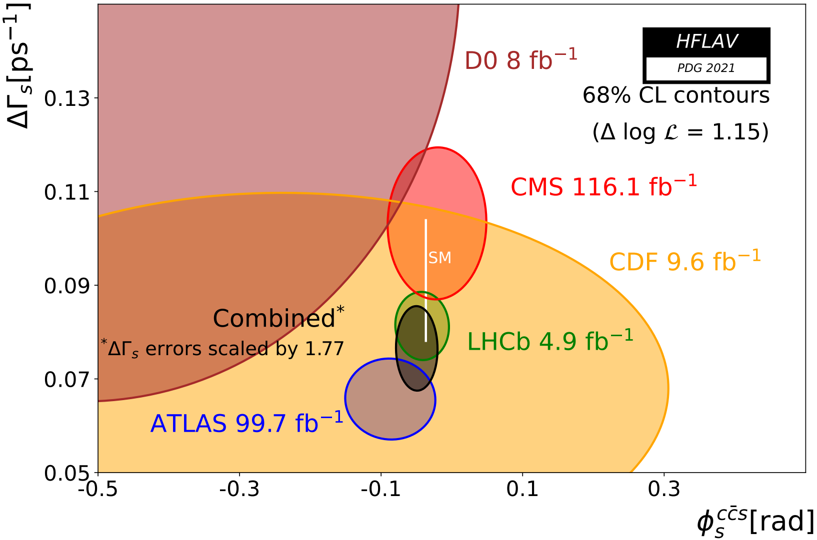
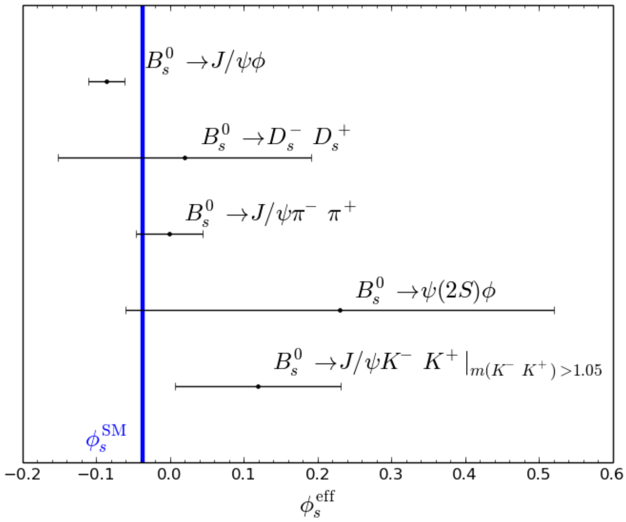
Status of Penguin Pollution to ϕ_s

Kristof De Bruyn

Workshop ϕ_s and a_{SL} in B-mesogenesis
April 19th, 2021


HFLAV
PDG 2021
68% CL contours
(Δ log $\mathcal{L}$ = 1.15)
D0 8 fb^{-1}
CMS 116.1 fb^{-1}
CDF 9.6 fb^{-1}
LHCb 4.9 fb^{-1}
ATLAS 99.7 fb^{-1}
SM
Combined*
*$\Delta\Gamma_s$ errors scaled by 1.77
$\Delta\Gamma_s$[ps^{-1}]
0.13
0.11
0.09
0.07
0.05
-0.5
-0.3
-0.1
0.1
0.3
$\phi_s^{c\bar{c}s}$[rad]

This is Not the End of the Game!



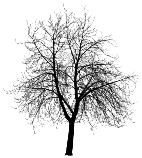
- There is more room for New Physics than you think!
- Naive average is spot on Standard Model . . . but misleading
- Each decay channel is affected by "penguin polution"
- A more careful analysis is necessary

- Time-dependent CP asymmetry

$$a_{\rm CP}(t) \equiv \frac{|A(B_s^0(t)\to f)|^2 - |A(\bar{B}_s^0(t)\to f)|^2}{|A(B_s^0(t)\to f)|^2 + |A(\bar{B}_s^0(t)\to f)|^2} = \frac{\mathcal{A}_{\rm CP}^{\rm dir}\cos(\Delta m_s t) + \mathcal{A}_{\rm CP}^{\rm mix}\sin(\Delta m_s t)}{\cosh(\Delta\Gamma_s t/2) + \mathcal{A}_{\Delta\Gamma}\sinh(\Delta\Gamma_s t/2)}$$

- At leading order

$$|A(B_s^0 \to f)|^2 = \left| \quad \right|^2$$



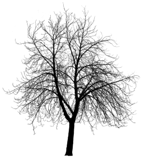
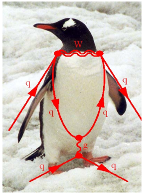
- Introducing the dependence on the B_s–$\bar{B}_s$ mixing phase

$$\mathcal{A}_{\rm CP}^{\rm dir} = 0 \qquad \text{and} \qquad \eta_f \mathcal{A}_{\rm CP}^{\rm mix} = \sin\phi_s$$

- Time-dependent CP asymmetry

$$a_{\rm CP}(t) \equiv \frac{|A(B_s^0(t)\to f)|^2 - |A(\bar{B}_s^0(t)\to f)|^2}{|A(B_s^0(t)\to f)|^2 + |A(\bar{B}_s^0(t)\to f)|^2} = \frac{\mathcal{A}_{\rm CP}^{\rm dir}\cos(\Delta m_s t) + \mathcal{A}_{\rm CP}^{\rm mix}\sin(\Delta m_s t)}{\cosh(\Delta\Gamma_s t/2) + \mathcal{A}_{\Delta\Gamma}\sinh(\Delta\Gamma_s t/2)}$$

- At next-to-leading order

$|A(B_s^0 \to f)|^2 = \Big|$  $+\ \epsilon$ 

$\Big|^2$

- So you measure an effective mixing phase

$$\mathcal{A}_{\rm CP}^{\rm dir} \neq 0 \qquad \text{and} \qquad \frac{\eta_f \mathcal{A}_{\rm CP}^{\rm mix}(B_s \to f)}{\sqrt{1 - \left(\mathcal{A}_{\rm CP}^{\rm dir}(B_s \to f)\right)^2}} = \sin\left(\phi_s^{\rm eff}\right) = \sin\left(\phi_s + \Delta\phi_s\right)$$

The Penguin Shift $\Delta\phi_s$

$$\frac{\eta_f \mathcal{A}_{\rm CP}^{\rm mix}(B_s \to f)}{\sqrt{1-\left(\mathcal{A}_{\rm CP}^{\rm dir}(B_s \to f)\right)^2}} = \sin\left(\phi_s^{\rm eff}\right) = \sin\left(\phi_s^{\rm SM} + \phi_s^{\rm NP} + \Delta\phi_s\right)$$

- Penguin shift $\Delta\phi_s$ is affected by non-perturbative, long-distance QCD contributions

$\Rightarrow$ $\Delta\phi_s$ is decay mode specific

- Spoiler: $\Delta\phi_s^{J/\psi\phi} = \left(0.14^{+0.54}_{-0.70}\right)^\circ$

- Controlling $\Delta\phi_s$ is mandatory to constrain $\phi_s^{\rm NP}$

- If no action is taken, could easily become the leading systematic uncertainty for the Hi-Lumi LHC.

Estimating $\Delta\phi_s$

- Non-perturbative, long-distance QCD contributions make it difficult to determine $\Delta\phi_s$ from first principles.
- Direct calculations have been attempted, for example in arXiv:1309.0313 or arXiv:1503.00859
- Preferred strategy: Data-driven techniques relying on $SU(3)$ flavour symmetry arguments.
- $SU(3)$ flavour symmetry: In the limit of massless quarks, QCD does not differentiate between u, d and s

$SU(3)$ Flavour Symmetry Strategy:

1. Find a control channel where contributions from penguin topologies are not suppressed
2. Estimate the size of the penguin effects using the CP asymmtries of the control mode
3. Use $SU(3)$ flavour symmetry to relate the result to the mode measuring ϕ_s^{eff}
4. Estimate $\Delta\phi_s$ based on the size of the penguin effects in the control mode
5. Main systematic uncertainty: $SU(3)$ symmetry breaking

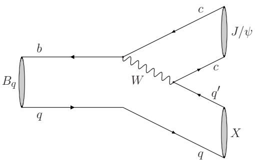
Current Status on Controlling Penguin Effects to ϕ_s

Decay Channel	Control Mode	Latest Penguin Analysis
$B_s^0 \to J/\psi\phi$	$B_d^0 \to J/\psi\rho^0$	arXiv:2010.14423
$B_s^0 \to D_s^- D_s^+$	$B_d^0 \to D_d^- D_d^+$	arXiv:1505.01361
$B_s^0 \to J/\psi f_0(980)$	$B_d^0 \to J/\psi f_0(980)$	arXiv:1109.1112; Control mode not yet measured
$B_s^0 \to \psi(2S)\phi$	$B_d^0 \to \psi(2S)\rho^0$	None Yet; Control mode not yet measured
$B_s^0 \to J/\psi K^- K^+\|_{m(K^-K^+)>1.05}$		None Yet

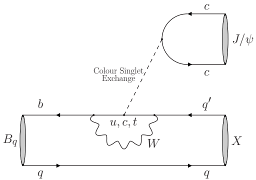
- Many groups involved, see references in the listed papers
- $B_s^0 \to J/\psi \bar{K}^{*0}$ as an alternative for $B_d^0 \to J/\psi\rho^0$
  But measures only direct CP asymmetry, making it more difficult to determine the penguin effects cleanly
- I will focus on $B_s^0 \to J/\psi\phi$ for the remainder

Decay Topologies for $B_s^0 \to J/\psi\phi$

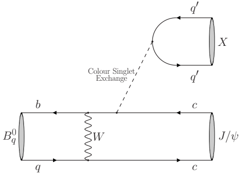
Tree



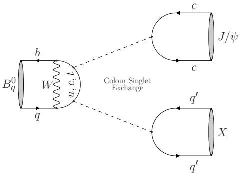
Penguin



Exchange



Penguin-Annihilation

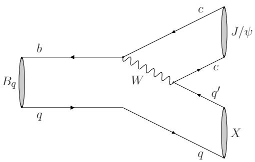


- Fill in $q' = s$ and $q = s$ to get $X = \phi$
- Expect the hierarchy: Tree > Penguin > Exchange/Penguin-Annihilation
- Will ignore contributions from Exchange/Penguin-Annihilation
- They could be probed using $B_d^0 \to J/\psi\phi$

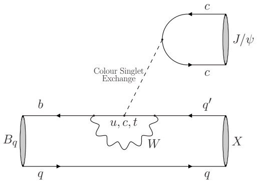
$$\mathcal{B}(B_d^0 \to J/\psi\phi) < 1.1 \times 10^{-7} \qquad \text{at 90\% CL}$$

arXiv:2011.06847

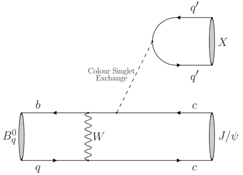
Tree



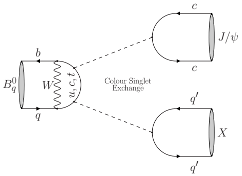
Penguin



Exchange



Penguin-Annihilation



- For $B_s^0 \to J/\psi\phi$: $q' = s$ and $q = s$ to get $X = \phi$
- For $B_d^0 \to J/\psi\rho$: $q' = d$ and $q = d$ to get $X = \rho^0$

- Decays are related via U-spin symmetry: interchange all $s \leftrightarrow d$ quarks

- 1-to-1 correspondence between **all** decay topologies

The Penguin Suppressed Mode:

$$A(B_s^0 \to J/\psi\phi) = \left(1 - \frac{1}{2}\lambda^2\right) \mathcal{A}' \left[1 + \epsilon a' e^{i\theta'} e^{i\gamma}\right] , \qquad \epsilon \equiv \frac{\lambda^2}{1-\lambda^2} \approx 0.052$$

- $\mathcal{A}'$: overall normalisation, represents the tree topology,
- a': the relative contribution from the penguin topologies,
- θ': the associated strong phase difference,
- γ: UT angle and the associated relative weak phase difference.

The Penguin Enhanced Mode:

$$A(B_d^0 \to J/\psi\rho^0) = -\lambda\mathcal{A} \left[1 - a e^{i\theta} e^{i\gamma}\right] , \qquad \lambda \approx 0.225$$

$SU(3)$ Flavour Symmetry Strategy

1. Use CP asymmetries in $B_d^0 \to J/\psi \rho^0$ to determine a and θ

$$\mathcal{A}_{\rm CP}^{\rm dir} = \text{function}(a, \theta, \gamma)$$
$$\mathcal{A}_{\rm CP}^{\rm mix} = \text{function}(a, \theta, \gamma, \phi_d)$$

2. γ and ϕ_d are external inputs
3. Use $SU(3)$ symmetry relation

$$a' = a \qquad \& \qquad \theta' = \theta$$

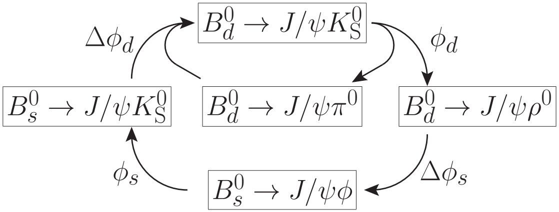
4. Determine the penguin shift $\Delta\phi_s$

$$\Delta\phi_s = \text{function}(a', \theta', \gamma)$$

5. Correct $\phi_s^{\rm eff}$

$$\phi_s = \phi_s^{\rm eff} - \Delta\phi_s$$

Interplay between ϕ_d and ϕ_s:

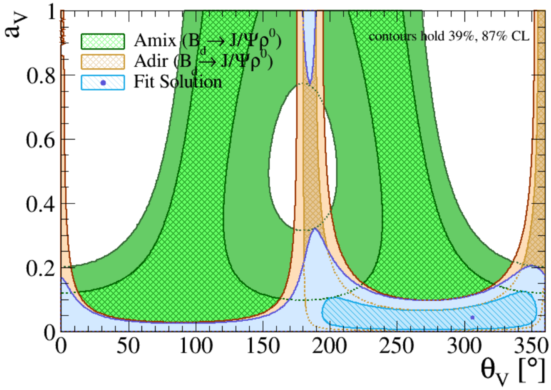


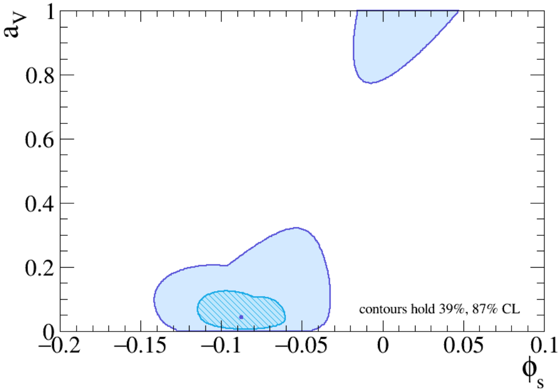
Assumptions:

1. Ignore contributions from Exchange and Penguin-Annihilation topologies
2. Ignore polarisation-dependent effects (due to lack of data)
3. Ignore $SU(3)$-breaking effects

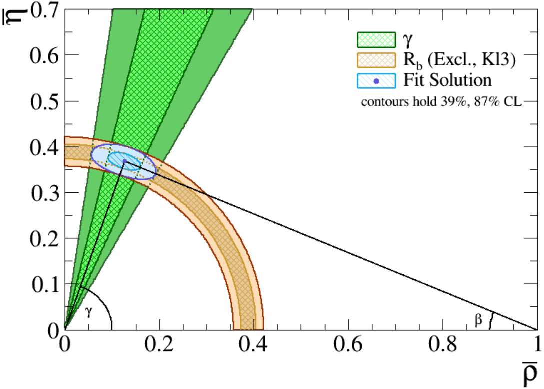
Fit to Current Data

arXiv:2010.14423





$$a_V = 0.043^{+0.082}_{-0.037}\,, \qquad \theta_V = \left(306^{+\ 48}_{-112}\right)^\circ\,, \qquad \phi_s = -0.088^{+0.028}_{-0.027} = \left(-5.0^{+1.6}_{-1.5}\right)^\circ\,,$$



- Experimentally measure

$$\phi_{s,J/\psi\phi}^{\text{eff}} = -0.085 \pm 0.025 = (-4.9 \pm 1.4)^\circ$$

- Correct penguin pollution

$$\Delta\phi_s = 0.003^{+0.010}_{-0.012} = \left(0.14^{+0.54}_{-0.70}\right)^\circ$$

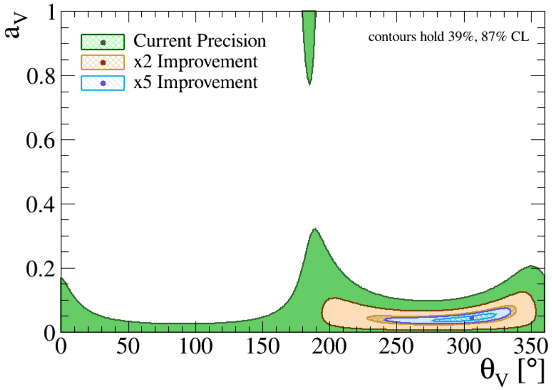
$$\phi_s = -0.088^{+0.028}_{-0.027} = \left(-5.0^{+1.6}_{-1.5}\right)^\circ$$

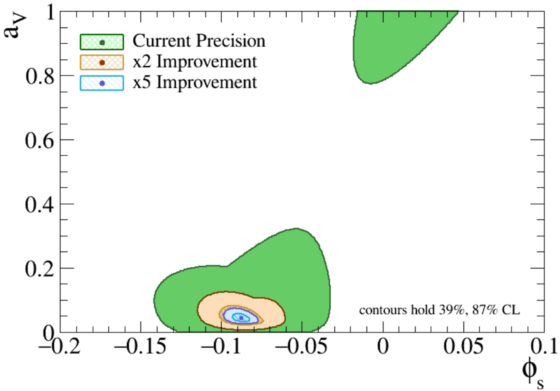
- Compare with a SM prediction

$$\phi_s^{\text{SM}} = -0.0376 \pm 0.0020 = (-2.15 \pm 0.11)^\circ$$

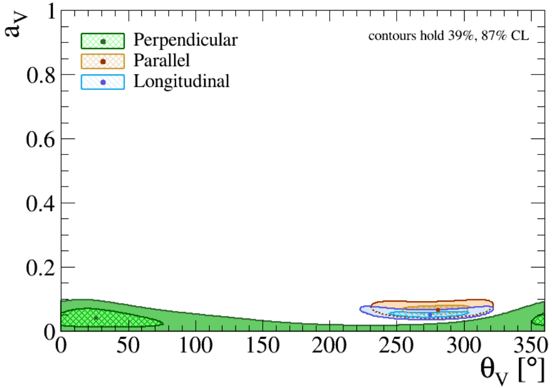
- Space left for New Physics

$$\phi_s^{\text{NP}} = -0.050 \pm 0.028 = (-2.9 \pm 1.6)^\circ$$

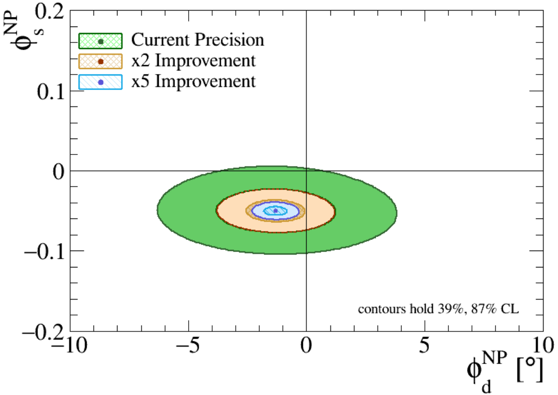




- Requires equal (relative) improvements to both $B_s^0 \to J/\psi\phi$ and $B_d^0 \to J/\psi\rho^0$
- Excellent prospects to control penguin effects to $B_s^0 \to J/\psi\phi$



- Hadronic effects are polarisation-dependent
  $\rightarrow$ thus also the penguin pollution
- With a $\times 5$ improvement in precision we could see differences between the polarisation states
- Need polarisation-dependent measurements
- Illustration based on polarisation-dependent results in $B_d^0 \rightarrow J/\psi \rho^0$ arXiv:1411.1634



- Based on

$$\phi_d^{SM} = (45.7 \pm 2.0)^\circ$$
$$\phi_s^{SM} = -0.0376 \pm 0.0020 = (-2.15 \pm 0.11)^\circ$$

- Could still uncover NP in ϕ_s with 5σ significance
- Situation less favourable for ϕ_d:
Dominated by uncertainty in SM prediction

Conclusion

$$\phi_{s,J/\psi\phi}^{\text{eff}} = -0.085 \pm 0.025 = (-4.9 \pm 1.4)^\circ$$

$$\Delta\phi_s = 0.003^{+0.010}_{-0.012} = \left(0.14^{+0.54}_{-0.70}\right)^\circ$$

$$\phi_s = -0.088^{+0.028}_{-0.027} = \left(-5.0^{+1.6}_{-1.5}\right)^\circ$$

- Effects due to penguin pollution in $B_s^0 \to J/\psi\phi$ are small ...
  ... but we are fast approaching the experimental precision where that still matters

- Effects due to penguin pollution are decay channel specific and polarisation-dependent
  $\rightarrow$ Requires careful analysis when combining experimental results
  $\rightarrow$ Strong case to publish polarisation-dependent results

- It is easier for the theoretical interpretation if also $\mathcal{A}_{\text{CP}}^{\text{dir}}$ and $\mathcal{A}_{\text{CP}}^{\text{mix}}$ are given
  (or C and S in the alternative convention)