Future contributions to ϕ_s measurements

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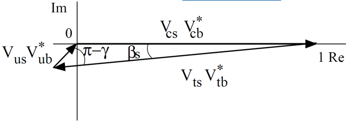
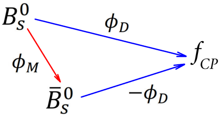
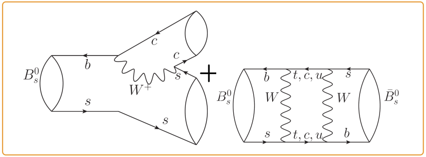
Introduction to ϕ_s

- $\phi_s = -2\beta_s$ - angle in B_s^0 system analogous to β in B^0 system
- Possibility of measurement in interference between B_s^0 direct decay and mixing,
  e.g. via $b \to c\bar{c}s$ transitions, $B_s^0 \to J/\psi\phi$
- Contributions from SM "tree", higher order "penguin" and New Physics







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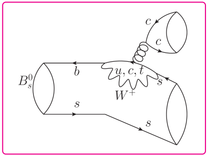

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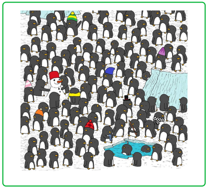


$$\phi_s = \phi_M - 2\phi_D = -2\beta_s + \Delta\phi_s^{Peng} + \delta_s^{NP}$$

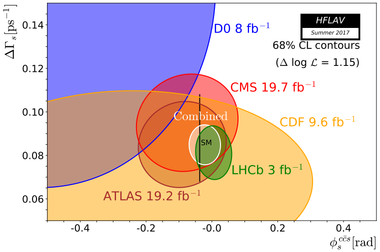
ϕ_s determined via global fit to experimental results ignoring penguin diagrams contributions [CKMFitter]:

$$\phi_s \equiv -2\arg\left(-\frac{V_{ts}V_{tb}^*}{V_{cs}V_{cb}^*}\right) = -37.6^{+0.7}_{-0.8}\ \text{mrad}$$

Prediction is very precise!

Status of ϕ_s measurement

- First measured by CDF and D0 (Tevatron experiments)
- Extensively studies by LHCb, ATLAS, CMS during Run1 of the LHC



LHCb:

- $J/\psi\phi$ [PRL 114 (2015) 041801]
- $J/\psi K^+K^-$ above $\phi(1020)$ [JHEP 08 (2017) 037]
- $J/\psi\pi^+\pi^-$ [PLB 736 (2014) 186]
- $\psi(2S)\phi$ [PLB 762 (2016) 253-262]
- $D_s^+D_s^-$ [PRL 113 (2014) 211801]

CMS:

- $J/\psi\phi$ [PLB 757 (2016) 97-120]

ATLAS:

- $J/\psi\phi$ [JHEP 08 (2016) 147]

$\phi_s = -21 \pm 31$ mrad [HFLAV Summer 2017] $\qquad$ $\phi_s^{SM} = -37.6^{+0.7}_{-0.8}$ mrad [CKMFitter]

- World average (dominated by LHCb) consistent with SM predictions
  But still far from the SM uncertainty ($\sigma^{SM} \sim$1 mrad)$\Rightarrow$ plenty of room for NP
- Significant increase in ATLAS and CMS sensitivity is expected thanks to the new pixel detectors: $\sigma_t \sim$60 fs instead $\sigma_t \sim$90 fs in Run1 [ATL-PHYS-PUB-2013-010][CMS-TDR-11]

Future of ϕ_s at LHCb

Estimations for main channels (only σ_{stat}) [LHCb-PUB-2014-040]

Decay mode $\sigma_{\text{stat}}(\phi_s)$ [mrad]	Run1 (3 fb^{-1}) (2010-12)	Run2 (8 fb^{-1}) (2015-18)	Phase-I Upgrade (2021-29, $\sim$50 fb^{-1})	Theory limit
$B_s^0 \to J/\psi KK$	49	25	9	$\sim$1
$B_s^0 \to J/\psi f_0$	68	35	12	$\sim$10

Ongoing new analyses and updates:

- $B_s^0 \to J/\psi(\to e^+e^-)\phi$ with Run1
- $B_s^0 \to (K^+\pi^-)(K^-\pi^+)$ with Run1
- $B_s^0 \to J/\psi K^+K^-$ and $B_s^0 \to J/\psi\pi^+\pi^-$ with Run2

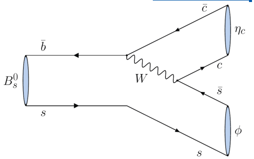
Future contributions with more data statistics (Run2/3/4):

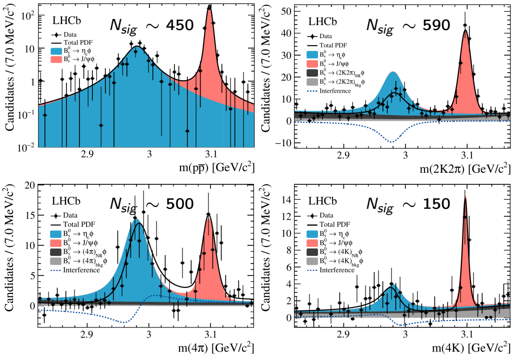
- $B_s^0 \to \eta_c\phi$
- $B_s^0 \to J/\psi\eta(\to \gamma\gamma)$
- $B_s^0 \to \phi(\to K^+K^-)\pi^+\pi^-$

Observation of $B_s^0 \to \eta_c \phi$

[JHEP 1707 (2017) 021]

- Dominantly decay through the $b \to c\bar{c}s$ transition
- Purely $\mathcal{CP}$-even state $\Rightarrow$ no angular analysis is required
- $\eta_c \to$ into $p\bar{p}$, $2K2\pi$, 4π and $4K$ final states
- J/ψ decaying to same final states is used as normalisation





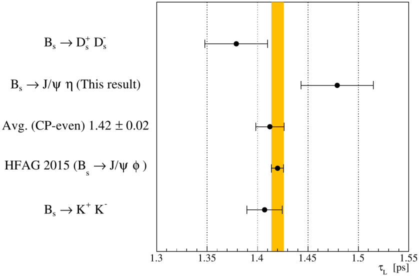
- Total decay amplitude $|A(m_i; c_k^i, \vec{x})|^2 = \sum_J |\sum_k c_k^i R_k^J(m_i; \vec{x})|^2$
- Interference between η_c and non-resonant states taken into account
- First evidence for the $B_s^0 \to \eta_c(\to p\bar{p})\pi^+\pi^-$ (decay proceeds via the $f_0(980)$ resonance)
- Expected the ϕ_s measurement with more data statistics

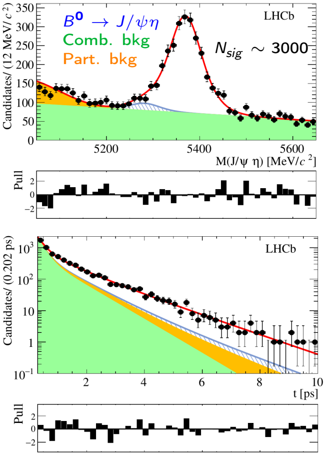
$$\mathcal{B}(B_s^0 \to \eta_c\phi) = (5.01 \pm 0.53(\text{stat}) \pm 0.27(\text{syst}) \pm 0.63(\mathcal{B})) \cdot 10^{-4}$$
$$\mathcal{B}(B_s^0 \to \eta_c\pi^+\pi^-) = (1.76 \pm 0.59(\text{stat}) \pm 0.12(\text{syst}) \pm 0.29(\mathcal{B})) \cdot 10^{-4}$$

$B_s^0 \to J/\psi\eta(\to \gamma\gamma)$ lifetime efficiency

[PLB 762 (2016) 484]

- Purely $\mathcal{CP}$-even state $\Rightarrow$ no angular analysis is required
- **First step**: measure Γ_L from decay time distribution
- $\sigma_M \approx$48 MeV/c^2 $\Rightarrow$ overlapping with $B^0 \to J/\psi\eta$ component





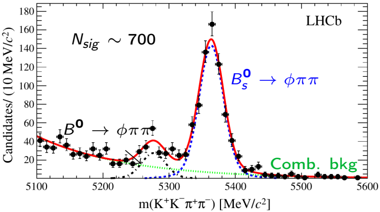
$$\tau_{\text{eff}} = 1.479 \pm 0.034(\text{stat}) \pm 0.011(\text{syst}) \text{ ps}$$

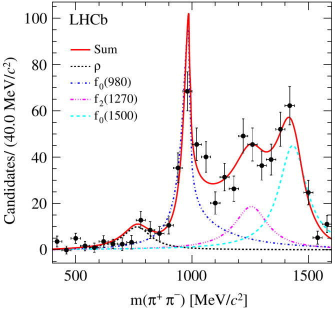
- Limited size of data sample
- Main systematic uncertainty is due to the decay time acceptance model
- Consistent with the effective lifetime determined using other B_s^0 decay modes

Observation of $B_s^0 \to \phi(\to K^+K^-)\pi^+\pi^-$

[PRD 95 (2017) 012006]

- Gluonic $b \to s$ penguin transition $\Rightarrow \mathcal{B}(B_s^0 \to \phi f_0(980))^{\text{theor}} \approx 2 \cdot 10^{-6}$
- Isospin-violating $\Delta\mathcal{I} = 1$ transition is mediated by a combination of an e/w penguin and suppressed $b \to u$ transiton$\Rightarrow \mathcal{B}(B_s^0 \to \phi\rho_0)^{\text{theor}} = 4.4^{+2.2}_{-0.7} \cdot 10^{-7}$
- Time dependent angular amplitude analysis, $B_s^0 \to \phi\phi$ as normalization mode

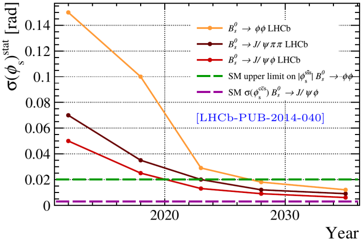




$$\mathcal{B}(B_s^0 \to \phi f_0(980)) = (1.12 \pm 0.16(\text{stat})^{+0.09}_{-0.08}(\text{syst}) \pm 0.11(\mathcal{B})) \cdot 10^{-6}$$
$$\mathcal{B}(B_s^0 \to \phi\rho^0) = (2.7 \pm 0.7(\text{stat}) \pm 0.2(\text{syst}) \pm 0.2(\mathcal{B})) \cdot 10^{-7}$$

Conclusions

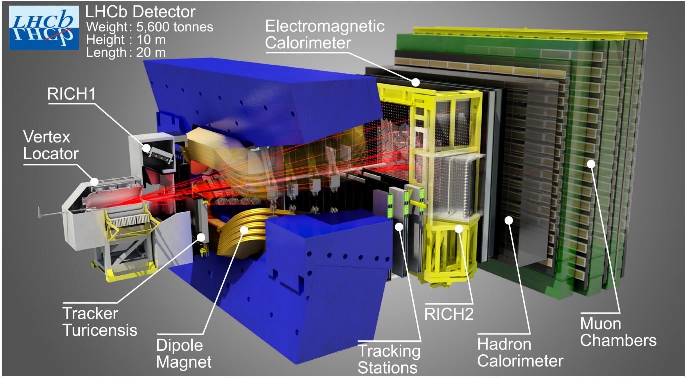
- Recent measurements of ϕ_s in the B_s^0 system are consistent with the SM
  $\Rightarrow$ But still a lot of room for NP effects



- Penguin effects in B_s^0 mixing are taken under control: $\Delta\phi_s^{Peng} \lesssim 20$ mrad
  [JHEP 11 (2015) 082][PLB 742 (2015) 38][JHEP 06 (2015) 131]
- Run2 data from the LHC will allow the inclusion of more modes and improved uncertainties on the ones already measured $\Rightarrow$ STAY TUNED

Thank you for your attention!

Backups

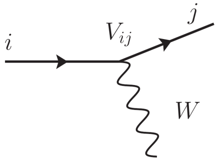


- Single-arm forward spectrometer, covering $2 < \eta < 5$ ($10 < \theta < 300$ (250) mrad)
- Momentum resolution: $\Delta p/p = 0.5\%$ at 5 GeV/c to 1.0% at 200 GeV/c
- Impact parameter resolution: 20 μm for high p_T tracks
- Decay time resolution: $\sim$ 45 fs
- Invariant mass resolution: $\sim$ 8 MeV/c^2 for $B \to J/\psi X$ decays with J/ψ mass constraint

[Prog.Theor.Phys. 49 (1973) 652]

The Cabibbo-Kobayashi-Maskawa matrix is a 3×3 unitary matrix which consists of information about flavour changing weak decays

$$\begin{pmatrix} u \\ c \\ t \end{pmatrix} \leftrightarrow \begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \cdot \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$



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

$$\lambda \approx 0.22$$

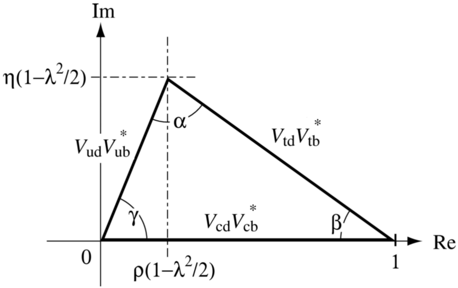
[PRL 53 (1984) 1802]

Unitary triangles

[PRL 10 (1963) 531]

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

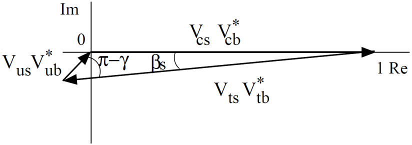
Triangle (db)



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

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

Triangle (sb)



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

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

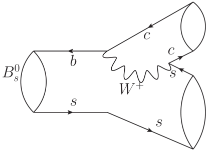
"Golden" mode

$B^0 \to J/\psi K_S$: $(\bar{b}d) \to (c\bar{c})(d\bar{s})$

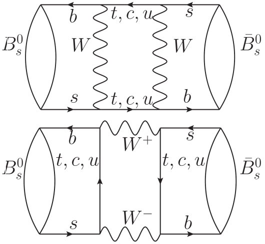
$B_s^0 \to J/\psi\phi$: $(\bar{b}s) \to (c\bar{c})(s\bar{s})$

Violation of the $\mathcal{CP}$ symmetry

- **Direct** (in decay amplitudes):
  $\phi_D = \arg(V_{cs} V_{cb}^*)$
  *Ignoring sub-leading penguin contributions

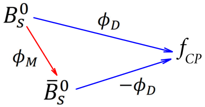


- **Mixing** (indirect): $\phi_M = 2\arg(V_{ts} V_{tb}^*)$
  - Described by phenomenological Schrödinger equation:
    $i\frac{d}{dt}\begin{pmatrix}|B_s^0(t)\rangle \\ |\bar{B}_s^0(t)\rangle\end{pmatrix} = \left(\mathbf{M} - \frac{i}{2}\Gamma\right)\begin{pmatrix}|B_s^0(t)\rangle \\ |\bar{B}_s^0(t)\rangle\end{pmatrix}$
  - Solutions give two mass eigenstates: B_L and B_H
    $|B_{L/H}\rangle = p|B_s^0\rangle \pm q|\bar{B}_s^0\rangle$
  - Mixing parameters
    $\Delta m_s = M_H - M_L$ $\quad\Delta\Gamma_s = \Gamma_L - \Gamma_H$
    $\Gamma_s = \frac{\Gamma_L + \Gamma_H}{2}$ $\quad\phi_{12} = \arg(-M_{12}/\Gamma_{12})$



- **Interference** between direct decays and decays with mixing

$$\phi_s \equiv -\arg(\lambda_f) \equiv -\arg\left(\frac{q}{p}\frac{\bar{A}_f}{A_f}\right) \neq 0 \qquad |\lambda| \equiv \left|\frac{q}{p}\frac{\bar{A}_f}{A_f}\right| \approx 1$$



$$\phi_s^{SM} = \phi_M - 2\phi_D = -2\arg\left(-\frac{V_{ts}V_{tb}^*}{V_{cs}V_{cb}^*}\right) = -2\beta_s$$