A 2-SLITS EXPERIMENT

- Will focus on $B_s$ decays to a flavourless final state

- CP violation from interference of two paths: direct decay and decay preceded by a flavour oscillation

- CP violation encoded by the complex parameter

\[ \lambda_f = \frac{q}{p} \frac{\overline{A}_f}{A_f} \]

- Measure phase and module

\[ \phi_f = \arg(\lambda_f) \text{ and } |\lambda_f| \]
>6 years (>9 fb$^{-1}$) of 7-8-13 TeV proton-proton collisions at 40 MHz.

About 0.5% of collisions yields beauty pairs, $O(10^3/s)$ in acceptance. Store online 30-80% of them using muons, $p_T$ and displacement.

10% of them are $B_s$. Talking about several hundred thousands of decays.
Decay-time resolution of \( \sim 45 \text{ fs} \) (\( \sim 1/7 \) of \( B_{s^0} \) oscillations period)
New measurements of $\phi_s$ with $B_s^0 \rightarrow J/\psi \phi$, $B_s^0 \rightarrow J/\psi \pi\pi$ and $B_s^0 \rightarrow \phi\phi$ decays using 2015-2016 (1.9 fb$^{-1}$) Run-2 data

See also Biplab Dey’s talk for first CPV measurement in radiative $B_s^0 \rightarrow \phi\gamma$ decays
CP-violating phase $\varphi_s = \arg(\lambda_{ccs})$

In tree-dominated decays like $B_s^0 \to J/\psi \phi$ and $B_s^0 \to J/\psi \pi \pi$, $\varphi_s = -2\beta_s = 2\arg(V_{ts}V_{tb}^*/V_{cs}V_{cb}^*)$ assuming SM. Global CKM fit gives a precise expectation, $-0.03686^{+0.00096}_{-0.00068}$ rad

Deviations would indicate new physics.

Neglecting higher-order amplitudes (penguin loops)
\[ A_{CP}(t) = \frac{N[\bar{B}_s \rightarrow f](t) - N[B_s \rightarrow f](t)}{N[\bar{B}_s \rightarrow f](t) + N[B_s \rightarrow f](t)} \propto \eta_{CP} \sin \phi_s \sin(\Delta m_s t) \]

- Need to know initial $B_s$ flavour
- Need to resolve oscillations, good decay-time resolution
- Need to know $\eta_{CP}$, CP-parity of final states
A mixture of CP-even and CP-odd components, need an angular analysis to disentangle them.

Mainly CP-odd, requires angular analysis to assess effect of the small CP-even component.

\[ B_s^0 \rightarrow J/\psi \, \phi \]

117K signal candidates

\[ B_s^0 \rightarrow J/\psi \, \pi^+\pi^- \]

34K signal candidates


arXiv:1903.05530
\[ A_{CP}(t) \equiv \frac{N_{[\bar{B}_s \to f]}(t) - N_{[B_s \to f]}(t)}{N_{[\bar{B}_s \to f]}(t) + N_{[B_s \to f]}(t)} \]

**B_{s}^{0}** OR **\bar{B}_{s}^{0}**?
Extremely challenging task in hadron collisions.

**Hadronisation process.**
The charge of the kaon accompanying the $B_s$ is correlated to the flavour.
• Extremely challenging task in hadron collisions.

• **Hadronisation process.**
  The charge of the kaon accompanying the $B_s$ is correlated to the flavour.

• **Decay products of the other $b$-hadron in the events.**
  The charge might be correlated with the $b$-hadron flavour, which is opposite to the signal $B_s$ flavour.

**Figure 1.12:**
Model prediction and the CDF upper limit are also visible.

**Figure 1.11:**
Examples of Feynman diagrams for $(b,c,d)$.

**NB:** no coherent production!
CALIBRATION AND PERFORMANCE

- A wrong tag dilutes the asymmetry (dilution about 30%)
- Need good knowledge of wrong-tag probability. Use control samples of flavour-specific $B_s^0 \to D_s\pi$ decay for SSK, and self-tagging $B^+ \to J/\psi K^+$ decay for OS.
- **Effective tagging efficiency of about 5%, a relative +20% w.r.t. previous analyses.**

SSK calibration using $B_s^0 \to D_s\pi$ data

Mistag probability calibrated by resolving the flavour oscillations in the $B_s^0 \to D_s\pi$ decay

DECAY TIME RESOLUTION

- Another dilution of the asymmetry, damped by
  \[ D = e^{-\sigma^2 \Delta m_s^2 / 2} \]

- Calibrate with a large sample of “prompt” $J/\psi\phi$ candidates selected w/o lifetime biasing requirements.

- The peak is the resolution function (right tail from B-decays). Resolution of $45\text{ fs}$, $D \sim 70\%$.

Calibration with “prompt” $J/\psi\phi$ candidates

\[ \sigma \sim 45\text{ fs} \]

DEcAY TiME EFFICIENCY

• Mostly flat after a cut at 0.3 ps. Yet, small corrections for a high-precision measurement of the $\Gamma_s$ and $\Delta \Gamma_s$.

• Acceptance from data using similar decay $B^0 \rightarrow J/\psi K^*$. Correct with simulation residual differences between $B^0$ and $B_s^0$ decays. **Will measure** $\Gamma_s - \Gamma_d$.

• Validate the method with a measurement of $\Gamma_u - \Gamma_d$ using 1.6M of $B^+ \rightarrow J/\psi K^+$ decays. **Get value consistent with WA** with 0.003 ps$^{-1}$ precision.
**CP OF THE FINAL STATE**

- $J/\psi\phi$ is a vector-vector final state: 3 angular momenta allowed. L=0, 2 are **CP-even** and L=1 is **CP-odd**. KK can also be in a **S-wave** state (not from a $\phi$ decay), **CP-odd**.

- $J/\psi\pi\pi$ mostly $J/\psi f_0(980)$ **CP-odd** but rich structures of resonances to disentangle with an amplitude analysis.
• Disentangle the CP mixture of the final state through an analysis of the angles of final-state particles.

• Need to correct for the efficiency as a function of the angles. Use simulation.

• Validate the method on $B^0 \rightarrow J/\psi K^*$ and $B^+ \rightarrow J/\psi K^+$ data (with a 0.1% precision).
$(SOME)\ FIT\ PROJECTIONS$

$B^0_s \rightarrow J/\psi \phi$


$\cos \theta_{\mu}$

$\cos \theta_K$

$LHCb$ preliminary

Weighted cands. / 0.05

$\Gamma_L$

$\Gamma_H$

$S$-wave, $\sim \Gamma_H$

$C\text{-even}, \sim \Gamma_L$

$C\text{-odd}$

Weighted cands. / (0.3 ps)

Decay time [ps]

$LHCb$ preliminary

Weighted cands. / (0.05 ps)

$\pi$

$LHCb$ preliminary

Weighted cands. / (0.05 \text{rad})

$LHCb$
**RESULTS**

\[ \text{Bs}^0 \rightarrow \text{J}/\psi \phi \]

\[ \phi_s = -0.083 \pm 0.041 \pm 0.006 \text{ rad} \]
\[ |\lambda| = 1.012 \pm 0.016 \pm 0.006 \]
\[ \Gamma_s - \Gamma_d = -0.0041 \pm 0.0024 \pm 0.0015 \text{ ps}^{-1} \]
\[ \Delta \Gamma_s = 0.0773 \pm 0.0077 \pm 0.0026 \text{ ps}^{-1} \]

\[ \text{Bs}^0 \rightarrow \text{J}/\psi \pi^+ \pi^- \]

\[ \phi_s = -0.057 \pm 0.060 \pm 0.011 \text{ rad} \]
\[ |\lambda| = 1.01^{+0.08}_{-0.06} \pm 0.03 \]
\[ \Gamma_H - \Gamma_d = -0.050 \pm 0.004 \pm 0.004 \text{ ps}^{-1} \]

By combining the two and with previous Run 1 LHCb results:

\[ \phi_s = -0.041 \pm 0.025 \text{ rad} \]
\[ |\lambda| = 0.993 \pm 0.010 \]
\[ \Gamma_s = 0.6562 \pm 0.0021 \text{ ps}^{-1} \]
\[ \Delta \Gamma_s = 0.0816 \pm 0.0048 \text{ ps}^{-1} \]

World best results. All compatible with SM.
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By combining the two and with previous Run 1 LHCb results

\[ \Gamma_s / \Gamma_d = 0.9938 \pm 0.0036 \pm 0.0023 \]
in agreement with HQE value, 1.0006 \pm 0.0025

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World best results. All compatible with SM.
Preliminary HFLAV combination yields

\[ \phi_s = -0.055 \pm 0.021 \text{ rad} \]
\[ \Delta \Gamma_s = 0.0764^{+0.0034}_{-0.0033} \text{ ps}^{-1} \]

Includes recent ATLAS preliminary results. [ATLAS-CONF-2019-009]
FROM TREE TO PENGUIN

• **CP-violating phase** \( \phi_{s}^{(s \bar{s} s)} = \arg (\lambda_{s \bar{s} s}) \)

In penguin-dominated decays \( B_s^0 \rightarrow \phi \phi \), it gets very close to zero assuming SM. Its measurement is a null test of the SM.
FROM TREE TO PENGUIN

- Use 2011-2016 data (4.9fb⁻¹) to select about 9000 signal decay in the \([K^+K^-][K^+K^-]\) final state.
- Again, flavour-tagged, time-dependent and angular analysis.
- Lifetime-biasing online selection. Non-trivial decay-time acceptance.

\[
\phi_s^{S\overline{S}S} = -0.073 \pm 0.115 \text{ (stat)} \pm 0.027 \text{ (syst)} \text{ rad}
\]
\[
|\lambda| = 0.99 \pm 0.05 \text{ (stat)} \pm 0.01 \text{ (syst)}.
\]

In agreement with the SM expectation.
CONCLUSION

- New world best measurement of $\phi_s$ from $B_s^0 \to J/\psi KK, J/\psi\pi\pi$
- New measurement of $\phi_s$ from $B_s^0 \to \phi\phi$
- All compatible with SM expectations. All statistically limited.
BACKUP
Preliminary HFLAV combination yields

\[ \varphi_s = -0.055 \pm 0.021 \text{ rad} \]
\[ \Delta \Gamma_s = 0.0764^{+0.0034}_{-0.0033} \text{ ps}^{-1} \]

Includes recent ATLAS preliminary results.
[ATLAS-CONF-2019-009]

NB: 4\(\sigma\) discrepancy in \(\Gamma_s\) between LHCb and ATLAS
LHCb \(0.6538 \pm 0.0033\) ps\(^{-1}\)
ATLAS \(0.6690 \pm 0.0014\) ps\(^{-1}\)
WA(’18) \(0.6629 \pm 0.0018\) ps\(^{-1}\)
### Table 3: Summary of the systematic uncertainties.

| Source                          | $\phi_s$ [rad] | $|\lambda|$ | $\Gamma_s - \Gamma_d$ [ps$^{-1}$] | $\Delta \Gamma_s$ [ps$^{-1}$] |
|---------------------------------|----------------|-------------|-----------------------------------|---------------------------------|
| Mass: width parametrisation     | -              | -           | -                                 | 0.0002                          |
| Mass: $t$ & angles dependence   | 0.004          | 0.0037      | 0.0007                            | **0.0022**                      |
| Multiple candidates             | 0.0011         | 0.0011      | 0.0003                            | 0.0001                          |
| Fit bias                        | 0.001          | -           | -                                 | 0.0003                          |
| $C_{SP}$ factors                | 0.001          | 0.0010      | -                                 | 0.0001                          |
| Time res.: model applicability  | -              | -           | -                                 | -                               |
| Time res.: $t$ bias             | **0.0032**     | 0.0010      | 0.0002                            | **0.0003**                      |
| Time res.: wrong PV             | -              | -           | -                                 | -                               |
| Ang. acc.: sim. sample size     | 0.0011         | 0.0018      | -                                 | -                               |
| Ang. acc.: weighting            | **0.0022**     | 0.0043      | 0.0001                            | 0.0002                          |
| Ang. acc.: clone candidates     | 0.0005         | 0.0014      | 0.0002                            | **0.0001**                      |
| Ang. acc.: $t$ & $\sigma_t$ dependence | 0.0012     | 0.0007      | 0.0002                            | **0.0010**                      |
| Dec.-time eff.: statistical     | -              | -           | **0.0012**                        | 0.0008                          |
| Dec.-time eff.: kin. weighting  | -              | -           | 0.0002                            | -                               |
| Dec.-time eff.: PDF weighting   | -              | -           | 0.0001                            | **0.0001**                      |
| Dec.-time eff.: $\Delta \Gamma_s$ = 0 sim. | -           | -           | 0.0003                            | **0.0005**                      |
| Length scale                    | -              | -           | -                                 | -                               |
| Quadratic sum of syst.          | 0.0061         | 0.0064      | 0.0015                            | 0.0026                          |

**$B_s^0 \rightarrow J/\psi \phi$**

Bottom-line: still negligible compared to the statistical uncertainty

- $\phi_s$ dominated by decay-time resolution and angular acceptance
- $\Delta \Gamma_s$ dominated by fit hypothesis (mass-factorisation)
- $\Gamma_s$ dominated by decay-time efficiency correction

Bottom-line: still negligible compared to the statistical uncertainty

$\phi_s$ dominated by resonances model of the $\pi\pi$ final state

$\Gamma_H$ dominated by background description

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| Source                               | $\Gamma_H - \Gamma_{B^0}$ | $|\lambda|$ | $\phi_s$ |
|--------------------------------------|-----------------------------|-------------|----------|
|                                      | [fs$^{-1}$]                 | [$\times 10^{-3}$] | [mrad]   |
| Decay-time acceptance                | 2.0                         | 0.0         | 0.3      |
| $\tau_{B^0}$                         | 0.2                         | 0.5         | 0.0      |
| Efficiency ($m_{\pi\pi}$, $\Omega$) | 0.2                         | 0.1         | 0.0      |
| Decay-time resolution width          | 0.0                         | 4.3         | 4.0      |
| Decay-time resolution mean           | 0.3                         | 1.2         | 0.3      |
| Background                            | 3.0                         | 2.7         | 0.6      |
| Flavour tagging                      | 0.0                         | 2.2         | 2.3      |
| $\Delta m_s$                         | 0.3                         | 4.6         | 2.5      |
| $\Gamma_L$                           | 0.3                         | 0.4         | 0.4      |
| $B_c^+$                              | 0.5                         | -           | -        |
| Resonance parameters                 | 0.6                         | 1.9         | 0.8      |
| Resonance modelling                  | 0.5                         | 28.9        | 9.0      |
| Production asymmetry                 | 0.3                         | 0.6         | 3.4      |
| **Total**                            | 3.8                         | 29.9        | 11.0     |

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**B$_s^0 \to J/\psi\pi^+\pi^-$**

arXiv:1903.05530
Among other channels, competitive precision can be obtained with which have been found to be dominated by the LHCb detector has excellent time resolution (information can be obtained from improving it will be essential to have good control over possible hadronic e. There remains space for new physics contributions of precision of the world average is dominated by the LHCb measurement which itself is dominated mass. Detailed understanding of any variation of e. CP angular momentum between the two vector resonances. In addition, there is a small (interfering used in LHCb to suppress backgrounds e. To a high trigger e. has a relatively high branching fraction and the presence of two muons in the final state leads time-dependent angular analysis of the measurements.

Sign of physics beyond the SM, strongly motivating the need for more precise experimental based upon global fits to experimental data [43]. Deviations from this value would be a clear Scaling of the statistical precision on Figure 3.3:
\[ A(t) \equiv \frac{N_{\text{unmix}}(t) - N_{\text{mix}}(t)}{N_{\text{unmix}}(t) + N_{\text{mix}}(t)} \propto (1 - 2\omega) \cos(\Delta m_s t) \]

Measure the fraction of wrong tags \( \eta \) vs the predicted wrong fraction.