Time dependent CP asymmetry in beauty @ LHCb

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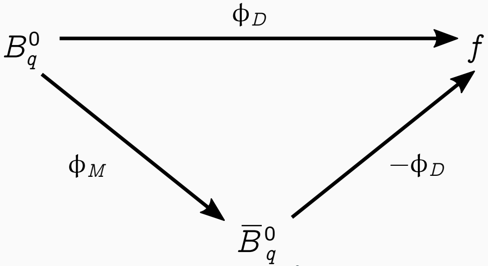
Why time dependent CP violation?

Interference between mixing and decay is sensitive to:

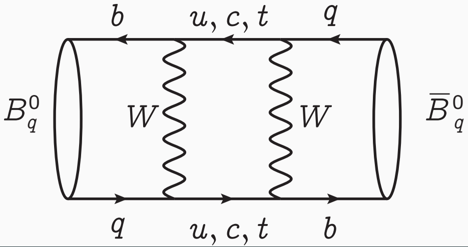
- The weak mixing phases themselves
- Several CKM angles (β, β_s, γ, α)

Probing beyond the standard model:

- FCNC in the mixing
  $\rightarrow$ Possible non SM contributions
- Some final states are not allowed at tree level
  $\rightarrow$ Further non SM contributions



Accessible weak phase: $\phi_q^f = \phi_M - 2\phi_D$



Formalism

Time dependent decay rates:

$$\frac{d\Gamma_{B_q^0\to f}(t)}{dt} = |A_f| \quad \frac{1}{1+C_f} e^{-\Gamma_q t}\left[\cosh\left(\frac{\Delta\Gamma_q t}{2}\right) + A_f^{\Delta\Gamma} \sinh\left(\frac{\Delta\Gamma_q t}{2}\right) + C_f \cos\left(\Delta m_q t\right) - S_f \sin\left(\Delta m_q t\right)\right]$$

$$\frac{d\Gamma_{\overline{B}_q^0\to f}(t)}{dt} = |A_f| \frac{p}{q} \frac{1}{1+C_f} e^{-\Gamma_q t}\left[\cosh\left(\frac{\Delta\Gamma_q t}{2}\right) + A_f^{\Delta\Gamma} \sinh\left(\frac{\Delta\Gamma_q t}{2}\right) - C_f \cos\left(\Delta m_q t\right) + S_f \sin\left(\Delta m_q t\right)\right]$$

$$C_f = \frac{1-|\lambda_f|^2}{1+|\lambda_f|^2} \qquad A_f^{\Delta\Gamma} = -\frac{2\Re(\lambda_f)}{1+|\lambda_f|^2}$$

$$S_f = \frac{2\Im(\lambda_f)}{1+|\lambda_f|^2} \qquad \lambda_f = \frac{q}{p}\frac{\overline{A}_f}{A_f};$$

$arg(\lambda_f)$ is a combination of the strong and weak mixing and decay phases
$\rightarrow$ allows a determination of CKM angles (depending on the final state)

In case of a CP eigenstate f:

$C_f \triangleq$ CP violation in decay/mixing $\qquad S_f \triangleq$ CP violation in interference

Experimantal ingredients

Time dependent decay rates:

$$\frac{d\Gamma_{B_q^0\to f}(t)}{dt} = |A_f| \quad \frac{1}{1+C_f} e^{-\Gamma_q t}\left[\cosh\left(\frac{\Delta\Gamma_q t}{2}\right) + A_f^{\Delta\Gamma}\sinh\left(\frac{\Delta\Gamma_q t}{2}\right) + C_f\cos\left(\Delta m_q t\right) - S_f\sin\left(\Delta m_q t\right)\right]$$

$$\frac{d\Gamma_{\bar{B}_q^0\to f}(t)}{dt} = |A_f| \frac{p}{q} \frac{1}{1+C_f} e^{-\Gamma_q t}\left[\cosh\left(\frac{\Delta\Gamma_q t}{2}\right) + A_f^{\Delta\Gamma}\sinh\left(\frac{\Delta\Gamma_q t}{2}\right) - C_f\cos\left(\Delta m_q t\right) + S_f\sin\left(\Delta m_q t\right)\right]$$

Oscillation:

- Large mass splitting in the B_s^0 system requires excellent **decay time resolution**
- Depending on the final state LHCb reaches **O(45 fs)**

Decay width (difference):

- A precise knowledge of the **decay time acceptance** shape is crucial

Initial flavour:

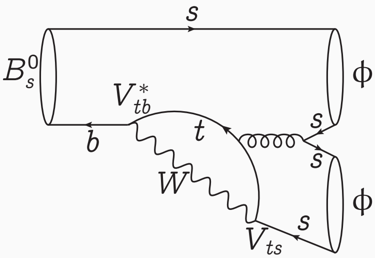
- The effective power of the flavor tagging is directly linked to the CPV sensitivity (**O(4 − 6%)** of effective tagged sample size)

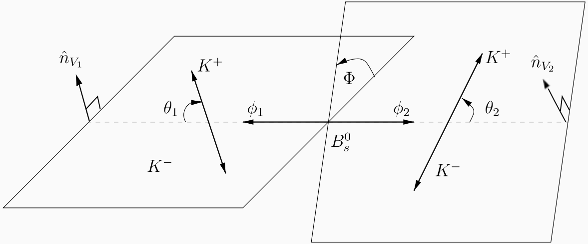
What do we measure there?

$$\phi_s^{s\bar{s}s} \coloneqq arg(\lambda_f) = arg\left(\frac{q}{p}\frac{\bar{A}_f}{A_f}\right)$$

$$\overset{1.\text{order}}{\approx} arg\left(\frac{V_{tb}^* V_{ts}}{V_{tb} V_{ts}^*}\frac{V_{tb} V_{ts}^*}{V_{tb}^* V_{ts}}\right) = 0$$

SM upper limit: $\phi_s^{s\bar{s}s} \leq 0.02\,\text{rad}$





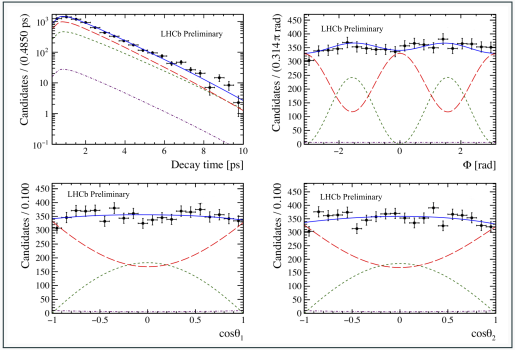
Experimental complications

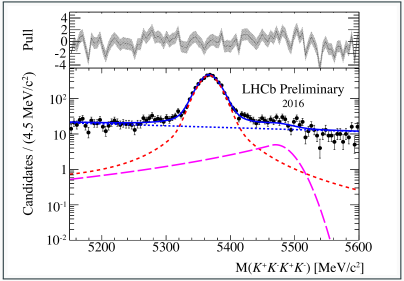
- $B_s^0 \to \phi\phi$ is a P→VV decay
  $\Rightarrow$ No CP eigenstate:
  $CP\,|\phi\phi\rangle = (-1)^l\,|\phi\phi\rangle$
- S-wave contributions (VS and SS) from non-resonant and $f_0(980)$

$\Rightarrow$ Angular analysis is necessary

- Background subtraction by fit to B_s^0 mass
- Γ_s, $\Delta\Gamma_s$ and Δm_s constrained to values from HFLAV and LHCb

CP-even *P*-wave *CP*-odd *P*-wave *S*-wave





Signal
$\Lambda_b \to \phi p K^-$
Combinatorial bkg.

Results:

$$\phi_s^{s\bar{s}s} = -0.07 \pm 0.13(\text{stat.}) \pm 0.03(\text{syst.})\ \text{rad}$$

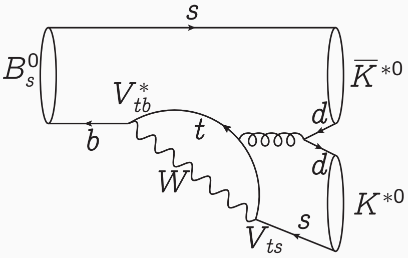
$$|\lambda| = 1.02 \pm 0.05(\text{stat.}) \pm 0.03(\text{syst.})$$

$$|A_0|^2 = 0.382 \pm 0.008(\text{stat.}) \pm 0.011(\text{syst.})$$

$$|A_\perp|^2 = 0.287 \pm 0.008(\text{stat.}) \pm 0.005(\text{syst.})$$

$$\delta_\perp = 2.81 \pm 0.21(\text{stat.}) \pm 0.10(\text{syst.})\ \text{rad}$$

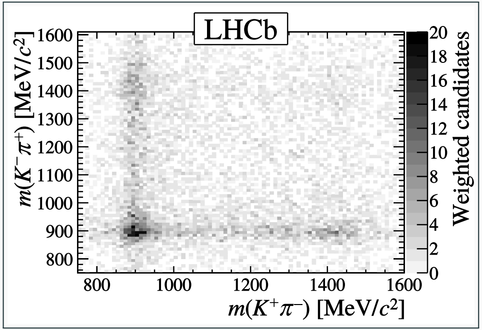
$$\delta_\parallel = 2.52 \pm 0.05(\text{stat.}) \pm 0.07(\text{syst.})\ \text{rad}$$



What do we measure there?

In analogy to $B_s^0 \to \phi\phi$:

$$\phi_s^{d\bar{d}s} := arg(\lambda_f) = arg\left(\frac{q}{p}\frac{\bar{A}_f}{A_f}\right) \overset{1.\text{order}}{\approx} arg\left(\frac{V_{tb}^* V_{ts}}{V_{tb} V_{ts}^*}\frac{V_{tb} V_{ts}^*}{V_{tb}^* V_{ts}}\right) = 0$$



Experimental complications

- Rich $(K^-\pi^+)$ spectrum: $K_0^*(800)^0$, $K_0^*(1430)^0$, $K^*(892)^0$, $K_2^*(1430)^0$
- Many amplitudes with different CP eigenvalues

$\Rightarrow$ Full time dependent amplitude analysis

Analysis of $B_s^0 \to (K^+\pi^-)(K^-\pi^+)$ $(3\,\mathrm{fb}^{-1})$

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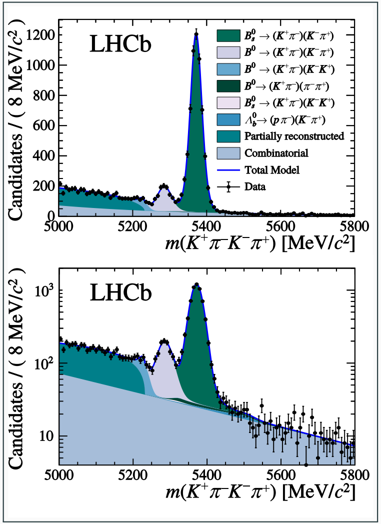
Scalar (S), Vector (V) and Tensor (T) contributions:

Decay	Polarization amplitudes
$B_s^0 \to (K^+\pi^-)_0^*(K^+\pi^-)_0^*$	SS
$B_s^0 \to (K^+\pi^-)_0^*\overline{K}^*(892)^0$	SV
$B_s^0 \to K^*(892)^0(K^+\pi^-)_0^*$	VS
$B_s^0 \to (K^+\pi^-)_0^*\overline{K}_2^*(1430)^0$	ST
$B_s^0 \to K_2^*(1430)^0(K^-\pi^+)_0^*$	TS
$B_s^0 \to K^*(892)^0\overline{K}^*(892)^0$	VV0, VV$\parallel$, VV$\perp$
$B_s^0 \to K^*(892)^0\overline{K}_2^*(1430)^0$	VT0, VT$\parallel$, VT$\perp$
$B_s^0 \to K_2^*(1430)^0\overline{K}^*(892)^0$	TV0, TV$\parallel$, TV$\perp$
$B_s^0 \to K_2^*(1430)^0\overline{K}_2^*(1430)^0$	TT0, TT$\parallel_1$, TT$\perp_1$, TT$\parallel_2$, TT$\perp_2$

In total 19 different polarization amplitudes!



$N_{signal} = 6080 \pm 83$

Results:

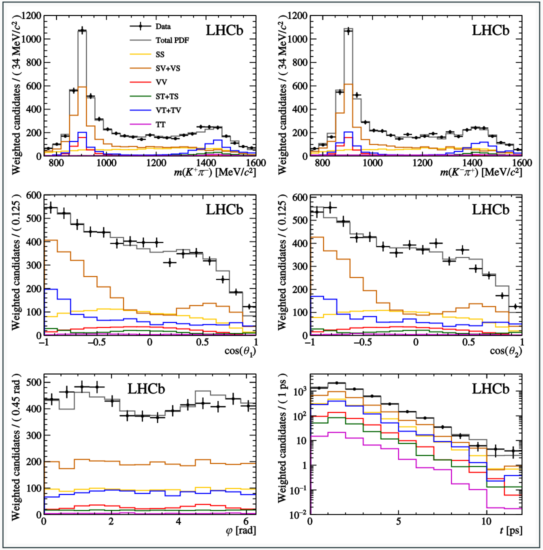
- Most precice measurement of the 19 polarization amplitudes

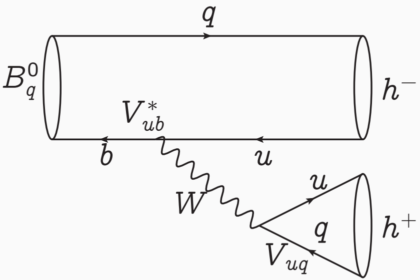
  E.g.:
  $f_L^{VV} = 0.208 \pm 0.032(stat.) \pm 0.046(syst.)$

- ***CP* observables (Common for all polarizations):**

$$\phi_s^{d\bar{d}s} = -0.10 \pm 0.13(stat.) \pm 0.14(syst.)\,\mathrm{rad}$$
$$|\lambda| = 1.035 \pm 0.034(stat.) \pm 0.089(syst.)$$

Systematic dominated by size of simulation samples





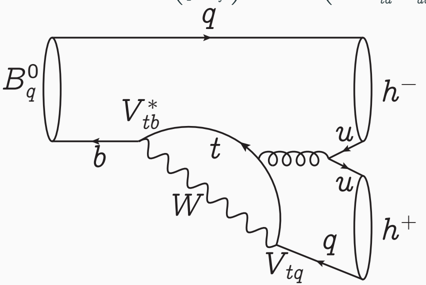
What do we measure there?

$\boldsymbol{B_s^0 \to K^- K^+}$:

$$arg(\lambda_f) = arg\left(\frac{q}{p}\frac{\bar{A}_f}{A_f}\right) \not\approx arg\left(\frac{V_{tb}^* V_{ts}}{V_{tb} V_{ts}^*}\frac{V_{ub} V_{us}^*}{V_{ub}^* V_{us}}\right) \approx -2\gamma + 2\beta_s$$

$\boldsymbol{B^0 \to \pi^- \pi^+}$:

$$arg(\lambda_f) = arg\left(\frac{q}{p}\frac{\bar{A}_f}{A_f}\right) \not\approx arg\left(\frac{V_{tb}^* V_{td}}{V_{tb} V_{td}^*}\frac{V_{ub} V_{ud}^*}{V_{ub}^* V_{ud}}\right) = \alpha \,||\, -2\gamma - 2\beta$$



But: The situation is not that easy!

- Tree level heavily CKM suppressed
- Penguin diagrams not negligible

$\Rightarrow$ Will only measure CP observables C, S and $A^{\Delta\Gamma}$

But: γ/α and β_s can be inferred by relating $B_s^0 \to K^- K^+$ and $B^0 \to \pi^-\pi^+$ via U-spin symmetry

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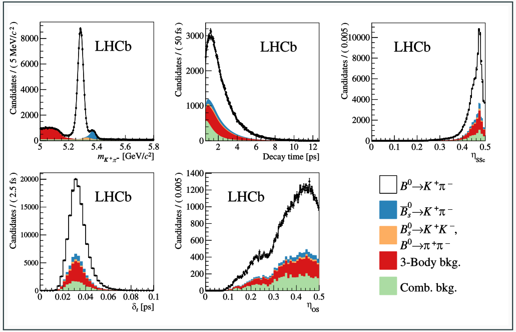
Analysis strategy:

- Simultaneous fit to three samples:
  K^-K^+(for $B_s^0 \to K^-K^+$), $\pi^+\pi^-$(for $B^0 \to \pi^+\pi^-$) and $K^\pm\pi^\mp$(for $B^0 \to K^+\pi^-$, $B_s^0 \to K^-\pi^+$)
- Fitting $m(h^+h^-)$, decay time, per event decay time uncertainty, and tagging parameter (η) distributions of all three samples

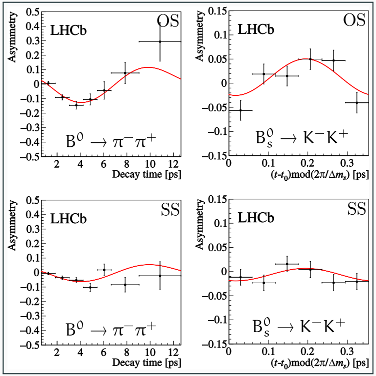
Including flavour specific decays:

- On the fly calibration of many of the tagging parameters
- Determination of time integrated CP asymmetries
- Disentangling of B production asymmetries and direct CP asymmetries



Nice visualization of the results: Projections of the time dependent asymmetry

$$A_{CP}(t) = \frac{\Gamma_{\overline{B}_q^0\to f}(t) - \Gamma_{B_q^0\to f}(t)}{\Gamma_{\overline{B}_q^0\to f}(t) + \Gamma_{B_q^0\to f}(t)} = \frac{-C_f\cos(\Delta m_q t) + S_f\sin(\Delta m_q t)}{\cosh(\frac{\Delta\Gamma_q}{2}t) + A_f^{\Delta\Gamma}\sinh(\frac{\Delta\Gamma_q}{2}t)}$$



$$C_{\pi^+\pi^-} = -0.34 \pm 0.06 \pm 0.01$$
$$S_{\pi^+\pi^-} = -0.63 \pm 0.05 \pm 0.01$$
$$C_{K^+K^-} = 0.20 \pm 0.06 \pm 0.02$$
$$S_{K^+K^-} = 0.18 \pm 0.06 \pm 0.02$$
$$A^{\Delta\Gamma}_{K^+K^-} = -0.79 \pm 0.07 \pm 0.10$$

$$A_{CP}^{B^0\to K^+\pi^-} = -0.084 \pm 0.004 \pm 0.003$$
$$A_{CP}^{B_s^0\to K^-\pi^+} = 0.213 \pm 0.015 \pm 0.007$$

4σ significance for TD CPV in B_s^0 system!

What do we measure there?

$$arg(\lambda_f) = arg\left(\frac{q}{p}\frac{\bar{A}_f}{A_f}\right) \approx \delta + arg\left(\frac{V_{tb}^* V_{ts}}{V_{tb} V_{ts}^*}\frac{V_{ub} V_{cs}^*}{V_{cb}^* V_{us}}\right) \approx \delta - (\gamma - 2\beta_s)$$

δ: strong phase difference between $\bar{A}_{D_s^- K^+}$ and $A_{D_s^- K^+}$

Five observables for three unknowns:

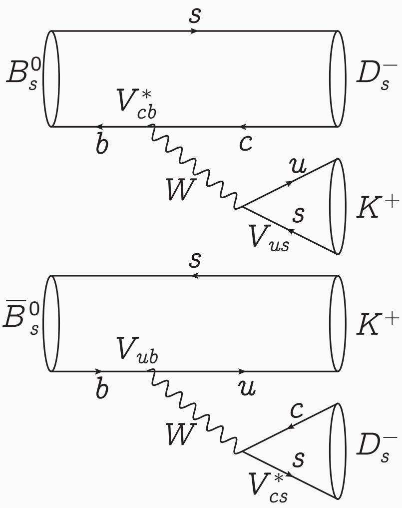
(No CPV in decay and mixing)

$$C_f = \frac{1 - r_{D_s K}^2}{1 + r_{D_s K}^2} = -C_{\bar{f}}$$

$$A_f^{\Delta\Gamma} = \frac{-2 r_{D_s K} \cos(\delta - (\gamma - 2\beta_s))}{1 + r_{D_s K}^2} \quad A_{\bar{f}}^{\Delta\Gamma} = \frac{-2 r_{D_s K} \cos(\delta + (\gamma - 2\beta_s))}{1 + r_{D_s K}^2}$$

$$S_f = \frac{2 r_{D_s K} \sin(\delta - (\gamma - 2\beta_s))}{1 + r_{D_s K}^2} \quad S_{\bar{f}} = \frac{-2 r_{D_s K} \sin(\delta + (\gamma - 2\beta_s))}{1 + r_{D_s K}^2}$$

Determine $\gamma - 2\beta_s$, δ and $r_{D_s K} = |\lambda_{D_s K}|$



What do we measure there?

$$arg(\lambda_f) = arg\left(\frac{q}{p}\frac{\bar{A}_f}{A_f}\right)$$
$$\approx \delta + arg\left(\frac{V_{tb}^* V_{td}}{V_{tb} V_{td}^*}\frac{V_{ub} V_{cd}^*}{V_{cb}^* V_{ud}}\right) \approx \delta - (\gamma + 2\beta)$$

δ: strong phase difference between $\bar{A}_{D^-\pi^+}$ and $A_{D^-\pi^+}$

Difference to $B_s^0 \to D_s^- K^+$:

CKM: $r_{D\pi} \approx 0.02 \quad \Rightarrow C$ indistinguishable from unity

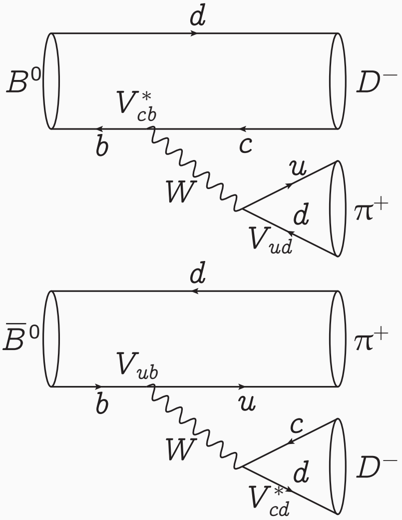
B^0 system: $\Delta\Gamma = 0 \Rightarrow$ No access to $A_f^{\Delta\Gamma}$

Two observables for three unknowns:

(No CPV in decay and mixing)

$$S_f = \frac{2r_{D\pi}\sin(\delta-(\gamma+2\beta))}{1+r_{D\pi}^2} \quad S_{\bar{f}} = \frac{-2r_{D\pi}\sin(\delta+(\gamma+2\beta))}{1+r_{D\pi}^2}$$

External input needed to determine $\gamma + 2\beta$



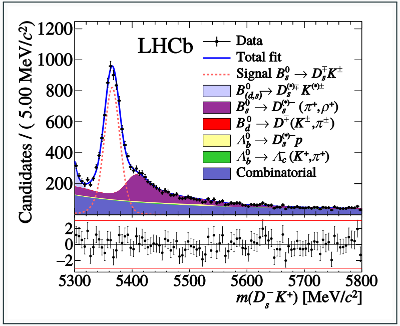
Analysis of $B_s^0 \to D_s^{\mp} K^{\pm}$

Advantages:

- Large interference effects
- Additional observables due to $\Delta\Gamma_s \neq 0$
- Nice control channel: $B_s^0 \to D_s^- \pi^+$

Disadvantages:

- Small yield ($N_{sig} = 5955 \pm 90$)



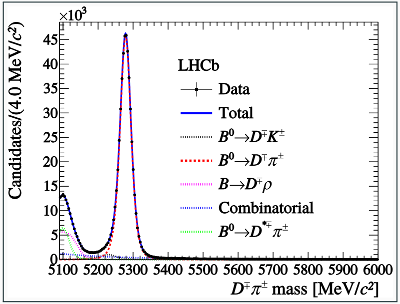
Analysis of $B^0 \to D^{\mp} \pi^{\pm}$

Advantages:

- Huge yield ($N_{sig} = 479.000 \pm 700$)
- Direct tagging calibration (exploit $C_f = 1$)

Disadvantages:

- Small interference effects
- Less observables

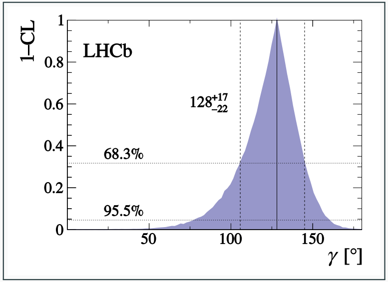


Analysis of $B_s^0 \to D_s^{\mp} K^{\pm}$

Results: JHEP 03 (2018) 059

$$
\begin{aligned}
C_f &= 0.730 \pm 0.142 \pm 0.045 \\
A_f^{\Delta\Gamma} &= 0.387 \pm 0.277 \pm 0.153 \\
A_{\bar{f}}^{\Delta\Gamma} &= 0.308 \pm 0.275 \pm 0.152 \\
S_f &= -0.519 \pm 0.202 \pm 0.070 \\
S_{\bar{f}} &= -0.489 \pm 0.196 \pm 0.068
\end{aligned}
$$

Using ϕ_s to extract γ:



Analysis of $B^0 \to D^{\mp}\pi^{\pm}$

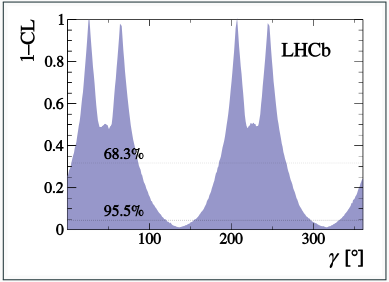
Results: JHEP 06 (2018) 084

$$
\begin{aligned}
S_f &= -0.058 \pm 0.020 \pm 0.011 \\
S_{\bar{f}} &= -0.038 \pm 0.020 \pm 0.007
\end{aligned}
$$

Extracting γ (using 2β):

Use SU(3) symmetry to estimate $r_{D\pi}$:

$r_{D\pi} = 0.0182 \pm 0.0012 \pm 0.0036(\mathrm{SU(3)\ breaking})$



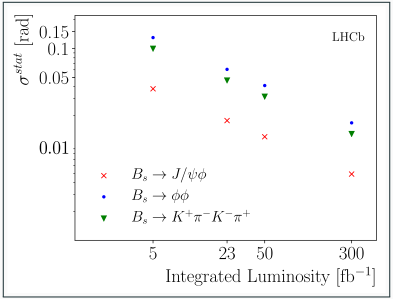
Summary and outlook

What was presented: Only the most recent time dependent CPV measurements

- SM null-tests: $B_s^0 \to \phi\phi$ and $B_s^0 \to (K^+\pi^-)(K^-\pi^+) \Rightarrow$ Consistent with SM at O(0.1rad)
- Measurements of CP observables related to combinations of β, β_s with γ:
  - In $B_q^0 \to h^+h^-$ (puts constraints on γ and β_s)
  - In $B_s^0 \to D_s^- K^+ \to 2\sigma$ tension to other γ measurements ($\gamma \approx (130 \pm 20)^\circ$)
  - In $B^0 \to D^-\pi^+ \to$ Although not ideal, will add interesting sensitivity

What is to come?

- Updating old measurements:
  ($B_s^0 \to J/\psi\phi$, $B^0 \to J/\psi K_s^0$,..) with Run II data
- Other interesting new measurements.
  E.g.: γ from $B_s^0 \to D_s^\mp K^\pm\pi^+\pi^-$
- Statistically dominated measurements $\Rightarrow$ will scale



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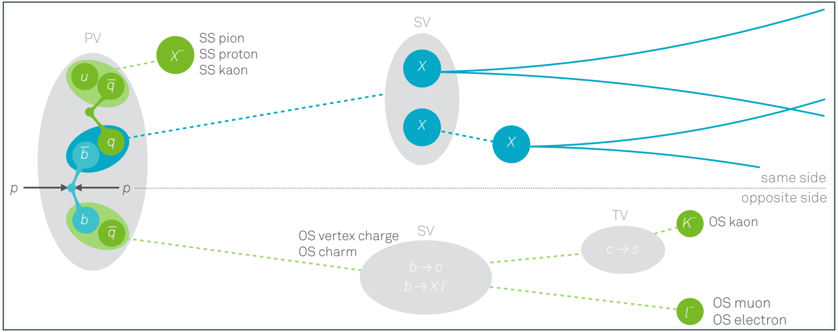
Thanks for your attention!

Backup

Flavour tagging

Relies on the reconstruction of the rest of the event $\rightarrow$ Charge of other particles

Classification in **same side** (hadronisation of the signal B) and **opposite side** (decay products of the other B)



Tagging efficiency: ε_{tag}

Mistag probability: ω

Effective tagging power:

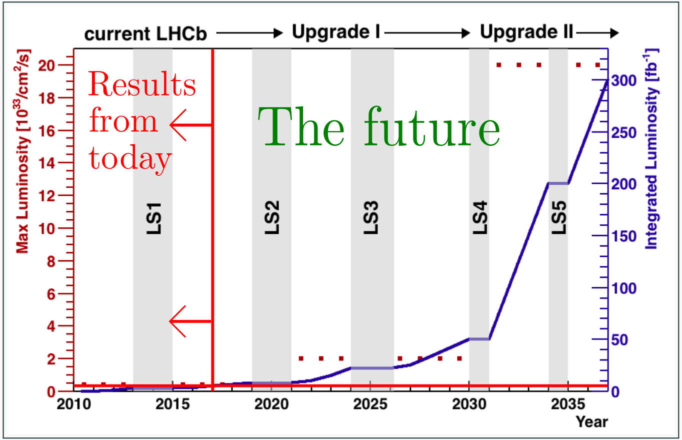
$$\varepsilon_{eff} = \varepsilon_{tag}(1-2\omega)^2$$

$$\sigma^{stat} \propto \frac{1}{\sqrt{\varepsilon_{eff} N}}$$

Combining opposite and same sign taggers yields ε_{eff} **of O(4 − 6%)**

Outlook

What is to come?



For details see:
LHCb-PUB-2018-009

A teaser:

	σ_{stat}	
	Now	@50 fb^{-1}
$\phi_s^{c\bar{c}s}$	0.049 rad	0.0065 rad
$\sin(\phi_d^{c\bar{c}s})$	0.035	0.006
Γ from $B_s^0 \to D_s^{\mp} K^{\pm}$	20°	2.5°

Just getting started!