Overview of $\mathcal{CP}$V parameter ϕ_s determination

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Outline

$\mathcal{CP}$ Violation

- CKM matrix
- Introduction to ϕ_s

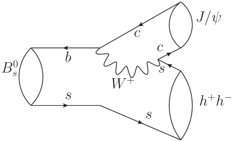
ϕ_s measurement

- Analysis method
- $B_s^0 \to J/\psi(\to \mu^+\mu^-)\phi(\to K^+K^-)$
- $B_s^0 \to J/\psi(\to \mu^+\mu^-)\pi^+\pi^-$
- $B_s^0 \to \psi(2S)(\to \mu^+\mu^-)\phi(\to K^+K^-)$
- $B_s^0 \to J/\psi K^+K^-$ in high $M(KK)$
- Experimental results

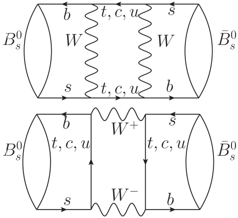
Conclusion

Violation of the $\mathcal{CP}$ symmetry

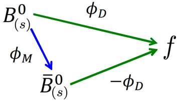
Three mechanisms of $\mathcal{CP}$ violation exist:



- Direct (in decay amplitudes)
- Mixing (indirect)
  - 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_H and B_L
    $$|B_L\rangle = p|B_s^0\rangle + q|\bar{B}_s^0\rangle$$
    $$|B_H\rangle = p|B_s^0\rangle - q|\bar{B}_s^0\rangle$$
  - 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



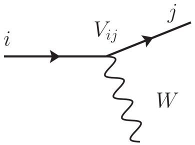
In the Standard Model $\mathcal{CP}$ violation is described by the CKM matrix

CKM - quark mixing matrix

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

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

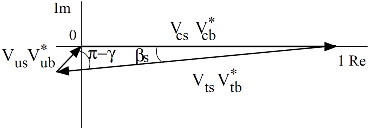
$$\begin{pmatrix} u \\ c \\ t \end{pmatrix} \leftrightarrow \begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \cdot \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$



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

$\lambda \approx 0.22$ [PRL 53 (1984) 1802]

- 6 unitary triangles
  Triangle (sb):
  $V_{us}V_{ub}^* + V_{cs}V_{cb}^* + V_{ts}V_{tb}^* = 0$



Introduction to ϕ_s

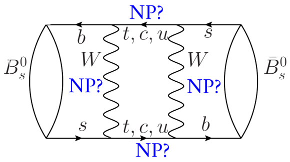
- SM prediction is very small and precise:

$$\phi_s^{c\bar{c}s} = \text{-}2\beta_s = \text{-}2arg\left(-\frac{V_{ts}V_{tb}^*}{V_{cs}V_{cb}^*}\right)$$
$$\phi_s^{c\bar{c}s} = \text{-}0.0376^{+0.0008}_{-0.0007} \text{ rad}$$

[CKMFitter, PRD 84 (2011) 033005]

***Ignoring subleading penguin contributions**

- If new particles contribute to "box" diagrams, then value of ϕ_M will be different than SM prediction

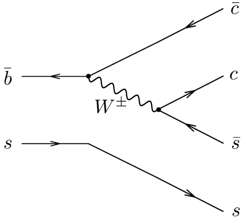


$$\phi_M = \phi_M^{SM} + \Delta\phi_M^{NP}$$
$$\phi_s^{c\bar{c}s} = \phi_M - 2\phi_D = -2\beta_s + \Delta\phi_M^{NP}$$

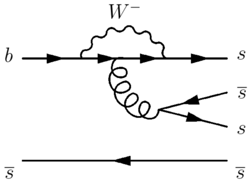
$\phi_s^{c\bar{c}s}$ is an excellent probe for possible NP!

Measurement of the phase ϕ_s

- $b \to c\bar{c}s$ transition
  - $B_s^0 \to J/\psi K^+K^-$
  - $B_s^0 \to J/\psi \pi^+\pi^-$
  - $B_s^0 \to \psi(2S)\phi$
  - $B_s^0 \to D_s^+ D_s^-$



- $b \to s\bar{s}s$ transition
  - $B_s^0 \to \phi\phi$

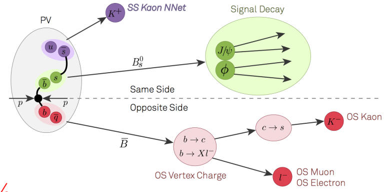


Analysis method

Time dependent angular flavour tagged analysis:

$$\frac{d^4\Gamma(B_s^0 \to J/\psi\phi)}{dtd\Omega} \propto \sum_{k=1}^{N} h_k(t) f_k(\theta_K, \theta_l, \phi)$$

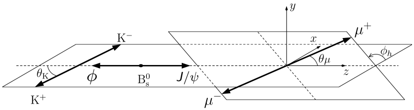
- $h_k(t)$ time dependent part: $\phi_s, \Delta\Gamma_s, \Gamma_s, \Delta m_s, A_i, \delta_i (i = 0, \perp, \parallel, S)$
- $f_k(\Omega)$ angular dependent part: θ_K, θ_l, ϕ
- Flavour tagging is determined using two algorithms:
  - Same Side - charge kaon which is correlated with B_s^0
  - Opposite Side - charge lepton or kaon from second B decay
  - Self tagging decays to calibrate the algorithms: $B^+ \to J/\psi K^+$ for OS and $B_s^0 \to D_s^- \pi^+$ for SS
  - Estimation of the algorithm efficiency:
    - tagging efficiency ε_{tag} and corrected mistag probability ω
    - total efficiency $\varepsilon_{eff} = \varepsilon_{tag}(1\text{-}2\omega)^2 = (3.73 \pm 0.15)\%$ for $B_s^0 \to J/\psi\phi$

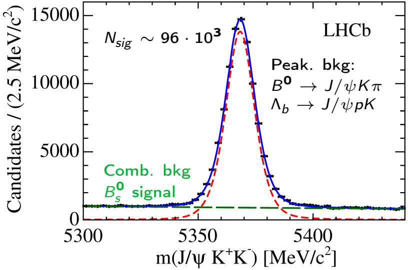


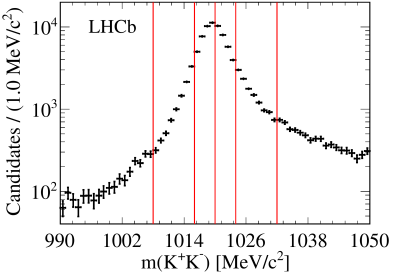
$B_s^0 \to J/\psi(\to \mu^+\mu^-)\phi(\to K^+K^-)$ (1)

[PRL 114 (2015) 041801]

- P→VV decay ⇒ final state is an admixture of $\mathcal{CP}$-even and $\mathcal{CP}$-odd eigenstates
- Amplitudes:
  3 $\mathcal{P}$-wave $(A_0, A_\perp, A_\parallel)$ + 1 $\mathcal{S}$-wave $(A_\mathcal{S})$







- Fit is carried out in 6 bins of $m(K^+K^-)$ region to measure $\mathcal{S}$-wave contribution

$B_s^0 \to J/\psi(\to \mu^+\mu^-)\phi(\to K^+K^-)$ (2)

Experiment	ϕ_s [rad]	$\Delta\Gamma_s$ [ps^{-1}]	Reference
CDF (9.6 fb^{-1})	[-0.60,+0.12], 68% CL	+0.068±0.026±0.009	[PRL 109 (2012) 171802]
D0 (8.0 fb^{-1})	$-0.55^{+0.38}_{-0.36}$	$+0.163^{+0.065}_{-0.064}$	[PRD 85 (2012) 032006]
ATLAS (19.2 fb^{-1})	-0.090±0.078±0.041	+0.085±0.011±0.007	[JHEP 08 (2016) 147]
CMS (19.7 fb^{-1})	-0.075±0.097±0.031	+0.095±0.013±0.007	[PLB 757 (2016) 97-120]
LHCb (3.0 fb^{-1})	-0.058±0.049±0.006	+0.0805±0.0091±0.0032	[PRL 114 (2015) 041801]

⋆ First uncertainty is statistical, second is systematic uncertainty

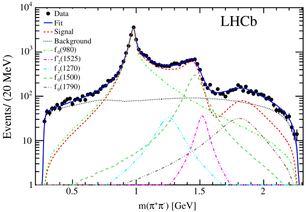
- $B_s^0 \to J/\psi K^+K^-$ is a golden channel: measurement of ϕ_s, Γ_s, $\Delta\Gamma_s$, Δm_s
- Consistent with SM predictions; no direct $\mathcal{CP}$ violation
- LHCb dominant contribution to systematic uncertainty gives decay time efficiency, angular efficiency and background subtraction
- No polarisation-dependent $\mathcal{CP}$ violation observed

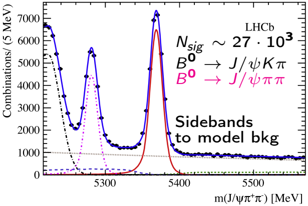
Most precise measurement of lifetime parameters to date by LHCb!

$B_s^0 \to J/\psi(\to \mu^+\mu^-)\pi^+\pi^-$

[PRD 89 (2014) 092006]
[PRL 114 (2015) 041801]

- Amplitude analysis to study resonance structure of $\pi^+\pi^-$ states $\Rightarrow$ $\mathcal{CP}$-odd state of $\pi^+\pi^-$ is >97.7% at 95% CL
- Largest component in resonant states is the $f_0(980)$ with $\sim$ 70%





$\phi_s = 0.070 \pm 0.068 \pm 0.008$ rad

Combination with $B_s^0 \to J/\psi\phi$
$\phi_s =$ -0.010$\pm$0.039 rad

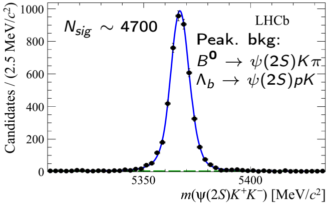
* First uncertainty is statistical, second is systematic uncertainty

- Consistent with SM predictions; no direct $\mathcal{CP}$ violation assumed equal for all $\pi^+\pi^-$ states
- Main contribution to systematic uncertainty from known $\pi^+\pi^-$ resonance model

Most precise $\phi_s^{c\bar{c}s}$ measurement from combination of $B_s^0 \to J/\psi K^+K^-$ and $B_s^0 \to J/\psi\pi^+\pi^-$ to date!

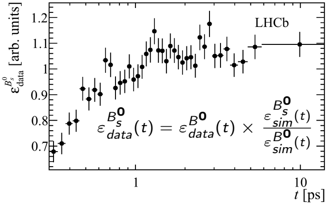
$B_s^0 \to \psi(2S)(\to \mu^+\mu^-)\phi(\to K^+K^-)$ [PLB 762 (2016) 253-262]

- Replace $J/\psi \to \psi(2S)$. The B_s^0 yield is decreased by factor ~ 20
- Prompt J/ψ events are used to calibrate decay time resolution model
- Decay time efficiency is determined using control $B^0 \to \psi(2S)K^*(\to K^+\pi^-)$ channel



$$
\begin{aligned}
\phi_s &= 0.23^{+0.29}_{-0.28} \pm 0.02 \text{ rad} \\
\Gamma_s &= 0.668 \pm 0.011 \pm 0.006 \text{ ps}^{-1} \\
\Delta\Gamma_s &= 0.066^{+0.041}_{-0.044} \pm 0.007 \text{ ps}^{-1}
\end{aligned}
$$

* First uncertainty is statistical, second is systematic uncertainty

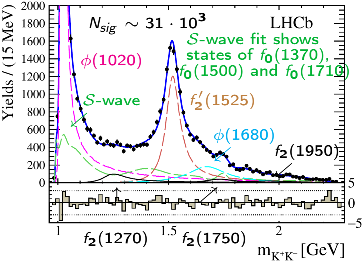


- Consistent with $B_s^0 \to J/\psi K^+K^-$ fit results
- Limited size of data sample
- Systematic uncertainty is $< 0.2\sigma_{stat}$ except for Γ_s ($\sim 0.6\sigma_{stat}$)

$B_s^0 \to J/\psi K^+ K^-$ in high $M(KK)$ region

[JHEP 08 (2017) 037]

- $B_s^0 \to J/\psi KK$ with $M(KK) > 1.05$ GeV higher than $M(\phi(1020))$
- Formalism of the analysis is the same as used in $B_s^0 \to J/\psi\phi$
- Decay time efficiency is determined using control $B^0 \to J/\psi K^*(\to K^+\pi^-)$ channel



$$\begin{aligned} \phi_s &= 0.119 \pm 0.107 \pm 0.034 \text{ rad} \\ \Gamma_s &= 0.650 \pm 0.006 \pm 0.004 \text{ ps}^{-1} \\ \Delta\Gamma_s &= 0.066 \pm 0.018 \pm 0.010 \text{ ps}^{-1} \end{aligned}$$

Combination with $B_s^0 \to J/\psi\phi$

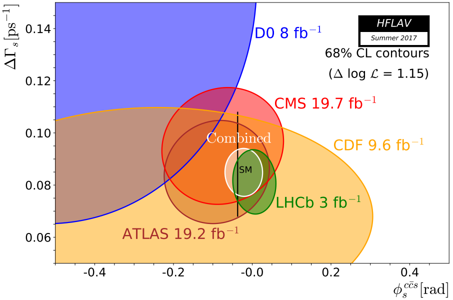
$$\begin{aligned} \phi_s &= -0.025 \pm 0.045 \pm 0.008 \text{ rad} \\ \Gamma_s &= 0.6588 \pm 0.0022 \pm 0.0015 \text{ ps}^{-1} \\ \Delta\Gamma_s &= 0.0813 \pm 0.0073 \pm 0.0036 \text{ ps}^{-1} \end{aligned}$$

* First uncertainty is statistical, second is systematic uncertainty

- Combination with $B_s^0 \to J/\psi\phi$ improves a precision of the ϕ_s measurement by over 9%
- Main fractions: $\sim$70% $\phi(1020)$, $\sim$10% $f_2'(1525)$ and $\mathcal{S}$-wave each
- Largest contribution to systematic uncertainty from the resonance fit model ($\pm$0.0236 rad)

ϕ_s experimental measurements

- $\phi_s^{c\bar{c}s} \stackrel{\text{SM}}{=}$ -0.0370±0.0006 rad **[CKMFitter, PRD 84 (2011) 033005]**
- $\Delta\Gamma_s \stackrel{\text{SM}}{=}$ 0.088±0.020 ps^{-1} **[M. Artuso et al, arXiv:1511.09466]**



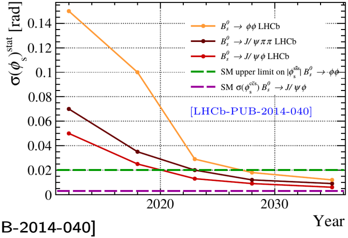
HFLAV combination

$\phi_s^{c\bar{c}s}$ = -0.021±0.031 rad
$\Delta\Gamma_s$ = 0.085±0.006 ps^{-1}
Γ_s = 0.6640±0.0020 ps^{-1}

- $B_s^0 \rightarrow J/\psi KK$ gives the lowest uncertainties
- LHCb dominates world average
- Consistent with SM predictions but still a lot of window for NP

Conclusion

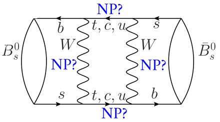
- Most precise measurement of ϕ_s in the B_s^0 system has been made at LHCb using Run I data
- Future perspectives:
  - Run I: $B_s^0 \to J/\psi(\to e^+e^-)KK$, $B_s^0 \to (K^+\pi^-)(K^-\pi^+)$
  - Run II: new modes with more data



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

Decay mode $\sigma_{stat}(\phi_s)$ [rad]	Run I (3 fb^{-1}) (2010-2012)	Run II (8 fb^{-1}) (2015-2018)	LHCb upgrade (+2020, 50 fb^{-1})	Theory limit
$B_s^0 \to J/\psi KK$	0.049	0.025	0.009	∼0.001
$B_s^0 \to J/\psi f_0$	0.068	0.035	0.012	∼0.01

- Penguin effects in B_s^0 mixing are under control: $\Delta\phi_s \sim 0.001 \pm 0.020$ rad ... but more work still be needed for LHCb upgrade

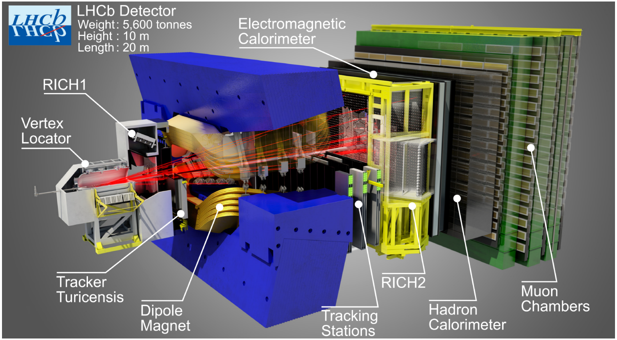


[JHEP 11 (2015) 082]
[PLB 742 (2015) 38]

Thank you for your attention!

Backups

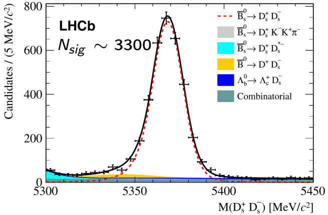
Large Hadron Collider beauty Detector [JINST 3 (2008) S08005]



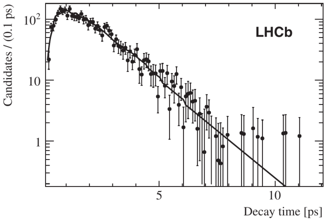
- Single-arm forward spectrometer, covering $2 < \eta < 5$ ($10 < \theta < 300$ (250) mrad)
- Momentum resolution: $\Delta p/p = 0.5\%$ at 5 GeV/c to 1.0% at 200 GeV/c
- Impact parameter resolution: 20 μm for high p_T tracks
- Decay time resolution: $\sim$ 45 fs
- Invariant mass resolution: $\sim$ 8 MeV/c^2 for $B \to J/\psi X$ decays with J/ψ mass constraint
- $\mathcal{L} = 3$ fb^{-1} collected in Run I at $\sqrt{s} =$ 7-8 TeV

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

[PRL 113 (2014) 211801]



- Purely $\mathcal{CP}$-even state $\Rightarrow$ no angular analysis is required
- Candidates are reconstructed in four final states $\Rightarrow$ combinations of $D_s^{\pm}$ into $KK\pi$, $K\pi\pi$ and $\pi\pi\pi$
- $B^0 \to D^-(\to K^+ 2\pi^-) D_s^+(\to K^{\pm}\pi^+)$ is used as control channel



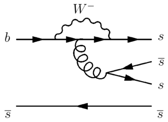
$$\phi_s = 0.02 \pm 0.17 \pm 0.02 \text{ rad}$$

* First uncertainty is statistical, second is systematic uncertainty

- Consistent with SM predictions, no direct $\mathcal{CP}$ violation
- Systematics dominated by the decay time resolution
- Decay time uncertainty calibrated from the simulation

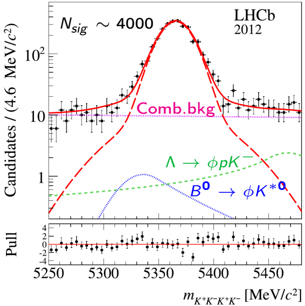
$B_s^0 \to \phi(\to K^+K^-)\phi(\to K^+K^-)$ [PRD 90 (2014) 052011]

- $b \to s\bar{s}s$ penguin process is sensitive to NP on the loops
- P→VV + P→VS and P→SS due to proximity to $f_0(980)$ resonance ⇒ angular analysis
- Amplitudes:
  3 $\mathcal{CP}$-even $(A_0, A_\parallel, A_{SS})$ + 2 $\mathcal{CP}$-odd $(A_\perp, A_S)$



$|\phi_s^{s\bar{s}s}|^{SM}$ <0.02 rad

[NPB 774 (2007) 64-101]
[arXiv:0810.0249]
[PRD 80 (2009) 114026]



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

* First uncertainty is statistical, second is systematic uncertainty

- Consistent with SM predistions, no $\mathcal{CP}$V in $b \to s\bar{s}s$ decay amplitude
- Fraction of $\mathcal{S}$-wave is found to be consistent with zero
- Most significant systematics arise from the angular and decay time acceptance