Measurements of CP Violating Phases in B Decays

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On behalf of the LHCb Collaboration

Lake Louise Winter Institute 2015
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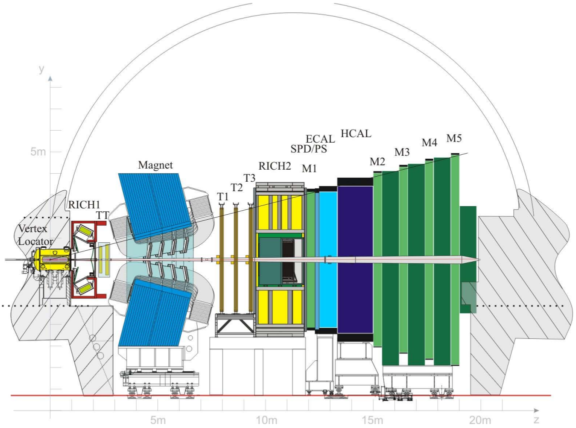
The LHCb Detector

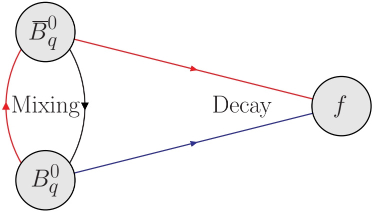


Forward arm spectrometer to study b- and c-hadron decays

- Pseudo-rapidity coverage: $2 < \eta < 5$

- Good impact parameter resolution to identify secondary vertices: 20 μm
- Decay time resolution: 46 fs ($B_s^0 \to J/\psi K^+K^-$)
- Invariant mass resolution: 8 MeV/c^2 ($B \to J/\psi X$) 22 MeV/c^2 ($B \to hh$)
- Excellent particle identification: 95 % K ID efficiency (5 % $\pi \to K$ mis-ID)
- Versatile & efficient trigger for b- and c-hadrons and forward EW signals

Measuring CP Violation: Interfering Paths



Mixing-Induced CP Violation: $\text{Prob}(B_q^0 \to f) \neq \text{Prob}(B_q^0 \to \overline{B}_q^0 \to f)$

- Interference between direct decay and decay after mixing
- Key Measurements: ϕ_d from $B^0 \to J/\psi K_S^0$; ϕ_s from $B_s^0 \to J/\psi h^+h^-$

New Results on CP Violation in B Decays: (3 fb^{-1}– Full Run 1)

✓ Update on the measurement of ϕ_s from $B_s^0 \to J/\psi K^+K^-$
✓ First CP asymmetry measurement in $B^0 \to J/\psi \rho^0$
✓ First CP asymmetry measurement in $B_s^0 \to J/\psi K_S^0$ **[New]**

CP Formalism

HFAG Convention

CP Asymmetry

$$a_{CP}(t) \equiv \frac{\Gamma(\overline{B}(t) \to f) - \Gamma(B(t) \to f)}{\Gamma(\overline{B}(t) \to f) + \Gamma(B(t) \to f)} = \frac{S_f \sin(\Delta m\, t) - C_f \cos(\Delta m\, t)}{\cosh(\Delta\Gamma\, t/2) + \mathcal{A}_{\Delta\Gamma} \sinh(\Delta\Gamma\, t/2)}$$

- where $\Delta m \equiv m_{\rm H} - m_{\rm L}$ and $\Delta\Gamma \equiv \Gamma_{\rm L} - \Gamma_{\rm H}$
- *CP* observables are

$$\mathcal{A}_{\Delta\Gamma} \equiv -\frac{2\,\mathcal{R}\mathrm{e}[\lambda_f]}{1+|\lambda_f|^2}\,, \qquad C_f \equiv \frac{1-|\lambda_f|^2}{1+|\lambda_f|^2}\,, \qquad S_f \equiv \frac{2\,\mathcal{I}\mathrm{m}[\lambda_f]}{1+|\lambda_f|^2}$$

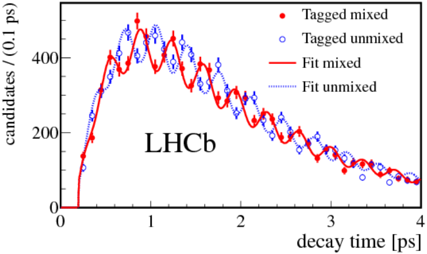
- in terms of B–$\overline{B}$ mixing phase ϕ

$$\lambda_f \equiv -e^{i\phi}\,\frac{A(\overline{B} \to f)}{A(B \to f)} = -|\lambda_f|\, e^{i\phi^{\rm eff}}$$

Effective Mixing Phase

- Measure $|\lambda_f|$ and $\phi^{\rm eff}$

$$S_f = -\eta_f\,\frac{2|\lambda_f|\,\sin\phi^{\rm eff}}{1+|\lambda_f|^2}$$



NJP 15 (2013), arXiv:1304.4741

Update on measurement of ϕ_s from $B_s^0 \to J/\psi K^+K^-$

Mixing in the Neutral B Meson Systems

B_s^0–$\overline{B}_s^0$ mixing ϕ_s

- One of the CKM angles ⇒ Important test of the Standard Model
- Precise SM prediction: J. Charles *et al.*, [arxiv:1501.05013]

$$\phi_s^{\text{SM}} = -0.0365 \pm 0.0013\,\text{rad}$$

- Small magnitude offers excellent probe to search for New Physics

$$\phi_s = \phi_s^{\text{SM}} + \phi_s^{\text{NP}}$$

- Experimentally accessible through CPV in:

$$B_s^0 \to J/\psi\,\phi, \qquad B_s^0 \to J/\psi\, f_0(980), \qquad B_s^0 \to D_s^+ D_s^-$$

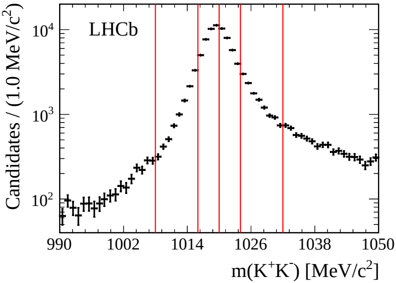
- Extended scope: $B_s^0 \to J/\psi\, K^+K^-$ and $B_s^0 \to J/\psi \pi^+\pi^-$

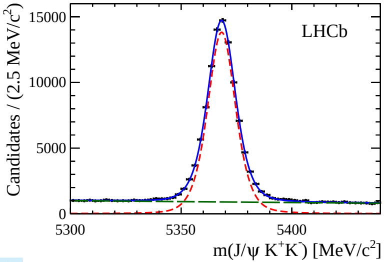
$B_s^0 \to J/\psi K^+K^-$ at LHCb: Selection

PRL 114 (2015), arXiv:1411.3104

Selection:

- Analysis done in 6 bins of K^+K^- mass
- Angular analysis to disentangle CP-even and CP-odd contributions
- 3 polarisation states $(f_0,\ f_\parallel,\ f_\perp)$ + S-wave
- Event Yield:
  95 690 $\pm$ 350 signal candidates.





Time Resolution

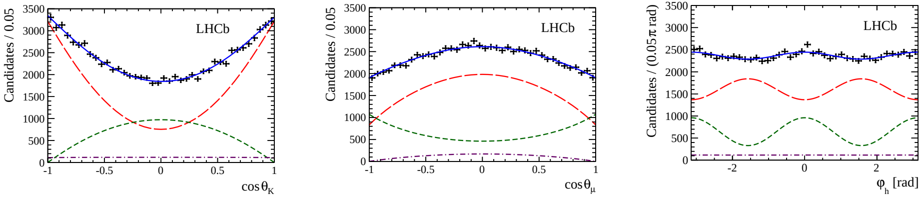
- Using per-event resolution model
- Effective resolution: 46 fs

Flavour Tagging

- Including Opposite Side (OS) and Same Side Kaon (SSK) tagging
- Tagging power
  $\epsilon_{\text{tag}}\mathcal{D}^2 = (3.73 \pm 0.15)\,\%$

ϕ_s from $B_s^0 \to J/\psi K^+K^-$: Results

PRL 114 (2015), arXiv:1411.3104



CP-even CP-odd S-wave Total

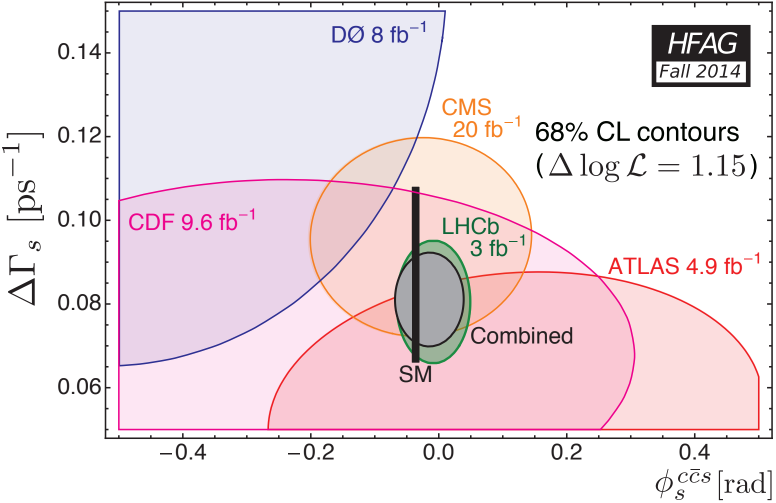
Polarisation-Independent Fit

$$\phi_s^{\text{eff}} = -0.058 \pm 0.049 \text{ (stat)} \pm 0.006 \text{ (syst) rad}$$
$$|\lambda_{J/\psi\,\phi}| = 0.964 \pm 0.019 \text{ (stat)} \pm 0.007 \text{ (syst)}$$
$$\Gamma_s = 0.6603 \pm 0.0027 \text{ (stat)} \pm 0.0015 \text{ (syst)} \text{ ps}^{-1}$$
$$\Delta\Gamma_s = 0.0805 \pm 0.0091 \text{ (stat)} \pm 0.0032 \text{ (syst)} \text{ ps}^{-1}$$

- Compatible with the SM

World Average for ϕ_s–$\Delta\Gamma_s$

HFAG, arXiv:1412.7515



$$\phi_s = -0.015 \pm 0.035 \text{ rad}$$

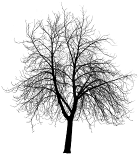
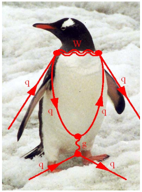
$$\Delta\Gamma_s = 0.081 \pm 0.006 \text{ ps}^{-1}$$

First CP asymmetry measurement in $B^0 \to J/\psi \rho^0$

Towards (Even) Higher Precision Measurements of ϕ_s

Subleading Effects:

- A closer look at $B_s^0 \to J/\psi\, \phi$:

$$|A(B_s^0 \to J/\psi\, \phi)|^2 = \Bigg|$$  $$+\ \epsilon$$ 

$$+\ \ldots \Bigg|^2$$

- Experimentally measure an effective mixing phase

$$\phi_s^{\text{eff}}(B_s^0 \to J/\psi\, \phi) = \phi_s + \Delta\phi_s$$

- $\Delta\phi_s$ is a shift due to penguin topologies
- Controlling these higher order hadronic effects becomes mandatory!
- Relying on $SU(3)$ flavour symmetry: constrain with $B^0 \to J/\psi\, \rho^0$.

See for example: De Bruyn & Fleischer, arXiv:1412.6834

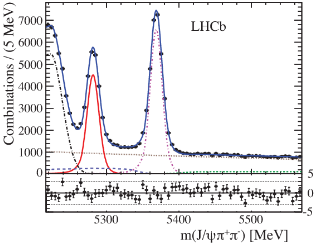
$B^0 \to J/\psi \pi^+\pi^-$ at LHCb: Selection

arXiv:1411.1634

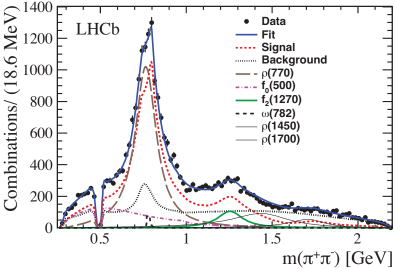
Selection:

- Selection based on Boosted Decision Tree
  trained on Simulation (Signal) and Data (Background)
- Event Yield: 17 650 $\pm$ 200 candidates
  in 20 MeV around B^0 peak
- Angular + Dalitz analysis:
  identify the resonant contributions

Zhang & Stone PLB 719 (2013), arXiv:1212.6434



Resonances:



Veto $K_S^0 \to \pi^+\pi^-$

Component	Fraction [%]
$B^0 \to J/\psi \rho^0$	65.6 ± 1.9
$B^0 \to J/\psi f_0(500)$	20.1 ± 0.7
$B^0 \to J/\psi f_2(1270)$	7.8 ± 0.6
$B^0 \to J/\psi \omega(782)$	$0.64^{+0.19}_{-0.13}$
$B^0 \to J/\psi \rho^0(1450)$	9.0 ± 1.8
$B^0 \to J/\psi \rho^0(1700)$	3.1 ± 0.7

PRD 90 (2014), arXiv:1404.5673

$B^0 \to J/\psi \pi^+\pi^-$: Polarisation-Independent Fit

arXiv:1411.1634

Effective Mixing Phase

$$\phi_d^{\text{eff}}(B^0 \to J/\psi \rho^0) = (41.7 \pm 9.6\,(\text{stat})^{+2.8}_{-6.3}\,(\text{syst}))^\circ$$
$$\Delta\phi_d^{\text{eff}}(\text{other modes} - \rho) = (3.6 \pm 3.6\,(\text{stat})^{+0.9}_{-0.8}\,(\text{syst}))^\circ$$

CP Asymmetry

$$\alpha_{CP}(B^0 \to J/\psi \rho^0) = -(32 \pm 28\,(\text{stat})^{+7}_{-9}\,(\text{syst})) \times 10^{-3}$$
$$\alpha_{CP}(\text{other modes}) = -(1 \pm 25\,(\text{stat})^{+14}_{-7}\,(\text{syst})) \times 10^{-3}$$

$$\alpha_{CP} \equiv \frac{1 - |\lambda|}{1 + |\lambda|}$$

CP Asymmetries for $B^0 \to J/\psi \rho^0$

$$C_{J/\psi \rho^0} = -0.063 \pm 0.056\,(\text{stat})^{+0.019}_{-0.014}\,(\text{syst})$$
$$S_{J/\psi \rho^0} = -0.66^{+0.13}_{-0.12}\,(\text{stat})^{+0.09}_{-0.03}\,(\text{syst})$$

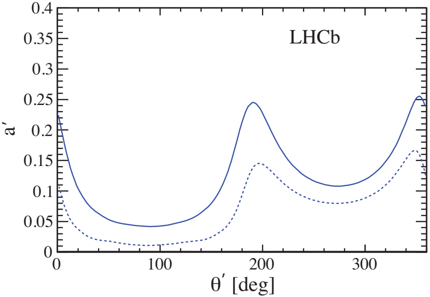
Constraining Penguin Contributions

arXiv:1411.1634

Penguin Parameters

$$A(B^0 \to J/\psi \rho^0) = \mathcal{N}\left[1 - a\, e^{i\theta} e^{i\gamma}\right], \qquad A(B_s^0 \to J/\psi \phi) = \mathcal{N}'\left[1 + \epsilon a'\, e^{i\theta'} e^{i\gamma}\right]$$

- a and θ can be constrained using the CP asymmetries
- Assume no $SU(3)$ symmetry breaking: $a = a'$ and $\theta = \theta'$



Results

$$a' = 0.035^{+0.082}_{-0.035}$$

$$\theta' = (285^{+69}_{-95})^\circ$$

Confidence Bands

- Dashed Line = 68% C.L.
- Solid Line = 95% C.L.

Constraint on Penguin Shift

$$\Delta\phi_s = (0.05 \pm 0.56)^\circ = [-1.05^\circ, +1.18^\circ] \text{ at } 95\,\%\text{C.L.}$$

First CP asymmetry measurement in $B_s^0 \to J/\psi K_S^0$

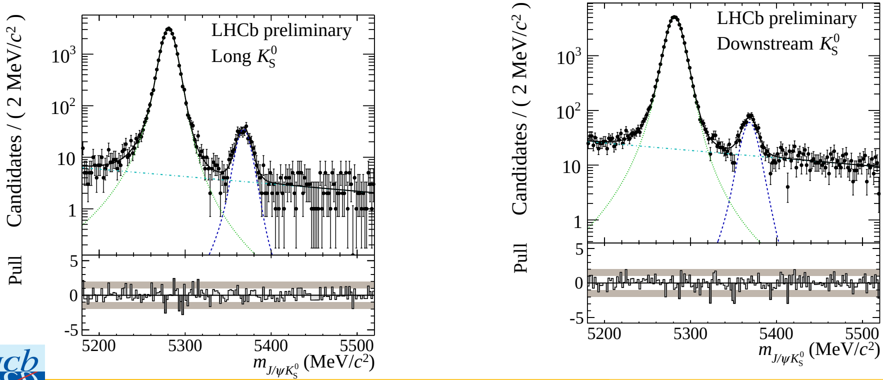
$B_s^0 \to J/\psi K_S^0$ at LHCb: Selection

LHCb-PAPER-2015-005

Selection:

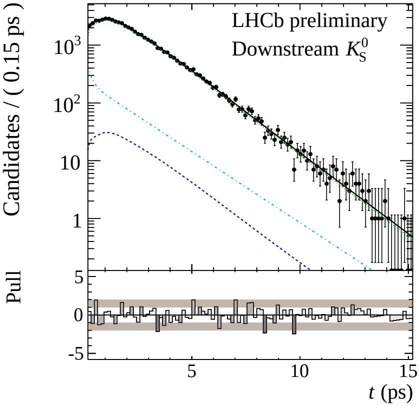
- Selection based on artificial neural network
  trained entirely on data using $B^0 \to J/\psi K_S^0$ as a proxy (Signal)
- K_S^0 split into two categories:
  Long K_S^0 (with Velo hits) and Downstream K_S^0 (without Velo hits)
- Event Yield: 307 ± 20 Long K_S^0 and 601 ± 30 Downstream K_S^0

Invariant Mass:



$B_s^0 \to J/\psi K_S^0$ at LHCb

LHCb-PAPER-2015-005



Fit Model

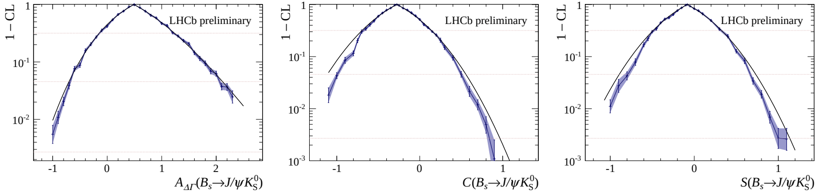
- Fully Model $B_s^0 \to J/\psi K_S^0$ and $B^0 \to J/\psi K_S^0$
- Dotted: $B^0 \to J/\psi K_S^0$
- Dashed: $B_s^0 \to J/\psi K_S^0$
- Dash-Dotted: Combi. Bkg.

Tagging

- OS + SSK tagging
- Tagging power ($B_s^0 \to J/\psi K_S^0$): $\epsilon_{tag}\mathcal{D}^2 = (3.80 \pm 0.18)$ %
- Tagging power ($B^0 \to J/\psi K_S^0$): $\epsilon_{tag}\mathcal{D}^2 = (2.60 \pm 0.05)$ %
- Difference: small SSK tagging power for $B^0 \to J/\psi K_S^0$

$B_s^0 \to J/\psi K_S^0$: Preliminary Results

LHCb-PAPER-2015-005



CP Asymmetries

Preliminary

$$\mathcal{A}_{\Delta\Gamma} = 0.49 \pm {}^{0.77}_{0.65}\,(\text{stat}) \pm 0.06\,(\text{syst})$$
$$C_{J/\psi K_S^0} = -0.28 \pm 0.41\,(\text{stat}) \pm 0.08\,(\text{syst})$$
$$S_{J/\psi K_S^0} = -0.08 \pm 0.40\,(\text{stat}) \pm 0.08\,(\text{syst})$$

Conclusion

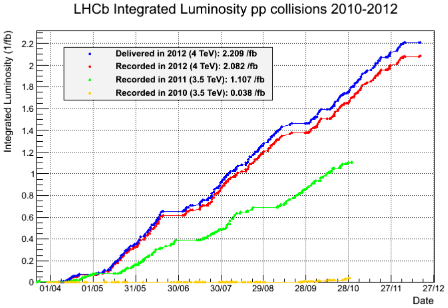
- LHCb providing high precision measurements of B–$\overline{B}$ mixing phases ϕ_d and ϕ_s
- Controlling penguin contributions to these measurements becomes mandatory!
- LHCb started to measure decay channels that can be used to control them:
$$B^0 \to J/\psi\,\rho^0 \text{ and } B_s^0 \to J/\psi\,K_S^0$$

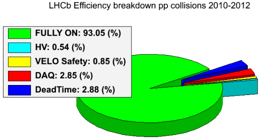
Expect more CPV measurements soon!

Back-up

Performance of the LHCb Detector

Data Taking





- Data taking efficiency: 93.05%
- Percentage of working detector channels: $\approx$ 99%

Efficiencies

- Trigger efficiency:
  Dimuon channels: $\approx$ 90%
- Track reconstruction efficiency: $>$ 96%

Resolution

- Momentum resolution:
  $\Delta p/p = 0.4\%$ at 5 GeV/c
  $\Delta p/p = 0.6\%$ at 100 GeV/c
- ECAL resolution: $1\% \pm 10\%$

$B_s^0 \to J/\psi K^+K^-$: Polarisation-Dependent Fit

PRL 114 (2015), arXiv:1411.3104

Parameter	Value
$\lvert\lambda^0\rvert$	1.012 ± 0.058 (stat) ± 0.013 (syst)
$\lvert\lambda^\parallel/\lambda^0\rvert$	1.02 ± 0.12 (stat) ± 0.05 (syst)
$\lvert\lambda^\perp/\lambda^0\rvert$	0.97 ± 0.16 (stat) ± 0.01 (syst)
$\lvert\lambda^\mathrm{S}/\lambda^0\rvert$	0.86 ± 0.12 (stat) ± 0.04 (syst)
ϕ_s^0 [rad]	-0.045 ± 0.053 (stat) ± 0.007 (syst)
$\phi_s^\parallel - \phi_s^0$ [rad]	-0.018 ± 0.043 (stat) ± 0.009 (syst)
$\phi_s^\perp - \phi_s^0$ [rad]	-0.014 ± 0.035 (stat) ± 0.006 (syst)
$\phi_s^\mathrm{S} - \phi_s^0$ [rad]	0.015 ± 0.061 (stat) ± 0.021 (syst)

$B^0 \to J/\psi \pi^+\pi^-$: Polarisation-Dependent Fit

arXiv:1411.1634

Effective Mixing Phase

$$\phi_d^{\text{eff}}(B^0 \to (J/\psi\,\rho)_0) = (44.1 \pm 10.2\,(\text{stat})^{+3.0}_{-6.9}\,(\text{syst}))^\circ$$
$$\Delta\phi_d^{\text{eff}}(\rho_\parallel - \rho_0) = -(0.8 \pm 6.5\,(\text{stat})^{+1.3}_{-1.9}\,(\text{syst}))^\circ$$
$$\Delta\phi_d^{\text{eff}}(\rho_\perp - \rho_0) = -(3.6 \pm 7.2\,(\text{stat})^{+1.4}_{-2.0}\,(\text{syst}))^\circ$$
$$\Delta\phi_d^{\text{eff}}(\text{other modes} - \rho_0) = (2.7 \pm 3.9\,(\text{stat})^{+1.0}_{-0.9}\,(\text{syst}))^\circ$$

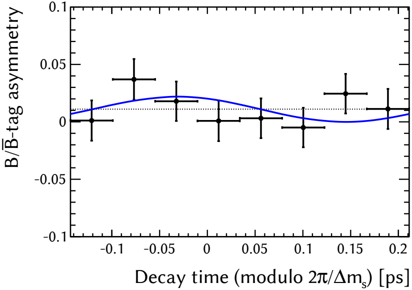
CP Asymmetry

$$\alpha_{CP}(B^0 \to (J/\psi\,\rho)_0) = -(47 \pm 34\,(\text{stat})^{+10}_{-11}\,(\text{syst})) \times 10^{-3}$$
$$\alpha_{CP}(B^0 \to (J/\psi\,\rho)_\parallel) = -(61 \pm 60\,(\text{stat})^{+6}_{-8}\,(\text{syst})) \times 10^{-3}$$
$$\alpha_{CP}(B^0 \to (J/\psi\,\rho)_\perp) = (17 \pm 109\,(\text{stat})^{+22}_{-15}\,(\text{syst})) \times 10^{-3}$$
$$\alpha_{CP}(\text{other modes}) = -(6 \pm 27\,(\text{stat})^{+14}_{-9}\,(\text{syst})) \times 10^{-3}$$

$$\alpha_{CP} \equiv \frac{1-|\lambda|}{1+|\lambda|}$$

Asymmetry Plots

$B_s^0 \to J/\psi \phi$



$B^0 \to J/\psi \rho^0$