Measurement of the CP-violating phase $\phi_s$ in the $B_s^0 \rightarrow J/\psi\phi$ decay using ATLAS 2015-2017 data, 13 TeV

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Motivation - Measurement of the CP-violating phase $\phi_s$ in the $B^0_s \rightarrow J/\psi\phi$ decay

CP violation - history

- In Standard Model the CP violation now well understood
  - Firstly observed in the system of neutral kaons [ref.]
  - CPV occurs due to interference between a direct decay and a decay with $B^0_s - \bar{B}^0_s$ mixing

Transitions between quarks can be described by the CKM matrix:

$$
\begin{bmatrix}
|V_{ud}| & |V_{us}| & |V_{ub}| \\
|V_{cd}| & |V_{cs}| & |V_{cb}| \\
|V_{td}| & |V_{ts}| & |V_{tb}|
\end{bmatrix} =
\begin{bmatrix}
0.97370 \pm 0.00014 & 0.2245 \pm 0.0008 & 0.00382 \pm 0.00024 \\
0.221 \pm 0.004 & 0.987 \pm 0.011 & 0.0410 \pm 0.0014 \\
0.0080 \pm 0.0003 & 0.0388 \pm 0.0011 & 1.013 \pm 0.030
\end{bmatrix}
$$
Motivation

New physics

- In the presence of new physics phenomena, sources of CP violation can arise in addition to those predicted by the Standard Model

\[ B^0_s \rightarrow J/\psi (\mu^+ \mu^-) \phi (K^+ K^-) \]

- CPV in \( B^0_s \rightarrow J/\psi \phi \) is described by the parameters \( \phi_s, \Gamma_s^L, \Gamma_s^H (\Gamma_s, \Delta \Gamma_s) \) [ref.]
- \( \phi_s \) is related to the CKM matrix elements: \( \phi_s \approx 2 \arg[-(V_{ts} V_{tb}^*)/(V_{cs} V_{cb}^*)] \)
  - \( |V_{tb}| \approx |V_{cs}| \approx 1; |V_{ts}| \approx |V_{cb}| \approx 0.04 \)
- \( \phi_s \) can be predicted in the SM with high precision (3%)
  - \( \phi_s = -0.03696^{+0.00072}_{-0.00082} \) rad by CKMFitter group
  - \( \phi_s = -0.03700 \pm 0.00104 \) rad according to UTfit Collaboration
- Very precise measurement needed
Motivation

Accessible through a measurement of the time dependent angular distribution

\[ \frac{d^4 \Gamma}{dt d\Omega} = \sum_{k=1}^{10} O_k(t) g_k^k (\theta_T, \psi_T, \phi_T) \]

Theoretical description
Probability density function for $B^0_s \to J/\psi \phi$

<table>
<thead>
<tr>
<th>$k$</th>
<th>$O^{(k)}(t)$</th>
<th>$g^{(k)}(\theta_T, \psi_T, \phi_T)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>$\frac{1}{2}</td>
<td>A_0(0)</td>
</tr>
<tr>
<td>2</td>
<td>$\frac{1}{2}</td>
<td>A_{</td>
</tr>
<tr>
<td>3</td>
<td>$\frac{1}{2}</td>
<td>A_{\perp}(0)</td>
</tr>
<tr>
<td>4</td>
<td>$\frac{1}{2}</td>
<td>A_0(0)</td>
</tr>
<tr>
<td>5</td>
<td>$</td>
<td>A_{</td>
</tr>
<tr>
<td></td>
<td>$\pm e^{-\Gamma_{s}t}(\sin(\delta_{</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>$</td>
<td>A_0(0)</td>
</tr>
<tr>
<td></td>
<td>$\pm e^{-\Gamma_{s}t}(\cos(\delta_{\perp} - \delta_{S}) \cos(\Delta m_s t) - \cos(\delta_{</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>$\frac{1}{2}</td>
<td>A_S(0)</td>
</tr>
<tr>
<td>8</td>
<td>$</td>
<td>A_S(0)</td>
</tr>
<tr>
<td></td>
<td>$\pm e^{-\Gamma_{s}t}(\cos(\delta_{</td>
<td></td>
</tr>
</tbody>
</table>
Data collection


Measurement of the CP-violating phase $\phi_s$ in the $B^0_s \to J/\psi \phi$ decay
Data selection - $B^0 \rightarrow J/\psi(\mu^+\mu^-)\phi(K^+K^-)$

1. step) $J/\psi$ reconstruction
- $\mu$ triggers ($p_T(\mu) > 4$ GeV or 6 GeV)
- $\mu^+\mu^-$ refitted to a common vertex ($\chi^2/\text{ndof} < 10$)
- 3 pseudorapidity bins with different $m(\mu\mu)$ window

2. step) $\phi$ reconstruction
- $p_T(K^\pm) > 1$ GeV
- $m(KK) \in (1008.5, 1030.5)$ MeV

3. step) $B^0 \rightarrow J/\psi(\mu^+\mu^-)\phi(K^+K^-)$
- 4 tracks - ID momentum measurement only
- $B^0$ candidates refitted from $J/\psi$ and $\phi$
  - $m(J/\psi)$ fixed to the PDG value
  - $m(B^0) \in (5150, 5650)$ MeV
  - $\chi^2/\text{ndof}(SV) < 3$
  - $B$ candidate with the smallest $\chi^2/\text{ndof}$ is selected
- In 2015-2017, 2 977 526 $B^0_s$ candidates were collected.
Flavour tagging

Opposite-site tagging

- Knowledge of $B_s/\bar{B}_s$ flavour at production significantly increases signal PDF sensitivity to $\phi_s$
- Four taggers: Tight muon, electron, Low-$p_T$ muon, $b$-jet
- Key variable: $Q_X$ - charge of $p_T$-weighted tracks in a cone ($\Delta R$) around the opposite side primary object ($\mu$, $e$, $b$-jet), used to build per-candidates $B_s$ tag probability
  
  $Q_X = \frac{\sum_{i=1}^{N_{\text{tracks}}} p_{T,\nu}^c q_i}{\sum_{i=1}^{N_{\text{tracks}}} p_{T,\nu}^c}$

- Calibration on self-tagged $B^\pm \rightarrow J/\psi K^\pm$
- Tagging probability is propagated into the likelihood
Maximal Likelihood Fit: mass + lifetime + 3 angles + conditional observables

The unbinned maximum likelihood fit was performed for:

- Observables: $B_s^0$ mass ($m_i$), decay time ($t_i$) and the decay angles $\Omega = (\theta_T, \Psi_T, \phi_T)$
- Conditional observables: $\sigma_{m_i}, \sigma_{t_i}, \rho_{T_i}$ and $B$-tagging probability: $P(B|Q)$
- Physics parameters:
  - CPV phase $\phi_s$
  - Decay widths: $\Delta \Gamma_s, \Gamma_s$
  - Decay amplitudes: $|A_0(0)|^2, |A_{||}(0)|^2, \delta_{||}, \delta_{\perp}$
  - S-wave: $|A_S(0)|^2, \delta_S$
  - and $\Delta m_s$ fixed to PDG, $\lambda=1$ (no direct CPV)

$$
\ln \mathcal{L} = \sum_{i=1}^{N_{\text{events}}} \left\{ w_i \cdot \ln(f_s \cdot \mathcal{F}_s(m_i, t_i, \sigma_m, \sigma_t, \Omega_i, P(B|Q), \rho_{T_i})) + f_s \cdot f_{B_d^0} \cdot \mathcal{F}_{B_d^0}(m_i, t_i, \sigma_m, \sigma_t, \Omega_i, P(B|Q), \rho_{T_i}) + f_s \cdot f_{\Lambda_b} \cdot \mathcal{F}_{\Lambda_b}(m_i, t_i, \sigma_m, \sigma_t, \Omega_i, P(B|Q), \rho_{T_i}) + (1 - f_s \cdot (1 + f_{B_d^0} + f_{\Lambda_b})) \cdot \mathcal{F}_{\text{bkg}}(m_i, t_i, \sigma_m, \sigma_t, \Omega_i, P(B|Q), \rho_{T_i})) \right\}
$$
Mass and Proper decay time projections

Fit with a good agreement with data

Measurement of the CP-violating phase $\phi_s$ in the $B^0_S \rightarrow J/\psi \phi$ decay
Decay angles projections

Fit with a good agreement with data

Measurement of the CP-violating phase $\phi_S$ in the $B_S^0 \rightarrow J/\psi \phi$ decay
\[ \phi_s = -0.087 \pm 0.036 \text{ (stat.)} \pm 0.021 \text{ (syst.)} \]

- Statistical uncertainty still dominant

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Solution (a)</th>
<th>Statistical uncertainty</th>
<th>Systematic uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \phi_s ) [rad]</td>
<td>-0.087</td>
<td>0.036</td>
<td>0.021</td>
<td></td>
</tr>
<tr>
<td>( \Delta \Gamma_s ) [ps(^{-1})]</td>
<td>0.0657</td>
<td>0.0043</td>
<td>0.0037</td>
<td></td>
</tr>
<tr>
<td>( \Gamma_s ) [ps(^{-1})]</td>
<td>0.6703</td>
<td>0.0014</td>
<td>0.0018</td>
<td></td>
</tr>
<tr>
<td>(</td>
<td>A_\parallel(0)</td>
<td>^2 )</td>
<td>0.2220</td>
<td>0.0017</td>
</tr>
<tr>
<td>(</td>
<td>A_0(0)</td>
<td>^2 )</td>
<td>0.5152</td>
<td>0.0012</td>
</tr>
<tr>
<td>(</td>
<td>A_S</td>
<td>^2 )</td>
<td>0.0343</td>
<td>0.0031</td>
</tr>
<tr>
<td>( \delta_{\parallel} ) [rad]</td>
<td>3.22</td>
<td>0.10</td>
<td>0.05</td>
<td></td>
</tr>
<tr>
<td>( \delta_{\parallel} ) [rad]</td>
<td>3.36</td>
<td>0.05</td>
<td>0.09</td>
<td></td>
</tr>
<tr>
<td>( \delta_{\perp} - \delta_S ) [rad]</td>
<td>-0.24</td>
<td>0.05</td>
<td>0.04</td>
<td></td>
</tr>
</tbody>
</table>

- \( \phi_s \) in agreement with the SM value
- ATLAS is consistent with CMS and LHCb
Summary

Conclusion

Results from ATLAS 2015-2017 combined with Run 1 were presented

- Measurement is consistent with the SM prediction and LHCb and CMS measurements
  
  \[ \phi_s^{\text{ATLAS}} = -0.087 \pm 0.036 \text{ (stat.)} \pm 0.021 \text{ (syst.)} \]
  
  \[ \phi_s^{\text{SM}} = -0.03696^{+0.00072}_{-0.00082} \text{ rad (CKMFitter)} \]
  
  \[ \phi_s^{\text{SM}} = -0.03700 \pm 0.00104 \text{ rad (UTfit)} \]

- Next step towards a more precise measurement
  
  - to add 60 \( fb^{-1} \) from 2018

Stay tuned for more results

- \( B_d \) lifetime measurement with \( B_d^0 \rightarrow J/\psi K^* \) (\( \Gamma_s/\Gamma_d \))
- \( B_s \) lifetime measurement with \( B_s \rightarrow \mu\mu \)
- Measurement of the CP violation in \( B_s \rightarrow J/\psi \phi \) with full Run 2 statistics
Thank you for your attention!