Experimental prospects on time-dependent CP Violation and Mixing in $B^0_{(s)}$ Meson decays

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including results from LHCb and other experiments

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Questions asked by the organizers:

- How precise should we measure time-dependent CP asymmetries, such as ϕ_s and $\sin 2\beta$?
- How should we deal with penguin pollution?
- How precise should we measure mixing ($\Delta m_{s,d}$) and lifetimes ($\Gamma_{s,d}$ and $\Delta\Gamma_{s,d}$)?
- Please include tree $b \to c\bar{c}$ (e.g. $B_s^0 \to J/\psi\phi$) diagrams and $b \to s\bar{s}$ (e.g. $B_s^0 \to \phi\phi$) penguin decays.
  The talk should cover LHCb, but also ATLAS and CMS results/prospects (e.g. on ϕ_s and $\Delta\Gamma_{s,d}$).

Outline

How precise should we measure a parameter x?

Usual "5σ criteria". To claim a discovery, one needs:

$$\frac{|x_{\rm exp} - x_{\rm theo}|}{\sqrt{\sigma^2_{x_{\rm exp}} + \sigma^2_{x_{\rm theo}}}} > 5$$

- $x_{\rm exp}$ should be significantly different than $x_{\rm theo}$ (Nature decides!)
- Experimental and theoretical uncertainties should be sufficiently small $\rightarrow$ Our work!

Reminder on B mixing and lifetime (1)

The neutral B_q $(q = d, s)$ system is described by the following equation

$$i\frac{d}{dt}\begin{pmatrix} |B_q(t)\rangle \\ |\bar{B}_q(t)\rangle \end{pmatrix} = \left(\hat{M}^q - \frac{i}{2}\hat{\Gamma}^q\right)\begin{pmatrix} |B_q(t)\rangle \\ |\bar{B}_q(t)\rangle \end{pmatrix}$$

The famous box diagrams give rise to off-diagonal elements M_{12}^q and Γ_{12}^q in the mass matrix $\hat{M}^q$ and the decay rate matrix $\hat{\Gamma}^q$

Diagonalization of $\hat{M}^q$ and $\hat{\Gamma}^q$ gives the mass eigenstates

$$\text{CP-odd:} \quad B_H^q = p\,B_q + q\,\bar{B}_q \quad , \quad \text{CP-even:} \quad B_L^q = p\,B_q - q\,\bar{B}_q$$

$$(|p|^2 + |q|^2 = 1)$$

with the corresponding masses M_H^q, M_L^q and widths Γ_H^q, Γ_L^q

Reminder on B mixing and lifetime (2)

e.g. [arXiv:1103.4962]

$|M_{12}^q|$, $|\Gamma_{12}^q|$ and $\phi_{12}^q = \arg(-M_{12}^q/\Gamma_{12}^q)$ are related to 3 measurable quantities:

- **Mass difference:** $\Delta M_q = M_H^q - M_L^q = 2|M_{12}^q| \left(1 + \frac{1}{8}\frac{|\Gamma_{12}^q|^2}{|M_{12}^q|^2}\sin^2\phi_{12}^q + \ldots\right)$
- **Decay rate difference:**
  $\Delta\Gamma_q = \Gamma_L^q - \Gamma_H^q = 2|\Gamma_{12}^q|\cos\phi_{12}^q \left(1 - \frac{1}{8}\frac{|\Gamma_{12}^q|^2}{|M_{12}^q|^2}\sin^2\phi_{12}^q + \ldots\right)$
- **Flavor specific / semileptonic CP asymmetries:**

$$A_{\mathrm{SL}}^q = \mathrm{Im}\frac{\Gamma_{12}^q}{M_{12}^q} + \mathcal{O}\left(\frac{\Gamma_{12}^q}{M_{12}^q}\right)^2 = \frac{\Delta\Gamma_q}{\Delta M_q}\tan\phi_{12q} + \mathcal{O}\left(\frac{\Gamma_{12}^q}{M_{12}^q}\right)^2$$

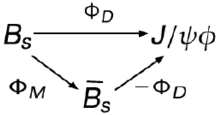
$\rightarrow$ See talk by M. Vesterinen

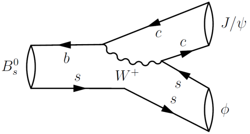
Beware: $\phi_M^q = \arg(M_{12}^q)$ is convention dependent, while ϕ_{12}^q is not.

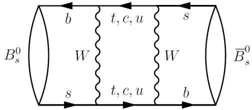
$b \to c\bar{c}s$ mixing-induced CPV in B_s^0

Mixing-induced CPV in B_s^0

- Interference between B_s^0 decay to $J/\psi\,\phi$ either directly or via B_s^0–$\overline{B}_s^0$ oscillation gives rise to a CP violating phase $\phi_s^{c\bar{c}s} \equiv \phi_s = \phi_{\rm M} - 2\phi_{\rm D}$





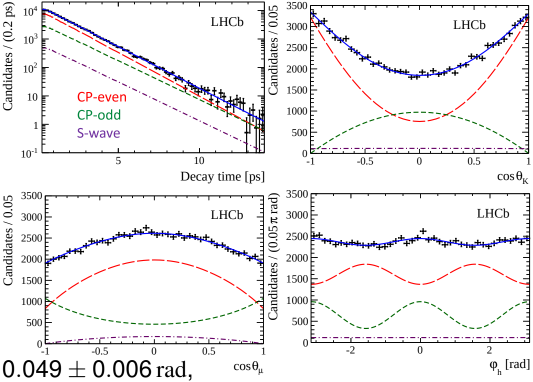


- In SM, assuming the decay is dominated by the above $\bar{b} \to \bar{c}c\bar{s}$ tree diagram: $\phi_D = \arg(V_{cs}V_{cb}^*)$ and $\phi_M = 2\arg(V_{ts}V_{tb}^*)$, so that the resulting measurable phase is: $\phi_s \simeq -2\arg\left(-V_{ts}V_{tb}^*/V_{cs}V_{cb}^*\right) = -2\beta_s$ with $\beta_s = \arg\left(-V_{ts}V_{tb}^*/V_{cs}V_{cb}^*\right)$
- Indirect fit to experimental data gives: $-2\beta_s = -0.0376^{+0.0007}_{-0.0008}$ [CKMfitter]
- We will discussed about the sub-leading contributions later.
- NP could enter in the $B_s^0 - \overline{B}_s^0$ mixing box diagram.

- ϕ_s Measured by fitting differential decay rates for B_s^0 and $\bar{B}_s^0$:

$$\frac{\mathrm{d}^4\Gamma(B_s^0 \to J/\psi\phi)}{\mathrm{d}t\, \mathrm{d}\cos\theta_\mu\, \mathrm{d}\varphi_h\, \mathrm{d}\cos\theta_K} = f(\phi_s, \Delta\Gamma_s, \Gamma_s, \Delta m_s, M(B_s^0), |A_\perp|, |A_\parallel|, |A_S|, \delta_\perp, \delta_\parallel, ...)$$

- Unbinned maximum likelihood fit (time, mass, angles, initial flavor), $3\,\mathrm{fb}^{-1}$



- $\phi_s = -0.058 \pm 0.049 \pm 0.006\,\mathrm{rad}$,
- $\Gamma_s \equiv (\Gamma_\mathrm{L} + \Gamma_\mathrm{H})/2 = 0.6603 \pm 0.0027 \pm 0.0015\,\mathrm{ps}^{-1}$
- $\Delta\Gamma_s \equiv \Gamma_\mathrm{L} - \Gamma_\mathrm{H} = 0.0805 \pm 0.0091 \pm 0.0032\ \mathrm{ps}^{-1}$

Mixing-induced CPV in B_s^0

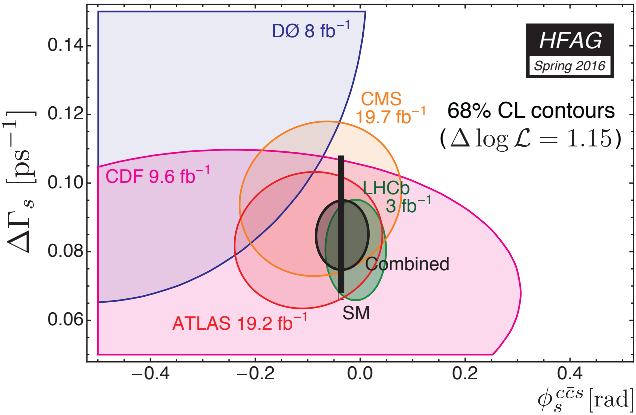
ϕ_s, $\Delta\Gamma_s$, Γ_s also measured in other modes and in other experiments

Exp., fb^{-1}	Mode	ϕ_s	$\Delta\Gamma_s$(ps^{-1})	Γ_s(ps^{-1})
ATLAS[a], 19.2	$J/\psi\,\phi$	$-0.098 \pm 0.084 \pm 0.040$	$0.083 \pm 0.011 \pm 0.007$	$0.677 \pm 0.003 \pm 0.003$
CMS[b], 20	$J/\psi\,\phi$	$-0.075 \pm 0.097 \pm 0.031$	$0.095 \pm 0.013 \pm 0.007$	$0.670 \pm 0.004 \pm 0.006$
LHCb, 3	$J/\psi\,KK$	$-0.058 \pm 0.049 \pm 0.006$	$0.0805 \pm 0.0091 \pm 0.0032$	$0.6603 \pm 0.0027 \pm 0.0015$
LHCb, 3	$J/\psi\,\pi\pi$	$+0.070 \pm 0.068 \pm 0.008$	—	—
LHCb, 3	$J/\psi\,hh$	-0.010 ± 0.040(tot)	—	—
LHCb, 3	$D_s D_s$	$+0.02 \pm 0.17 \pm 0.02$	—	—
LHCb, 3	$J/\psi\,hh$, $D_s D_s$	-0.009 ± 0.038(tot)	—	—
All combined		-0.033 ± 0.033	0.0827 ± 0.006	0.6643 ± 0.0020
SM		$-0.0376^{+0.0007}_{-0.0008}$	0.088 ± 0.020	$\in [0.27,\ 1.11]$[c]

[a][ATLAS, arXiv:1601.03297], [b][CMS, PLB 757, 97 (2016)], [c][A. Lenz, arXiv:1405.3601]

- LHCb is dominating the world average
- $B_s^0 \to J/\psi\,KK$ is the golden mode. Measure not only ϕ_s, but also $\Delta\Gamma_s$, Γ_s and Δm_s
- Second best mode is $B_s^0 \to J/\psi\,\pi^+\pi^-$. The other modes bring marginal improvement on ϕ_s, but nevertheless interesting because involve not exactly the same diagrams ($D_s^+ D_s^-$, $\psi(2S)\phi$, ...)

SM prediction from [CKMfitter] for ϕ_s and [M. Artuso et al., arXiv:1511.09466] for $\Delta\Gamma_s$



- Assuming we can average ϕ_s in $J/\psi KK$, $J/\psi \pi\pi$ and $D_s^+ D_s^-$:
  $\phi_s^{\text{HFAG WA}} = -0.033 \pm 0.033$
- Compatible with SM, but still room for NP!

Systematics uncertainties on ϕ_s, $\Delta\Gamma_s$, Γ_s [LHCb, PRL 114, 041801 (2015)]

Source	Γ_s [ps^{-1}]	$\Delta\Gamma_s$ [ps^{-1}]	$\lvert A_\perp(t)\rvert^2$	$\lvert A_0(t)\rvert^2$	$\delta_\parallel$ [rad]	$\delta_\perp$ [rad]	ϕ_s [rad]	$\lvert\lambda\rvert$	Δm_s [ps^{-1}]
Total stat. uncertainty	0.0027	0.0091	0.0049	0.0034	$^{+0.10}_{-0.17}$	$^{+0.14}_{-0.15}$	0.049	0.019	$^{+0.055}_{-0.057}$
Mass factorization	–	0.0007	0.0031	0.0064	0.05	0.05	0.002	0.001	0.004
Signal weights (stat.)	0.0001	0.0001	–	0.0001	–	–	–	–	–
b-hadron background	0.0001	0.0004	0.0004	0.0002	0.02	0.02	0.002	0.003	0.001
B_c^+ feed-down	0.0005	–	–	–	–	–	–	–	–
Angular resolution bias	–	–	0.0006	0.0001	$^{+0.02}_{-0.03}$	0.01	–	–	–
Ang. efficiency (reweighting)	0.0001	–	0.0011	0.0020	0.01	–	0.001	0.005	0.002
Ang. efficiency (stat.)	0.0001	0.0002	0.0011	0.0004	0.02	0.01	0.004	0.002	0.001
Decay-time resolution	–	–	–	–	–	0.01	0.002	0.001	0.005
Trigger efficiency (stat.)	0.0011	0.0009	–	–	–	–	–	–	–
Track reconstruction (simul.)	0.0007	0.0029	0.0005	0.0006	$^{+0.01}_{-0.02}$	0.002	0.001	0.001	0.006
Track reconstruction (stat.)	0.0005	0.0002	–	–	–	–	–	–	0.001
Length and momentum scales	0.0002	–	–	–	–	–	–	–	0.005
S-P coupling factors	–	–	–	–	0.01	0.01	–	0.001	0.002
Fit bias	–	–	0.0005	–	–	0.01	–	0.001	–
Quadratic sum of syst.	0.0015	0.0032	0.0036	0.0067	$^{+0.06}_{-0.07}$	0.06	0.006	0.007	0.011

- ϕ_s: $\sigma_{\rm syst} = 0.10\sigma_{\rm stat}$ systematics very small and can be reduced easily: dominant one is the limited size of the MC used to computed the angular acceptance! Total syst $\sim 2\,\mathrm{mrad}$ achievable!
- $\Delta\Gamma_s$: $\sigma_{\rm syst} = 0.35\sigma_{\rm stat}$: work needed on track reconstruction
- Γ_s: $\sigma_{\rm syst} = 0.55\sigma_{\rm stat}$: work needed on track reconstruction. Ultimate syst = LHCb length scale

Now come 2 complications:

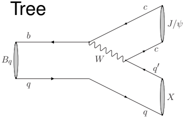
1. $B_s^0 \to J/\psi KK$: superposition of 4 polarized final states $0, \perp, \|, S$

Parameter	Value
ϕ_s^0	$-0.045 \pm 0.053 \pm 0.007$
$\phi_s^{\|} - \phi_s^0$	$-0.018 \pm 0.043 \pm 0.009$
$\phi_s^{\perp} - \phi_s^0$	$-0.014 \pm 0.035 \pm 0.006$
$\phi_s^{S} - \phi_s^0$	$0.015 \pm 0.061 \pm 0.021$
$\lvert\lambda^0\rvert$	$1.012 \pm 0.058 \pm 0.013$
$\lvert\lambda^{\|}/\lambda^0\rvert$	$1.02 \pm 0.12 \pm 0.05$
$\lvert\lambda^{\perp}/\lambda^0\rvert$	$0.97 \pm 0.16 \pm 0.01$
$\lvert\lambda^{S}/\lambda^0\rvert$	$0.86 \pm 0.12 \pm 0.04$

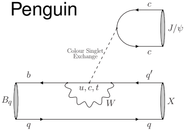
Mixing induced (ϕ_s) and direct CPV parameters (λ) are measured.
So far, no ϕ_s polarization-dependence measured [LHCb, PRL 114, 041801 (2015)]

2. Decay $b \to c\bar{c}s$ involves not only tree, but also gluonic, electroweak penguins, exchange and penguin annihilation topologies!
What we measured in $B_s^0 \to J/\psi\phi$ is $\phi_s = -2\beta_s + \Delta\phi_s^{\rm peng} + \Delta\phi_s^{\rm NP}$.
Mandatory to control $\Delta\phi_s^{\rm peng}$ to claim NP!

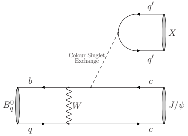
Tree



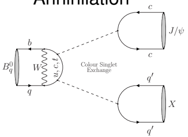
Penguin



Exchange



Penguin-Annihilation



Penguin pollution in $B_s^0 \to J/\psi\phi$

Various approaches to estimate the sub-leading contributions beyond the tree in $B_s^0 \to J/\psi\phi$ decay:

- Using $SU(3)$ flavour symmetry and control modes like $B^0 \to J/\psi\,\rho^0$, $B_s^0 \to J/\psi\,\overline{K}^{*0}$, in which the penguin is not suppressed [R. Fleischer, NIM A446:1-17,2000], [S. Faller et al. PRD79, 014005 (2009)]
- Attempt to compute directly the penguin-to-tree ratio, without $SU(3)$ approximation. [P. Frings et al. arXiv:1503.00859] $\to$ see talk by U. Nierste
- Perturbative QCD [Liu et al., PRD89, 094010 (2014)]
- Many other work on penguin pollution (ϕ_s and ϕ_d), e.g. [R. Fleischer, arxiv:hep-ph/9903455], [M. Ciuchini et al. arxiv:hep-ph/0507290], [S. Faller et al., arxiv:0809.0842], [M. Ciuchini et al., arxiv:1102.0392], [M. Jung, arxiv:1206.2050], [K. De Bruyn et al., arxiv:1412.6834], [R. Fleischer, arxiv:0705.4421], [M. Jung et al., arxiv:1410.8396], [L. Bel et al., arxiv:1505.01361], [Z. Ligeti et al., PRL 115, 251801 (2015)], [B. Bhattacharya et al., Int. J. Mod. Phys. A 28, 1350063 (2013)]

In the following, we present the $SU(3)$ method [S. Faller et al. PRD79, 014005 (2009)]
(the method that was most thorough so far in LHCb, data driven)

Penguin pollution in $B_s^0 \to J/\psi\phi$ [S. Faller et al. PRD79, 014005 (2009)]

1. $b \to c\bar{c}s$ decay amplitude ($i = 0, \perp, \parallel$):

$$A_i'(B_s^0 \to J/\psi\phi) = (1 - \frac{\lambda^2}{2})\mathcal{A}'_i[1 + \epsilon a_i' e^{i\theta_i'} e^{i\gamma}], \quad \epsilon \equiv \frac{\lambda^2}{1-\lambda^2} \simeq 0.053$$

   - Penguin are doubly Cabibbo suppressed wrt tree
   - $a_i' e^{i\theta_i'} \equiv$ "Penguin/Tree ratio" in the $B_s^0 \to J/\psi\phi$ channel
     $a_i' e^{i\theta_i'} = (1 - \frac{\lambda^2}{2})\, |V_{ub}/(\lambda V_{cb})| \left[\frac{P_u^i + P_t^i}{T_c^i + P_c^i - P_t^i}\right]$
     Penguin amplitude : $P_q, q = u, t, c$. Tree amplitude : T_c
   - $\mathcal{A}'_i = \lambda^2 |V_{cb}| \left[T_c^i + P_c^i - P_t^i\right]$
   - γ: angle of the unitarity triangle

2. $b \to c\bar{c}d$ decay amplitude

$$A_i(B^0 \to J/\psi\,\rho^0) = -\lambda\mathcal{A}_i[1 - a_i e^{i\theta_i} e^{i\gamma}]$$

   - Penguin NOT suppressed with respect to tree
   - $a_i e^{i\theta_i} \equiv$ "Penguin/Tree ratio" in the $B^0 \to J/\psi\,\rho^0$ channel

3. Decays related by $s \leftrightarrow d$ interchange (U-spin, sub-group of $SU(3)$), assume $a = a'$ and $\theta = \theta'$, fit (a, θ) and compute $\Delta\phi_s = f(a, \theta)$

Penguin pollution in $B_s^0 \to J/\psi\phi$ [S. Faller et al. PRD79, 014005 (2009)]

Two $B_s^0 \to J/\psi\phi$ partners to control polarization dependent effects:

Partner 1: $B^0 \to J/\psi\,\rho^0$:

$$A_i(B^0 \to J/\psi\,\rho^0) = -\lambda\mathcal{A}_i\left[1 - a_i e^{i\theta_i} e^{i\gamma}\right]$$

- Has Exchange and Penguin-Annihilation topologies, like $B_s^0 \to J/\psi\phi$
- $\rho^0 \to \pi^+\pi^-$: Access to direct and mixing-induced CP asymmetries

Partner 2: $B_s^0 \to J/\psi\overline{K}^{*0}$:

$$A_i(B_s^0 \to J/\psi\overline{K}^{*0}) = -\lambda\tilde{\mathcal{A}}_i\left[1 - \tilde{a}_i e^{i\tilde{\theta}_i} e^{i\gamma}\right]$$

- Only Tree and Penguin topologies (no PA, E)
- Not reconstructed as a CP eigenstate ($\overline{K}^{*0} \to K^-\pi^+$), only access to direct CP asymmetries
- Need additional information from BR $\to$ larger theoretical uncertainty

Fit penguin contributions in data [LHCb, JHEP11(2015)082]

Fit (a, θ) on LHCb $3\,\mathrm{fb}^{-1}$ data:

- $B^0 \to J/\psi\,\rho^0$ [LHCb, PLB742 (2015) 38-49]: BR, direct CP asym, mixing-induced CP asym
- $B^0_s \to J/\psi \overline{K}^{*0}$ [LHCb, JHEP11(2015)082]: BR, direct CP asym

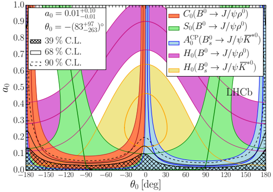
Assumptions:

- Perfect $SU(3)$: there is one universal a and θ variable
- Exchange & Penguin-Annihilation contributions are small and can be ignored
- Relate the hadronic amplitudes

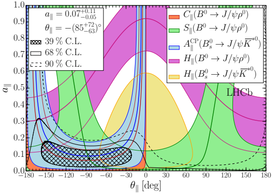
$$\left|\frac{\mathcal{A}'_i(B^0_s \to J/\psi\phi)}{\mathcal{A}_i(B^0 \to J/\psi\,\rho^0)}\right| = \left|\frac{\mathcal{A}'_i(B^0_s \to J/\psi\phi)}{\tilde{\mathcal{A}}_i(B^0_s \to J/\psi\overline{K}^{*0})}\right|$$

Penguin pollution in $B_s^0 \to J/\psi\phi$ [LHCb, JHEP11(2015)082]

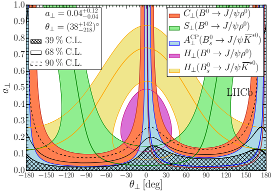
Longitudinal



Parallel



Perpendicular



Results from χ^2 fit:

$$a_0 = 0.01^{+0.10}_{-0.01}\,, \qquad \theta_0 = -\left(82^{+98}_{-262}\right)^\circ, \qquad \Delta\phi_s^{(J/\psi\,\phi)_0} = -0.000^{-0.009}_{+0.011}\,(\text{stat.})^{-0.004}_{+0.009}\,(\text{syst})$$

$$a_\parallel = 0.07^{+0.11}_{-0.05}\,, \qquad \theta_\parallel = -\left(85^{+71}_{-63}\right)^\circ, \qquad \Delta\phi_s^{(J/\psi\,\phi)_\parallel} = 0.001^{-0.010}_{+0.014}\,(\text{stat.}) \pm 0.008\,(\text{syst}$$

$$a_\perp = 0.04^{+0.12}_{-0.04}\,, \qquad \theta_\perp = \left(38^{+142}_{-218}\right)^\circ, \qquad \Delta\phi_s^{(J/\psi\,\phi)_\perp} = 0.003^{-0.010}_{+0.014}\,(\text{stat.}) \pm 0.008\,(\text{syst})$$

Assuming no polarization-dependence and 50% $SU(3)$ breaking, $B^0 \to J/\psi\,\rho^0$ [LHCb, PLB742 (2015) 38-49] gives: $\Delta\phi_s = (0.9 \pm 10(\text{stat}) \pm 15(SU(3)))$ mrad

$\to$ Penguins are small, but $SU(3)$ approximation has to be monitored

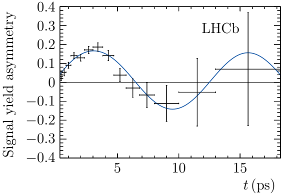
$$\phi_s(\text{CKMFitter, no peng}) = -2\beta_s = -0.0376^{+0.0007}_{-0.0008}$$

$$\to \phi_s^{\text{theo}} = -0.0376 \pm 0.018 \text{ (peng. incl)}$$

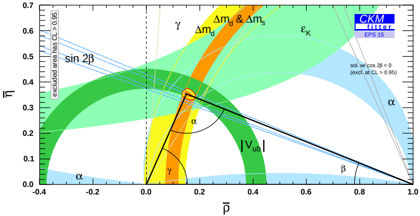
$b \to c\bar{c}s$ mixing-induced CPV in B^0

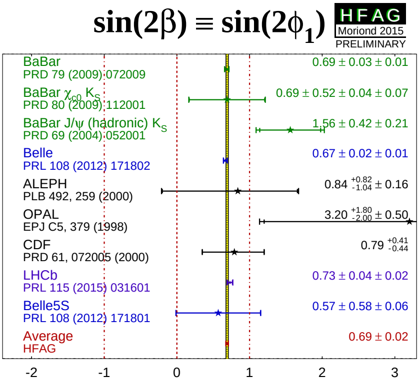
Mixing-induced CP violation in B^0

- $B^0 \to J/\psi K^0_S$ = analogous of $B^0_s \to J/\psi\phi$ in the B^0-system
- $\mathcal{A}_f^{\mathrm{CP}}(t) = \frac{\Gamma(\bar{B}(t)\to f)-\Gamma(B(t)\to f)}{\Gamma(\bar{B}(t)\to f)+\Gamma(B(t)\to f)} \propto \sin 2\beta$
  $f = J/\psi\, K^0_{\mathrm{S}},\ J/\psi\, K^0_{\mathrm{L}},\ \eta_c K^0_{\mathrm{S}}, \ldots$
- $\beta = \arg\left(-\frac{V_{cd}V^*_{cb}}{V_{td}V^*_{tb}}\right)$
- [LHCb, PRL 115 (2015) 031601], Precision similar to b-factories, excellent agreement.



- $\sigma_{\mathrm{syst}} \simeq 0.5\sigma_{\mathrm{syst}}$. Work needed, especially on flavour tagging.
- SM prediction: $\sin 2\beta = 0.748^{+0.030}_{-0.032}$ [CKMfitter, meas not in the fit, no peng]





Penguin pollution in $B^0 \to J/\psi K^0_\mathrm{s}$

- Situation similar to $B^0_s \to J/\psi \phi$, however $B^0 \to J/\psi K^0_\mathrm{s}$ does not have E+PA contributions
- Control mode ($d \leftrightarrow s$) is $B^0_s \to J/\psi K^0_\mathrm{s}$: 1-to-1 correspondence between all topologies. [K. De Bruyn et al., JHEP 1503 (2015) 145]
- However, stat currently too low to constraint the penguin pollution. Use other control modes like: $B^0 \to J/\psi \pi^0$ [BaBar, Belle]
- $\Delta^{\mathrm{peng}}(\phi_d) = -0.018^{+0.012}_{-0.015}$ [K. De Bruyn PhD thesis, 2015]
  $\to \sin 2\beta^{\mathrm{theo}} = 0.730^{+0.032}_{-0.035}$ peng. incl., perfect $SU(3)$
- Extrapolated to LHCb upgrade ($50\,\mathrm{fb}^{-1}$), and taking 20% $SU(3)$ breaking: $\Delta^{\mathrm{peng}}(\phi_d) = -0.018^{+0.004}_{-0.003}(\mathrm{stat})^{+0.003}_{-0.004}(SU(3))$ [K. De Bruyn PhD thesis, 2015]

Roadmap to control sub-leading contributions in $B_s^0 \to J/\psi\phi$ and $B^0 \to J/\psi K_S^0$ [K. De Bruyn et al.]

Control Modes for $B_s^0 \to J/\psi\phi$:

1. High precision CP analysis of $B^0 \to J/\psi\,\rho^0$: determination of penguin parameters.
2. High precision CP analysis of $B_s^0 \to J/\psi \bar{K}^{*0}$: cross-checks & access to hadronic amplitude information, but no E+PA
3. Search for $B_s^0 \to J/\psi\,\rho$ and/or $B^0 \to J/\psi\,\phi$: control contribution from E + PA.

[LHCb, Phys. Rev. D89 (2014) 092006], [LHCb,PRD 88 (2013) 072005]

Control Modes for $B^0 \to J/\psi K_S^0$:

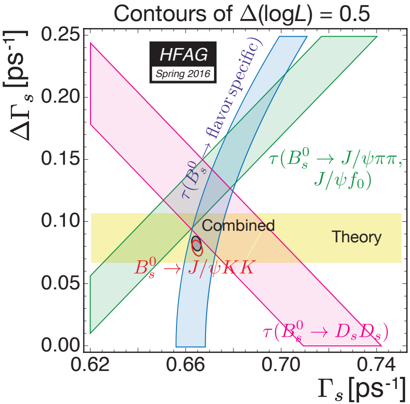
1. High precision CP analysis of $B_s^0 \to J/\psi K_S^0$: determination of penguin parameters.
2. High precision CP analysis of $B^0 \to J/\psi\,\pi^0$: determination of penguin parameters. Cross-checks with more stat (Belle2?), but has E + PA.
3. Search for $B_s^0 \to J/\psi\,\pi^0$: control contributions from E + PA in $B^0 \to J/\psi\,\pi^0$

Very challenging!

$\Rightarrow$ Work towards a global fit of all these modes to determine simultaneously ϕ_s, ϕ_d as well as sub-leading contributions (P, E, PA)

B_s^0 and B^0 lifetimes, $\Delta\Gamma_s$, $\Delta\Gamma_d$, Δm_s, Δm_d

B_s^0 lifetime: experimental status



$\Delta\Gamma_s = 0.0827 \pm 0.006\,\mathrm{ps}^{-1}$
$\Gamma_s = 0.6643 \pm 0.0020\,\mathrm{ps}^{-1}$
More precise than and compatible with SM predictions

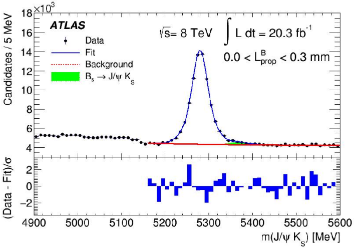
World average, using:

- CP-odd final state: $B_s^0 \to J/\psi\, f_0(980)$, $B_s^0 \to J/\psi\, \pi^+\pi^-$,
- CP-even final state: $B_s^0 \to D_s^+ D_s^-$,
- mixture of CP-odd and CP-even: $B_s^0 \to J/\psi\phi$, $B_s^0 \to J/\psi\, KK$,
- flavour-specific final state: $B_s^0 \to D_s^- \pi^+$, $B_s^0 \to D_s^- \ell^+ \nu_\ell$, $B_s^0 \to D_s^- D^+$

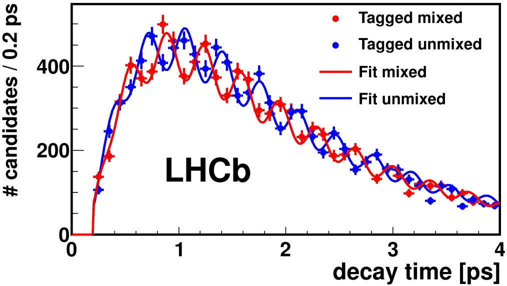
B_s^0 and B^0 lifetimes

- Theoretical predictions of absolute lifetimes suffer from very large uncertainties ($\propto m_b^5$). Typically $\tau_B = 1.65 \pm 0.24\,\text{ps}$ [A. Lenz, arXiv:1405.3601]
- Much better prediction using lifetime ratios, e.g. $\tau_{B_s^0}/\tau_{B^0} = 1.00050 \pm 0.00108 - 0.0225\delta$, where δ quantify a possible quark-hadron duality violation. [T. Jubb et al, arXiv:1603.07770]
  See talk by M. Kirk this afternoon.
- Experimental measurement: $\tau_{B_s^0}/\tau_{B^0} = 0.990 \pm 0.004$ [HFAG]
- 2.5σ discrepancy: stat fluctuation, NP or duality violation?
- Need more precision!
- HFAG: $\tau_{B^0} = 1.520 \pm 0.004\,\mathrm{ps}$, $\tau_{B_s^0} = 1.505 \pm 0.004\,\mathrm{ps}$

$\Delta\Gamma_d$

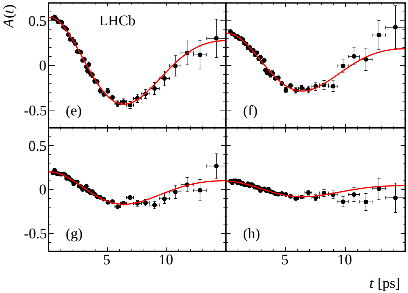


- This year, ATLAS presented the world best measurement of $\Delta\Gamma_d$, using 25.2 fb^{-1}. [ATLAS, arXiv:1605.07485]: $\Delta\Gamma_d/\Gamma_d = (-1.0 \pm 11 \pm 9.0) \times 10^{-3}$
- Compare decay time of $B^0 \to J/\psi K^{*0}$ and $B^0 \to J/\psi K^0_S$, following [BaBar, PRD 70 (2004) 012007]
- HFAG average: $\Delta\Gamma_d/\Gamma_d = -(2.0 \pm 10) \times 10^{-3}$
- Compatible with theo prediction: $(3.97 \pm 0.90) \times 10^{-3}$ [M. Artuso et al., arXiv:1511.09466]
- $\sigma_{\rm syst}/\sigma_{\rm stat} = 0.8$, but main systematics can be reduced ($B^0 \to J/\psi K^0_S$ fit mass range)



- World best measurement by LHCb, 1 fb^{-1}, $B_s^0 \to D_s^- \pi^+$ [New J. Phys. 15 (2013) 053021]: $\Delta m_s = 17.768 \pm 0.023$ (stat) $\pm$ 0.006 (syst) ps^{-1}
- Systematics: decay length and momentum scale (both = 0.004 ps^{-1}).
- HFAG World average $\Delta m_s = 17.757 \pm 0.021\ \text{ps}^{-1}$ (0.1% rel uncertainty!)
- Theoretical prediction 18.3 $\pm$ 2.7, i.e. with an uncertainty 129 times larger! [M. Artuso et al., arXiv:1511.09466] $\rightarrow$ more precise prediction on ratios, e.g. $\Delta m_s / \Delta m_d$ or $\Delta m_s / \Delta \Gamma_s$
- Δm_s also useful to constraint indirectly the B_s^0-meson decay constant $f_{B_s^0}$ and bag parameter $B_{B_s^0}$. e.g. CKMfitter uses $f_{B_s^0} = (224 \pm 1.0 \pm 2.0)$ MeV from Lattice in input. Output of the global CKM fit, not using the $f_{B_s^0}$ from Lattice $\Rightarrow f_{B_s^0}^{\text{ind.}} = (225.8^{+6.4}_{-6.7})$ MeV

Δm_d

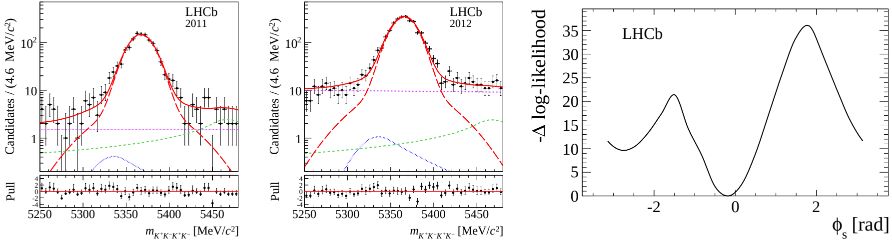


- World best measurement by LHCb, 3 fb^{-1}, $B^0 \to D^{(*)-}\mu^+\nu_\mu$ [arXiv:1604.03475]:
  $\Delta m_d = 505.5 \pm 2.1 \pm 1.0\,\mathrm{ns}^{-1}$
- Systematics: backgrounds, fit and k-factor.
- HFAG World average $\Delta m_d = 506.4 \pm 1.9\,\mathrm{ns}^{-1}$
- Theoretical prediction $528 \pm 78\,\mathrm{ns}^{-1}$ [M. Artuso et al., arXiv:1511.09466] , i.e. with an uncertainty 41 times larger → more precise prediction on ratios, e.g. $\Delta m_d/\Delta\Gamma_d$ or $\Delta m_s/\Delta m_d$
- $\frac{\Delta m_s}{\Delta m_d} = \frac{M_{Bs}}{M_{Bd}}\xi^2 \left|\frac{V_{ts}}{V_{td}}\right|^2$, $\xi = 1.206 \pm 0.018 \pm 0.006$ [Fermilab-MILC, PRD 93, 113016 (2016)]

(See talk by A. El-Khadra)

$b \to s\bar{s}s$ mixing-induced CPV in B_s^0

$B_s^0 \to \phi\phi$ [PRD 90 (2014) 052011]



- Pure $b \to s\bar{s}s$ penguin mode
- Tagged time-dependent angular analysis, 3 fb^{-1} , 4000 $B_s^0 \to \phi\phi$ candidates
- SM expectation for CP violating weak phase $|\phi_s^{s\bar{s}s}| < 0.02^\dagger$
- $\phi_s^{s\bar{s}s} = -0.17 \pm 0.15 \pm 0.03$
- Main systematics: angular and time acceptance
- Also measured Triple Products asymmetries [A. Datta et al, PRD 86, 076011 (2012)] compatible with expectation.

† [Bartsch et al., arXiv:8010.0249], [Beneke et al., Nucl.Phys. B774 (2007)64], [Cheng et al., PRD 80 (2009) 114026].

Summary

Parameter	Experiment	$\frac{\sigma_{\rm syst}}{\sigma_{\rm stat}}$	Theory	$\frac{\sigma_{\rm theo}}{\sigma_{\rm exp}}$
$\phi_s^{c\bar{c}s}$	-0.033 ± 0.033	0.10	-0.0376 ± 0.018 (peng. incl)	0.6
$\Delta\Gamma_s$ (ps^{-1})	0.0827 ± 0.006	0.35	0.088 ± 0.020	3.3
Δm_s (ps^{-1})	17.757 ± 0.021	0.26	18.3 ± 2.7	129
$\phi_s^{s\bar{s}s}$	-0.17 ± 0.15	0.20	≤ 0.02	0.13
$\sin 2\beta$	0.691 ± 0.017	0.50	$0.730^{+0.032}_{-0.035}$ (peng. incl)	2.0
$\Delta\Gamma_d/\Gamma_d$	$-(2 \pm 10) \times 10^{-3}$	0.82	$(3.97 \pm 0.90) \times 10^{-3}$	0.09
Δm_d (ns^{-1})	506.4 ± 1.9	0.48	528 ± 78	41

- All experimental uncertainties currently dominated by statistics.
  But "wall" of systematics not far, e.g. for $\Delta\Gamma_d$, $\Delta\Gamma_s$, Δm_d, $\sin 2\beta$.
- $\sigma_{\rm theo} > \sigma_{\rm exp}$ for $\sin 2\beta$ and "soon" for $\phi_s^{c\bar{c}s}$.
  $\rightarrow$ continue work on sub-leading contributions
- $\sigma_{\rm theo} > \sigma_{\rm exp}$ for $\Delta\Gamma_s$, Δm_s, and Δm_d:
  - ratios like $\Delta m_s/\Delta m_d$ or $\Delta\Gamma_s/\Delta m_s$ better predicted, useful to constraint $|V_{ts}/V_{td}|$ or e.g. to test quark-hadron duality (see talk by M. Kirk).
  - Δm_s also useful, e.g. to constraint $f_{B_s^0}$ decay constant in global fits.
- $\sigma_{\rm theo} < \sigma_{\rm exp}$ for $\Delta\Gamma_d/\Gamma_d$ and $\phi_s^{s\bar{s}s}$: experimental work ongoing

Conclusions and prospects

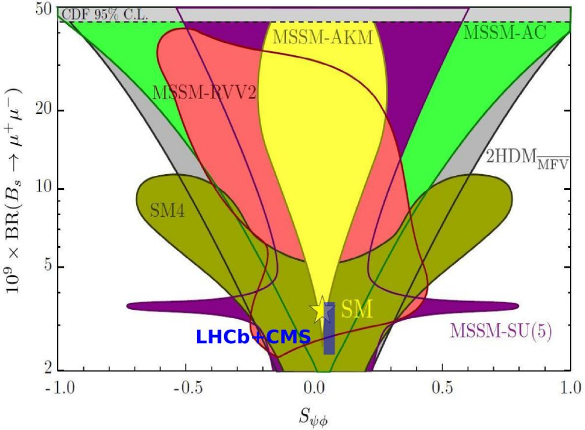
- ϕ_s: LHCb 50 fb^{-1}: $\sigma(\phi_s) \simeq 9\,\mathrm{mrad}$, using $B_s^0 \to J/\psi\phi$ alone. With 300 fb^{-1} + more decays modes + ATLAS and CMS, could reach $\sigma_{\rm exp}(\phi_s) \leq 2\,\mathrm{mrad}$!
  $\sigma_{\rm theo}(\phi_s) \simeq 15\,\mathrm{mrad}$, $SU(3)$ breaking effects.
  We already have a roadmap to control P, PA and E topologies, but will be challenging to reach the experimental precision.
  It is still possible to discover NP with the ϕ_s measurement!
  Assume a $+1\sigma$ upwards statistical fluctuation, and $\sigma_{\rm theo} = \sigma_{\rm exp} = 10\,\mathrm{mrad}$
  $\Rightarrow 5\sigma$ discovery!
- **sin 2β**: Theo limited. Roadmap to control sub-leading contrib similar to ϕ_s.
- $\Delta\Gamma_s$: Theo limited. Experimental systematics soon problematic.
- $\Delta\Gamma_d$: Exp limited, new results soon.
- Δm_s, Δm_d: $\sigma_{\rm exp} \ll \sigma_{\rm theo}$, still interesting to improve the measurements.
  Ratio $\Delta m_s/\Delta m_d$ or $\Delta\Gamma_s/\Delta m_s$ more precise.
- ***B*-meson lifetimes**: still need more accuracy.
  In particular $\tau_{B_s^0}/\tau_{B^0}$ gives a nice test of HQE.
- $\phi_s^{s\bar{s}s}$: $\sigma_{\rm exp} \simeq \sigma_{\rm theo}$ when LHCb will reach $\sim 50\,\mathrm{fb}^{-1}$.
- Exciting work-plan in the coming years, with crucial interplay between experiment and theory (Lattice, HQE, LCSR, ...)

Backup

ϕ_s and $B_s^0 \to \mu^+\mu^-$ implications

- $S_{\psi\phi} = -\sin\phi_s$
- Modified from [D. Straub, Nuovo Cim. C035N1 (2012) 249 and arXiv:1012.3893] UNOFFICIAL
- Blue: 68% CL LHCb+CMS

  2014 constraints

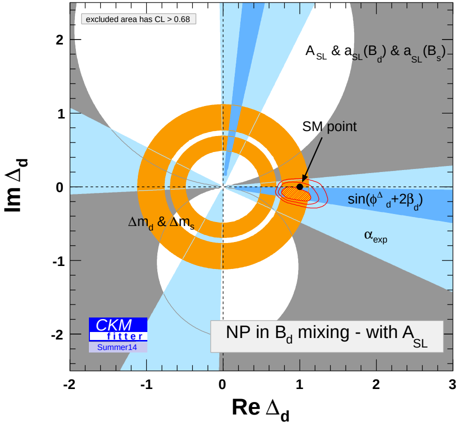


Strong constraints on many NP models:

- SM4: Standard Model with a sequential fourth generation
- Left-handed currents only (MSSM-LL)
- Ross, Velasco-Sevilla and Vives (MSSM-RVV2)
- Antusch, King and Malinsky (MSSM-AKM)
- RSc: Randall-Sundrum model with custodial protection
- Agashe and Carone (MSSM-AC)

NP in B^0 mixing

PRD91:073007,2015



$$M_{12}^d = M_{12}^{\mathrm{SM},d}\Delta_d\,, \quad \Delta_d = |\Delta_d| e^{i\phi_d^\Delta}$$

$$Re(\Delta_d) = 0.88^{+0.22}_{-0.10} \text{ at } 68\% CL$$

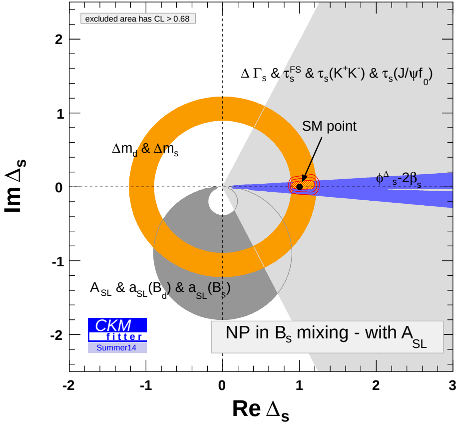
$$Im(\Delta_d) = -0.11^{+0.07}_{-0.05} \text{ at } 68\% CL$$

[CKMfitter (J. Charles et al.), EPJ. C41, 1-131 (2005), updated results and plots available at: http://ckmfitter.in2p3.fr]

See also e.g. M. Bona et al. [UTfit Collaboration], JHEP 0803 (2008) 049. A. Lenz et al, PRD 86 (2012) 033008.

NP in B_s^0 mixing

PRD91:073007,2015



$$M_{12}^s = M_{12}^{\mathrm{SM},s}\Delta_s\,,\quad \Delta_s = |\Delta_s|e^{i\phi_s^\Delta}$$

$$Re(\Delta_s) = 1.01^{+0.17}_{-0.09}\ \text{at } 68\%CL$$

$$Im(\Delta_s) = 0.02^{+0.04}_{-0.04}\ \text{at } 68\%CL$$

[CKMfitter (J. Charles et al.), EPJ. C41, 1-131 (2005), updated results and plots available at: http://ckmfitter.in2p3.fr]

NP in mixing-induced CPV?

ϕ_s and ϕ_d are already well measured and close to SM expectation: finding NP will require much effort.
Need to carefully estimate sub-leading contribution, beyond the leading tree
Need to be careful with averages

New physics effects

General parametrization of new physics effects in mixing e.g. Lenz et al., arXiv:1008.1593
PRD91:073007,2015

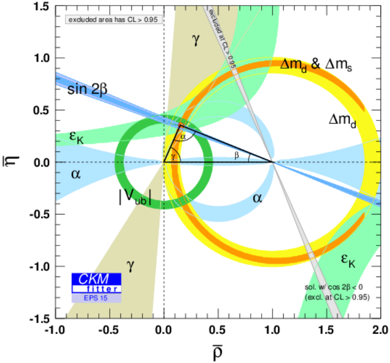
$$\Gamma_{12,s} = \Gamma_{12,s}^{\mathrm{SM}}\,, \qquad M_{12,s} = M_{12,s}^{\mathrm{SM}} \cdot \Delta_s\,; \qquad \Delta_s = |\Delta_s| e^{i\phi_s^\Delta}$$

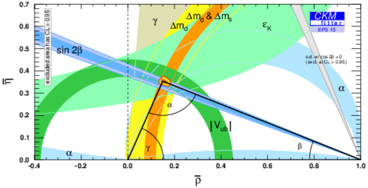
leads to the following relations for observables

$$\begin{aligned}
\Delta M_s &= 2|M_{12,s}^{\mathrm{SM}}| \cdot |\Delta_s| \\
\Delta\Gamma_s &= 2|\Gamma_{12,s}| \cdot \cos\left(\phi_{12s}^{\mathrm{SM}} + \phi_s^\Delta\right) \\
A_{\mathrm{SL}}^s &= \frac{|\Gamma_{12,s}|}{|M_{12,s}^{\mathrm{SM}}|} \cdot \frac{\sin\left(\phi_{12s}^{\mathrm{SM}} + \phi_s^\Delta\right)}{|\Delta_s|} \\
\phi_s^{J/\psi\phi} &= -2\beta_s + \phi_s^\Delta + \delta_{\mathrm{Peng.}}^{\mathrm{SM}} + \delta_{\mathrm{Peng.}}^{\mathrm{NP}}
\end{aligned}$$

Remember: $\phi_{12s}^{\mathrm{SM}} = \arg(-M_{12}^s/\Gamma_{12}^s)$ and $\beta_s = \arg\left(-V_{ts}V_{tb}^*/V_{cs}V_{cb}^*\right)$

CKMfitter plots

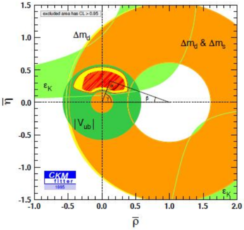




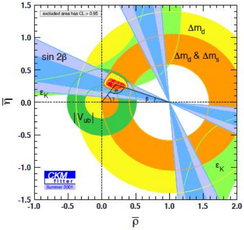
[CKMfitter (J. Charles et al.), EPJ. C41, 1-131 (2005), updated results and plots available at: `http://ckmfitter.in2p3.fr`]

20 years of CKM fits

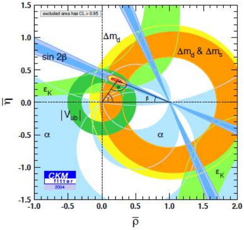
[CKMfitter, LEP, KTeV, NA48, BaBar, Belle, CDF, DØ, LHCb, CMS, ...]



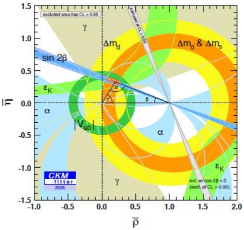
1995



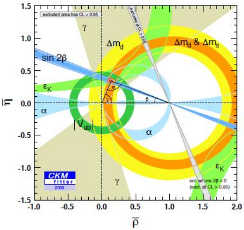
2001



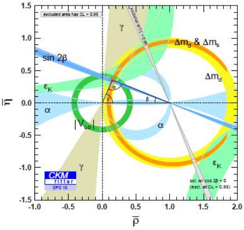
2004



2006

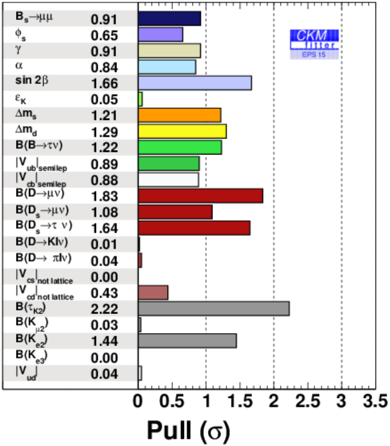


2009



2015

CKMfitter plots



A way to introduce β_s

V_{CKM} can be written with 4 independent parameters:

- the « usual » Wolfenstein parameters λ, A, ρ, η

$$V_{\rm CKM} = \begin{pmatrix} 1-\frac{1}{2}\lambda^2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\frac{1}{2}\lambda^2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} + \mathcal{O}(\lambda^4)$$

- Or $|V_{us}|$, $|V_{ub}|$, $|V_{cb}|$, $|V_{td}|$ [Branco 1988]
- Or 4 independent phases: γ, β, β_s, β_K

$$\gamma = \arg\left(-\frac{V_{\rm ud}V_{\rm ub}^*}{V_{\rm cd}V_{\rm cb}^*}\right)$$

$$\beta = \arg\left(-\frac{V_{\rm cd}V_{\rm cb}^*}{V_{\rm td}V_{\rm tb}^*}\right)$$

$$\beta_{\rm s} = \arg\left(-\frac{V_{\rm ts}V_{\rm tb}^*}{V_{\rm cs}V_{\rm cb}^*}\right)$$

$$\beta_{\rm K} = \arg\left(-\frac{V_{\rm us}V_{\rm ud}^*}{V_{\rm cs}V_{\rm cd}^*}\right)$$

- References:

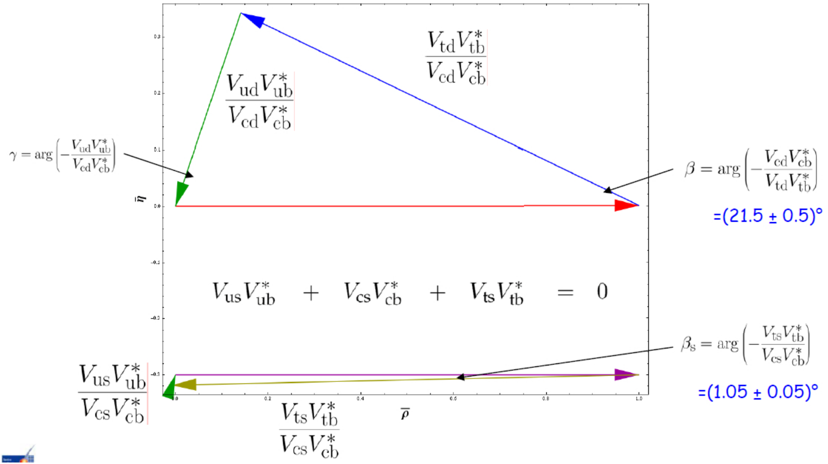
  - G. C. Branco and L. Lavoura, Phys. Lett. B 208, 123 (1988).
  - G. C. Branco et al., CP violation, Oxford University Press, (1999)
  - R. Aleksan, B. Kayser, and D. London. Determining the Quark Mixing Matrix from CP-Violating Asymmetries. *Phys. Rev. Lett.*, 73:18.20, 1994, hep-ph/9403341
  - See also: J. Silva, hep-ph/0410351

b–d and b–s unitarity triangles

SM values, both triangles on the same scale, bs triangle shifted by etabar-0.3 to be visible

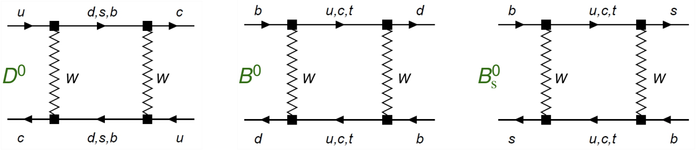
b-d triangIde divided by VcdVcb*; while bs triangle divided by VcsVcb*

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



Mixing and CP violation

In Standard Model, neutral mesons (H^0) mix with their antiparticles ($\bar{H}^0$) via box diagrams ($H^0 = K^0, D^0, B^0, B^0_s$)

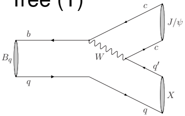


3 types of CP violation:

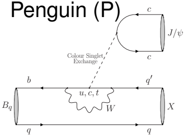
- "In the mixing": rates of $H^0 \to \overline{H}^0$ and $\overline{H}^0 \to H^0$ differ
- "In the decay": amplitudes from a process and its conjugate differ
- "In the interference between mixing and decay"

Decay topologies

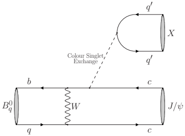
Tree (T)



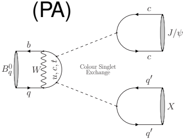
Penguin (P)



Exchange (E)



Penguin-Annihilation (PA)



Decomposition

- $B^0 \to J/\psi\, K^0$: T + P
- $B_s^0 \to J/\psi\phi$: T + P + E + PA
- $B_s^0 \to D_s^+ D_s^-$: T + P + E + PA
- $B_s^0 \to J/\psi\, K^0$: T + P
- $B_s^0 \to J/\psi \overline{K}^{*0}$: T + P
- $B^0 \to J/\psi\, \rho^0$: T + P + E + PA
- $B_s^0 \to J/\psi\, \rho^0$: E + PA

General assumption on the hierarchy:

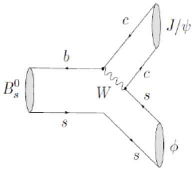
$\boxed{\text{Tree} > \text{Penguin} > \text{Exchange and Penguin-Annihilation}}$

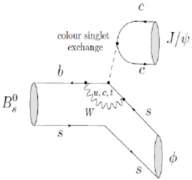
Penguin pollution in $B_s^0 \to J/\psi\phi$

- LHCb, arXiv:1411.1634 (PLB). Using $B^0 \to J/\psi\,\rho^0$, shift on ϕ_s due to penguin pollution = $0.009 \pm 0.031\,\mathrm{rad}$ at 95% CL (including 50% $SU(3)$ breaking effects).
- Method proposed in [S. Faller et al. arXiv:0810.4248], using $B_s^0 \to J/\psi\overline{K}^{*0}$
- Other approaches to reduce penguin pollution:
  B. Bhattacharya et al., Int.J.Mod.Phys. A28 (2013) 1350063.
  M. Jung, arXiv:1212.4789.
  P. Frings, U. Nierste, M. Wiebusch, arXiv:1503.00859 Attempt to compute directly the penguin-to-tree, without $SU(3)$ approximation. The up-quark penguin contribution is described in an effective theory, resulting from an additional OPE in $1/q^2$ with $q^2 \sim M^2_{J/\psi}$. Still some approximation needed for the matrix element. Results: $|\Delta\phi_d| \leq 0.68^\circ$,
  $|\Delta\phi_s^0| \leq 0.97^\circ$ $|\Delta\phi_s^\perp| \leq 1.22^\circ$ $|\Delta\phi_s^\parallel| \leq 0.99^\circ$

Penguin pollution in $B_s^0 \to J/\psi\phi$

[S. Faller et al. arXiv:0810.4248]

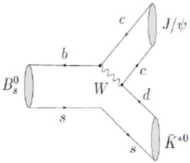


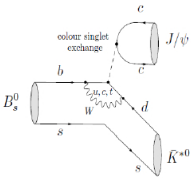


$$\bar{b} \to \bar{s}c\bar{c}$$

Penguins suppressed by λ^2

$$A(B_s^0 \to (J/\psi\phi)_f) = \left(1 - \frac{\lambda^2}{2}\right) \mathcal{A}_f \left[1 + \epsilon a_f e^{i\theta_f} e^{i\gamma}\right] \qquad \epsilon \equiv \lambda^2/(1-\lambda^2)$$



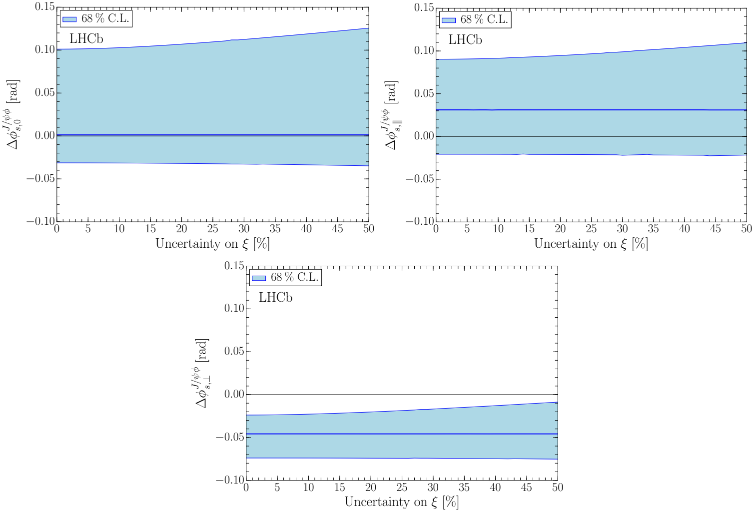


$$\bar{b} \to \bar{d}c\bar{c}$$

Penguins NOT suppressed
wrt tree

$$A(B_s^0 \to (J/\psi \bar{K}^{*0})_f) = \lambda \mathcal{A}'_f \left[1 - a'_f e^{i\theta'_f} e^{i\gamma}\right]$$

Penguin pollution in $B_s^0 \to J/\psi\phi$: $SU(3)$ [LHCb, JHEP11(2015)082]



$a' = \xi a$

Connecting $B_s^0 \to J/\psi\phi$ and $B_s^0 \to J/\psi\overline{K}^{*0}$

[Faller et al. PRD 79 (2009)]

- Penguin parameters:
  - a_i' and θ_i' for $B_s^0 \to J/\psi\phi$
  - a_i and θ_i for $B_s^0 \to J/\psi\overline{K}^{*0}$
- Approximations of SU(3) flavour (quarks u, d, s are identical)

$$a_i = a_i', \quad \theta_i = \theta_i'$$

- Shift on ϕ_s due to penguin diagrams ($\epsilon = \frac{\lambda^2}{1-\lambda^2}$)

$$\boxed{\Delta\phi_s^{i,\mathrm{peng}} = \arctan\left(\frac{2\epsilon a_i' \cos\theta_i' \sin\gamma + \epsilon^2 a_i'^2 \sin 2\gamma}{1 + 2\epsilon a_i' \cos\theta_i' \cos\gamma + \epsilon^2 a_i'^2 \cos 2\gamma}\right)}$$

Accessing penguin parameters [Faller et al. PRD 79 (2009)]

- Direct CP violation in $B_s^0 \to J/\psi \overline{K}^{*0}$

$$A_i^{CP} = \frac{\Gamma_i(\overline{B}_s^0) - \Gamma_i(B_s^0)}{\Gamma_i(\overline{B}_s^0) + \Gamma_i(B_s^0)} = \frac{2a_i \sin\theta_i \sin\gamma}{1 - 2a_i \cos\theta_i \cos\gamma + a_i^2}$$

- The parameter H_i

$$H_i \propto \frac{1}{\epsilon}\left|\frac{\mathcal{A}_i'}{\mathcal{A}_i}\right|^2 \frac{\mathcal{B}(B_s^0 \to J/\psi \overline{K}^{*0})}{\mathcal{B}(B_s^0 \to J/\psi \phi)} \frac{f_i}{f_i'} = \frac{1 - 2a_i \cos\theta_i \cos\gamma + {a_i}^2}{1 + 2\epsilon a_i \cos\theta_i \cos\gamma + \epsilon^2 {a_i}^2}$$

  - $\left|\frac{\mathcal{A}'_i}{\mathcal{A}_i}\right|^2$: hadronic factor with large theoretical uncertainty!
  - f_i': polarization fractions in $B_s^0 \to J/\psi \phi$
  - f_i : polarization fractions in $B_s^0 \to J/\psi \overline{K}^{*0}$

A_i^{CP} and H_i allow to extract a_i and $\theta_i \Rightarrow \Delta\phi_s^{i,\mathrm{peng}}$

Penguin pollution using $B_s^0 \to J/\psi \bar{K}^{*0}$ channel

[S. Faller et al. PRD79, 014005 (2009)]

- polarization-dependent *CP* asymmetries:

$$A_i^{CP} = -\frac{2a_i \sin\theta_i \sin\gamma}{1 - 2a_i \cos\theta_i \cos\gamma + a_i^2} \,.$$

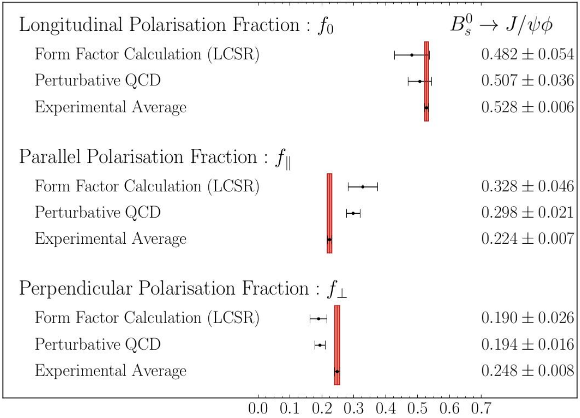
- branching fractions and polarization fractions:

$$H_i \equiv \frac{1}{\epsilon}\left|\frac{\mathcal{A}_i'}{\mathcal{A}_i}\right|^2 \frac{\Phi\left(\frac{m_{J/\psi}}{m_{B_s^0}}, \frac{m_\phi}{m_{B_s^0}}\right)}{\Phi\left(\frac{m_{J/\psi}}{m_{B_s^0}}, \frac{m_{\bar{K}^{*0}}}{m_{B_s^0}}\right)} \frac{\mathcal{B}(B_s^0 \to J/\psi \bar{K}^{*0})_{\text{theo}}}{\mathcal{B}(B_s^0 \to J/\psi\phi)_{\text{theo}}} \frac{f_i}{f_i'} \,,$$

$$= \frac{1 - 2a_i \cos\theta_i \cos\gamma + a_i^2}{1 + 2\epsilon a_i' \cos\theta_i' \cos\gamma + \epsilon^2 a_i'^2} \,,$$

$\Phi(x, y) = \sqrt{(1-(x-y)^2)(1-(x+y)^2)}$ is the phase-space factor

Polarization amplitude in $B_s^0 \to J/\psi\phi$



Comparison between the theoretically calculated and experimentally measured values of the three polarization fractions in the $B_s^0 \to J/\psi\phi$ decay. 3σ tension for $f_{\perp}$ and $f_{\parallel}$.

K. De Bruyn thesis, 2015

ϕ–ω Mixing [K. De Bruyn]

Octet and Singlet Contributions:

- ϕ is a pure $s\bar{s}$ state, and therefore an admixture of octet and singlet state
- In this analysis, only the octet contribution is considered
  - Only needed for the H observable:
    to relate form factors of $B_s^0 \to \phi$ and $B_s^0 \to K^{*0}$ or $B^0 \to \rho^0$
  - E+PA contributions are ignored

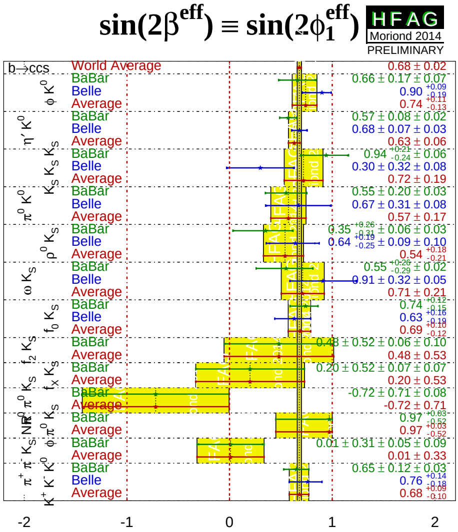
Mixing:

- Can mix with the orthogonal ω state: parameterized by mixing angle δ
- Relation between branching ratios [arxiv:0806.3584]

$$\mathcal{B}(B_s^0 \to J/\psi\,\omega) = \tan^2\delta \times \mathcal{B}(B_s^0 \to J/\psi\,\phi)$$

- Alternatively, also the E+PA diagrams contain information about mixing
- These can be controlled using $\mathcal{B}$ information on $B_s^0 \to J/\psi\,\rho$ and/or $B^0 \to J/\psi\,\phi$

B^0: $b \to s\bar{s}d$ penguins [HFAG]



Current Situation: a Fit to the $B_q \to J/\psi\, P$ Data [K. De Bruyn]

$$A(B \to J/\psi\, f) = -\lambda \mathcal{A}\left[1 - a\, e^{i\theta} e^{i\gamma}\right]$$

Group I: Cabibbo-Allowed Penguins:

- $B^+ \to J/\psi\, \pi^+$: $\mathcal{B}$, $\mathcal{A}^{\text{dir}}$
- $B^0 \to J/\psi\, \pi^0$: $\mathcal{B}$, $\mathcal{A}^{\text{dir}}$, $\mathcal{A}^{\text{mix}}$
- $B_s^0 \to J/\psi K_S^0$: $\mathcal{B}$, $(\mathcal{A}^{\text{dir}}, \mathcal{A}^{\text{mix}})$

Group II: Cabibbo-Suppressed Penguins:

$$A(B \to J/\psi\, f) = \left(1 - \tfrac{1}{2}\lambda^2\right) \mathcal{A}\left[1 + \epsilon a\, e^{i\theta} e^{i\gamma}\right]$$

- $B^+ \to J/\psi\, K^+$: $\mathcal{B}$, $\mathcal{A}^{\text{dir}}$
- $B^0 \to J/\psi K_S^0$: $\mathcal{B}$, $\mathcal{A}^{\text{dir}}$, $\mathcal{A}^{\text{mix}}$

Assumptions:

- Ignore non-factorisable $SU(3)$ breaking: There is one universal a and θ variable
- Exchange & (Penguin-)Annihilation contributions are small and can be ignored
- We have control channels to cross-check this assumption:
  $B_s^0 \to J/\psi\, \pi^0$ and $B_s^0 \to J/\psi\, \rho^0$

Grand Fit: Setup & Results [K. De Bruyn]

Inputs:

- *CP* asymmetries & branching ratios listed previously
- Gaussian constraint: $\gamma = (73.2^{+6.3}_{-7.0})^\circ$ [CKMFitter (2014)]

Fit Results:

$$a = 0.17^{+0.14}_{-0.12}\,, \qquad \theta = (179.3 \pm 4.2)^\circ\,,$$

$$\phi_d = (43.9 \pm 1.7)^\circ\,, \qquad \gamma = \left(73.9^{+6.2}_{-6.8}\right)^\circ\,,$$

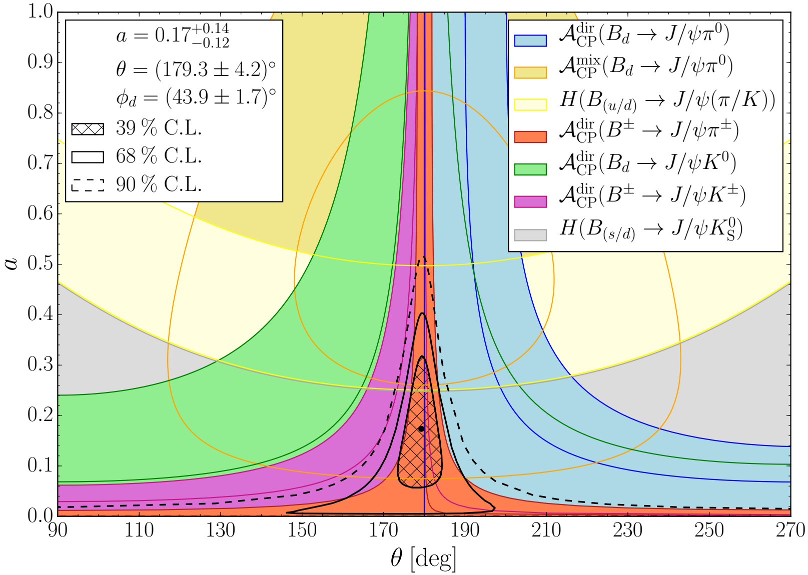
- with $\chi^2_{\text{min}} = 3.0$ for 4 degrees of freedom
- This corresponds to

$$\Delta\phi_d^{J/\psi K^0_S} = -\left(1.03^{+0.69}_{-0.85}\right)^\circ$$

Caveats:

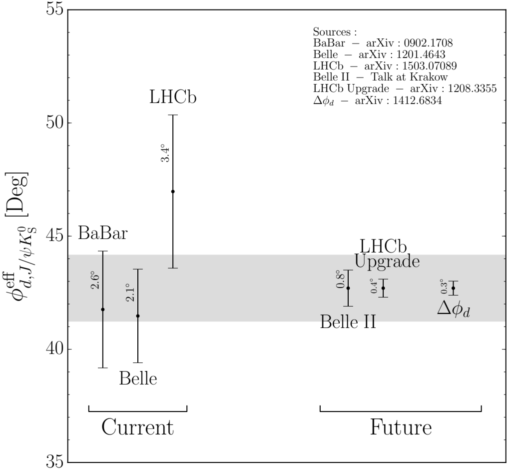
- $\mathcal{A}^{\text{mix}}(B^0 \to J/\psi\,\pi^0)$ and $\mathcal{A}^{\text{mix}}(B^0 \to J/\psi K^0_S)$ depend on ϕ_d
- Directly determined in the fit by explicitly including $\Delta\phi_d(a, \theta, \gamma)$
- Time-integrated $B^0_s \to J/\psi K^0_S$ branching ratio is converted to the theoretical one

Grand Fit: Contours [K. De Bruyn]

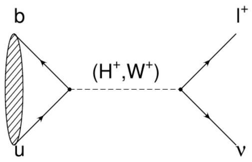


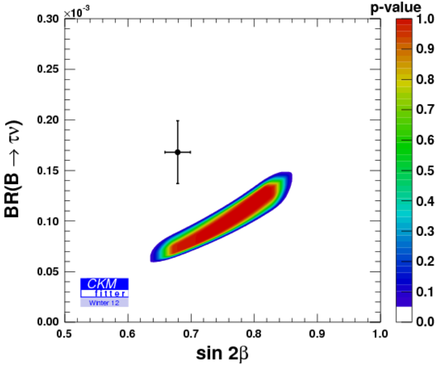
Prospects for ϕ_d [K. De Bruyn]

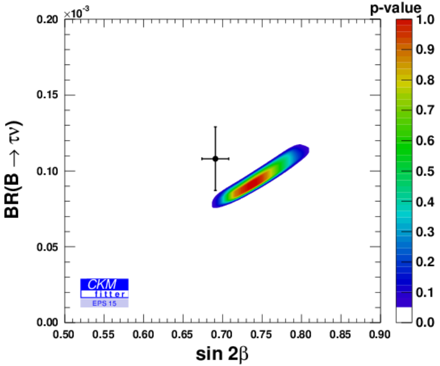
We will be able to control the penguin effects!



$\sin 2\beta - \mathcal{B}(B^+ \to \tau^+\nu_\tau)$ correlations







2012 $\to$ 2015: tension disappeared with more statistics
(latest Belle $B^+ \to \tau^+\nu_\tau$ result: [arXiv:1503.05613])

Systematics on $\Delta\Gamma_d/\Gamma_d$, ATLAS

[ATLAS, arXiV:1605.07485]

Source	$\delta(\Delta\Gamma_d/\Gamma_d)$, 2011	$\delta(\Delta\Gamma_d/\Gamma_d)$, 2012
K_S decay length	0.21×10^{-2}	0.16×10^{-2}
K_S pseudorapidity	0.14×10^{-2}	0.01×10^{-2}
$B^0 \to J/\psi K_S$ mass range	0.47×10^{-2}	0.59×10^{-2}
$B^0 \to J/\psi K^{*0}$ mass range	0.30×10^{-2}	0.15×10^{-2}
Background description	0.16×10^{-2}	0.09×10^{-2}
$B_s^0 \to J/\psi K_S$ contribution	0.11×10^{-2}	0.08×10^{-2}
L^B_{prop} resolution	0.29×10^{-2}	0.29×10^{-2}
Fit bias (Toy MC)	0.07×10^{-2}	0.07×10^{-2}
B^0 production asymmetry	0.01×10^{-2}	0.01×10^{-2}
MC sample	1.54×10^{-2}	0.45×10^{-2}
Total uncertainty	1.69×10^{-2}	0.84×10^{-2}

$\Delta\Gamma_s$, Γ_s [HFAG]

I. $B_s \to J/\psi f_0(980)$ lifetime measurements from CDF and D0, and $B_s \to J/\psi\pi^+\pi^-$ lifetime measurement from LHCb (pure CP-odd final states), which average to $\tau(B_s \to \text{CP-odd}) = 1.658 \pm 0.032$ ps, taken to be equal to $(1/\Gamma_H)\times[1-(\varphi_s^{c\bar{c}s})^2\times\Delta\Gamma_s/4]$;

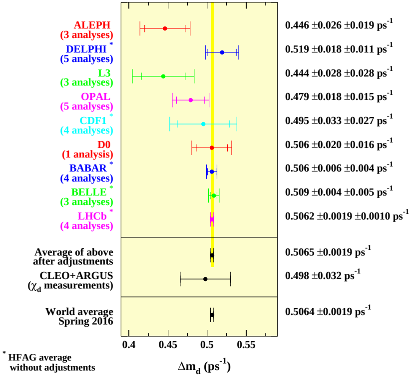
II. $B_s \to D_s^+ D_s^-$ lifetime measurement from LHCb (pure CP-even final states), which average to $\tau(B_s \to \text{CP-even}) = 1.379 \pm 0.031$ ps, taken to be equal to $(1/\Gamma_L)\times[1+(\varphi_s^{c\bar{c}s})^2\times\Delta\Gamma_s/4]$;

III. flavour-specific B_s lifetime average $\tau(B_s \to \text{flavour specific}) = 1.511 \pm 0.014$ ps, taken to be equal to $(1/\Gamma_s) \times (1 + (\Delta\Gamma_s/\Gamma_s)^2/4) / (1 - (\Delta\Gamma_s/\Gamma_s)^2/4)$.

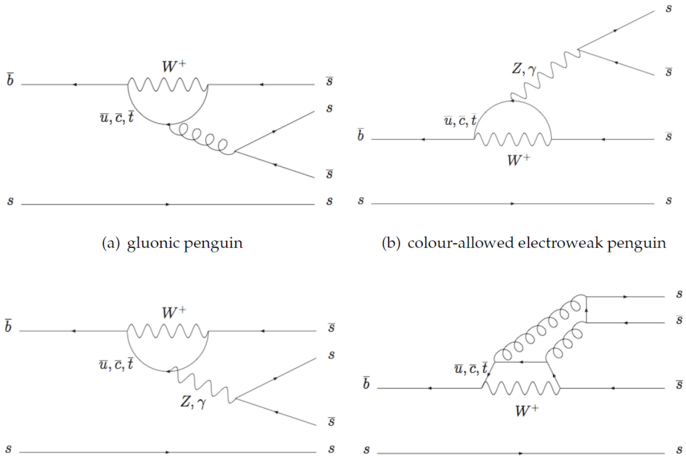
The implementation of contraints I and II, described in full in the literature [R. Fleischer and R. Knegjens, Eur. Phys. J. C (2011) 1789], neglects here possible sub-leading Penguin contributions and possible direct CP violation. The table below shows the results with and without these additional constraints. The default (i.e. recommended) set of results is the one with all the constraints applied.

Fit results from ATLAS, CDF, CMS, D0 and LHCb data	without constraint from effective lifetime measurements	with constraints I and II	**with constraints I, II and III**
Γ_s	0.6647 ± 0.0022 ps^{-1}	0.6640 ± 0.0021 ps^{-1}	**0.6643 ± 0.0020 ps^{-1}**
$1/\Gamma_s$	1.504 ± 0.005 ps	1.506 ± 0.005 ps	**1.505 ± 0.004 ps**
$\tau_{\text{Short}} = 1/\Gamma_L$	1.420 ± 0.006 ps	1.417 ± 0.006 ps	**1.417 ± 0.006 ps**
$\tau_{\text{Long}} = 1/\Gamma_H$	1.599 ± 0.011 ps	1.607 ± 0.011 ps	**1.605 ± 0.010 ps**
$\Delta\Gamma_s$	$+0.079 \pm 0.006$ ps^{-1}	$+0.083 \pm 0.006$ ps^{-1}	**$+0.083 \pm 0.006$ ps^{-1}**
$\Delta\Gamma_s/\Gamma_s$	$+0.119 \pm 0.010$	$+0.125 \pm 0.009$	**$+0.124 \pm 0.009$**
correlation $\rho(\Gamma_s, \Delta\Gamma_s)$	-0.324	-0.293	**-0.239**

Experiment	Method	Data set		$\Delta m_s (\mathrm{ps}^{-1})$		
CDF2	$D_s^{(*)-}\ell^+\nu$, $D_s^{(*)-}\pi^+$, $D_s^-\rho^+$		1 fb^{-1}	17.77	± 0.10	± 0.07
D0	$D_s^-\ell^+X$, $D_s^-\pi^+X$		2.4 fb^{-1}	18.53	± 0.93	± 0.30
LHCb	$D_s^-\pi^+$, $D_s^-\pi^+\pi^-\pi^+$	2010	0.034 fb^{-1}	17.63	± 0.11	± 0.02
LHCb	$D_s^-\mu^+X$	2011	1.0 fb^{-1}	17.93	± 0.22	± 0.15
LHCb	$D_s^-\pi^+$	2011	1.0 fb^{-1}	17.768	± 0.023	± 0.006
LHCb	$J/\psi K^+K^-$	2011–2012	3.0 fb^{-1}	17.711	${}^{+0.055}_{-0.057}$	± 0.011
Average of CDF and LHCb measurements			17.757	0.020	0.007	



$B_s^0 \to \phi\phi$



(a) gluonic penguin

(b) colour-allowed electroweak penguin

(c) colour-suppressed electroweak penguin

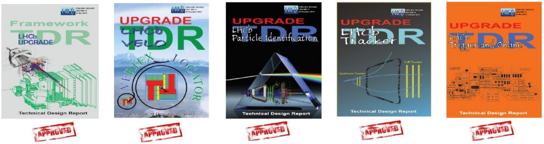
(d) singlet penguin

LHCb plans

- Run 2 (2016-2018): 5 fb^{-1} at $\sqrt{s} = 13\,\text{TeV}$, improved trigger
- Some major experimental measurements (e.g. γ, $B_s^0 \to \phi\phi$) are not yet at the level of theoretical prediction
- Above a luminosity of $\sim 4 \times 10^{32}\text{cm}^{-2}\text{s}^{-1}$, LHCb efficiency to trigger hadronic modes saturates, because of the L0-trigger bottleneck which can not cope with more than 1 MHz output rate.

$\Rightarrow$ upgrade the LHCb experiment in 2018–2019:

- Full software trigger: read all detector at 40 MHz $\to$ $\times 2$ efficiency for hadronic final state.
- Luminosity up to $2{\times}10^{33}\text{cm}^{-2}\text{s}^{-1}$, new challenges: high pile-up, large occupancies, radiation damages
- Detector upgrades: VELO (pixels), tracker (Silicon strips and scintillating fibers), RICH (multi-anode PMTs), CALO& MUON (new electronics), ...
- Aim to collect $\sim$50 fb^{-1}. Annual yields wrt published analyses: $\times$10 for muonic final states and $\times$20 for hadronic modes.



Expected performances of LHCb upgrade [LHCb-PUB-2014-040]

Type	Observable	LHC Run 1	LHCb 2018	**LHCb upgrade**	Theory
B_s^0 mixing	$\phi_s(B_s^0 \to J/\psi\,\phi)$ (rad)	0.049	0.025	**0.009**	~ 0.003
	$\phi_s(B_s^0 \to J/\psi\, f_0(980))$ (rad)	0.068	0.035	**0.012**	~ 0.01
	$A_{\rm sl}(B_s^0)$ (10^{-3})	2.8	1.4	**0.5**	0.03
Gluonic penguin	$\phi_s^{\rm eff}(B_s^0 \to \phi\phi)$ (rad)	0.15	0.10	**0.018**	0.02
	$\phi_s^{\rm eff}(B_s^0 \to K^{*0}\bar{K}^{*0})$ (rad)	0.19	0.13	**0.023**	< 0.02
	$2\beta^{\rm eff}(B^0 \to \phi K_S^0)$ (rad)	0.30	0.20	**0.036**	0.02
Right-handed currents	$\phi_s^{\rm eff}(B_s^0 \to \phi\gamma)$ (rad)	0.20	0.13	**0.025**	< 0.01
	$\tau^{\rm eff}(B_s^0 \to \phi\gamma)/\tau_{B_s^0}$	5%	3.2%	**0.6%**	0.2 %
Electroweak penguin	$S_3(B^0 \to K^{*0}\mu^+\mu^-; 1 < q^2 < 6\,{\rm GeV}^2/c^4)$	0.04	0.020	**0.007**	0.02
	$q_0^2\, A_{\rm FB}(B^0 \to K^{*0}\mu^+\mu^-)$	10%	5%	**1.9%**	$\sim$ 7%
	$A_{\rm I}(K\mu^+\mu^-; 1 < q^2 < 6\,{\rm GeV}^2/c^4)$	0.09	0.05	**0.017**	~ 0.02
	$\mathcal{B}(B^+ \to \pi^+\mu^+\mu^-)/\mathcal{B}(B^+ \to K^+\mu^+\mu^-)$	14%	7%	**2.4%**	$\sim$ 10%
Higgs penguin	$\mathcal{B}(B_s^0 \to \mu^+\mu^-)$ (10^{-9})	1.0	0.5	**0.19**	0.3
	$\mathcal{B}(B^0 \to \mu^+\mu^-)/\mathcal{B}(B_s^0 \to \mu^+\mu^-)$	220%	110%	**40%**	$\sim$ 5 %
Unitarity triangle angles	$\gamma(B \to D^{(*)}K^{(*)})$	7°	4°	**0.9°**	negligible
	$\gamma(B_s^0 \to D_s^{\mp}K^{\pm})$	17°	11°	**2.0°**	negligible
	$\beta(B^0 \to J/\psi\, K_S^0)$	1.7°	0.8°	**0.31°**	negligible
Charm *CP* violation	$A_\Gamma(D^0 \to K^+K^-)$ (10^{-4})	3.4	2.2	**0.4**	–
	ΔA_{CP} (10^{-3})	0.8	0.5	**0.1**	–

- $\phi_s^{\rm eff}(B_s^0 \to \phi\phi)$ with a precision of 0.018
- γ with a precision below 1°

Flavor future of ATLAS and CMS

ATLAS and CMS will continue to collect data with an instantaneous luminosity 10 to 40 larger than LHCb. However, since their priority is the high-p_{T} physics, they cannot afford a too low p_{T} threshold at the trigger level, hence a compromise is to be done for *b*-physics.

In ATLAS, New Inner B Layer (already in run2) interesting for flavor physics: improve decay resolution and flavor tagging.

Modified from [ECFA/13/284, 21 Nov 2013]

Expected sensitivities that can be achieved on key heavy flavor physics observables, using the total integrated luminosity recorded until the end of each LHC run period. The values for flavor-changing neutral-current top decays are expected 95% confidence level upper limits in the absence of signal.

		LHC era			HL-LHC era	
		Run 1 2010–12	Run 2 2015–17	Run 3 2019–21	Run 4 2024–26	Run 5+ 2028–30+
$\int \mathcal{L}dt$	LHCb	3 fb^{-1}	8 fb^{-1}	23 fb^{-1}	46 fb^{-1}	70 fb^{-1} (?)
$\int \mathcal{L}dt$	ATLAS, CMS	25 fb^{-1}	100 fb^{-1}	300 fb^{-1}	...	3000 fb^{-1}
$\frac{\mathcal{B}(B^0 \to \mu^+\mu^-)}{\mathcal{B}(B_s^0 \to \mu^+\mu^-)}$	CMS	$>$ 100%	71%	47%	...	21%
	LHCb	220%	110%	60%	40%	28%
$q_0^2\ A_{\mathrm{FB}}(K^{*0}\mu^+\mu^-)$	LHCb	10%	5%	2.8%	1.9%	1.3%
	Belle II	—	50%	7%	5%	—
$\phi_s(B_s^0 \to J/\psi\phi)$	ATLAS	0.11	0.05–0.07	0.04–0.05	...	0.020
	LHCb	0.05	0.025	0.013	0.009	0.006
$\phi_s(B_s^0 \to \phi\phi)$	LHCb	0.18	0.12	0.04	0.026	0.017
γ	LHCb	7°	4°	1.7°	1.1°	0.7°
	Belle II	—	11°	2°	1.5°	—
$A_\Gamma(D^0 \to K^+K^-)$	LHCb	3.4×10^{-4}	2.2×10^{-4}	0.9×10^{-4}	0.5×10^{-4}	0.3×10^{-4}
	Belle II	—	18×10^{-4}	$4–6 \times 10^{-4}$	$3–5 \times 10^{-4}$	—
$t \to qZ$	ATLAS	...	...	23×10^{-5}	...	$4.1–7.2 \times 10^{-5}$
	CMS	100×10^{-5}	...	27×10^{-5}	...	10×10^{-5}
$t \to q\gamma$	ATLAS	...	...	7.8×10^{-5}	...	$1.3–2.5 \times 10^{-5}$

ATLAS and CMS

- ATLAS
  1. installed a new Inner b-layer in 2015: improved decay time resolution
  2. New Muon Small Wheels+ additional barrel RPC's $\rightarrow$ better acceptance, less background
  3. Move track trigger to Level1 $\rightarrow$ better selectivity
- CMS:
  1. inner pixel layer in 2016: better vertex resolution
  2. New L1 track trigger

Experimental prospects

ϕ_s main experimental challenges: statistics limited.
Ways to increase statistics:

- deferred trigger and real-time calibration (already in run2)
- higher output rate (smaller average event size), real-time analysis
- more channels (tough job since $B_s^0 \to J/\psi\phi$ is so clean)
- improve tagging power and decay time resolution

My personal conclusions at Lake Louise 2016

Tantalizing tensions with respect to the SM:

Observable	Tension wrt SM	Limited by
$B \to D^{(*)}\tau\nu / B \to D^{(*)}\ell\nu,\ \ell = \mu, e$	4.0σ	experiment
$(g-2)_\mu$	3.6σ	exp. & theo.
$B^0 \to K^{*0}\mu\mu$ angular dist., BR	3.4σ	exp. & theo.
$B_s^0 \to \phi\mu\mu$ BR	3.0σ	experiment
Dimuon CP asymmetry	3.0σ	experiment
V_{ub} exclusive versus inclusive	3.0σ	exp. & theo.
ϵ'/ϵ (direct CPV in K)	2.9σ	theory
$B^+ \to K^+ee / B^+ \to K^+\mu\mu$	2.6σ	experiment
$h \to \tau\mu$	2.4σ	experiment

Many other interesting results exhibit no tension today, but put strong constraints on NP models.
They remain fundamental for future searches, e.g.: γ, B^0-D^0-K^0-mixing, ϕ_s, $\sin 2\beta$, $B_s^0 \to \mu\mu$, $B \to X_s\gamma$, V_{cb}, $B \to \tau\nu$, CPV in charm, CLVF, $K \to \pi\nu\bar{\nu}$, ...