Measurement of CP violation in Bs meson with the CMS detector

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Outline

- Underlying physics
  - CP symmetry
  - CP in the SM
  - CP measurement in $B_s$
- CMS experiment at LHC
- $B_s$ meson study
  - Reconstruction
  - Analysis
C-P symmetry

• P parity conjugation: mirror reflection in the space, invariance means that “left” and “right” cannot be defined
• C charge conjugation C: conjugation of charge and other additive quantum numbers, invariance means that particles and antiparticles give the same results
• CP conjugation: combination of the the C and P
• 1927 Wigner showed that parity is conserved in QED
• 1949 weak force was postulated, parity was assumed to be conserved
• 1956 Madame Wu studied the parity violation in Co\textsuperscript{60} nuclei decaying $\beta$
• 1964 Cronin-Fitch studied the CP violation in $K_L K_S$ system
• 2001 CP violation found in the $B_0$ meson
• 2011 CP violation evidence found in the D neutral meson
CP violation in the SM

- CP violation is taken into account in the Standard Model including a complex phase in the CKM (unitary) matrix which describes the quark mixing
- Unitary matrix → 4 free parameters

\[
\begin{bmatrix}
|d'\rangle \\
|s'\rangle \\
|b'\rangle
\end{bmatrix} = \begin{bmatrix}
V_{ud} & V_{us} & V_{ub} \\
V_{cd} & V_{cs} & V_{cb} \\
V_{td} & V_{ts} & V_{tb}
\end{bmatrix} \begin{bmatrix}
|d\rangle \\
|s\rangle \\
|b\rangle
\end{bmatrix}, \quad V_{CKM,\text{Wolfenstein}} = \begin{pmatrix}
|V_{ud}| & |V_{us}| & |V_{ub}| e^{-i\gamma} \\
-|V_{cd}| & |V_{cs}| & |V_{cb}| \\
|V_{td}| e^{-i\beta} & -|V_{ts}| e^{i\beta s} & |V_{tb}|
\end{pmatrix}.
\]

\[
V_{ud}V_{ud}^* + V_{us}V_{us}^* + V_{ub}V_{ub}^* = 1
\]

\[
V_{cd}V_{cd}^* + V_{cs}V_{cs}^* + V_{cb}V_{cb}^* = 1
\]

\[
V_{td}V_{td}^* + V_{ts}V_{ts}^* + V_{tb}V_{tb}^* = 1
\]
Unitary triangles

\[ \frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*} = V_{td}V_{tb}^* = 0 \]

\[ \begin{align*}
\beta_s &= \arg(-V_{ts}V_{tb}^*/V_{cs}V_{cb}^*) \\
\beta &= \arg(-V_{td}V_{tb}^*/V_{cd}V_{cb}^*) \\
\gamma &= \arg(-V_{us}V_{ub}^*/V_{cs}V_{cb}^*) \\
\end{align*} \]
**B_s study**

Studied channel:
\[ B_s \rightarrow J/\psi + \phi \rightarrow \mu^+ \mu^- K^+ K^- \]

The flavour eigenstates of B_s can oscillate among the B_s and \( \bar{B}_s \)

\[
\begin{align*}
|B_L\rangle & \equiv p|B^0\rangle + q|\bar{B}^0\rangle \\
|B_H\rangle & \equiv p|B^0\rangle - q|\bar{B}^0\rangle,
\end{align*}
\]

\[ \Delta m = m_H - m_L \]
\[ \Delta \Gamma = \Gamma_L - \Gamma_H \quad \text{where } \Gamma = 1/\tau \]
**B_s physics: overview**

- Interference between $B_s$ decay directly into $J/\psi\phi$ or via $B_s/\bar{B}_s$ mixing gives rise to a CP violation phase

\[
\begin{align*}
B_s & \xrightarrow{\Phi_D} J/\psi\phi \\
\phi_M & \xrightarrow{-\Phi_D} B_s \xrightarrow{-\phi_M} \bar{B}_s
\end{align*}
\]

\[\Phi_s = \Phi_M - 2\Phi_D\]

- In the Standard Model $2\beta_s = (0.0363 \pm 0.0017) \text{ rad} \ [\Phi_s \approx -2\beta_s]$
- If in the mixing box new physics is present, the measured parameter can be larger $[\Phi_s \approx \Phi_{\text{new physics}}]$
- Two CP eigenstates of $B_s$: $B_L$ and $B_H$
- A disentangling (angular) analysis is needed: $\text{CP}=(-1)^L$ and $L=0,1,2$ since $B_s$ is a pseudo-scalar (spin 0) while $J/\psi$ and $\phi$ are vector bosons, hence the final state is an admixture of states with pos. and neg. CP eigenstates
Disentangling time-angular distribution

\[ \frac{d^4 \Gamma}{dt \, d\Omega} \propto |A_0(t)|^2 \cdot f_1(\Omega) + |A_\| (t)|^2 \cdot f_2(\Omega) + |A_{\perp} (t)|^2 \cdot f_3(\Omega) + 3( A_0^*(t) A_\| (t) ) \cdot f_4(\Omega) + \Re ( A_0^*(t) A_\perp (t) ) \cdot f_5(\Omega) + 3( A_0^*(t) A_\perp (t) ) \cdot f_6(\Omega). \]

\[ |A_0(t)|^2 = |A_0(0)|^2 e^{-\Gamma_0 \cdot t} \left[ \cosh(\Delta \Gamma_0 \cdot t/2) - \cos \phi_s \sinh(\Delta \Gamma_0 \cdot t/2) + \sin \phi_s \sin(\Delta m_0 \cdot t) \right] \]

\[ |A_{\|}(t)|^2 = |A_{\|}(0)|^2 e^{-\Gamma_{\|} \cdot t} \left[ \cosh(\Delta \Gamma_{\|} \cdot t/2) - \cos \phi_s \sinh(\Delta \Gamma_{\|} \cdot t/2) + \sin \phi_s \sin(\Delta m_{\|} \cdot t) \right] \]

\[ |A_{\perp}(t)|^2 = |A_{\perp}(0)|^2 e^{-\Gamma_{\perp} \cdot t} \left[ \cosh(\Delta \Gamma_{\perp} \cdot t/2) + \cos \phi_s \sinh(\Delta \Gamma_{\perp} \cdot t/2) - \sin \phi_s \sin(\Delta m_{\perp} \cdot t) \right] \]

\[ \operatorname{Im}(A_0^*(t) A_{\|}(t)) = |A_{\|}(0)||A_{\perp}(0)| e^{-\Gamma_{\perp} \cdot t} \left[ \sin(\delta_{\perp} - \delta_{\|}) \cos(\Delta m_{\|} \cdot t) - \cos(\delta_{\perp} - \delta_{\|}) \cos \phi_s \sin(\Delta m_{\perp} \cdot t) - \sin \phi_s \sinh(\Delta \Gamma_{\perp} \cdot t/2) \cos(\delta_{\perp} - \delta_{\|}) \right] \]

\[ \operatorname{Re}(A_0^*(t) A_{\perp}(t)) = |A_{\|}(0)||A_{\perp}(0)| e^{-\Gamma_{\perp} \cdot t} \left[ \cos(\delta_{\perp} - \delta_{\|}) e^{-\Gamma_{\perp} \cdot t} \cosh(\Delta \Gamma_{\perp} \cdot t/2) - \cos \phi_s \sinh(\Delta \Gamma_{\perp} \cdot t/2) + \sin \phi_s \sin(\Delta m_{\perp} \cdot t) \right] \]

\[ \operatorname{Im}(A_0^*(t) A_{\perp}(t)) = |A_{\|}(0)| |A_{\perp}(0)| e^{-\Gamma_{\perp} \cdot t} \left[ \sin(\delta_{\perp} - \delta_{\|}) \cos(\Delta m_{\|} \cdot t) - \cos(\delta_{\perp} - \delta_{\|}) \cos \phi_s \sin(\Delta m_{\perp} \cdot t) - \sin \phi_s \sinh(\Delta \Gamma_{\perp} \cdot t/2) \cos(\delta_{\perp} - \delta_{\|}) \right] \]

(2.73)

The decay rates of the $\bar{B}$ are retrieved by substituting $\phi_s \to -\phi_s$ and $A_{\perp} \to A_{\perp} = -A_{\perp}$:

\[ |\bar{A}_0(t)|^2 = |A_0(0)|^2 e^{-\Gamma_{\perp} \cdot t} \left[ \cosh(\Delta \Gamma_{\perp} \cdot t/2) - \cos \phi_s \sinh(\Delta \Gamma_{\perp} \cdot t/2) - \sin \phi_s \sin(\Delta m_{\perp} \cdot t) \right] \]

\[ |\bar{A}_{\|}(t)|^2 = |A_{\|}(0)|^2 e^{-\Gamma_{\perp} \cdot t} \left[ \cosh(\Delta \Gamma_{\perp} \cdot t/2) - \cos \phi_s \sinh(\Delta \Gamma_{\perp} \cdot t/2) - \sin \phi_s \sin(\Delta m_{\perp} \cdot t) \right] \]

\[ |\bar{A}_{\perp}(t)|^2 = |A_{\perp}(0)|^2 e^{-\Gamma_{\perp} \cdot t} \left[ \cosh(\Delta \Gamma_{\perp} \cdot t/2) + \cos \phi_s \sinh(\Delta \Gamma_{\perp} \cdot t/2) + \sin \phi_s \sin(\Delta m_{\perp} \cdot t) \right] \]

\[ \operatorname{Im}(\bar{A}_0^*(t) \bar{A}_{\|}(t)) = -|A_{\|}(0)||A_{\perp}(0)| e^{-\Gamma_{\perp} \cdot t} \left[ \sin(\delta_{\perp} - \delta_{\|}) \cos(\Delta m_{\|} \cdot t) - \cos(\delta_{\perp} - \delta_{\|}) \cos \phi_s \sin(\Delta m_{\perp} \cdot t) + \sin \phi_s \sinh(\Delta \Gamma_{\perp} \cdot t/2) \cos(\delta_{\perp} - \delta_{\|}) \right] \]

\[ \operatorname{Re}(\bar{A}_0^*(t) \bar{A}_{\perp}(t)) = -|A_{\|}(0)||A_{\perp}(0)| e^{-\Gamma_{\perp} \cdot t} \left[ \cos(\delta_{\perp} - \delta_{\|}) e^{-\Gamma_{\perp} \cdot t} \cosh(\Delta \Gamma_{\perp} \cdot t/2) - \cos \phi_s \sinh(\Delta \Gamma_{\perp} \cdot t/2) + \sin \phi_s \sin(\Delta m_{\perp} \cdot t) \right] \]

\[ \operatorname{Im}(\bar{A}_0^*(t) \bar{A}_{\perp}(t)) = -|A_{\|}(0)||A_{\perp}(0)| e^{-\Gamma_{\perp} \cdot t} \left[ \sin(\delta_{\perp} - \delta_{\|}) \cos(\Delta m_{\|} \cdot t) - \cos(\delta_{\perp} - \delta_{\|}) \cos \phi_s \sin(\Delta m_{\perp} \cdot t) + \sin \phi_s \sinh(\Delta \Gamma_{\perp} \cdot t/2) \cos(\delta_{\perp} - \delta_{\|}) \right] \]

(2.74)

\[ |A_{\perp}(0)|^2 + |A_{\|}(0)|^2 + |A_0(0)|^2 = 1. \]

**Maximum likelihood fit**

: Definition of the three angles used for the description of the decay.
Flavour tagging

Flavour tagging: find the correlation between the initial flavour of the $B_s$ and the other particles in the events.

(Olivier Leroy)
LHC (Large Hadron Collider)

- Accelerator ring 27 km long
- Two proton beams circulating in opposite directions
- Energy in the center of mass:

$$\sqrt{s} = 7\ TeV \ (\Rightarrow 8)$$

$$1\ eV = 1.602 \times 10^{-19}\ joules$$
LHC (Large Hadron Collider)
CMS (Compact Muon Solenoid)
Detectors
Physics goals of CMS (not exhaustive)

• Find evidence for the Higgs boson
• Find the evidence for physics beyond the Standard Model of particles physics:
  • SUSY
  • Dark matter
  • Extra dimensions
  • more…
• Better measurement of the Standard Model parameters
Standard Model

B physics
Bs meson

\[ \tau \text{ (PDG)} = 1.425 \times 10^{-12} \text{ s} \]
\[ c\tau \text{ (PDG)} = 441 \mu \text{m} \]
\[ \text{mass (PDG)} = 5366.3 \text{ MeV} \]

Studied channel:
\[ B_s \rightarrow J/\psi \phi \rightarrow \mu^+ \mu^- K^+ K^- \]
Bs reconstruction and selections

- One pair of opposite sign muons with $p_T > 4$ GeV and $|\eta| < 2.2$;
- J/ψ candidate with a vertex probability $> 15\%$, $p_T > 7$ GeV, mass within 150 MeV the PDG mass, $\cos \alpha > 0.9$;
- One pair of opposite sign tracks (suppose to be kaons) $p_T > 0.7$ GeV and $> 5$ tracker hits;
- $B_s$ built from 4 track vertex, constraining the dimuon mass to be the J/psi PDG mass, vertex probability $> 2\%$, $5.2 < \text{mass} < 5.6$ GeV, $L_{xy}/\sigma > 3$.

Proper decay length

$ct = L^* m/p$

$ct = L_{xy}^* m/p_T$

Bs invariant mass peak
Fit Monte Carlo simulation distributions

- CP even (L=0,2)
- CP odd (L=1)

ct

\( \cos\theta \)

\( \cos\psi \)

\( \phi \)
Efficiencies (Unfolding)

Efficiency corrections (ct - angles) determined through Monte Carlo simulations (event simulation + detector response simulation).
A good description of all the data is obtained. A comparison of MC data generated with and without Pileup shows that there is no pileup dependency in this measurement. Shapes and yield of the peaking and non-peaking background were obtained from Monte Carlo simulations. The background is classified into two components consisting of the peaking and non-peaking part. The main background contributions for the $B_s \rightarrow J/\psi \phi$ decay are coming non-prompt $J/\psi$ peaking background. The non-peaking background from the prompt $J/\psi$ is not considered because the trigger conditions and the offline cuts reduce this background contribution to negligible. Contributions into the peaking background are evaluated using the $B_d \rightarrow J/\psi K^*$ and $B^+ \rightarrow J/\psi X$ decays.

4 Maximum Likelihood fit

In order to extract $\Delta \Gamma_s$, we perform a simultaneous unbinned maximum likelihood fit to our data by including the information on the invariant mass, decay time and the three decay angles for the signal and background. The single event likelihood function $L$ used in the 5-dimensional fit uses three PDFs with independent parameters one each for the signal and the two shapes of background:

$$L = PDF_{signal}(\epsilon(ct)\epsilon(\Theta)f(\Theta, \alpha, t, M)) \otimes (G(t, 0, \sigma(t))) + PDF_{background}^{peak}(\Theta, \alpha, t, M) + PDF_{background}^{non-peak}(\Theta, \alpha, t, M),$$

Input: ct, angles, ct per event resolution, mass, flavour tagging
Output: $\alpha (\Delta \Gamma_s, \phi_s, \ldots)$
Conclusions

- Challenges to deal with:
  - High luminosity → high number of interactions per single event
  - Lifetime measurement with decay length cut
  - No π-K discrimination in CMS

(LHCb – CDF – D0 results)