CP Violation in $B_s^0 \to J/\psi\phi$ - Theoretical Background

Lukáš Novotný

Agenda

1. *CP* Violation
2. CKM Mechanism
3. Mixing of neutral B mesons
4. Current experimental status of ϕ_s

Parity and Charge Conjugation

Parity:

Parity and Charge Conjugation

Parity:

- The parity converts a right handed coordinate system to left handed $(x, y, z \rightarrow -x, -y, -z)$.

$$\mathcal{P}\psi(\mathbf{r}) = \psi(-\mathbf{r})$$

- Eigenvalues are ± 1
- Any physical process will happen identically when viewed in a mirror image
- does not affect time, charge and angular momentum

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Charge conjugation

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Charge conjugation

- changes the sign of the all quantum charges

$$\mathcal{C}\psi(\mathbf{r}) = \bar{\psi}(-\mathbf{r})$$

- does not affect the mass, linear momentum and spin

Violation of Parity and Charge Conjugation

Parity Violation

- Chien-Shiung Wu 1956, ^{60}Co decay

$$^{60}_{27}\text{Co} \rightarrow {}^{60}_{28}\text{Ni} + e^- + \bar{\nu}_e + 2\gamma$$

- cobalt nuclei were placed in the magnetic field
- electrons would have no preferred direction of decay relative to the nuclear spin
- Most of the electrons favoured a very specific direction of decay, opposite to that of the nuclear spin

CP Violation

- Parity violated - is combination of $\mathcal{P}$ and $\mathcal{C}$ violated?
- Strong and EM interactions: $\mathcal{CP}$ conserved
- Weak interactions: $\mathcal{CP}$ violated:
  - Christenson, Cronin, Fitch and Turlay 1964
  - study of two neutral K mesons in the kaon decays, K_S^0 and K_L^0
  - if $\mathcal{CP}$ conserved:

$$K_S^0 \to 2\pi \qquad K_L^0 \to 3\pi$$

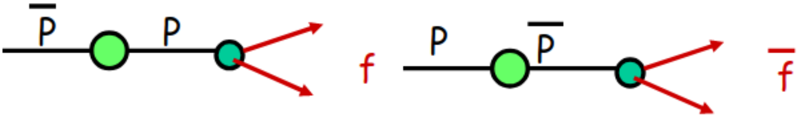
  - $K_L^0 \to 2\pi$ observed!!
  - $K^0 \bar{K}^0$ oscillation, $\mathcal{CP}$ violated
- Three types of $\mathcal{CP}$ violation:
  - in decay
  - in mixing
  - in interference of mixing and decay

$\mathcal{CP}$ Violation in Mixing

- probability of oscillation from meson to anti-meson is different from the probability of oscillation from anti-meson to meson

$$\mathrm{Prob}(P^0 \to \bar{P}^0) \neq \mathrm{Prob}(\bar{P}^0 \to P^0)$$

- Mass eigenstates are not CP eigenstates
- Charged-current semileptonic neutral meson decays $M, \bar{M} \to l^{\pm}X$

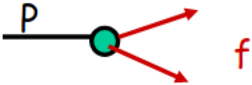


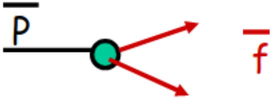
$\mathcal{CP}$ Violation in Decay

- decay amplitude of particle into the final state is different from the decay amplitude of its antiparticle into its final anti-state

$$\Gamma(M \to f) \neq \Gamma(\bar{M} \to \bar{f})$$

- In charged meson (and all baryon) decays, where mixing effects are absent, this is the only possible source of $\mathcal{CP}$ asymmetries

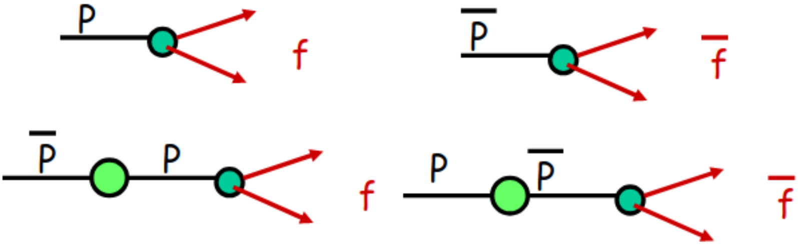




$\mathcal{CP}$ Violation in Interference of Mixing and Decay

- occurs in case both meson and antimeson decay into the same final state

$$M \to f \qquad M \to \bar{M} \to f$$



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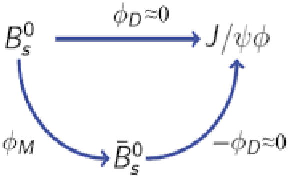
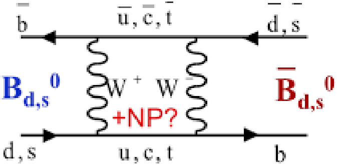




$\mathcal{CP}$ Violation in Standard Model

- Charged current part of Lagrangian for weak interactions of quarks

$$\mathcal{L}_Y^q = -\frac{g}{\sqrt{2}} \bar{u}_{L\,i}'\gamma^\mu \delta_{ij} \bar{d}_{L\,j}' W_\mu^+ + h.c.,$$

- interaction eigenvectors in term of mass eigenvectors $d_L' = V_{dL}^\dagger d_L$ and $\bar{u}_L' = V_{uL} u_L$

$$\mathcal{L}_Y^q = -\frac{g}{\sqrt{2}} \bar{u}_{L\,i}\gamma^\mu \bar{V}_{ij} \bar{d}_{L\,j} W_\mu^+ + h.c.,$$

- CKM matrix $V_{ij} = V_{uL}^\dagger V_{dL}$:

$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

CKM Matrix

- Complex 3×3 unitary matrix
- only four parameters are independent - 3 Euler mixing angles and one CP-violating CKM phase

$$V_{CKM} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-\imath\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{\imath\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} =$$

$$= \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-\imath\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{\imath\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{\imath\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{\imath\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{\imath\delta} & c_{23}c_{13} \end{pmatrix} \quad (1)$$

- Angle θ_{12} identified as Cabibbo angle

CKM Matrix

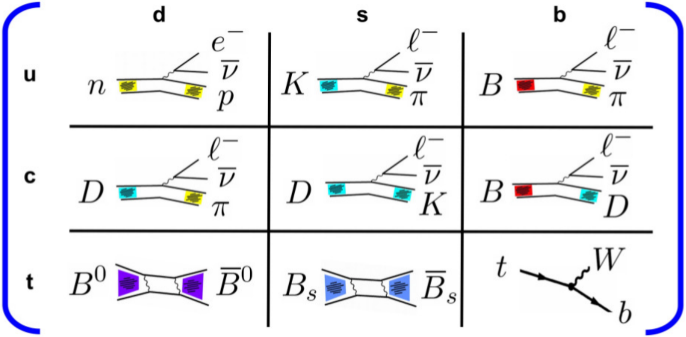
- Wolfenstein parametrization

$$V_{CKM} = \begin{pmatrix} 1-\frac{1}{2}\lambda^2-\frac{1}{8}\lambda^4 & \lambda & A\lambda^3(\rho-\imath\eta) \\ -\lambda & 1-\frac{1}{2}\lambda^2-\frac{1}{8}\lambda^4\left(1+4A^2\right) & A\lambda^2 \\ A\lambda^3(1-\rho-\imath\eta) & -A\lambda^2+\frac{1}{2}A\lambda^4(1-2(\rho+\imath\eta)) & 1-\frac{1}{2}A^4\lambda^4 \end{pmatrix} + \mathcal{O}(\lambda^5) \quad (2)$$

- $\lambda = 0.22506 \pm 0.00050$
- $A = 0.811 \pm 0.026$
- $\bar{\rho} = \rho\left(1-\frac{\lambda}{2}\right) = 0.124^{+0.019}_{-0.018}$
- $\bar{\eta} = \eta\left(1-\frac{\lambda}{2}\right) = 0.356 \pm 0.011$

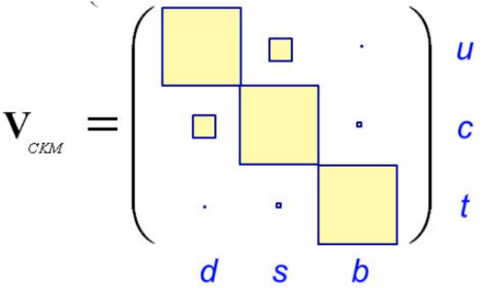
CKM Matrix

V =



CKM Matrix

$$V_{CKM} = \begin{pmatrix} 0.9742 & 0.2243 & 0.0039 \\ 0.218 & 0.997 & 0.0422 \\ 0.0081 & 0.0394 & 1.019 \end{pmatrix}$$



Unitarity Triangles

- unitarity $1 = V_{CKM} V_{CKM}^{\dagger}$:
- orthonormality of columns or rows in V_{CKM} expressed as

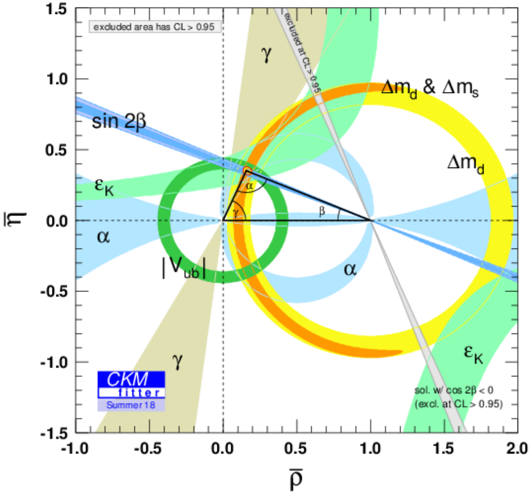
$$\sum_{\alpha=u,c,t} V_{\alpha i} V_{\alpha j}^{*} = \delta_{ij}, \quad \sum_{i=d,s,b} V_{\alpha i} V_{\beta i}^{*} = \delta_{\alpha\beta}$$

- One of triangles:

$$V_{ud} V_{ub}^{*} + V_{cd} V_{cb}^{*} + V_{td} V_{tb}^{*} = 0$$

$$V_{us} V_{ub}^{*} + V_{cs} V_{cb}^{*} + V_{ts} V_{tb}^{*} = 0$$

Unitarity Triangles - Experimental Results



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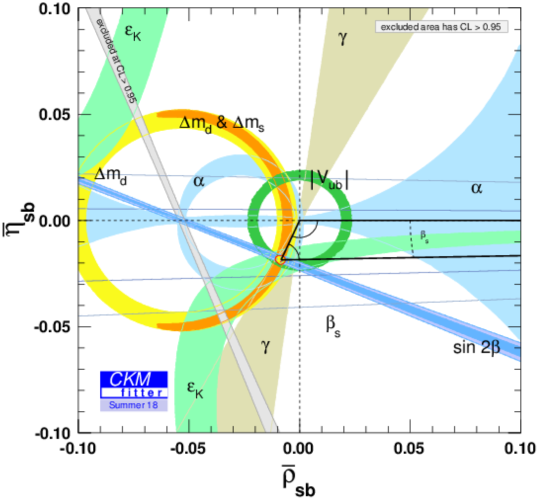


Mixing of Neutral B Mesons

- flavour eigenstates of the B^0 meson and the B_s^0 meson:

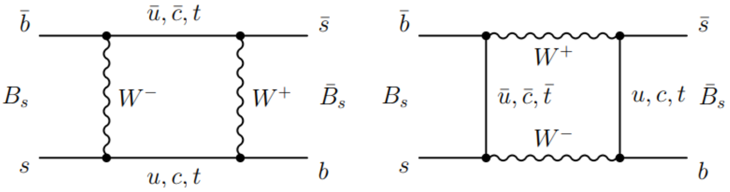
$$\left|B^0\right\rangle = \left|\bar{b}d\right\rangle \qquad \left|B_s^0\right\rangle = \left|\bar{b}s\right\rangle$$

$$\left|\bar{B}^0\right\rangle = \left|b\bar{d}\right\rangle \qquad \left|\bar{B}_s^0\right\rangle = \left|b\bar{s}\right\rangle$$

- Decay amplitudes of neutral meson (and anti-mesons) decays into final states:

$$A_f = \left\langle f|\mathcal{H}|B_q^0\right\rangle \qquad A_{\bar{f}} = \left\langle \bar{f}|\mathcal{H}|B_q^0\right\rangle$$

$$\bar{A}_f = \left\langle f|\mathcal{H}|\bar{B}_q^0\right\rangle \qquad \bar{A}_{\bar{f}} = \left\langle \bar{f}|\mathcal{H}|\bar{B}_q^0\right\rangle$$



Time developement of the mass eigenstates of B mesons

$$\imath\hbar\frac{\partial}{\partial t}\begin{pmatrix}\left|B^0(t)\right\rangle\\ \left|\bar{B}^0(t)\right\rangle\end{pmatrix} = \boldsymbol{H}\begin{pmatrix}\left|B^0(t)\right\rangle\\ \left|\bar{B}^0(t)\right\rangle\end{pmatrix} = \left(\boldsymbol{M} - \frac{\imath}{2}\boldsymbol{\Gamma}\right)\begin{pmatrix}\left|B^0(t)\right\rangle\\ \left|\bar{B}^0(t)\right\rangle\end{pmatrix}$$

- $\left|B^0(t)\right\rangle$ denotes the flavour state at $t = 0$
- $\boldsymbol{M}$, $\boldsymbol{\Gamma}$ hermitian matrices

$$\boldsymbol{M} = \begin{pmatrix} M_{11} & M_{12} \\ M_{12}^* & M_{22} \end{pmatrix},\ \boldsymbol{\Gamma} = \begin{pmatrix} \Gamma_{11} & \Gamma_{12} \\ \Gamma_{12}^* & \Gamma_{22} \end{pmatrix}$$

- Mass terms: $\boldsymbol{M}$, Decay matrix $\boldsymbol{\Gamma}$
- $\mathcal{CPT}$ conserved:

$$M_{11} = M_{22} = M,\ \Gamma_{11} = \Gamma_{22} = \Gamma$$

- non-diagonal elements correspond to the $B_s^0 - \bar{B}_s^0$ mixing

Time developement of the mass eigenstates of B mesons

$$\Gamma = \frac{1}{2}(\Gamma_L + \Gamma_H), \qquad M = \frac{1}{2}(M_L + M_H)$$

$$\Delta\Gamma = \Gamma_L - \Gamma_H = 2|\Gamma_{12}|\cos\phi_s, \qquad \Delta m = M_H - M_L = 2|M_{12}|$$

- $\Delta m > 0$, $\Delta\Gamma$ can have either signs ($\Delta\Gamma > 0$ sign convention in SM)
- Solving eigenvalues problem:

$$(\Delta m)^2 - \frac{1}{4}(\Delta\Gamma)^2 = 4|M_{12}|^2 - |\Gamma_{12}|^2$$

$$\Delta m \Delta\Gamma = 4\mathfrak{Re}(M_{12}\Gamma_{12})$$

Time developement of the mass eigenstates of B mesons

- Diagonalization of Hamiltonian leads to mass eigenstates:

$$\begin{aligned} |B_L\rangle &= p\left|B^0\right\rangle + q\left|\bar{B}^0\right\rangle \\ |B_H\rangle &= p\left|B^0\right\rangle - q\left|\bar{B}^0\right\rangle \end{aligned} \tag{3}$$

- Solution of the Schrödinger equation:

$$\begin{aligned} |B_L(t)\rangle &= e^{-iM_L t} e^{\frac{-\Gamma_L}{2} t} |B_L(0)\rangle\,, \\ |B_H(t)\rangle &= e^{-iM_H t} e^{\frac{-\Gamma_H}{2} t} |B_H(0)\rangle\,, \end{aligned} \tag{4}$$

Time developement of the flavor eigenstates of B mesons

- Time development of B^0 and $\bar{B}^0$:

$$\begin{aligned} \left|B^0(t)\right\rangle &= \frac{1}{2p}(|B_L(t)\rangle + |B_H(t)\rangle) \\ \left|\bar{B}^0(t)\right\rangle &= \frac{1}{2q}(|B_L(t)\rangle - |B_H(t)\rangle) \end{aligned} \tag{5}$$

- Substituting the solution of Schrödinger equation:

$$\begin{aligned} \left|B^0(t)\right\rangle &= \frac{1}{2p}\left\{e^{-iM_L t}e^{\frac{-\Gamma_L}{2}t}\left|B_L(0)\right\rangle + e^{-iM_H t}e^{\frac{-\Gamma_H}{2}t}\left|B_H(0)\right\rangle\right\} \\ \left|\bar{B}^0(t)\right\rangle &= \frac{1}{2q}\left\{e^{-iM_L t}e^{\frac{-\Gamma_L}{2}t}\left|B_L(0)\right\rangle - e^{-iM_H t}e^{\frac{-\Gamma_H}{2}t}\left|B_H(0)\right\rangle\right\} \end{aligned} \tag{6}$$

Time development of the flavor eigenstates of B mesons

$$
\begin{aligned}
\left|B^0(t)\right\rangle =& \frac{1}{2p}\left\{pe^{-iM_L t}e^{\frac{-\Gamma_L}{2}t}\left|B(0)\right\rangle + qe^{-iM_L t}e^{\frac{-\Gamma_L}{2}t}\left|\bar{B}(0)\right\rangle\right\} \\
&+\frac{1}{2p}\left\{pe^{-iM_H t}e^{\frac{-\Gamma_H}{2}t}\left|B(0)\right\rangle - qe^{-iM_H t}e^{\frac{-\Gamma_H}{2}t}\left|\bar{B}(0)\right\rangle\right\}
\end{aligned} \tag{7}
$$

- using $g_{\pm}(t) = \frac{1}{2}\left(e^{-iM_L t}e^{\frac{-\Gamma_L}{2}t} \pm e^{-iM_H t}e^{\frac{-\Gamma_H}{2}t}\right)$:

$$
\left|B^0(t)\right\rangle = g_+(t)\left|B^0\right\rangle + \frac{q}{p}g_-(t)\left|\bar{B}^0\right\rangle
$$

$$
\left|\bar{B}^0(t)\right\rangle = g_+(t)\left|\bar{B}^0\right\rangle - \frac{p}{q}g_-(t)\left|B^0\right\rangle
$$

Time development of the flavor eigenstates of B mesons

- $g_{\pm}(t) = \frac{1}{2}\left(e^{-iM_L t} e^{\frac{-\Gamma_L}{2} t} \pm e^{-iM_H t} e^{\frac{-\Gamma_H}{2} t}\right)$ squared:

$$\begin{aligned} |g_{\pm}(t)|^2 &= \frac{1}{2} e^{-\Gamma t}\left(\cosh\frac{\Delta\Gamma}{2} t \pm \cos\Delta m t\right) \\ g_{+}(t) g_{-}^{\star}(t) &= \frac{1}{2} e^{-\Gamma t}\left(-\sinh\frac{\Delta\Gamma}{2} t - i\sin\Delta m t\right) \\ g_{+}^{\star}(t) g_{-}(t) &= \frac{1}{2} e^{-\Gamma t}\left(-\sinh\frac{\Delta\Gamma}{2} t + i\sin\Delta m t\right) \end{aligned} \tag{8}$$

- Helpful parameter

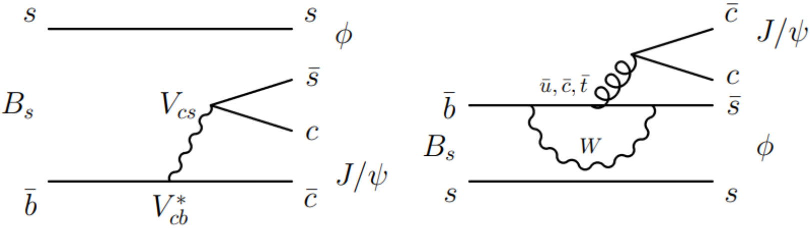
$$\lambda_f = \frac{q\bar{A}_f}{pA_f} = \eta_f e^{-i\phi_s}$$

Branching ratio (decay rate)

$$\Gamma\left(B_s^0(t) \to f\right) = |A_f|^2 \mathrm{e}^{-\Gamma t}\left[(1+|\lambda_f|)\cosh\frac{\Delta\Gamma_s t}{2} + (1-|\lambda_f|)\cos\Delta M t + 2\mathcal{R}e\left(\lambda_f\right)\sinh\frac{\Delta\Gamma_s t}{2} - 2\mathcal{I}m\left(\lambda_f\right)\sin\Delta M t\right] \quad (9)$$

$$\Gamma\left(\bar{B}^0(t) \to f\right) = |A_f|^2 \mathrm{e}^{-\Gamma t}\left[(1+|\lambda_f|)\cosh\frac{\Delta\Gamma_s t}{2} - (1-|\lambda_f|)\cos\Delta M t + 2\mathcal{R}e\left(\lambda_f\right)\sinh\frac{\Delta\Gamma_s t}{2} + 2\mathcal{I}m\left(\lambda_f\right)\sin\Delta M t\right] \quad (10)$$

$\mathcal{CP}$-violating phase ϕ_s in decay $B_s^0 \to J/\psi\phi$



$\mathcal{CP}$-violating phase ϕ_s in decay $B_s^0 \to J/\psi\phi$

- $\mathcal{CP}$ eigenvalues of the $J/\psi\phi$ final state are $\eta_f = \pm 1$, depending on the total angular momentum L:

$$\mathcal{CP}\,|J/\psi\phi\rangle = \eta_f\,|J/\psi\phi\rangle = (-1)^L\,|J/\psi\phi\rangle$$

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- B_s^0 is a spinless particle, total angular momentum: $\mathcal{J} = 0$
- Adding the spin of the the J/ψ and ϕ results into total spin

$$S \in \{0, 1, 2\}$$

- conservation of angular momentum: $L + S = 0$

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- $\mathcal{CP}$ even states: $\eta_f = 1,\ L = 0, 2$
  - parallel ($\|$) state: J/ψ and ϕ parallel with respect to the direction of their momentum
  - zero state: polarisation of J/ψ perpendicular to ϕ perpendicular with respect to the direction of their momentum
- $\mathcal{CP}$ odd states: $\eta_f = -1,\ L = 1$

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- $\mathcal{CP}$ odd states: $\eta_f = -1,\ L = 1$
  - perpendicular ($\perp$) state: polarisation of J/ψ perpendicular to ϕ and parallel with respect to the direction of their momentum

B_s^0 differential decay rate - time part

$$\frac{\mathrm{d}\Gamma(B_s^0 \to J/\psi\phi)}{\mathrm{d}t\mathrm{d}\Omega} = \sum_{i=1}^{6} A_i(t) f_i(\cos\theta, \varphi, \cos\psi)$$

$$\begin{aligned}
|A_0(\mathrm{t})|^2 &= |A_0(0)|^2 e^{-\Gamma_s t}\left[\cosh\left(\frac{\Delta\Gamma_s}{2}t\right) - \cos\phi_s \sinh\left(\frac{\Delta\Gamma_s}{2}t\right) + \sin\phi_s \sin\left(\Delta m_s t\right)\right] \\
\left|A_\parallel(\mathrm{t})\right|^2 &= \left|A_\parallel(0)\right|^2 e^{-\Gamma_s t}\left[\cosh\left(\frac{\Delta\Gamma_s}{2}t\right) - \cos\phi_s \sinh\left(\frac{\Delta\Gamma_s}{2}t\right) + \sin\phi_s \sin\left(\Delta m_s t\right)\right] \\
|A_\perp(\mathrm{t})|^2 &= |A_\perp(0)|^2 e^{-\Gamma_s t}\left[\cosh\left(\frac{\Delta\Gamma_s}{2}t\right) + \cos\phi_s \sinh\left(\frac{\Delta\Gamma_s}{2}t\right) - \sin\phi_s \sin\left(\Delta m_s t\right)\right] \\
\Im(A_\parallel^*(\mathrm{t})A_\perp(\mathrm{t})) &= \left|A_\parallel(0)\right| |A_\perp(0)| e^{-\Gamma_s t}\left[-\cos\left(\delta_\perp - \delta_\parallel\right)\sin\phi_s \sinh\left(\frac{\Delta\Gamma_s}{2}t\right)\right. \\
&\quad \left. + \sin\left(\delta_\perp - \delta_\parallel\right)\cos\left(\Delta m_s t\right) - \cos\left(\delta_\perp - \delta_\parallel\right)\cos\phi_s \sin\left(\Delta m_s t\right)\right] \\
\Re(A_0^*(\mathrm{t})A_\parallel(\mathrm{t})) &= |A_0(0)| \left|A_\parallel(0)\right| e^{-\Gamma_s t}\cos\delta_\parallel\left[\cosh\left(\frac{\Delta\Gamma_s}{2}t\right) - \cos\phi_s \sinh\left(\frac{\Delta\Gamma_s}{2}t\right)\right. \\
&\quad \left. + \sin\phi_s \sin\left(\Delta m_s t\right)\right] \\
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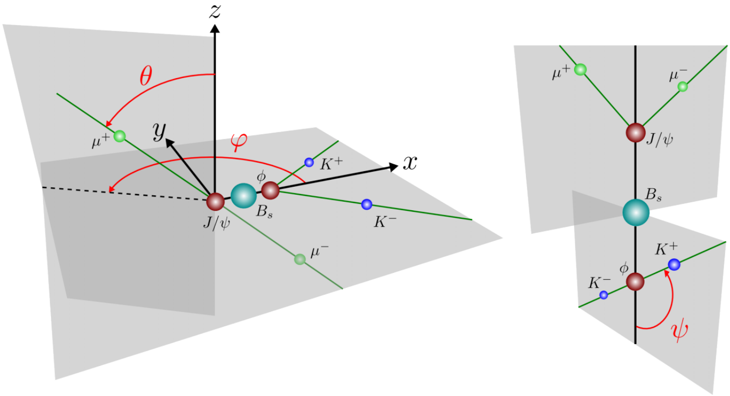
&\quad \left. + \sin\delta_\perp \cos\left(\Delta m_s t\right) - \cos\delta_\perp \cos\phi_s \sin\left(\Delta m_s t\right)\right]
\end{aligned}$$

B_s^0 differential decay rate - angular part



B_s^0 differential decay rate - angular part

i	$A_i\,(\mathrm{t})$	$\bar{A}_i\,(\mathrm{t})$	$f_i\,(\cos\theta, \varphi, \cos\psi)$
1	$\lvert A_0(\mathrm{t})\rvert^2$	$\lvert \bar{A}_0(\mathrm{t})\rvert^2$	$\frac{9}{32\pi} 2\cos^2\psi\left(1-\sin^2\theta\cos^2\varphi\right)$
2	$\lvert A_\parallel(\mathrm{t})\rvert^2$	$\lvert \bar{A}_\parallel(\mathrm{t})\rvert^2$	$\frac{9}{32\pi}\sin^2\psi\left(1-\sin^2\theta\sin^2\varphi\right)$
3	$\lvert A_\perp(\mathrm{t})\rvert^2$	$\lvert \bar{A}_\perp(\mathrm{t})\rvert^2$	$\frac{9}{32\pi}\sin^2\psi\sin^2\theta$
4	$\Im\left(A_\parallel^*(\mathrm{t})A_\perp(\mathrm{t})\right)$	$\Im\left(\bar{A}_\parallel^*(\mathrm{t})\bar{A}_\perp(\mathrm{t})\right)$	$-\frac{9}{32\pi}\sin^2\psi\sin 2\theta\sin\varphi$
5	$\Re\left(A_0^*(\mathrm{t})A_\parallel(\mathrm{t})\right)$	$\Re\left(\bar{A}_0^*(\mathrm{t})\bar{A}_\parallel(\mathrm{t})\right)$	$\frac{9}{32\pi\sqrt{2}}\sin 2\psi\sin^2\theta\sin 2\varphi$
6	$\Im\left(A_0^*(\mathrm{t})A_\perp(\mathrm{t})\right)$	$\Im\left(\bar{A}_0^*(\mathrm{t})\bar{A}_\perp(\mathrm{t})\right)$	$\frac{9}{32\pi\sqrt{2}}\sin 2\psi\sin 2\theta\cos\varphi$

S-wave contribution

- ϕ is a vector meson - the K^+K^- system is in a P-wave configuration
- Detected K^+K^- results from a non-resonant contribution or decay of the $f_0(980)$ which is a scalar meson
- In both cases: S-wave configuration
- Introduce the S-wave amplitude $A_s(t)$ with phase δ_s
- S-wave amplitude can also interfere with the P-wave
- The S-wave contributions have also its angular distributions

$$\frac{\mathrm{d}\Gamma(B_s^0 \to J/\psi\phi)}{\mathrm{d}t\mathrm{d}\Omega} = \sum_{i=1}^{10} A_i(t) f_i(\cos\theta, \varphi, \cos\psi)$$

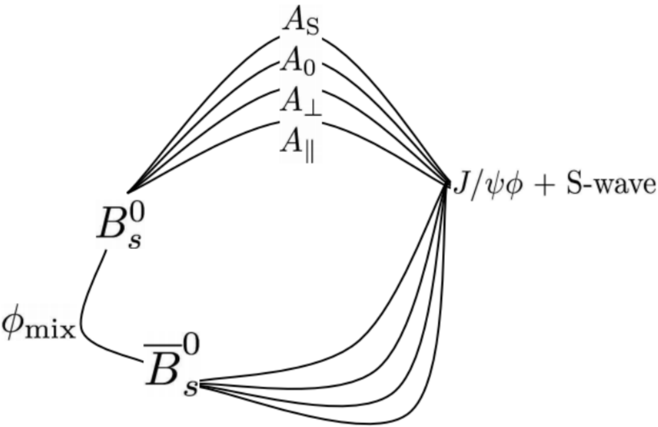
S-wave contribution

k	$\mathcal{O}^{(k)}(t)$	$g^{(k)}(\theta_T, \psi_T, \phi_T)$
1	$\frac{1}{2}\|A_0(0)\|^2 \left[(1+\cos\phi_s)\, e^{-\Gamma_L^{(s)}t} + (1-\cos\phi_s)\, e^{-\Gamma_H^{(s)}t}\right]$	$2\cos^2\psi_T(1-\sin^2\theta_T\cos^2\phi_T)$
2	$\frac{1}{2}\|A_\parallel(0)\|^2 \left[(1+\cos\phi_s)\, e^{-\Gamma_L^{(s)}t} + (1-\cos\phi_s)\, e^{-\Gamma_H^{(s)}t}\right]$	$\sin^2\psi_T(1-\sin^2\theta_T\sin^2\phi_T)$
3	$\frac{1}{2}\|A_\perp(0)\|^2 \left[(1-\cos\phi_s)\, e^{-\Gamma_L^{(s)}t} + (1+\cos\phi_s)\, e^{-\Gamma_H^{(s)}t}\right]$	$\sin^2\psi_T\sin^2\theta_T$
4	$\frac{1}{2}\|A_0(0)\|\|A_\parallel(0)\|\cos\delta_{\|\|}$ $\left[(1+\cos\phi_s)\, e^{-\Gamma_L^{(s)}t} + (1-\cos\phi_s)\, e^{-\Gamma_H^{(s)}t}\right]$	$-\frac{1}{\sqrt{2}}\sin 2\psi_T\sin^2\theta_T\sin 2\phi_T$
5	$\|A_\parallel(0)\|\|A_\perp(0)\|[\frac{1}{2}(e^{-\Gamma_L^{(s)}t} - e^{-\Gamma_H^{(s)}t})\cos(\delta_\perp - \delta_{\|\|})\sin\phi_s$	$\sin^2\psi_T\sin 2\theta_T\sin\phi_T$
6	$\|A_0(0)\|\|A_\perp(0)\|[\frac{1}{2}(e^{-\Gamma_L^{(s)}t} - e^{-\Gamma_H^{(s)}t})\cos\delta_\perp\sin\phi_s$	$\frac{1}{\sqrt{2}}\sin 2\psi_T\sin 2\theta_T\cos\phi_T$
7	$\frac{1}{2}\|A_S(0)\|^2 \left[(1-\cos\phi_s)\, e^{-\Gamma_L^{(s)}t} + (1+\cos\phi_s)\, e^{-\Gamma_H^{(s)}t}\right]$	$\frac{2}{3}\left(1-\sin^2\theta_T\cos^2\phi_T\right)$
8	$\|A_S(0)\|\|A_\parallel(0)\|[\frac{1}{2}(e^{-\Gamma_L^{(s)}t} - e^{-\Gamma_H^{(s)}t})\sin(\delta_\parallel - \delta_S)\sin\phi_s$	$\frac{1}{3}\sqrt{6}\sin\psi_T\sin^2\theta_T\sin 2\phi_T$
9	$\frac{1}{2}\|A_S(0)\|\|A_\perp(0)\|\sin(\delta_\perp - \delta_S)$ $\left[(1-\cos\phi_s)\, e^{-\Gamma_L^{(s)}t} + (1+\cos\phi_s)\, e^{-\Gamma_H^{(s)}t}\right]$	$\frac{1}{3}\sqrt{6}\sin\psi_T\sin 2\theta_T\cos\phi_T$
10	$\|A_0(0)\|\|A_S(0)\|[\frac{1}{2}(e^{-\Gamma_H^{(s)}t} - e^{-\Gamma_L^{(s)}t})\sin\delta_S\sin\phi_s$	$\frac{4}{3}\sqrt{3}\cos\psi_T\left(1-\sin^2\theta_T\cos^2\phi_T\right)$

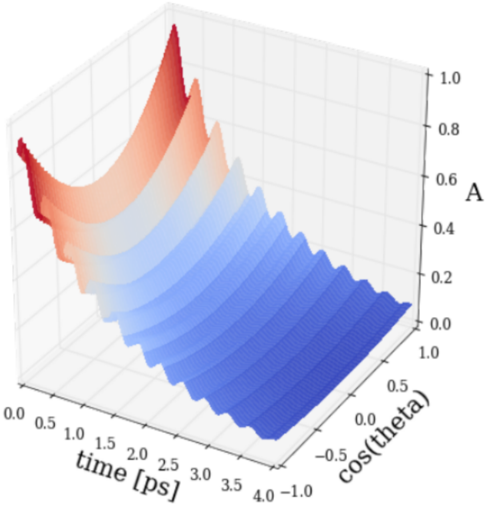
S-wave contribution

k	$\mathcal{O}^{(k)}(t)$ $\quad \pm \to B_s/\bar{B}_s$	$g^{(k)}(\theta_T, \psi_T, \phi_T)$
1	$\frac{1}{2}\|A_0(0)\|^2 \left[(1+\cos\phi_s)\, e^{-\Gamma_L^{(s)}t} + (1-\cos\phi_s)\, e^{-\Gamma_H^{(s)}t} \pm 2e^{-\Gamma_s t}\sin(\Delta m_s t)\sin\phi_s\right]$	$2\cos^2\psi_T(1-\sin^2\theta_T\cos^2\phi_T)$
2	$\frac{1}{2}\|A_\parallel(0)\|^2 \left[(1+\cos\phi_s)\, e^{-\Gamma_L^{(s)}t} + (1-\cos\phi_s)\, e^{-\Gamma_H^{(s)}t} \pm 2e^{-\Gamma_s t}\sin(\Delta m_s t)\sin\phi_s\right]$	$\sin^2\psi_T(1-\sin^2\theta_T\sin^2\phi_T)$
3	$\frac{1}{2}\|A_\perp(0)\|^2 \left[(1-\cos\phi_s)\, e^{-\Gamma_L^{(s)}t} + (1+\cos\phi_s)\, e^{-\Gamma_H^{(s)}t} \mp 2e^{-\Gamma_s t}\sin(\Delta m_s t)\sin\phi_s\right]$	$\sin^2\psi_T\sin^2\theta_T$
4	$\frac{1}{2}\|A_0(0)\|\|A_\parallel(0)\|\cos\delta_\parallel$ $\left[(1+\cos\phi_s)\, e^{-\Gamma_L^{(s)}t} + (1-\cos\phi_s)\, e^{-\Gamma_H^{(s)}t} \pm 2e^{-\Gamma_s t}\sin(\Delta m_s t)\sin\phi_s\right]$	$-\frac{1}{\sqrt{2}}\sin 2\psi_T\sin^2\theta_T\sin 2\phi_T$
5	$\|A_\parallel(0)\|\|A_\perp(0)\|[\frac{1}{2}(e^{-\Gamma_L^{(s)}t} - e^{-\Gamma_H^{(s)}t})\cos(\delta_\perp-\delta_\parallel)\sin\phi_s$ $\pm e^{-\Gamma_s t}(\sin(\delta_\perp-\delta_\parallel)\cos(\Delta m_s t) - \cos(\delta_\perp-\delta_\parallel)\cos\phi_s\sin(\Delta m_s t))]$	$\sin^2\psi_T\sin 2\theta_T\sin\phi_T$
6	$\|A_0(0)\|\|A_\perp(0)\|[\frac{1}{2}(e^{-\Gamma_L^{(s)}t} - e^{-\Gamma_H^{(s)}t})\cos\delta_\perp\sin\phi_s$ $\pm e^{-\Gamma_s t}(\sin\delta_\perp\cos(\Delta m_s t) - \cos\delta_\perp\cos\phi_s\sin(\Delta m_s t))]$	$\frac{1}{\sqrt{2}}\sin 2\psi_T\sin 2\theta_T\cos\phi_T$
7	$\frac{1}{2}\|A_S(0)\|^2 \left[(1-\cos\phi_s)\, e^{-\Gamma_L^{(s)}t} + (1+\cos\phi_s)\, e^{-\Gamma_H^{(s)}t} \mp 2e^{-\Gamma_s t}\sin(\Delta m_s t)\sin\phi_s\right]$	$\frac{2}{3}\left(1-\sin^2\theta_T\cos^2\phi_T\right)$
8	$\|A_S(0)\|\|A_\parallel(0)\|[\frac{1}{2}(e^{-\Gamma_L^{(s)}t} - e^{-\Gamma_H^{(s)}t})\sin(\delta_\parallel-\delta_S)\sin\phi_s$ $\pm e^{-\Gamma_s t}(\cos(\delta_\parallel-\delta_S)\cos(\Delta m_s t) - \sin(\delta_\parallel-\delta_S)\cos\phi_s\sin(\Delta m_s t))]$	$\frac{1}{3}\sqrt{6}\sin\psi_T\sin^2\theta_T\sin 2\phi_T$
9	$\frac{1}{2}\|A_S(0)\|\|A_\perp(0)\|\sin(\delta_\perp-\delta_S)$ $\left[(1-\cos\phi_s)\, e^{-\Gamma_L^{(s)}t} + (1+\cos\phi_s)\, e^{-\Gamma_H^{(s)}t} \mp 2e^{-\Gamma_s t}\sin(\Delta m_s t)\sin\phi_s\right]$	$\frac{1}{3}\sqrt{6}\sin\psi_T\sin 2\theta_T\cos\phi_T$
10	$\|A_0(0)\|\|A_S(0)\|[\frac{1}{2}(e^{-\Gamma_H^{(s)}t} - e^{-\Gamma_L^{(s)}t})\sin\delta_S\sin\phi_s$ $\pm e^{-\Gamma_s t}(\cos\delta_S\cos(\Delta m_s t) + \sin\delta_S\cos\phi_s\sin(\Delta m_s t))]$	$\frac{4}{3}\sqrt{3}\cos\psi_T\left(1-\sin^2\theta_T\cos^2\phi_T\right)$

S-wave contribution



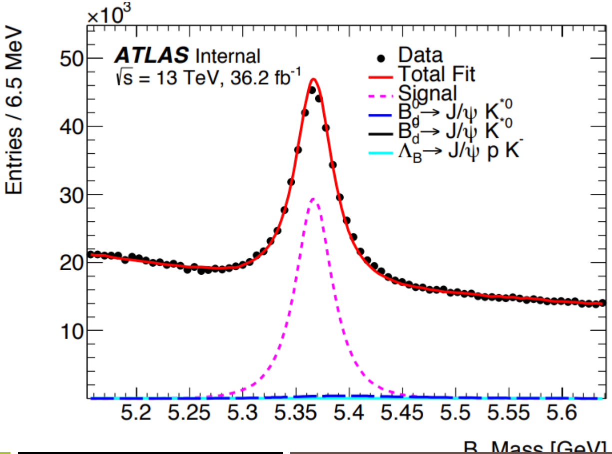
S-wave contribution



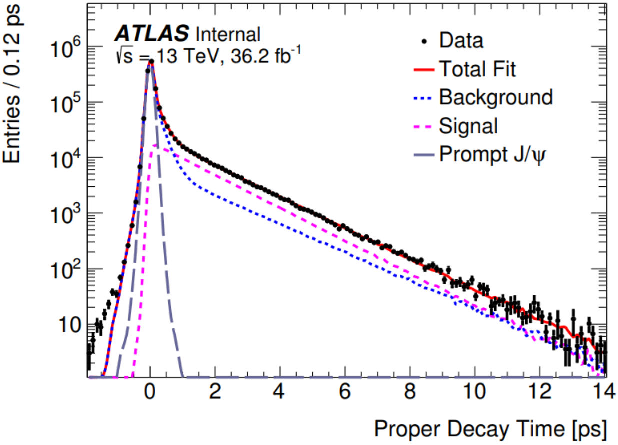
~~Theory~~

~~Theory~~ Measurements

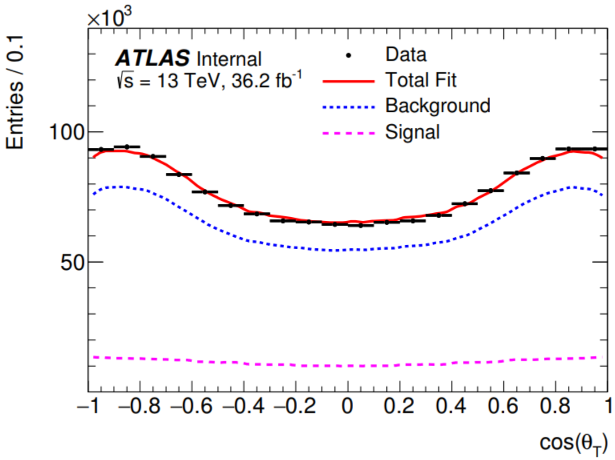
- Our analysis: 5 dimensional fit: mass, lifetime, 3 angles



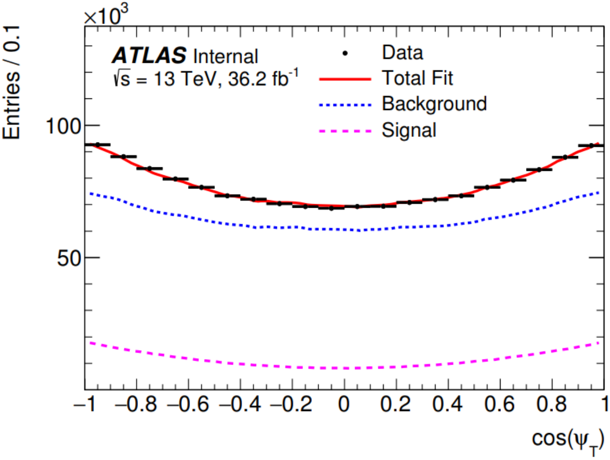
~~Theory~~ Measurements



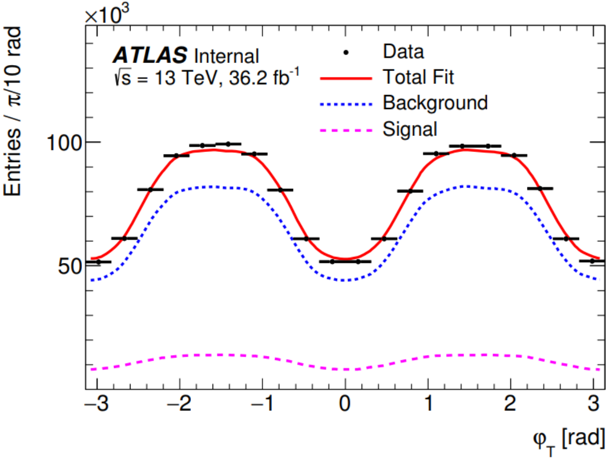
~~Theory~~ Measurements



~~Theory~~ Measurements



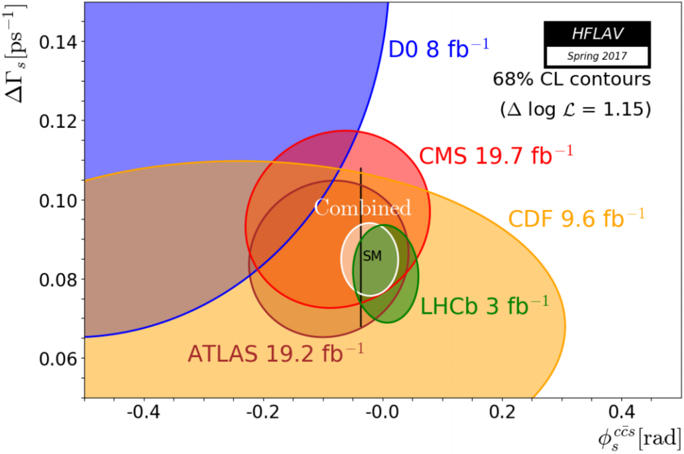
~~Theory~~ Measurements



Results

$$
\begin{aligned}
\phi_s &= -0.055 \pm 0.053\ (\text{stat.}) \pm 0.0069\ (\text{syst.})\ rad \\
\Delta\Gamma_s &= 0.080 \pm 0.007\ (\text{stat.}) \pm 0.0024\ (\text{syst.})\ \text{ps}^{-1} \\
\Gamma_s &= 0.667 \pm 0.002\ (\text{stat.}) \pm 0.0010\ (\text{syst.})\ \text{ps}^{-1} \\
|A_{\parallel}(0)|^2 &= 0.219 \pm 0.002\ (\text{stat.}) \pm 0.0012\ (\text{syst.}) \\
|A_0(0)|^2 &= 0.518 \pm 0.002\ (\text{stat.}) \pm 0.0028\ (\text{syst.}) \\
|A_S(0)|^2 &= 0.053 \pm 0.005\ (\text{stat.}) \pm 0.0072\ (\text{syst.}) \\
\delta_{\perp} &= 2.767 \pm 0.161\ (\text{stat.}) \pm\ 0.0390\ (\text{syst.})\ rad \\
\delta_{\parallel} &= 3.123 \pm 0.140\ (\text{stat.}) \pm\ 0.0054\ (\text{syst.})\ rad \\
\delta_{\perp} - \delta_S &= -0.113 \pm 0.025\ (\text{stat.}) \pm 0.0079\ (\text{syst.})\ rad.
\end{aligned}
$$

Results



HFLAV
Spring 2017
68% CL contours
(Δ log ℒ = 1.15)
D0 8 fb^{-1}
CMS 19.7 fb^{-1}
CDF 9.6 fb^{-1}
LHCb 3 fb^{-1}
ATLAS 19.2 fb^{-1}
Combined
SM
$\Delta\Gamma_s\,[\mathrm{ps}^{-1}]$
0.14
0.12
0.10
0.08
0.06
-0.4
-0.2
-0.0
0.2
0.4
$\phi_s^{c\bar{c}s}\,[\mathrm{rad}]$