Measurement of CP Violation in $\mathrm{B}_s^0 \to \mathrm{J}/\psi\,\phi$ decays

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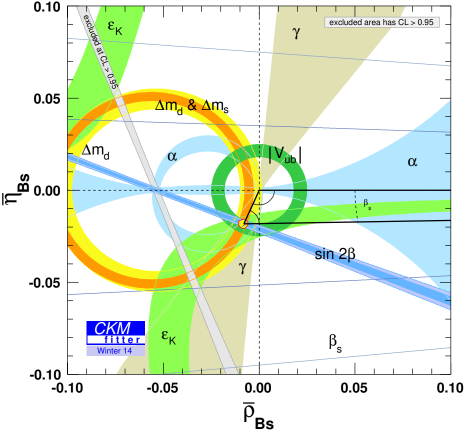
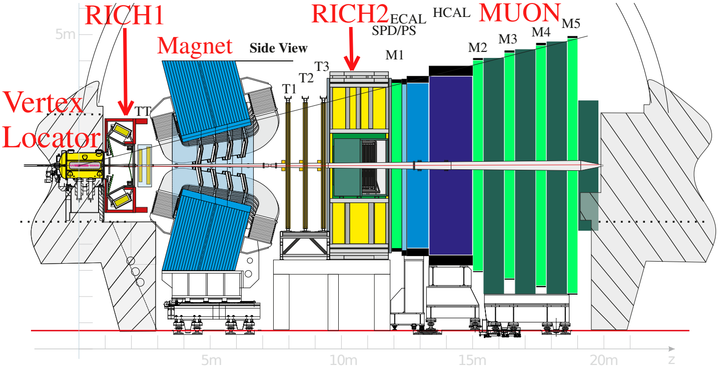
CP Violation

- CP Violation is a necessary condition for baryon asymmetry in the Universe
  [A. D. Sakharov, JETP Lett. 5, 24-27 (1967)]
- Present in the Standard Model, but too small by 10^{10} to explain asymmetry
- Heavy-quark hadrons are excellent place to search for new sources of CPV



LHCb Detector

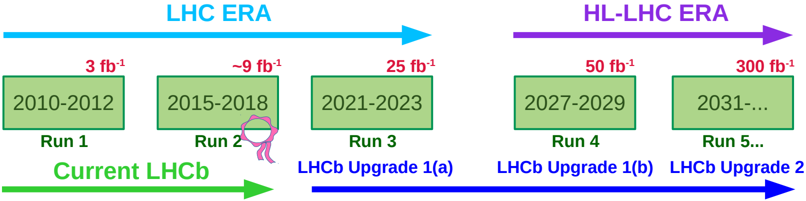


LHCb Detector Layout

- Interaction VErtex LOcator ($\varepsilon_{track} \approx 96\%$)
- Ring-Imaging Cherenkov ($\varepsilon_{PID}(K) \approx 95\%$) ($MisID(\mathrm{K} \to \pi) \approx 5\%$)
- High-granularity Muon ($\varepsilon_{PID}(\mu) \approx 97\%$) ($MisID(\mu \to \pi) \approx 3\%$)

- 4% of solid angle = 40% of heavy quark σ
- Decay time resolution: 45 fs
- Signature: detached $\mu\mu$
- nPVs: $\sim$2

Experimental timeline



LHC ERA

HL-LHC ERA

$3\ fb^{-1}$ 2010-2012 **Run 1**

$\sim 9\ fb^{-1}$ 2015-2018 **Run 2**

$25\ fb^{-1}$ 2021-2023 **Run 3**

$50\ fb^{-1}$ 2027-2029 **Run 4**

$300\ fb^{-1}$ 2031-... **Run 5...**

Current LHCb

LHCb Upgrade 1(a)

LHCb Upgrade 1(b)

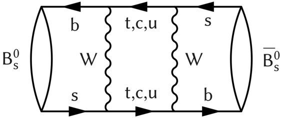
LHCb Upgrade 2

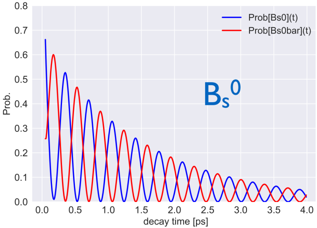
- Run 2 is almost finished
- Upgrade 1 is about to start
- End Run 3 → End Run 5 LHCb: $23\,\mathrm{fb}^{-1} \rightarrow 300\,\mathrm{fb}^{-1}$
- LHCb may be the only large-scale flavour physics experiment operating in the HL-LHC era.

Impact of Upgrade 2 comparable to moving from 14TeV to 27TeV for on-shell production!

CP Violation in Mixing

$\vert \mathrm{B^0}_{L,H}\rangle = p\vert \mathrm{B^0}\rangle + q\vert \overline{\mathrm{B}}^0\rangle$	Mass eigenstates
$\Delta m \equiv m_H - m_L$	Mixing frequency
$\Gamma \equiv \frac{(\Gamma_\mathrm{L} + \Gamma_\mathrm{H})}{2}$	Average decay width
$\Delta\Gamma \equiv \Gamma_\mathrm{H} - \Gamma_\mathrm{L}$	Width difference





$$P(\mathrm{B_s^0} \to \overline{\mathrm{B}}_\mathrm{s}^0) = \frac{\Gamma_\mathrm{s} e^{-\Gamma_\mathrm{s} t}}{2}[\cosh(\Delta\Gamma_\mathrm{s} t/2) - \cos(\Delta m_s t)]|q/p|^2$$

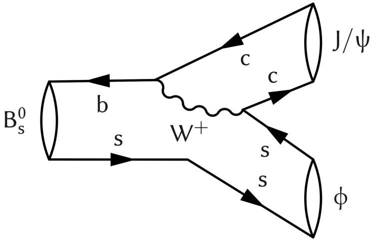
ϕ_s (CPV in interference of mixing and decay)

$$\mathcal{A}_{CP}(t) = \frac{\Gamma(\bar{B}^0_s \to f) - \Gamma(B^0_s \to f)}{\Gamma(\bar{B}^0_s \to f) + \Gamma(B^0_s \to f)} \approx \eta_f \sin\phi_s \sin(\Delta m_s t)$$

$$\begin{tikzcd}
B^0_s \arrow[rr, "A_f"] \arrow[dr, "q/p"'] & & f_{cp} \\
& \overline{B}^0_s \arrow[ur, "\bar{A}_f"'] &
\end{tikzcd}$$

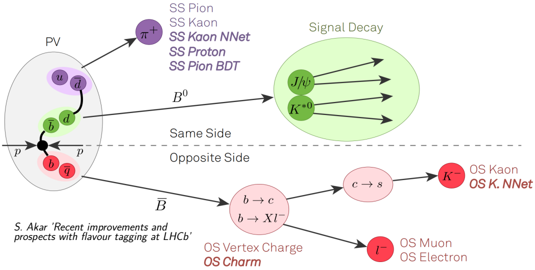
- ϕ_s : phase difference between amplitudes w/ and w/o oscillation in $b \to c\bar{c}s$ decays
- Sensitive probe of NP in B^0_s mixing and decay
- $\phi_s{}^{SM} = -0.0365 \pm 0.0013$ rad

Determining ϕ_{s} with $\mathrm{B}_{\mathrm{s}}^{0} \to \mathrm{J}/\psi\,\phi$ experimentally

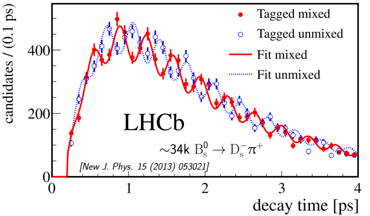


- $\mathrm{B}_{\mathrm{s}}^{0} \to \mathrm{J}/\psi\,\phi$ is the golden mode for measuring ϕ_{s}
- Measure ϕ_{s}, $\Delta\Gamma_s$, Γ_s
- Final state is a mixture of CP-even/CP-odd, requires angular analysis to disentangle $CP|\mathrm{J}/\psi\,\phi\rangle_\ell = (-1)^\ell|\mathrm{J}/\psi\,\phi\rangle_\ell$
- Good tagging performance to resolve $\mathrm{B}_{\mathrm{s}}^{0}$ flavour at production
- High decay-time resolution to see fast $\mathrm{B}_{\mathrm{s}}^{0}$ oscillation and determine Δm_s
- Flavour-tagged time-dependent angular fit
- Robust understanding and modelling of background and acceptance effects

Flavour Tagging



S. Akar 'Recent improvements and prospects with flavour tagging at LHCb'

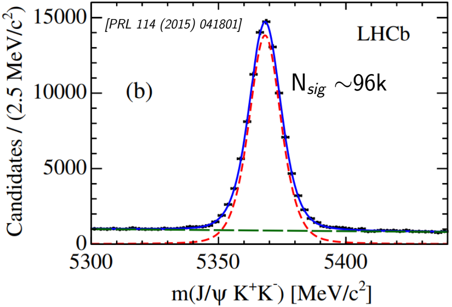


- Crucial to tag B_s^0 flavour at production
- Use information in the event (e.g., charge of K associated with b hadronisation) to tag B_s^0
- Calibrate tagging algorithm response using modes with known flavour (e.g., $\mathrm{B}^+ \to \mathrm{J}/\psi\, \mathrm{K}^+$, $\mathrm{B}_s^0 \to \mathrm{D}_s^- \pi^+$)
- Great proper time resolution

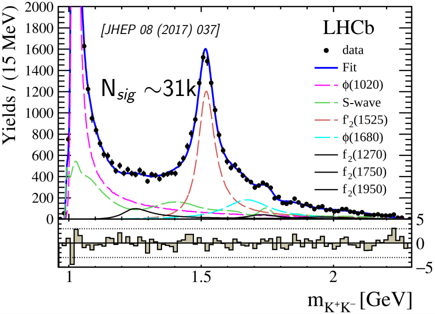
Tagging power: $\varepsilon D^2 \sim 4\%$

ε - tag efficiency $\quad D^2 \equiv (1-2\omega)^2 \quad$ ω - mistag probability

LHCb optimized for ϕ_s



Large signal yield ($B_s^0 \to J/\psi\,\phi$)

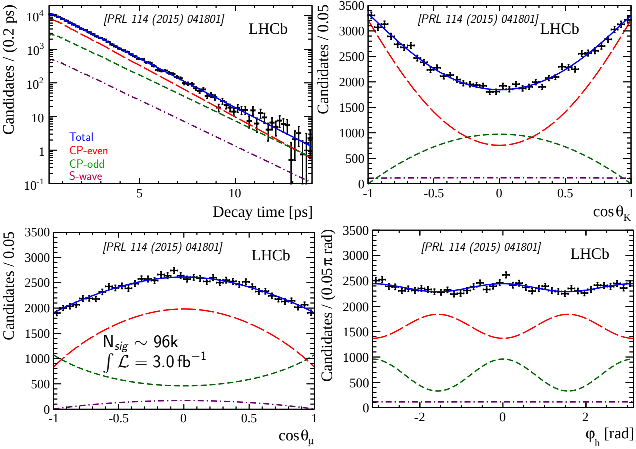


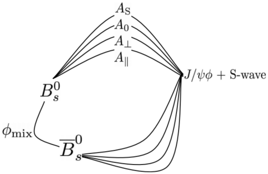
New modes above $\phi(1020)$

- Including more statistics from $m(K^+K^-) > m(\phi)$
- Determine resonant structure and ϕ_s, Γ_s and $\Delta\Gamma_s$ in fit to $m(K^+K^-)$
- Combination with $B_s^0 \to J/\psi\,\phi$ improves ϕ_s precision by over 7%

Fit Results

- $\mathrm{B}_s^0 \to \mathrm{J}/\psi\,\mathrm{K}^+\mathrm{K}^-$ is an admixture of CP-even and CP-odd eigenstates
  ϕ: CP-even($\mathcal{A}_0 + \mathcal{A}_\parallel$) + CP-odd($\mathcal{A}_\perp$)
  S-wave: CP-odd($\mathcal{A}_S$)
  → Use angular distribution (helicity angles) to disentangle CP-even and CP-odd components





- **Main systematic uncertainty**
  Angular acceptance (MC size):
  ±0.004 rad

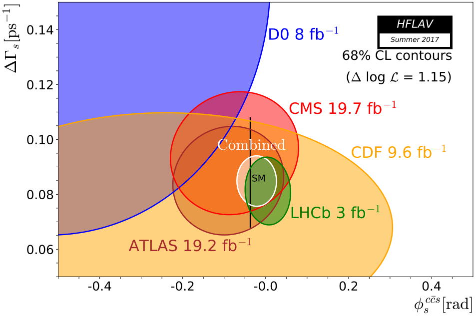
ϕ_s Results

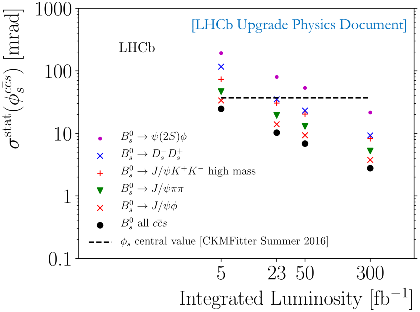
Final LHCb Run I results

$J/\psi K^+K^-$ in ϕ region	-58 ± 59 ± 6 mrad	[PRL 114 (2015) 041801]
$J/\psi K^+K^-$ in high-mass K^+K^- region	119 ± 107 ± 34 mrad	[JHEP 08 (2017) 037]
$J/\psi \pi^+\pi^-$	70 ± 68 ± 8 mrad	[PLB 713 (2012) 378]
Overall	1 ± 37 mrad	

- $B_s^0 \to J/\psi K^+K^-$ gives the lowest uncertainties

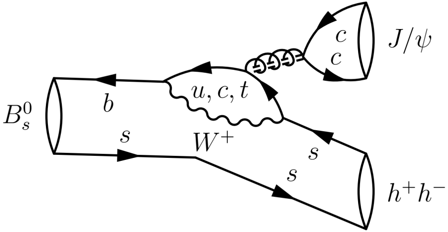
ϕ_s future prospects





- LHCb dominates world average
- Results consistent with SM prediction but still a lot of room for NP
- Uncertainty is statistically limited
- At 300 fb^{-1}: $\sigma^{stat}(\phi_\mathrm{s}) \sim 4$ mrad from $\mathrm{B}_\mathrm{s}^0 \to \mathrm{J}/\psi\,\phi$ only

Penguin Pollution



- With increasing precision crucial to understand penguin contribution
- Can use U-spin and SU(3) related modes, where penguin not suppressed [S. Faller, R. Fleischer, M. Jung, T. Mannel, arXiv:0809.0842]

$$\mathrm{b} \to \mathrm{c\bar{c}s} \text{ amplitude } (i = 0, \parallel, \perp)\text{:}\quad \mathcal{A}'_i(\mathrm{b} \to \mathrm{c\bar{c}s}) = (1 - \frac{\lambda^2}{2})\mathcal{A}'_i(1 + \varepsilon a'_i e^{i\theta'_i} e^{i\gamma})$$

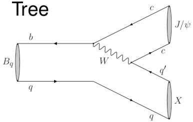
$$\mathrm{b} \to \mathrm{c\bar{c}d} \text{ amplitude:}\quad \mathcal{A}_i(\mathrm{b} \to \mathrm{c\bar{c}d}) = -\lambda\mathcal{A}_i(1 + a_i e^{i\theta_i} e^{i\gamma})$$

SU(3): $a'_i = a_i$, $\theta'_i = \theta_i$. Extract $\Delta\phi_\mathrm{s}(a_i, \theta_i)$ and $\Delta\beta^{peng}(a_i, \theta_i)$ from t to CP parameters and BF.

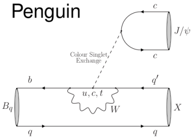
$\lambda \equiv |V_{us}| \approx 0.225$, $\epsilon \equiv \frac{\lambda^2}{1-\lambda^2} \approx 0.054$, γ unitarity triangle angle

Penguin Pollution

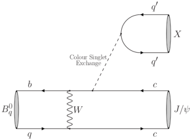
Tree



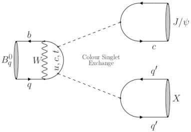
Penguin



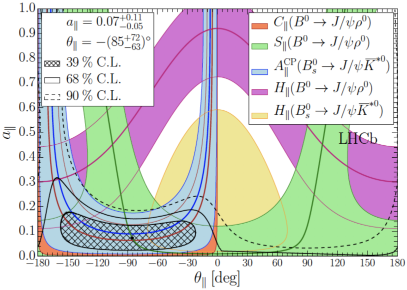
Exchange



Penguin-Annihilation



S. Faller, R. Fleischer, T. Mannel [JHEP 03 (2015) 145]



- $\mathrm{B}^0 \to \mathrm{J}/\psi\,\rho$ (BF, $\mathcal{C}$, $\mathcal{S}$)
- $\mathrm{B}_s^0 \to \mathrm{J}/\psi\,\mathrm{K}^*$ (BF, $\mathcal{C}$), has no PA and E

ϕ_s penguin pollution of $\mathrm{J}/\psi\,\phi$ LHCb with 3 fb^{-1} ($\mathrm{J}/\psi\,\mathrm{K}^*$ + $\mathrm{J}/\psi\,\rho$)

[JHEP 11 (2015) 082] [PLB 742 (2015) 38-49]

Consistent with zero:

$$\Delta\phi_s{}^0 = 0.000^{+0.011}_{-0.009}(\mathit{stat}) \pm^{+0.009}_{-0.004}(\mathit{syst})$$

$$\Delta\phi_s{}^\parallel = 0.000^{+0.011}_{-0.009}(\mathit{stat}) \pm^{+0.009}_{-0.004}(\mathit{syst})$$

$$\Delta\phi_s{}^\perp = 0.000^{+0.011}_{-0.009}(\mathit{stat}) \pm^{+0.009}_{-0.004}(\mathit{syst})$$

Summary & Outlook

- LHCb has the most precise measurement of ϕ_s
- ϕ_s will continue to be dominated by $B_s^0 \to J/\psi\,\phi$
  - Ultimate precision depends on ensuring excellent detector performance, e.g. flavour tagging at LHCb Upgrade
- **Penguin pollution** to be determined with increased precision in U-spin and SU(3)-related modes both by LHCb and Belle II

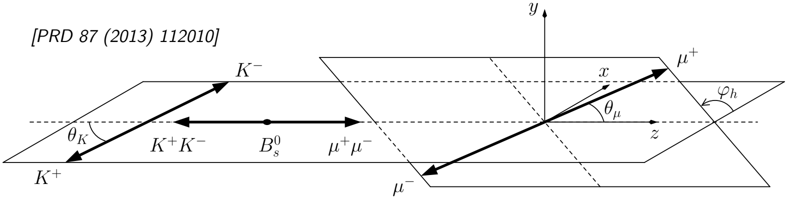
Future:

- Measurements statistically dominated → look forward to Run-2 updates (and LHCb-upgrade)

Thank you

Backup

Helicity Angle Observables



- θ_μ - angle between direction of μ in J/ψ rest frame and J/ψ direction in B_s^0 rest frame
- θ_K - angle between direction of K in ϕ rest frame and ϕ direction in B_s^0 rest frame
- φ_h - angle between decay plane of $J/\psi \to \mu\mu$ and $\phi \to KK$ decay plane