Flavour tagged time dependent angular analysis of the $B_s \to J/\psi\phi$ decay channel, measurement of the $\Delta\Gamma_s$ and the weak phase Φ_s

Muhammad Alibordi
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On behalf of CMS collaboration

Content to be delivered

1. Compact Muon Solenoid(CMS)
2. Importance of $B_s \to J/\psi\phi$ channel, analysis strategy and signal model
3. Reconstruction, flavour tagging
4. Fit, result and systematic uncertainty
5. Summary

Ref.

Physics Letters B 757(2016)97-120

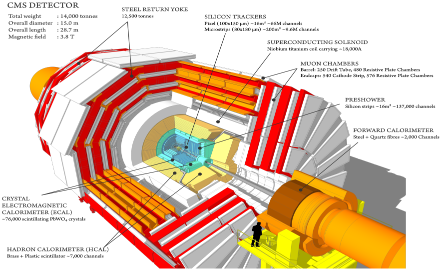
arxiv:1507.07527

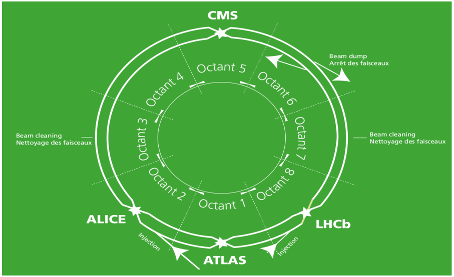
CMS consists of

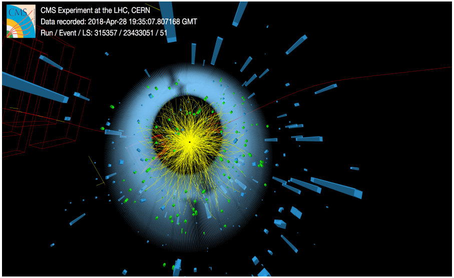
- Tracker(Pixel+Strips)
- Electromagnetic Calorimeter(ECAL)
- Hadron Calorimeter(HCAL)
- *NbTi* solenoid, $B \sim 4$T
- Muon Chamber(DT, RPC, CSC)

After collisions we apply-Trigger

- L1-hardware based, rejects non-physics data.
- HLT-software based, depends on physics interest.







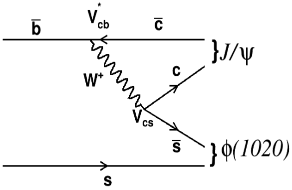
(https://cds.cern.ch/record/2255762/files/CERN-Brochure-2017-002-Eng.pdf)

Importance of $B_s^0 \to J/\psi\phi(1020)$ decays in modern physics scenario

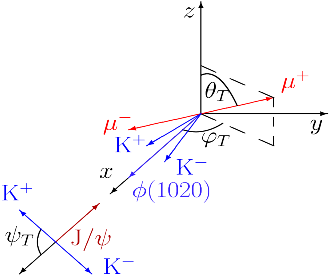
- The CP-violation$\Rightarrow$ matter-antimatter asymmetry, window$\Rightarrow$BSM+new physics(NP).
- Doubly Cabibbo suppressed(large $\mathcal{BF} \sim 1.07 \pm 0.09 \times 10^{-3}$)$\Rightarrow$ large signal(LHCb,arxiv:1304.6173v2, Chin. Phys. C,40,100001(2016))
- "…..its nice experimental signature, the final state is an admixture of different CP eigenstates" (PRD,63,114015,2001)
- "...small new physics effects could be clearly visible in the B_s^0 system"(RMP,88,2016)

$B_s^0 \to J\psi\phi(1020)$ needs at least three decay angles between the decay products in order to disentangle the two CP states of the final state θ_T,ϕ_T,ψ_T.The Differential decay rate of signal,

- $\frac{d^4\Gamma(B_s(t))}{d\Theta dt} = \sum_{i=1}^{10} \mathcal{O}_i(\alpha, t).g_i(\Theta)$
- **Mass eigenstates** $t = 0$,
  $|B_L\rangle = p\,|B_s\rangle + q\,|\bar{B}_s\rangle$,
  $|B_H\rangle = p\,|B_s\rangle - q\,|\bar{B}_s\rangle$, $|p|^2 + |q|^2 = 1$
- **Key quantities**: $\lambda = \frac{q}{p}(\frac{A_f}{\bar{A}_f})$; $C = \frac{1-|\lambda|^2}{1+|\lambda|^2}$;
  $S = -\frac{2|\lambda| sin\Phi_s}{1+|\lambda|^2}$; $D = -\frac{2|\lambda| cos\Phi_s}{1+|\lambda|^2}$

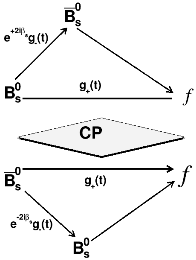


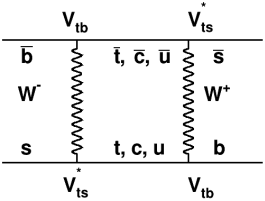
$B_s^0 \to J/\psi\phi$ at quark level $b \to sc\bar{c}$
$\phi(1020) \to K^+K^-$: BF=(48.9$\pm$0.5)%,
$J/\psi \to \mu^+\mu^-$: BF=5.961$\pm$0.033%(Chin. Phys. C,40,100001(2016))



Description

- The B_s meson decays into a final state $J/\psi\phi(1020)$, which is a mixture of two CP eigenstates (odd/even);
- The $B_s/\bar{B}_s$ mesons mix rapidly, and the decay width difference $\Delta\Gamma_s$ is relatively large;
- Interference between direct $B_s \to J/\psi\phi(1020)$ decay and decay via mixing gives rise to a CP violation phase $\Phi_s \sim -2\beta_s = -0.0363^{+0.0016}_{-0.0015}$ rad (**SM**), where $\beta_s = arg(\frac{-V_{ts}V^*_{tb}}{V_{cs}V^*_{cb}})$
- If the Φ_s differs w.r.t. the SM prediction, then **New Physics** might contribute in the mixing box diagram.

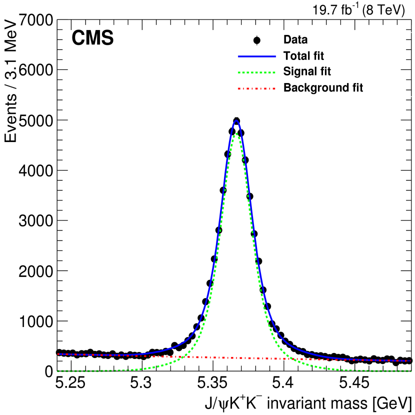




- We measure the weak phase Φ_s and decay width difference $\Delta\Gamma_s$ by distentangling the two cp final states of the B_s with a tagged angular analysis.
- The angles of the decay products are defined in the transversity basis. (UH-511-982-01, BELLE Note# 419)
- Opposite side lepton tagging is used to define the flavour at production time.

B_s reconstruction and selection

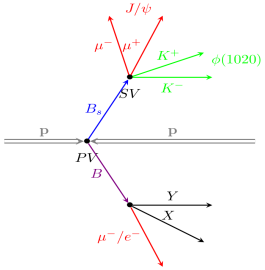
- Triggers $\rightarrow$ fired by displaced J/ψ vertex
- Muons with $p_t^{\mu} > 4$ GeV, $|\eta^{\mu}| < 2.1$
- $|m^{J/\psi} - m^{J/\psi}_{pdg}| < 150$ MeV
- $p_t^{J/\psi} > 7$ GeV
- Tracks with $p_t^K > 0.7$ GeV, Tacker hits > 5
- $|m^{\phi(1020)} - m^{\phi(1020)}{}_{pdg}| < 10$ MeV
- $\mu^+\mu^-K^+K^-$ vertex with J/ψ mass constraint and probability greater than 2%
- Proper decay length of B_s is within [0.02, 0.3] cm
- Mass of B_s is within [5.20, 5.65] GeV

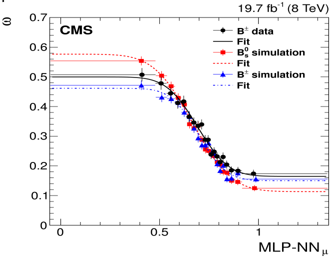


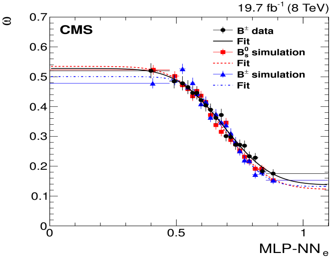
- **In the mass range [5.33,5.40] GeV S/BG ratio ∼6.8**
- **Signal events: 49k**
- **Main background: displaced J/ψ's (B hadrons)**

Opposite side flavour tagging

The mistag ratio $\omega = \frac{N_W}{N_{tag}}$ is parametrized as function of the multilayer perceptron neural network (MLP-NN) of the leptons

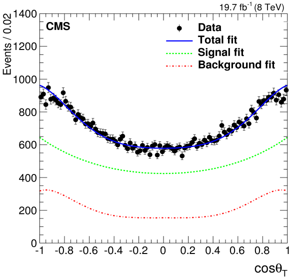


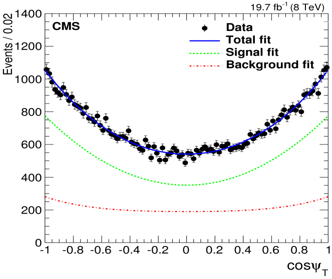


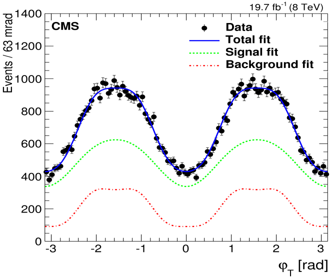


- Flavour of the B$_s$ signal were tagged with opposite side leptons
- Measurement of tagging performance has been performed on $B^+ \to J/\psi K^+$ data
- Performance of the lepton tagger (μ and e) : $\omega = 30.17 \pm 0.24 \pm 0.05\%$, $\epsilon = 8.31 \pm 0.03\%$, $P_{tag} = 1.307 \pm 0.031 \pm 0.007\%$

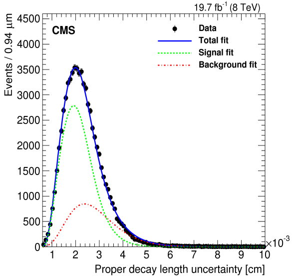
2012 data fit-angles

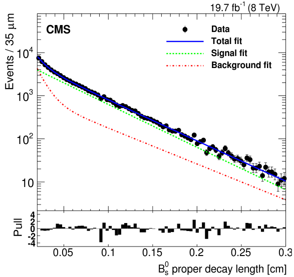






Extended maximum-likelihood 5-D fit of the tagged model on the 2012 data, with a Gaussian constraint of Δm_s to the PDG value 17.69 ± 0.08 $\hbar/ps$





Parameter	Fit result
ϕ_s [rad]	-0.075 ± 0.097
$\Delta\Gamma_s$ [ps^{-1}]	0.095 ± 0.013
$\lvert A_0 \rvert^2$	0.510 ± 0.005
$\lvert A_S \rvert^2$	$0.012\ ^{+0.009}_{-0.007}$
$\lvert A_\perp \rvert^2$	0.243 ± 0.008
$\delta_\parallel$ [rad]	$3.48\ ^{+0.07}_{-0.09}$
$\delta_{S\perp}$ [rad]	$0.37\ ^{+0.28}_{-0.12}$
$\delta_\perp$ [rad]	2.98 ± 0.36
$c\tau$ [μm]	447.2 ± 2.9

Efficiency and Resolution

- Lifetime and angular resolutions and angular efficiency has been measured using simulations
- The decay time resolution (~70 fs) is included in the model in a per event way
- Angular resolution is considered as systematic uncertainty
- Data-MC comparisons contribute to the

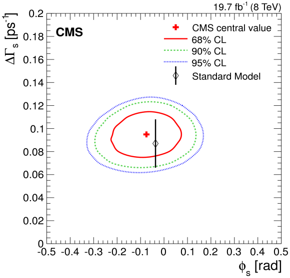
  systematics
  - Prompt J/ψ decay time resolution
  - Background subtracted kinematic distributions

Systematic Uncertainty

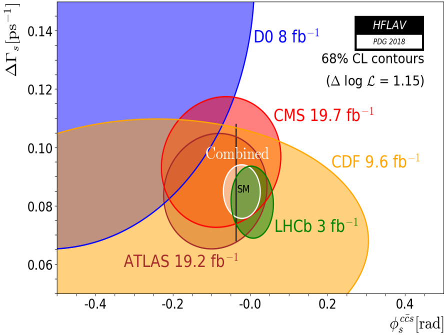
- The residual difference between data and simulation is the origin of systematic uncertainities from proper decay time efficiency and the kaon p_t distribution.
- Model bias is determined using a set of simulated pseudo-experiments.
- $|\lambda|$ has been left as free parameter for accounting the effect of possible other contribution in the weak phase.

Source of uncertainty	ϕ_s [rad]	$\Delta\Gamma_s$ [ps^{-1}]	$\lvert A_0\rvert^2$	$\lvert A_S\rvert^2$	$\lvert A_\perp\rvert^2$	$\delta_\parallel$ [rad]	$\delta_{S\perp}$ [rad]	$\delta_\perp$ [rad]	$c\tau$ [μm]
ct efficiency	0.002	0.0057	0.0015	—	0.0023	—	—	—	1.0
Angular efficiency	0.016	0.0021	0.0060	0.008	0.0104	0.674	0.14	0.66	0.8
Kaon p_T weighting	0.014	0.0015	0.0094	0.020	0.0041	0.085	0.11	0.02	1.1
ct resolution	0.006	0.0021	0.0009	—	0.0008	0.004	—	0.02	2.9
Mistag distribution modelling	0.004	0.0003	0.0006	—	—	0.008	0.01	—	0.1
Flavour tagging	0.003	0.0003	—	—	—	0.006	0.02	—	—
Model bias	0.015	0.0012	0.0008	—	—	0.025	0.03	—	0.4
pdf modelling assumptions	0.006	0.0021	0.0016	0.002	0.0021	0.010	0.03	0.04	0.2
$\lvert\lambda\rvert$ as a free parameter	0.015	0.0003	0.0001	0.005	0.0001	0.002	0.01	0.03	—
Tracker alignment	—	—	—	—	—	—	—	—	1.5
Total systematic uncertainty	0.031	0.0070	0.0114	0.022	0.0116	0.680	0.18	0.66	3.7
Statistical uncertainty	0.097	0.0134	0.0053	0.008	0.0075	0.081	0.17	0.36	2.9

Results



The accurate results are in agreement with the Standard Model and with other experiments*



The analysis has been performed on 2012 CMS data(20 fb^{-1} and the selected B$_s$ events were 49k, the measured value of

$$\Phi_s = -0.075 \pm 0.097(\text{stat}) \pm 0.031(\text{syst})\,\text{rad}$$

$$\Delta\Gamma_s = 0.095 \pm 0.013(\text{stat}) \pm 0.007(\text{syst})\,\text{ps}^{-1}$$

Contour plot constraining $\Delta\Gamma_s > 0$

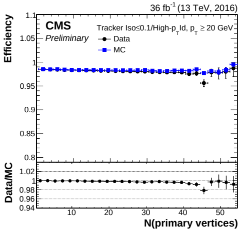
Summary

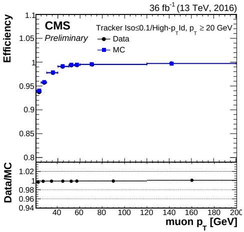
- It was the first CMS measurement of a time dependent, angular analysis of the $B_s \to J/\psi\phi$ flavour tagged decays using 2012 data(19.7fb^{-1}), corresponding to a total of 49k B_s signal events, the results are,

$$\Phi_s = -0.075 \pm 0.097(\mathrm{stat}) \pm 0.031(\mathrm{syst})\,\mathrm{rad}$$

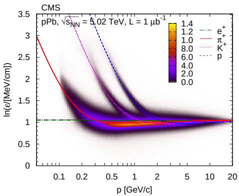
$$\Delta\Gamma_s = 0.095 \pm 0.013(\mathrm{stat}) \pm 0.007(\mathrm{syst})\,\mathrm{ps}^{-1}$$

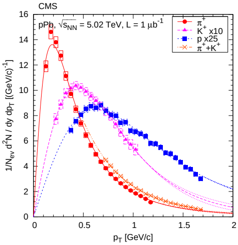
- The results are in agreement with standard model and with other experiments
- The measurement of Φ_s were statistically limited
- $\Delta\Gamma_s$ is nonzero





(https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsMUO)

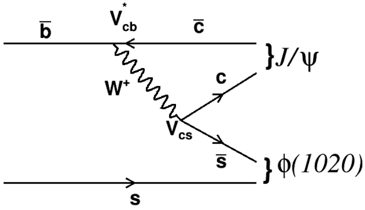




(https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsHIN12016)

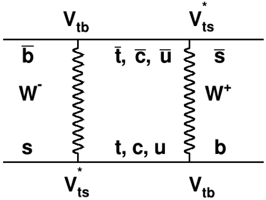
- **Mass eigenstates** $t = 0$,**Lighter:** $|B_L\rangle = p\,|B_s\rangle + q\,|\bar{B}_s\rangle$, **Heavier:** $|B_H\rangle = p\,|B_s\rangle - q\,\left|\bar{B}_s\right\rangle$, $|p|^2 + |q|^2 = 1$
- **Key quantities:** $\lambda = \frac{q\bar{A}_f}{pA_f}$; $C = \frac{1-|\lambda|^2}{1+|\lambda|^2}$; $S = -\frac{2|\lambda|sin\Phi_s}{a+|\lambda|^2}$; $D = -\frac{2|\lambda|cos\Phi_s}{1+|\lambda|^2}$
  [$A_f = \langle f|B_s\rangle$, $\bar{A}_f = \langle f|\bar{B}_s\rangle$, **C measures direct CP violation, S measures mixing-induced CP violation in the interference of** $B_s \to f$ **and** $\bar{B}_s \to f$, **and D plays a role if** $\Delta\Gamma_s$ **is sizeable and we use single** λ **for all amplitude.**]
- **Theoretical Expectation:** $\frac{\Delta\Gamma_s}{\Gamma} = 0.12 \pm 0.06$, $\Phi_s = 2\beta_s = 0.0364 \pm 0.0016$**rad**
  (Phys.Letters B 757(2016)97-120)

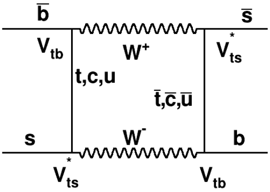
K$^\pm \to I(J^P) = \frac{1}{2}(0^-)$, $\mu \to J = \frac{1}{2}$, $B_s^0(s\bar{b}) \to I(J^P) = 0(0^-)$, **J/**$\psi(c\bar{c}) \to I^G(J^{PC}) = 0^-(1^{--})$,
$\phi \to I^G(J^{PC}) = 0^-(1^{--})$,
$B_s^0 \to J/\psi\phi$ **at quark level** $b \to sc\bar{c}$
$\phi(1020) \to K^+K^-$: **BF=(48.9±0.5)%,**
$J/\psi \to \mu^+\mu^-$: **BF=5.961±0.033%(Chin. Phys. C,40,100001(2016))**



*The plot shows, in the $(\phi_s^{c\bar{c}s}, \Delta\Gamma_s)$ plane, the individual 68% confidence-level contours of ATLAS, CMS, CDF, D0 and LHCb, their combined contour (white solid line and shaded area), as well as the Standard Model predictions (very thin black rectangle). The prediction for $\phi_s^{c\bar{c}s}$ is taken as the indirect determination of $2\beta_s$ via a global fit to experimental data within the Standard Model, $2\beta_s = 0.0370 \pm 0.0006$ [CKMfitter, Phys. Rev. D84, 033005 (2011), updated with Summer 2016 results], while the Standard Model prediction for $\Delta\Gamma_s = 0.088 \pm 0.020 ps^1$ [M. Artuso, G. Borissov and A. Lenz, arXiv:1511.09466 [hep-ph], Eq. 89]. The combined result is consistent with these predictions.

- **First** *CP*-**violation:** 1964 in K meson-motivation to study *CP*-violation in the heavy meson sector, B_s^0 is one of them
- **PDG info:** $B_s^0(s\bar{b})$, $(B = \pm 1, S = \mp 1)$, mass $m_{B_s^0} = 5366.82 \pm 0.22$ MeV, mean life $\tau = (1.510 \pm 0.005) \times 10^{-12}$s





- Three kind CP violation in heavy meson $(B/K/D)$ sector, (Phys.Letters B 757(2016)97-120, CMS AN-14-045)

  CP violation decays(direct): $|\frac{\bar{A}_{\bar{f}}}{A_f}| \neq 0$; $(A_f = \langle f|B_s\rangle, \bar{A}_f = \langle f|\bar{B}_s\rangle)$

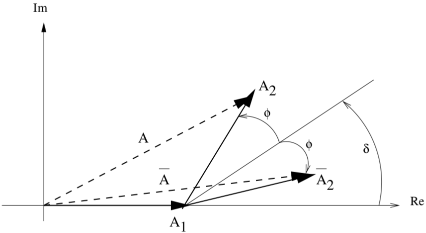
  CP violation mixing(indirect): $|\frac{p}{q}| \neq 1$

  CP violation in the interference before mixing and decays: $\lambda = \frac{q\bar{A}_f}{pA_f} \neq 1$

Back-up-III Condition of *cp*-violation, transversity basis

- No two up-type quarks or two down-type quarks are degenerate in mass, adding up to six conditions.
- No mixing angle is equal to 0 or $\frac{\pi}{2}$, adding up to six conditions.
- The physical phase is different from 0 or π, adding up to two conditions.
  Single condition
  $$det[C] \neq 0$$
  Where $C = [M'^{U} M'^{U\dagger}, M'^{D} M'^{D\dagger}]$ commutator of mass matrices.
- This decay is the equivalent of the $B_d^0 \rightarrow J/\psi K_S$ decay for the B_s system. A theoretically interesting aspect of the $B_s^0 \rightarrow J/\psi\phi$ channel is that the CP-violating phase in this decay is doubly Cabibbo suppressed, leading to an expectation of CP violation that is practically zero in the SM.The $B_s^0 \rightarrow J/\psi\phi$ decay offers the best sensitivity to the CP violating parameter ϕ_s , which, in the Standard Model, is expected to be small (-0.04rad).
- Non-SM new virtual processes might enhance observable CP-violation effects. In this way this measurement is both a search for CP violation, a test of the SM, and a probe to new physics, complementary to direct searches of new particles.
- Measurements by CDF and DO have hinted in the past towards deviations from the value expected in the SM. If new physics contributes significantly to the amplitude of processes, the measurement allows to determine both the magnitude and phase of the couplings of these new particles.
- The final state of the $B_s^0 \rightarrow J/\psi\phi$ decay is a superposition of CP eigenstates with odd and even orbital angular momentum. Hence the final state is an admixture of states with positive and negative CP eigenvalue, which contribute with different signs to the CP asymmetry, hereby diluting the observed CP asymmetry.
- In order to determine the sizes of the different polarizations, and hence the true CP violating phase, an angular analysis needs to be performed.

1. A particle decay occurs through two coherently contributing amplitudes, A_1 and A_2.
2. A_1 $\rightarrow$strong phase, does not change sign under CP conjugation
3. A_2 $\rightarrow$weak phase, does change sign under CP conjugation
4. Amplitude: can be written in terms of their strong phase difference δ, and weak phase difference ϕ decay rate of the unstable particle is found to be:$|A|^2 = |A_1|^2 + |A_2|^2 + 2|A_1||A_2|cos(\delta + \phi)$
5. CP-conjugated decay rate for the anti-particle: $|\bar{A}|^2 = |A_1|^2 + |A_2|^2 + 2|A_1||A_2|cos(\delta - \phi)$
6. CP-asymmetry A_{CP} equals: $A_{CP} = \frac{|A|^2 - |\bar{A}|^2}{|A|^2 + |\bar{A}|^2} = -\frac{2sin\phi sin\delta}{r+1/r+2cos\phi sin\delta}$



Importance:(CP violation in the B_s system, RMP,88,2016)

- Its heavy $m_B \backsimeq 5m_p$,
- Interacts most strongly with ultra-massive top quarks $m_B \backsimeq 175m_p$ but cant decay into top quark
- Long lifetime $\tau_B \backsimeq 1.5$ psec($c\tau_B = 450\mu m$), long mixing frequency and the full mixing in about 4.4 lifetime
- large CP-violation effects(10%-30%) which is much larger than kaon system (0.1%)

"The decay $B_s^0 \to J/\psi\phi$ is a golden channel for the measurement of B_s^0 mixing phase $2\beta_s = \Phi_s$ which is very sensitive probe of new physics" (JHEP09(2009)076)

- This doubly Cabibbo suppressed decay mode has large branching fraction $1.07 \pm 0.09 \times 10^{-3}$ compared to other **PS→VV** decay mode, turns out to large signal(LHCb,arxiv:1304.6173v2, Chin. Phys. C,40,100001(2016))
- "In the case of $B_s^0 \to J/\psi(l^+l^-)\phi(K^+K^-)$, which is particularly interesting for B-physics experiments at hadron machines because of its nice experimental signature, the final state is an admixture of different CP eigenstates" (PRD,63,114015,2001)
- "SM CP-violating effects are expected to be more highly suppressed than in B^0 meson decays. Therefore, even a relatively small contribution of new physics effects could be clearly visible in the B_s^0 system"(RMP,88,2016)
- Many kinematic observable (ct,θ_T, ϕ_T, ψ_T)

Differential decay rate in terms of proper time and angular variables can be represented as [arXiv:1304.2600],

$$\frac{d^4\Gamma(B_s(t))}{d\Theta dt} = f(\Theta, \alpha, t) = \sum_{i=1}^{10} \mathcal{O}_i(\alpha, t).g_i(\Theta)$$

g_i-angular distribution, α-physics parameters, Θ-angles and $\mathcal{O}_i$ is given by,

$$\mathcal{O}_i = N_i e^{-\Gamma_s t}[a_i cosh(\frac{1}{2}\Delta\Gamma_s t) + b_i sinh(\frac{1}{2}\Delta\Gamma_s t) + c_i cos(\Delta m_s t) + d_i sin(\Delta m_s t)]$$

i	$g_i(\theta_T, \psi_T, \varphi_T)$	N_i	a_i	b_i	c_i	d_i
1	$2\cos^2\psi_T(1-\sin^2\theta_T\cos^2\varphi_T)$	$\lvert A_0(0)\rvert^2$	1	D	C	$-S$
2	$\sin^2\psi_T(1-\sin^2\theta_T\sin^2\varphi_T)$	$\lvert A_\parallel(0)\rvert^2$	1	D	C	$-S$
3	$\sin^2\psi_T\sin^2\theta_T$	$\lvert A_\perp(0)\rvert^2$	1	$-D$	C	S
4	$-\sin^2\psi_T\sin 2\theta_T\sin\varphi_T$	$\lvert A_\parallel(0)\rvert\lvert A_\perp(0)\rvert$	$C\sin(\delta_\perp-\delta_\parallel)$	$S\cos(\delta_\perp-\delta_\parallel)$	$\sin(\delta_\perp-\delta_\parallel)$	$D\cos(\delta_\perp-\delta_\parallel)$
5	$\frac{1}{\sqrt{2}}\sin 2\psi_T\sin^2\theta_T\sin 2\varphi_T$	$\lvert A_0(0)\rvert\lvert A_\parallel(0)\rvert$	$\cos(\delta_\parallel-\delta_0)$	$D\cos(\delta_\parallel-\delta_0)$	$C\cos(\delta_\parallel-\delta_0)$	$-S\cos(\delta_\parallel-\delta_0)$
6	$\frac{1}{\sqrt{2}}\sin 2\psi_T\sin 2\theta_T\sin\varphi_T$	$\lvert A_0(0)\rvert\lvert A_\perp(0)\rvert$	$C\sin(\delta_\perp-\delta_0)$	$S\cos(\delta_\perp-\delta_0)$	$\sin(\delta_\perp-\delta_0)$	$D\cos(\delta_\perp-\delta_0)$
7	$\frac{2}{3}(1-\sin^2\theta_T\cos^2\varphi_T)$	$\lvert A_S(0)\rvert^2$	1	$-D$	C	S
8	$\frac{1}{3}\sqrt{6}\sin\psi_T\sin^2\theta_T\sin 2\varphi_T$	$\lvert A_S(0)\rvert\lvert A_\parallel(0)\rvert$	$C\cos(\delta_\parallel-\delta_S)$	$S\sin(\delta_\parallel-\delta_S)$	$\cos(\delta_\parallel-\delta_S)$	$D\sin(\delta_\parallel-\delta_S)$
9	$\frac{1}{3}\sqrt{6}\sin\psi_T\sin 2\theta_T\cos\varphi_T$	$\lvert A_S(0)\rvert\lvert A_\perp(0)\rvert$	$\sin(\delta_\perp-\delta_S)$	$-D\sin(\delta_\perp-\delta_S)$	$C\sin(\delta_\perp-\delta_S)$	$S\sin(\delta_\perp-\delta_S)$
10	$\frac{4}{3}\sqrt{3}\cos\psi_T(1-\sin^2\theta_T\cos^2\varphi_T)$	$\lvert A_S(0)\rvert\lvert A_0(0)\rvert$	$C\cos(\delta_0-\delta_S)$	$S\sin(\delta_0-\delta_S)$	$\cos(\delta_0-\delta_S)$	$D\sin(\delta_0-\delta_S)$

- **Key quantities**: $\lambda = \frac{q\bar{A}_f}{pA_f}$; $C = \frac{1-|\lambda|^2}{1+|\lambda|^2}$; $S = -\frac{2|\lambda|sin\Phi_s}{a+|\lambda|^2}$; $D = -\frac{2|\lambda|cos\Phi_s}{1+|\lambda|^2}$
- **Theoretical Expectation:** $\frac{\Delta\Gamma_s}{\Gamma} = 0.12 \pm 0.06$, $\Phi_s = 2\beta_s = 0.0364 \pm 0.0016$rad

[$A_f = \langle f|B_s\rangle$, $\bar{A}_f = \langle f|\bar{B}_s\rangle$, C measures direct CP violation, S measures mixing-induced CP violation in the interference of $B_s \to f$ and $\bar{B}_s \to f$, and D plays a role if $\Delta\Gamma_s$ is sizeable and we use single λ for all amplitude.]