such as β, $β_s$

CP violation formulas

$$A_f = A_1 e^{i\delta_1} e^{i\phi_1} + A_2 e^{i\delta_2} e^{i\phi_2}$$

δ_i strong phase

ϕ_i : weak phase

$$A_{CP} = \frac{|A_f|^2 - |\overline{A}_{\bar{f}}|^2}{|A_f|^2 + |\overline{A}_{\bar{f}}|^2} \propto 2 A_1 A_2 \sin(\delta_1 - \delta_2) \sin(\phi_1 - \phi_2)$$

Non zero decay CP asymmetry requires > 1 contribution

Mixing asymmetry

$$A_{sl}^q = \frac{\Gamma(\overline{B}_q^0 \to B_q^0 \to f) - \Gamma(B_q^0 \to \overline{B}_q^0 \to \bar{f})}{\Gamma(\overline{B}_q^0 \to B_q^0 \to f) + \Gamma(B_q^0 \to \overline{B}_q^0 \to \bar{f})} \approx \frac{\Delta\Gamma_q}{\Delta m_q} \tan(\phi_{12}^q)$$

→ **Mixing phase ~ 0 in SM**

Mixing + decay CP asymmetry

$$A_{CP}(t) = \frac{\Gamma(B^0(t) \to f_{CP}) - \Gamma(\overline{B}^0(t) \to f_{CP})}{\Gamma(B^0(t) \to f_{CP}) + \Gamma(\overline{B}^0(t) \to f_{CP})} = \frac{S_f \sin(\Delta M_B t) - C_f \cos(\Delta M_B t)}{\cosh(\Delta\Gamma_B t/2) + A_f^{\Delta\Gamma} \sinh(\Delta\Gamma_B t/2)}$$

For hadrons with small $\Delta\Gamma/\Gamma$:

$$A_{CP}(t) \simeq S_f \sin(\Delta M_B t) - C_f \cos(\Delta M_B t)$$

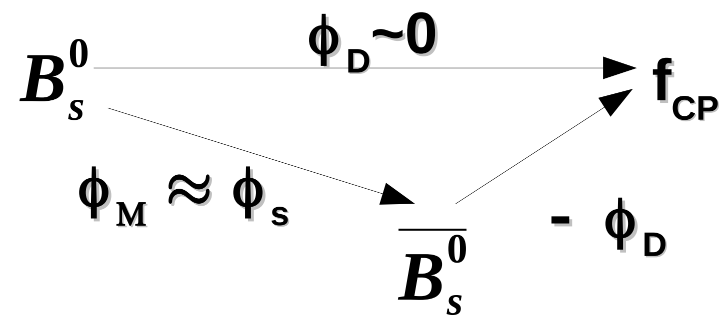
Weak phase = ϕ_{mix} - 2ϕ_{decay}

β_s angle results from $b \to c\bar{c}s$ tree decays

Mixing + decay

$$\phi_s^{SM} = -2\beta_s = -2\,arg\left(\frac{-V_{ts}V_{tb}^*}{V_{cs}V_{cb}^*}\right) = -0.036 \pm 0.001\,rad$$

Phys. Rev.D91(2015) 073007



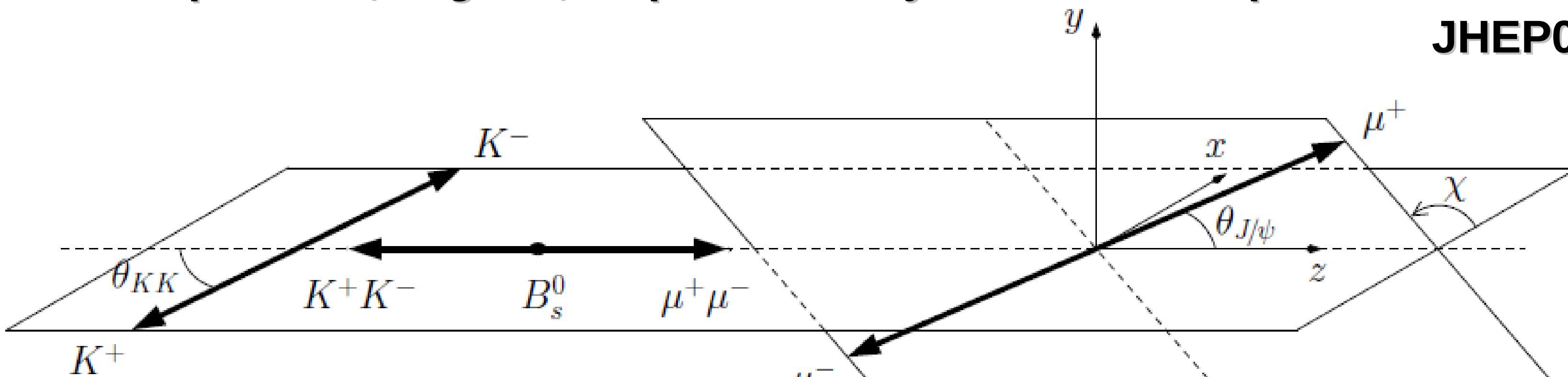
Final state	Result (rad)	publication
J/Ψ ππ (incl f_0)	+0.070±0.068±0.008	PLB B736 186 (2014)
D_sD_s	+0.02±0.17±0.02	PRL113 211801 (2014)
J/Ψ KK (incl ϕ)	-0.058±0.049±0.006	PRL114 041802 (2015)
Ψ(2S)ϕ	$+0.23\,^{+0.29}_{-0.28} \pm 0.02$	PLB B762, 252-262 (2016)
J/Ψ KK above ϕ	+0.119 ±0.107±0.034	JHEP08 (2017) 037

β_s angle result from Bs → J/Ψ KK above φ

Mixing + decay

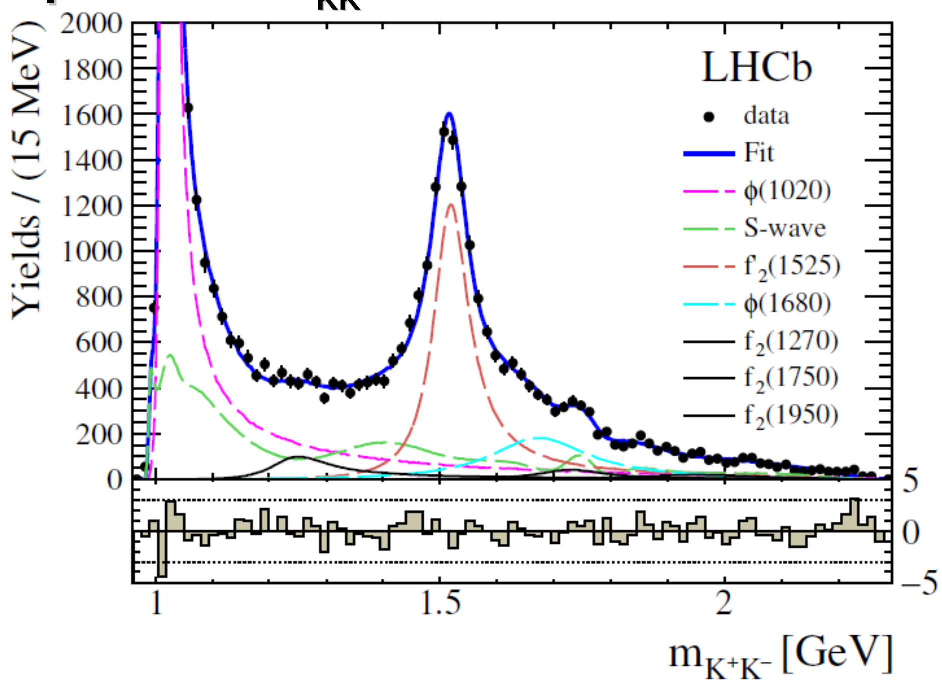
Time-dependent, angular, amplitude analysis of the KK spectrum

JHEP08 (2017) 037



Control channel $B^0 \to J/\Psi\, K^{*0}(K^+\pi^-)$

Spectrum m_{KK}>1.05 GeV/c² is dominated by the f_2(1525) tensor



For m_{KK}>1.05 GeV/c²

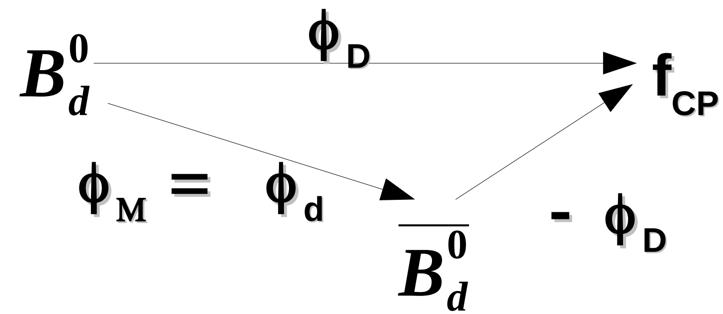
Parameter	Value
Γ_s [ps^{-1}]	$0.650 \pm 0.006 \pm 0.004$
$\Delta\Gamma_s$ [ps^{-1}]	$0.066 \pm 0.018 \pm 0.010$
ϕ_s [mrad]	$119 \pm 107 \pm 34$
$\vert\lambda\vert$	$0.994 \pm 0.018 \pm 0.006$

β angle results from $b \to c\bar{c}s$ tree decays

Mixing + decay

$$\phi_d^{SM} = 2\beta = 2\arg\left(\frac{-V_{cd}V_{cb}^*}{V_{td}V_{tb}^*}\right)$$

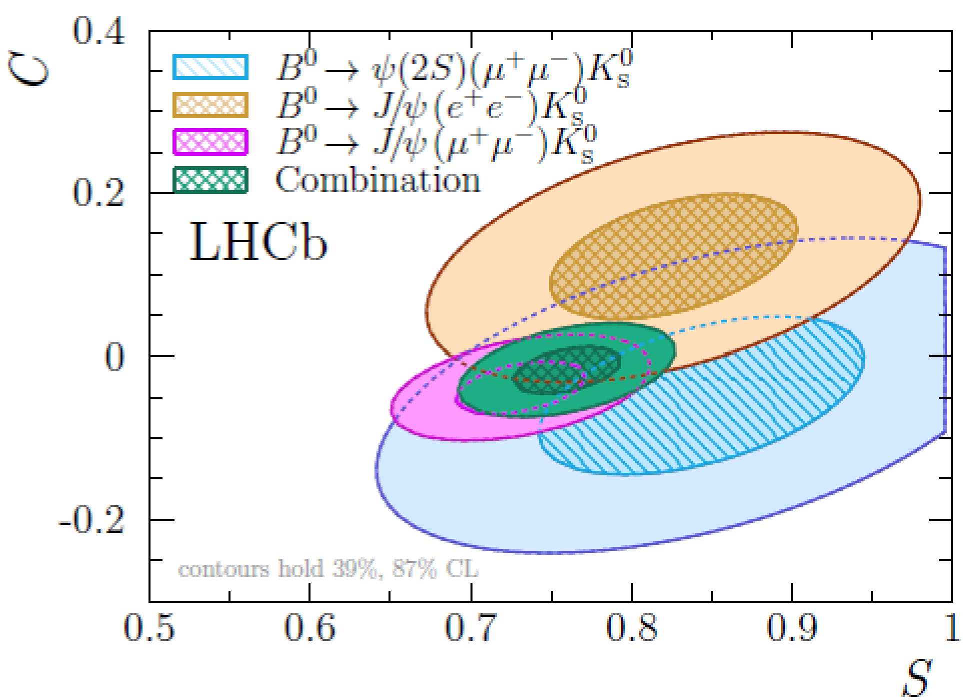
$$\sin(2\beta)^{SM} = 0.771^{+0.017}_{-0.041}$$ *Phys. Rev.D91(2015) 073007*



Known golden mode : $B^0 \to J/\Psi\, K_S^0$

LHCb Run 1 measurement **$\sin(2\beta) = 0.731 \pm 0.035(stat) \pm 0.020(syst)$** ***PRL 115, 031601 (2015)***

Recent publication LHCb-PAPER-2017-029 with $B^0 \to J/\Psi(ee)K_S^0$ $B^0 \to \Psi(2S)(\mu\mu)K_S^0$
$\to$ about to be submitted



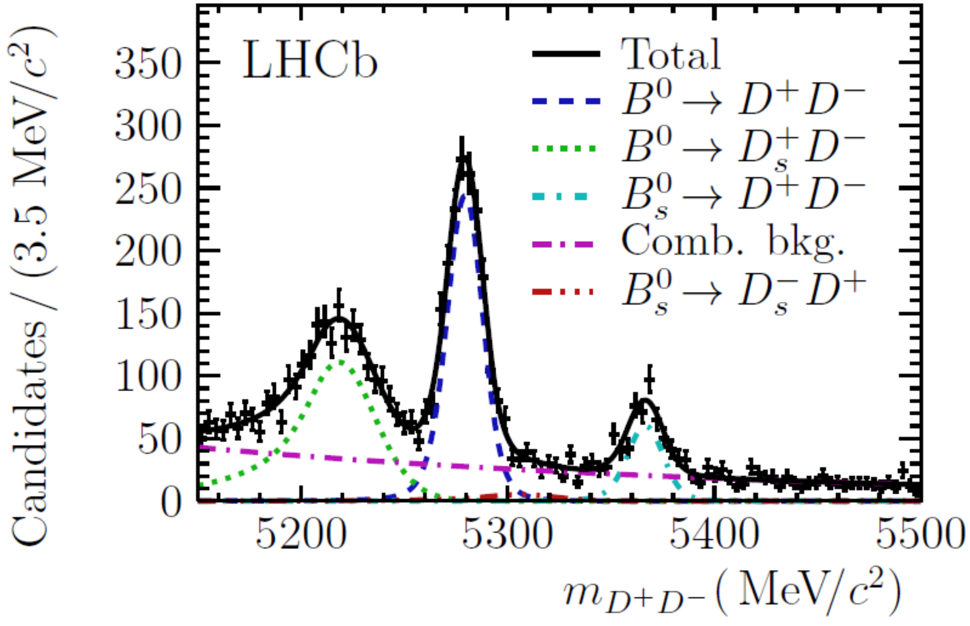
Overall LHCb average for sin(2β):

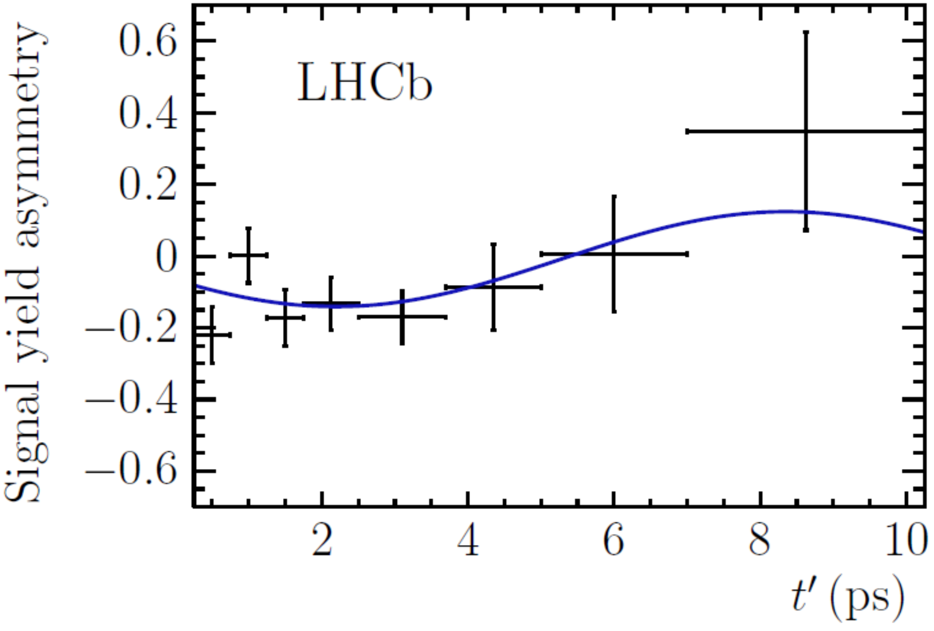
$$S(B^0 \to [c\bar{c}]K_S^0) = 0.760 \pm 0.034$$

β angle results from $B^0 \to D^+D^-$

PRL 117 261801(2016)

Recent LHCb measurement on ϕ_d + $\Delta\phi$ with
$\Delta\phi$ = = $-0.16\,^{+0.19}_{-0.21}$: small contribution from higher order diagrams





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

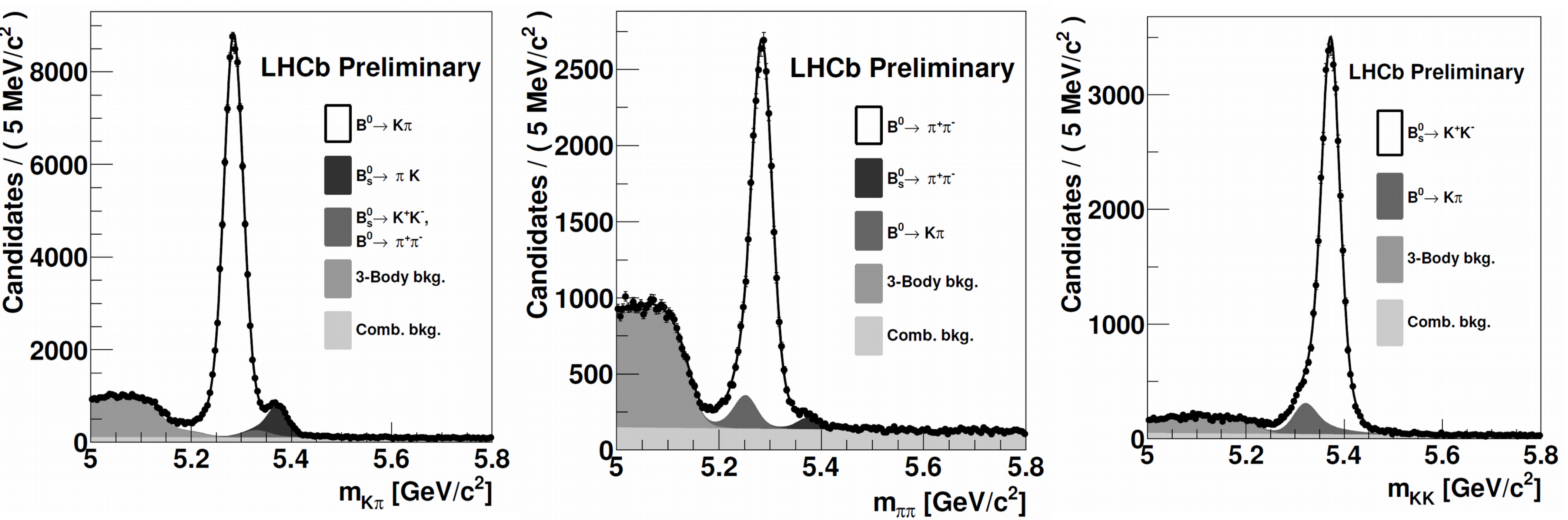
Mixing + decay

LHCb-CONF-2016-018

- Decays involving tree and loop diagrams: strong phases involved.

- U-spin symmetry: possibility to extract $2\beta_s$ or γ. Effects of U-spin symmetry breaking = limitation of the accuracy on the CKM angles

- Experimentally: simultaneous fit to 4 channels: $B^0 \to \pi^+\pi^-$, $B^0 \to K^+\pi^-$, $B^0_s \to K^+K^-$, $B^0_s \to K^+\pi^-$. Thorough modeling of misID and suppressed modes



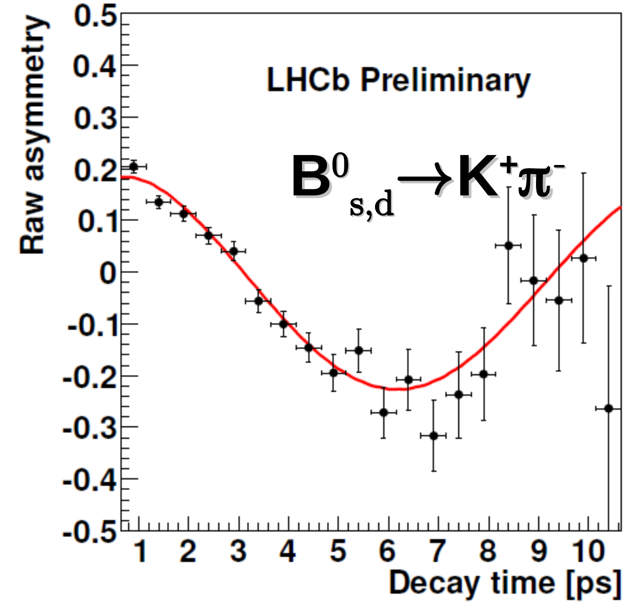
$B^0_{(s)} \rightarrow hh$ CP fit results

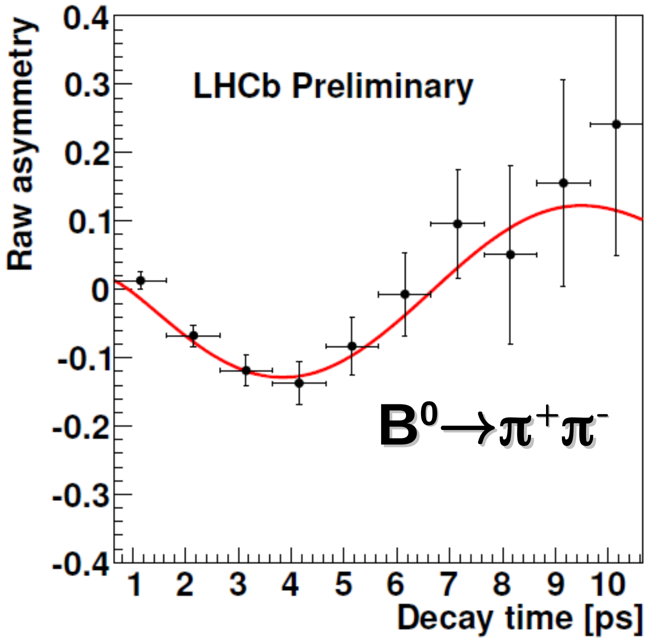
Mixing + decay

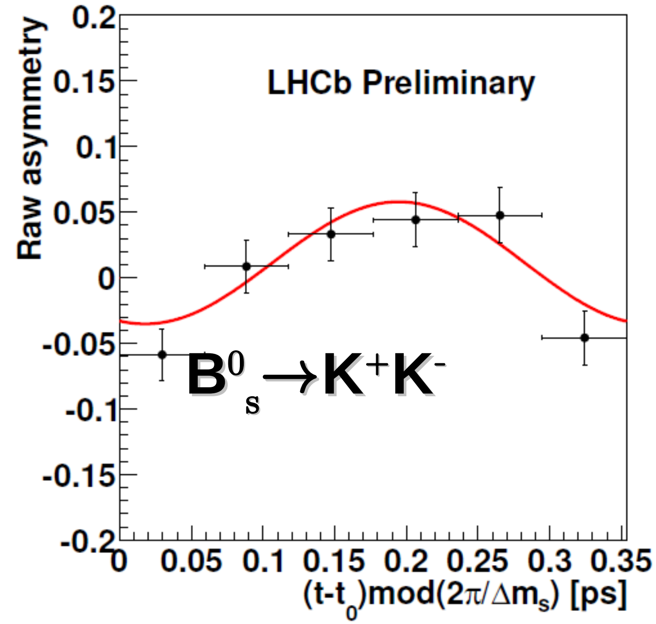
LHCb-CONF-2016-018

Fit performed with Γ, $\Delta\Gamma$ and Δm fixed

$$C_{\pi\pi} = -0.243 \pm 0.069$$
$$S_{\pi\pi} = -0.681 \pm 0.060$$
$$C_{KK} = +0.236 \pm 0.062$$
$$S_{KK} = +0.216 \pm 0.062$$
$$A_{KK}^{\Delta\Gamma} = -0.751 \pm 0.075$$



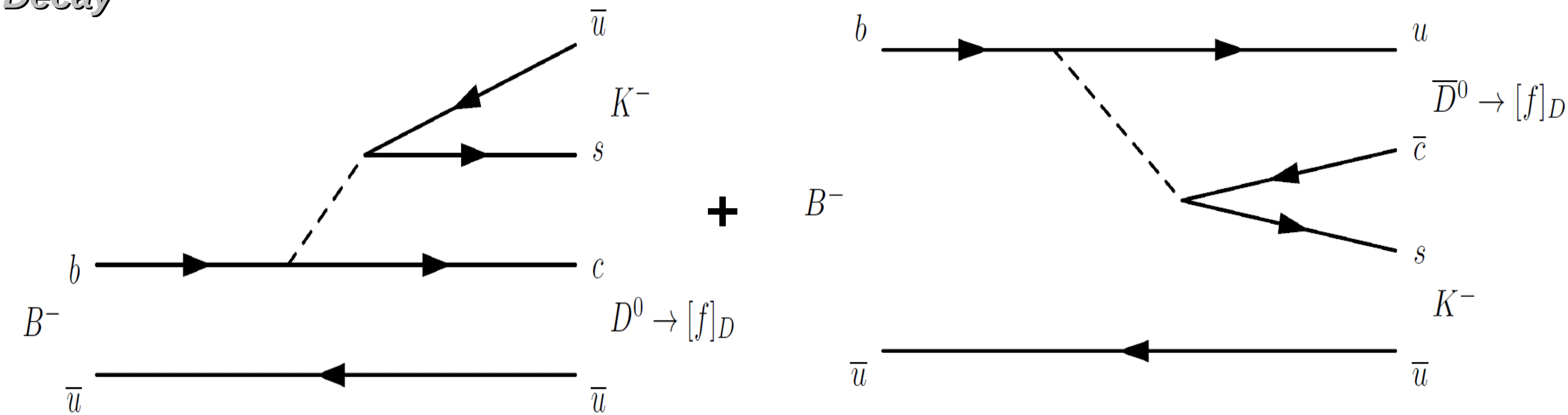




γ from B → DK(-like), the idea

Interference between tree decays leading to the same final state

Decay



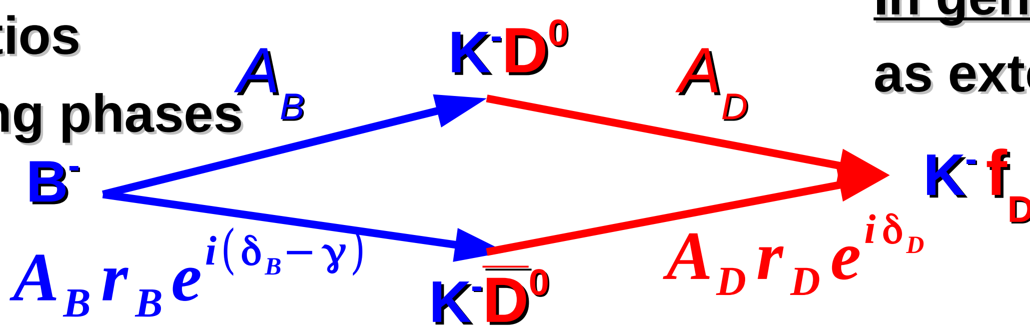
D^0 and $\overline{D}^0$ must decay to the same final state

Theoretically (very clean), $\delta\gamma/\gamma \sim 10^{-7}$ (JHEP 1401 (2014) 051)

r_i: amplitude ratios

δ_i: relative strong phases

<u>In general</u>: r_D and δ_D used as external inputs



γ from B → DK(-like), different techniques

Decay

- f_D = CP eigenstates, $D^0 \to K^+K^-$, $\pi^+\pi^-$, $K_S\pi^0$
  - Gronau, London, Wyler (GLW) 1991
- f_D = flavour states: $D^0 \to K^+\pi^-$, $K^-\pi^+$
  - Atwood, Dunietz, Soni (ADS) 1997
    - Extension to multiple body $K^{\pm}\pi^{-/+}\pi^+\pi^-$
- Multibody $K_sK^{\pm}\pi^{-/+}$, GLS
- f_D = multibody final states, Dalitz (variation of δ_D over phase space)
  - $K_sh^+h^-$ Giri, Grossman, Soffer, Zupan 2003; Poluektov 2004 (GGSZ-P)
- Some most recent channels involve neutrals, B^0 and Bs, and D^{*+} or $K^*/K\pi(\pi)$ in the final state

Observables: charge asymmetries and BF ratios of suppressed/favoured D decays (applies for self-tagging decays)

γ combination in LHCb : huge improvement in techniques and precision

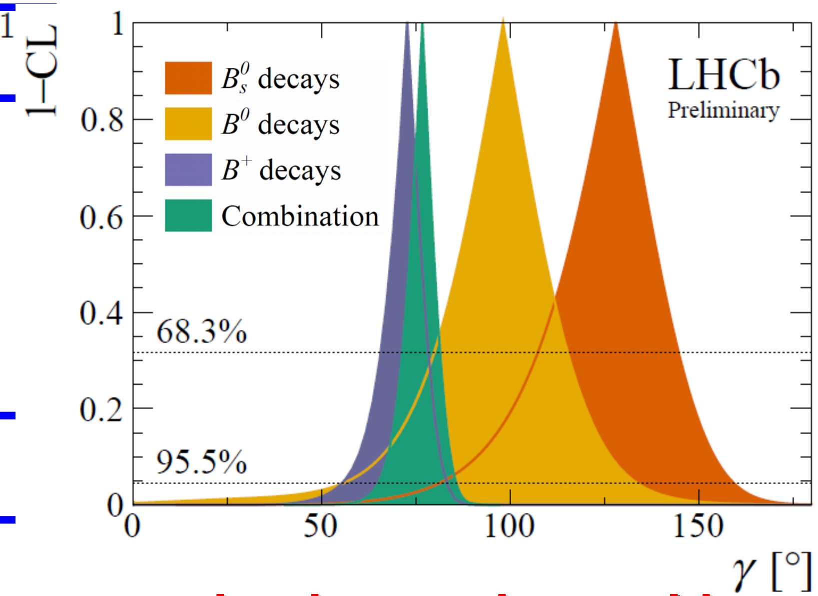
Decay

- **Many channels under study in LHCb**
  - **Using either CP, flavour, or multibody final states of D**

New comb LHCb-CONF-2017-004 since last one JHEP 12 (2016) 087, arXiv:1611.03076

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

$$\gamma = (76.8\,^{+5.1}_{-5.7})^\circ$$



dominates the world average: $(76.2\,^{+4.7}_{-5.0})^\circ$

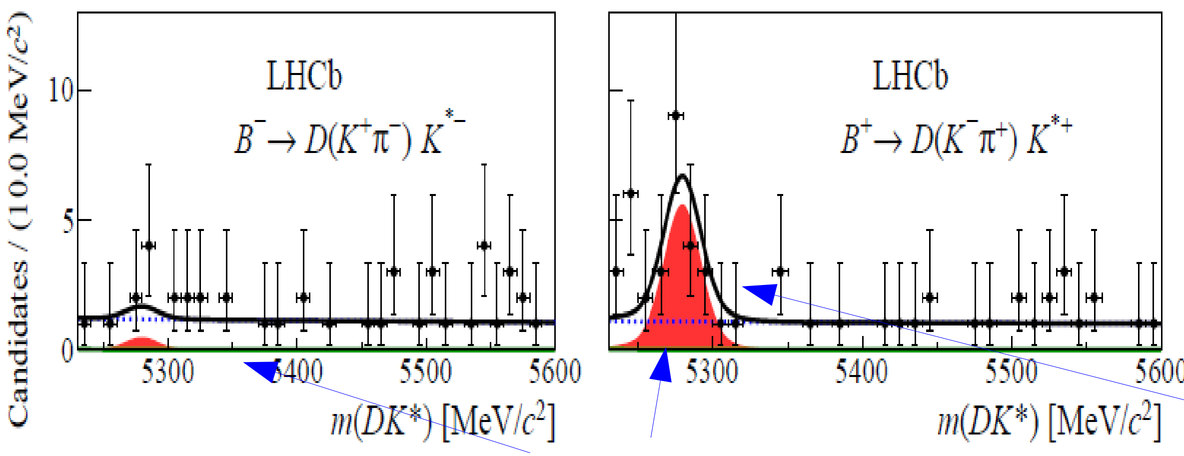
HFLAV, summer 2017

Recent study: γ from $B^+ \rightarrow DK^{*+}(K_S\pi^+)$

Decay

LHCb-PAPER-2017-030

Use 2 and 4 body D^0 modes, with Run1 + 2015 + 2016 data
Rates and CP asymmetries allow extraction of $r_B(DK^*)$ $\delta_B(DK^*)$ and γ



D decay mode	Yield
$B^\pm \rightarrow D(K^\pm\pi^\mp)K^{*\pm}$	2031 ± 49
$B^\pm \rightarrow D(K^+K^-)K^{*\pm}$	255 ± 18
$B^\pm \rightarrow D(\pi^+\pi^-)K^{*\pm}$	78 ± 11
$B^\pm \rightarrow D(K^\mp\pi^\pm)K^{*\pm}$	20 ± 7
$B^\pm \rightarrow D(K^\pm\pi^\mp\pi^+\pi^-)K^{*\pm}$	1144 ± 37
$B^\pm \rightarrow D(\pi^+\pi^-\pi^+\pi^-)K^{*\pm}$	115 ± 13
$B^\pm \rightarrow D(K^\mp\pi^\pm\pi^-\pi^+)K^{*\pm}$	13 ± 7

Charge asymmetry visible by eye

4.2σ evidence for suppressed $D^0 \rightarrow K\pi$

$$R^{\pm}_{K\pi} = \frac{\Gamma(B^\pm \rightarrow D(K^\mp\pi^\pm)K^{*\pm})}{\Gamma(B^\pm \rightarrow D(K^\pm\pi^\mp)K^{*\pm})} = \frac{r_B^2 + (r_D^{K\pi})^2 + 2\kappa r_B r_D^{K\pi}\cos(\delta_B + \delta_D^{K\pi} \pm \gamma)}{1 + r_B^2 (r_D^{K\pi})^2 + 2\kappa r_B r_D^{K\pi}\cos(\delta_B - \delta_D^{K\pi} \pm \gamma)}$$

$$R^+_{K\pi} = 0.020 \pm 0.006\,(\text{stat}) \pm 0.001\,(\text{syst})$$
$$R^-_{K\pi} = 0.002 \pm 0.004\,(\text{stat}) \pm 0.001\,(\text{syst})$$

κ: dilution factor due to $K_S\pi$ nonres component in K* spectrum

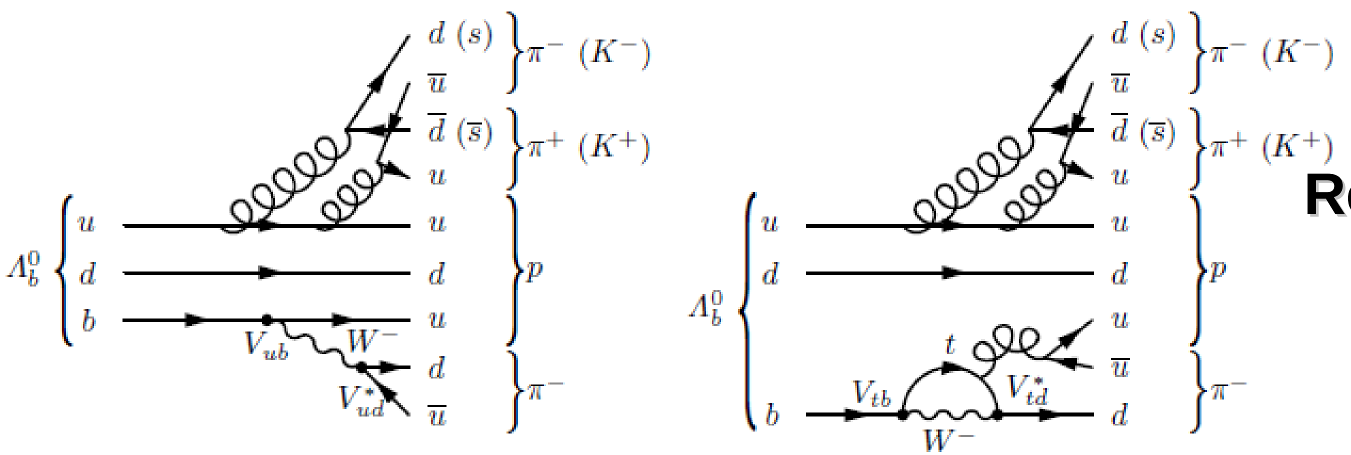
CP violation in baryon decays $\Lambda_b \to p\pi hh$

Decay

Nature Physics 13 391 (2017)

arXiv:1609.05216

CPV seen in B and K decays, never in baryons
Search for direct CPV in $\Lambda_b \to p\pi hh$ decays



Relative weak phase: α

Look at triple scalar products

$$C_{\hat{T}} = \vec{p}_p \cdot (\vec{p}_{h_1^-} \times \vec{p}_{h_2^+})$$

$$\overline{C}_{\hat{T}} = \vec{p}_{\overline{p}} \cdot (\vec{p}_{h_1^+} \times \vec{p}_{h_2^-})$$

$C_{\hat{T}} \neq -\overline{C}_{\hat{T}}$ **establishes CP violation** *See e.g., Phys. Rev. D 84, 096013 (2011)*

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

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

Observable measuring CPV :

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

Phys. Rev. D 92, 076013 (2015)

arXiv:1508.03054

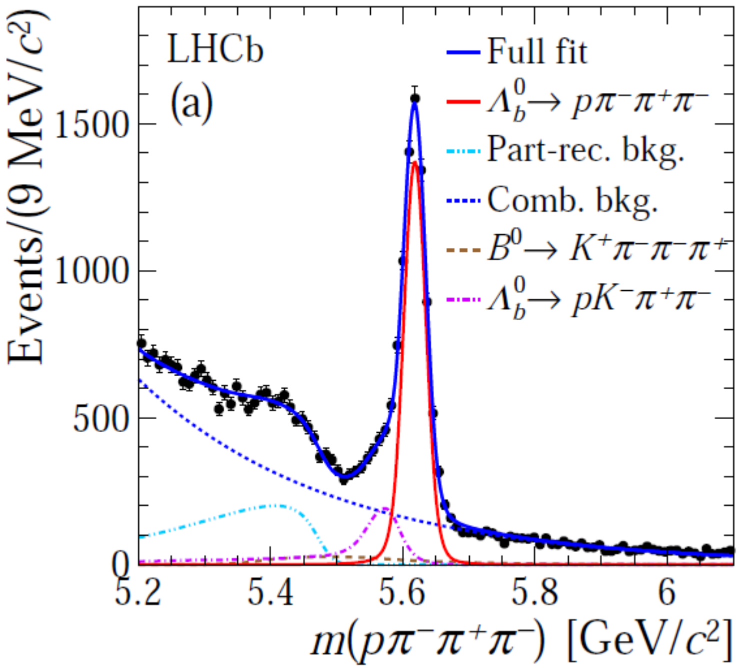
Decay

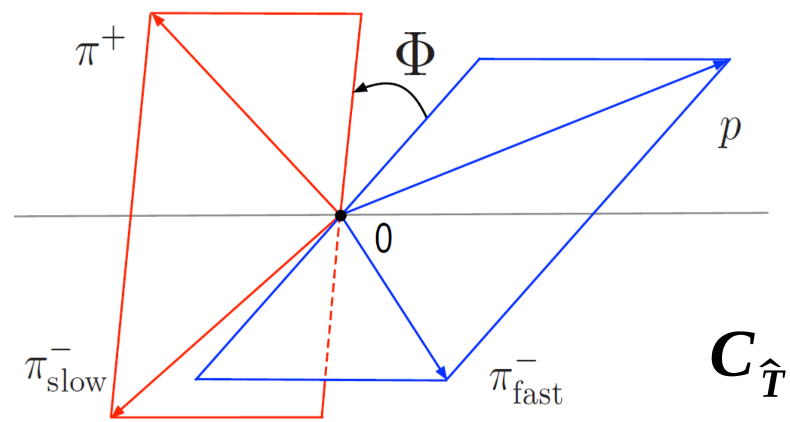
$\Lambda_b \to p\pi hh$ signals and CP

First observation of both $\Lambda_b \to p\pi KK$ and $\Lambda_b \to p\pi\pi\pi$

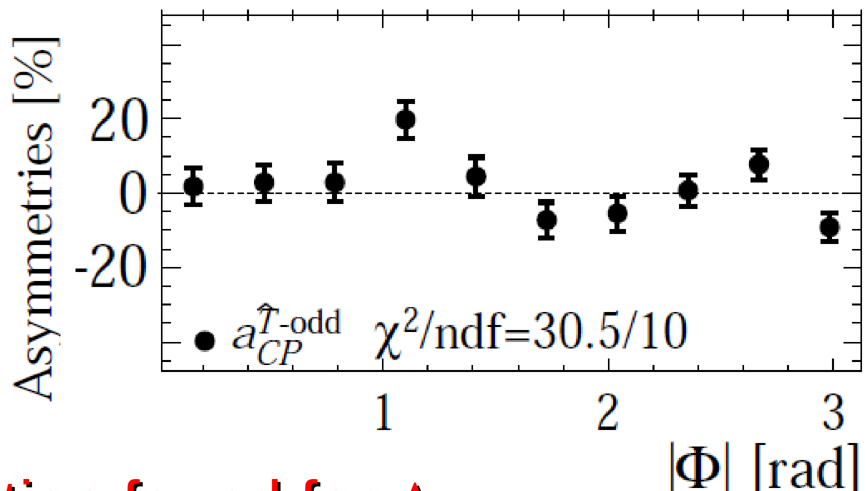
Nature Physics 13 391 (2017)

arXiv:1609.05216





$$C_{\hat{T}} \propto \sin(\Phi)$$



Overall 3.3σ CP violation found for $\Lambda_b \to p\pi\pi\pi$

First evidence of CP violation in baryon decays

No CP violation for $\Lambda_b \to p\pi KK$

A_{sl} asymmetries

Mixing

Cancels for B_s
time analysis for B_d

$$\frac{N(B_q^0 \to D_{(s)}^- \mu^+ \nu, t) - N(\bar{B}_q^0 \to D_{(s)}^+ \mu^- \nu, t)}{N(B_q^0 \to D_{(s)}^- \mu^+ \nu, t) + N(\bar{B}_q^0 \to D_{(s)}^+ \mu^- \nu, t)} = A_D + \frac{A_{sl}^q}{2} - \left(A_P + \frac{A_{sl}^q}{2}\right) \cdot \frac{\cos(\Delta M_q t)}{\cosh\left(\frac{\Delta \Gamma_q t}{2}\right)}$$

Detection asymmetry (inferred from control samples)

B_q^0 production asymmetry (~ 1%)

$A_{sl}^{s,d} \sim 10^{-5}, 10^{-4}$ **in SM**

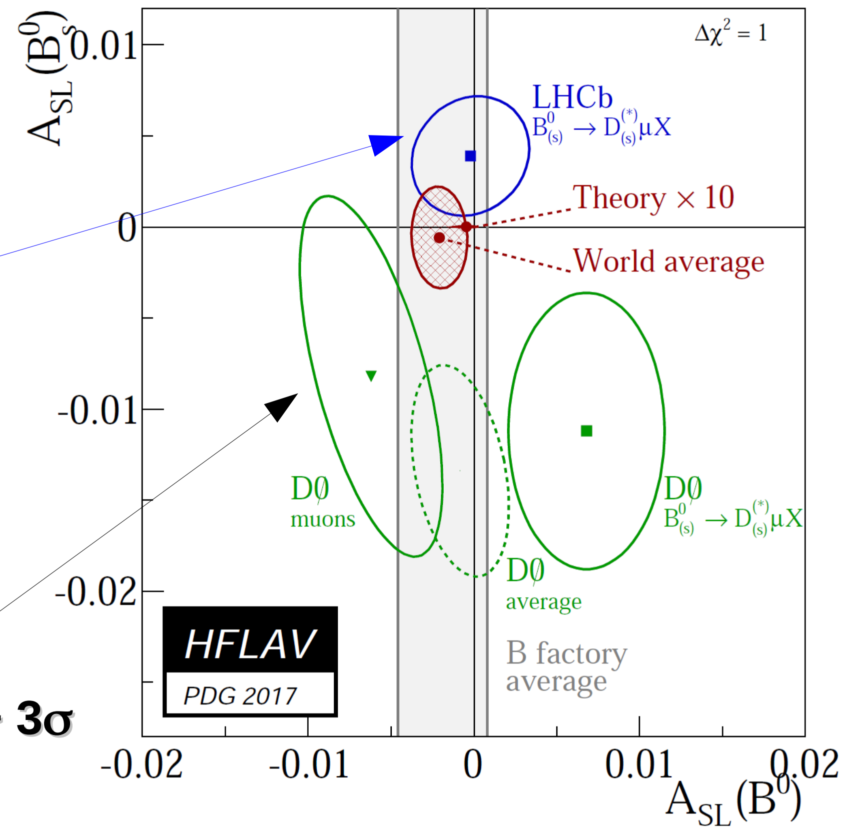
LHCb measures:

$$A_{sl}^d = (-0.02 \pm 0.19(stat) \pm 0.30(syst))\%$$

PRL 114, 041601 (2015)

$$A_{sl}^s = (0.39 \pm 0.26(stat) \pm 0.20(syst))\%$$

PRL 117, 061803 (2016)

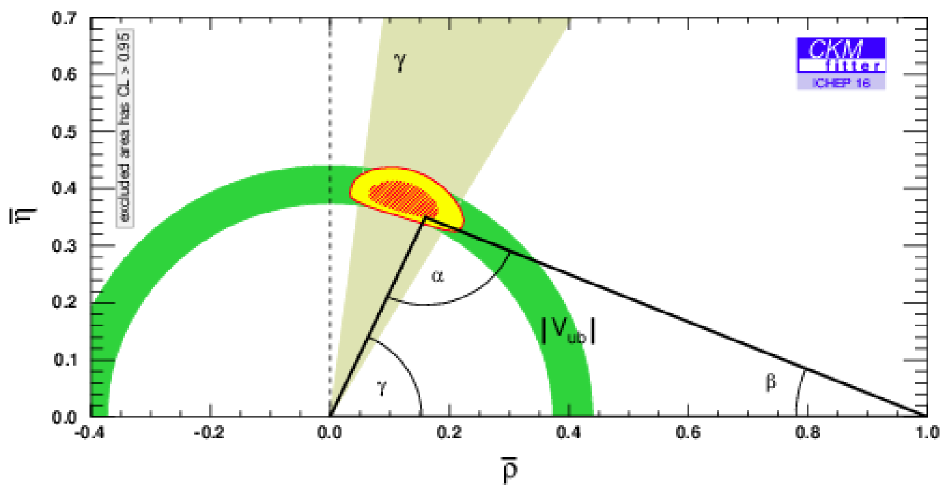


D0 dimuon result is ~ 3σ from SM

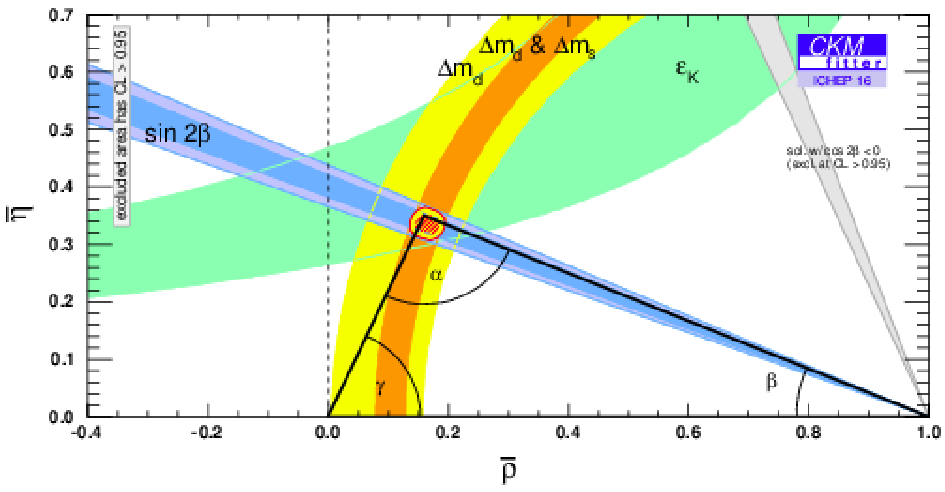
Summary

- Remarkable advances in CP studies with the b hadrons
- But still need for precision measurements with Run 2 (ongoing) and Run 3,4,... data
- E.g., will the CKM picture stay consistent between tree and loop diagrams?

Constrained UT from tree quantities



Constrained UT from loop quantities



Back up

Mixing formalism and assymetries

$$i\frac{\mathrm{d}}{\mathrm{d}t}\begin{pmatrix} |B^0(t)\rangle \\ |\overline{B}^0(t)\rangle \end{pmatrix} = \left[\begin{pmatrix} M_{11} & M_{12} \\ M_{12}^* & M_{22} \end{pmatrix} - \frac{i}{2}\begin{pmatrix} \Gamma_{11} & \Gamma_{12} \\ \Gamma_{12}^* & \Gamma_{22} \end{pmatrix}\right]\begin{pmatrix} |B^0(t)\rangle \\ |\overline{B}^0(t)\rangle \end{pmatrix}$$

$$\phi_{12} = \arg(-M_{12}/\Gamma_{12})$$

Mass and width differences between eigenstates:

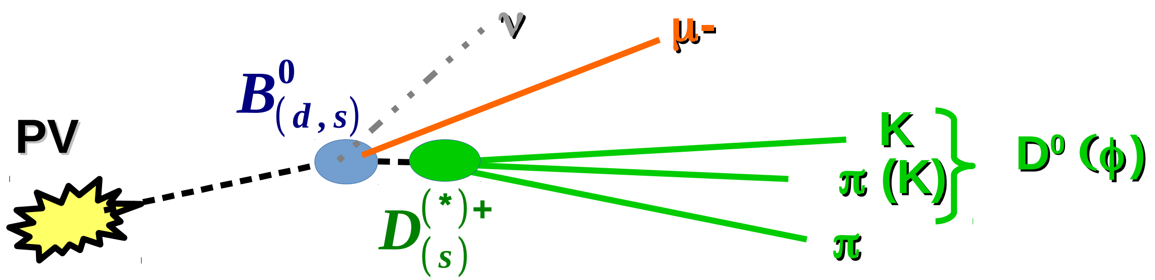
$$\Delta M \approx 2|M_{12}| \qquad \Delta\Gamma \approx 2|\Gamma_{12}|\cos\phi_{12}$$

$$B^0_{L,H} = p|B^0\rangle \pm q|\bar{B}^0\rangle \qquad \lambda_f \equiv \frac{q}{p}\frac{\bar{A}_f}{A_f}$$

$$A_{CP}(t) = \frac{\Gamma(B^0(t)\to f_{CP}) - \Gamma(\overline{B^0}(t)\to f_{CP})}{\Gamma(B^0(t)\to f_{CP}) + \Gamma(\overline{B^0}(t)\to f_{CP})} = \frac{S_f\sin(\Delta M_B t) - C_f\cos(\Delta M_B t)}{\cosh(\Delta\Gamma_B t/2) + A_f^{\Delta\Gamma}\sinh(\Delta\Gamma_B t/2)}$$

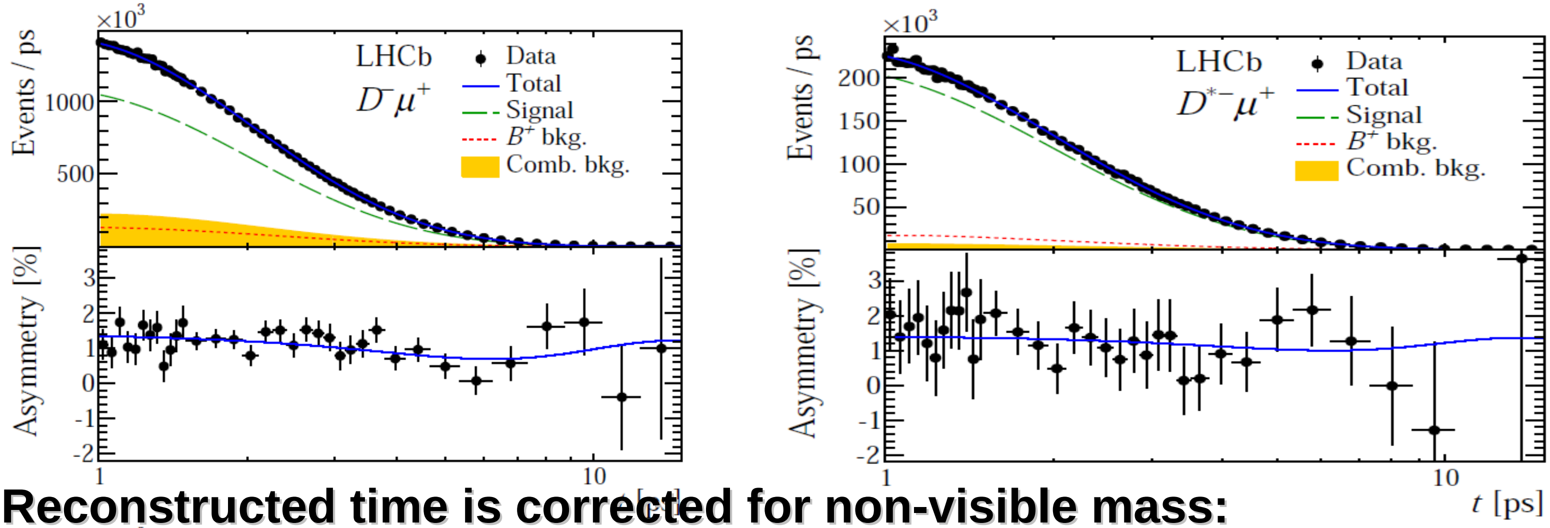
$$C_f \equiv \frac{1-|\lambda_f|^2}{1+|\lambda_f|^2}, \qquad S_f \equiv \frac{2\mathrm{Im}\lambda_f}{1+|\lambda_f|^2}, \qquad A_f^{\Delta\Gamma} \equiv -\frac{2\mathrm{Re}\lambda_f}{1+|\lambda_f|^2}$$

Semileptonic A_{sl} asymmetries



Topology of separated B and D vertices, restricting Kπ(K)πμ mass window

Fitting simultaneously mass and time distributions of Kπ(K)π candidates



Reconstructed time is corrected for non-visible mass:

$$t = \frac{L \cdot M_B^{nom}}{p_{vis}} K(M_{vis})$$

However, precise knowledge of K factor has limited impact on A_{sl}

p_{vis}/p_{true}, from simulation