# Measurements of penguin pollution effects

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UNIVERSITY OF Cincinnati

# Outline

- Introduction and physics motivations
- Controlling penguin topologies
- Prospects & summary

*Nature Methods 11,1242–1244 (2014)*

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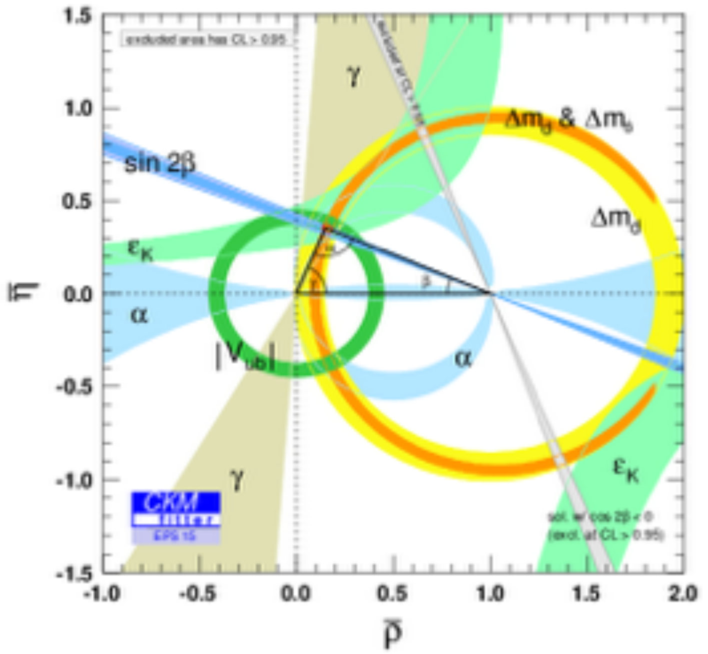
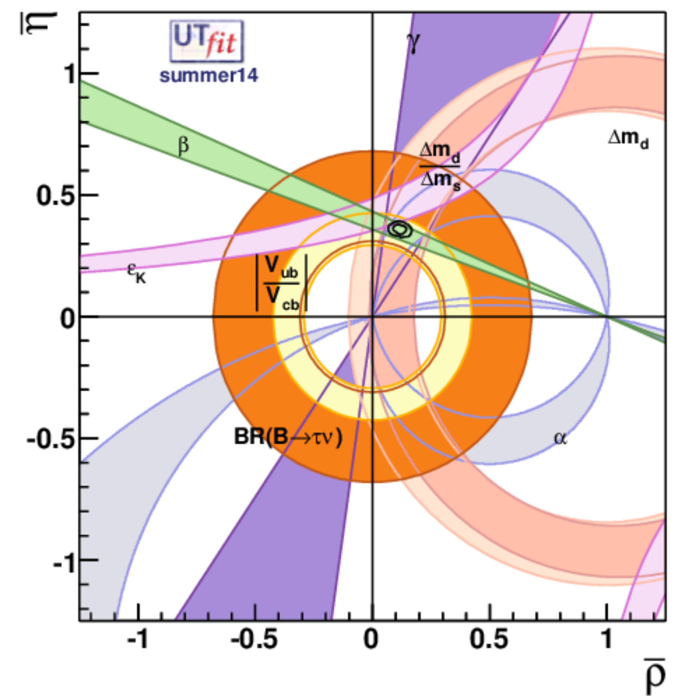
# Introduction and physics motivations

# Introduction

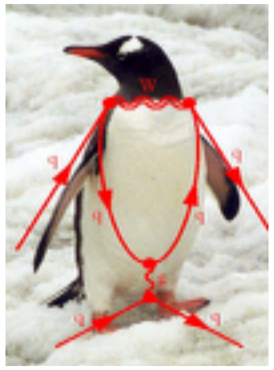
- CKM mechanism introduces *CP* violation and neutral meson mixing phenomena
  - The presence of new heavy particles exchanged in virtual loops could introduce additional phases altering the corresponding measurements
  - Constraining these phases put stringent limits on a large range of NP models
- *CP* violation is needed to explain baryon asymmetry in the Universe
  - Discovered in 1964 in the kaons, 2004 in the *B* and each time awarded with Nobel Prizes
  - Still missing 10 orders of magnitudes!
- Experimentally, *CP* violation observables accessed through ratios of measured quantities
  - Cancelation of many experimental systematics
  - Flagship measurements for LHCb and Belle II



# Introduction

- **CPV in interference between mixing and decay:**

$$|A(B \to J/\psi X)|^2 = \Bigg|$$  $$+ \quad \varepsilon$$  $$\overset{(?)}{+}$$  $$\Bigg|^2$$

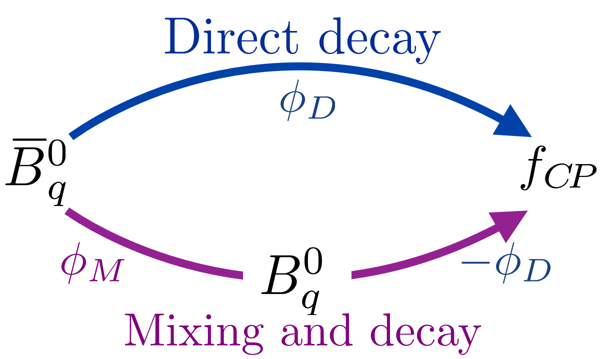
dominant SM "tree"contribution

higher order "penguin" contributions from non-perturbative hadronic effects that are difficult to calculate in QCD
[Nierste et al. *Phys. Rev. Lett. 115, 061802 (2015)*]
[Liu et al. *Phys. Rev. D 89, 094010 (2014)*]

NP could be comparable to penguins…

$$\phi_q^{\text{eff}} = \phi_M - 2\phi_D$$
$$= \pm 2\beta_q + \Delta\phi_q + \delta_q^{\text{NP}}$$

$$\beta_q = \arg\left(-\frac{V_{tq}V_{tb}^*}{V_{cq}V_{cb}^*}\right)$$




- **$\phi_s$ and $\phi_d$ determination via global fit to experimental results ignoring contributions from penguin diagrams:**

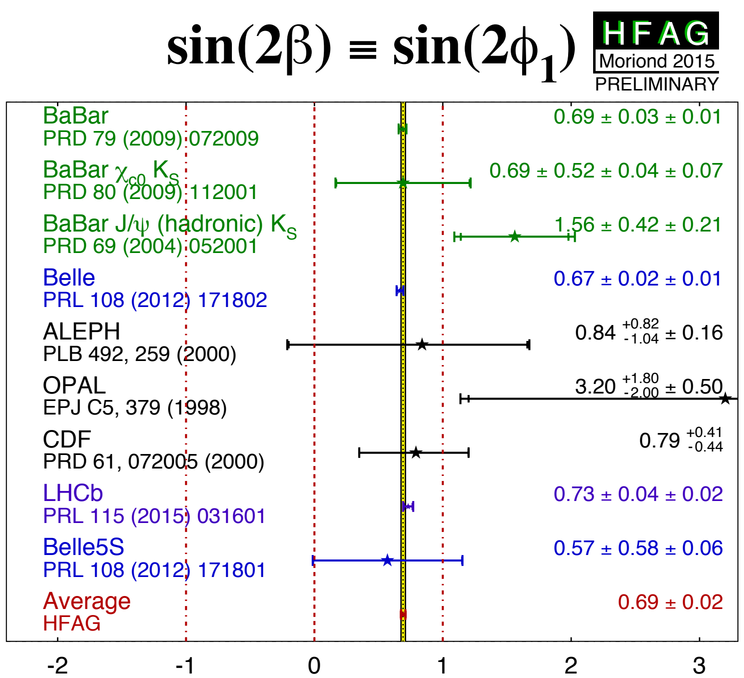
[CKMFitter]
[HFAG]

$$\phi_s^{\text{SM}} = -2\beta_s = [-0.0376^{+0.0007}_{-0.0008}]\ \text{rad}$$
$$\phi_d^{\text{SM}} = +2\beta_d = [48.6 \pm 2.6]^\circ$$

**Very precise theoretical predictions!**

# Current experimental status

## $B^0$—$\overline{B}^0$ mixing phase: $\phi_d$

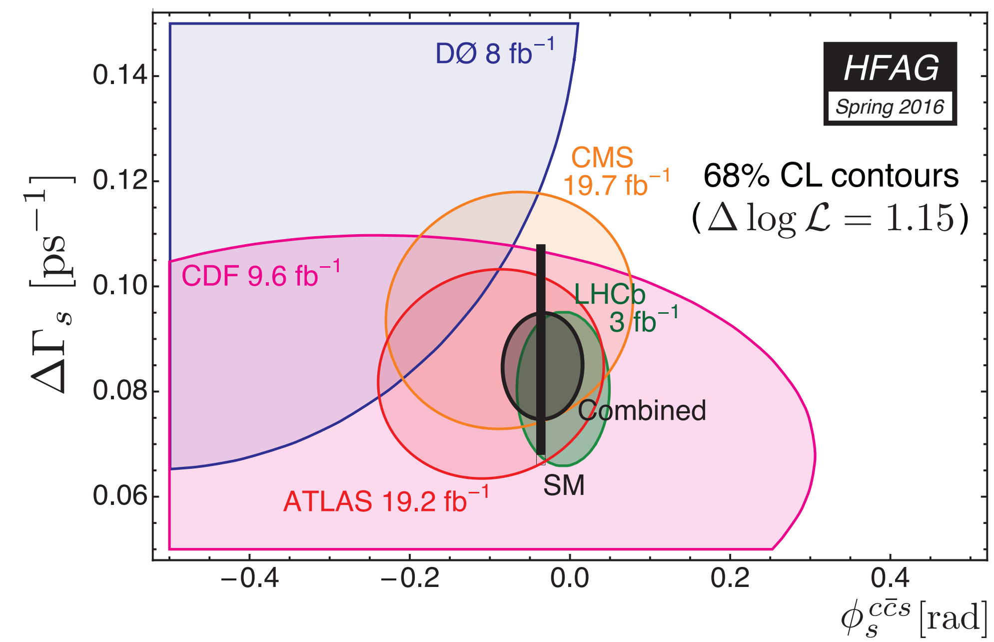



- **Golden mode: $B^0 \to J/\psi K^0_S$**

$$\phi^{\rm eff}_{d,J/\psi K^0_S} = [42.2 \pm 1.5]^\circ$$

$$\phi^{\rm SM}_d = [47.8 \pm 2.6]^\circ$$

## $B^0_s$—$\overline{B}^0_s$ mixing phase: $\phi_s$




- **Golden mode: $B^0_s \to J/\psi\, \phi$**

$$\phi^{\rm eff}_{s,c\bar{c}s} = [-0.030 \pm 0.033]\,{\rm rad} = [-1.7 \pm 1.9]^\circ$$

$$\phi^{\rm SM}_s = \left[-0.0376^{+0.0007}_{-0.0008}\right]\,{\rm rad} = \left[-2.16^{+0.04}_{-0.05}\right]^\circ$$

- **New physics contributions, if present, will be small!!**
- **Entering a new era of precision physics: Aim to reach a precision of $O(0.5^\circ)$ at the end of LHC Run-3**
- **Controlling contributions from penguin topologies becomes mandatory!**


*Nature Methods 11,1242–1244 (2014)*

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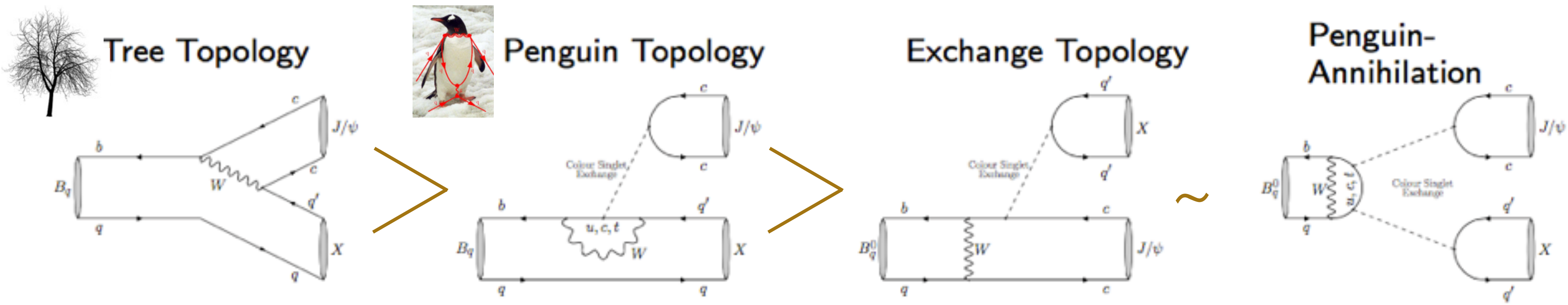
# Controlling penguin topologies

# General framework

- **Decay topologies**:




- **Decomposition**:
  - $B^0 \rightarrow J/\psi\, K_S^0$: **T + P**
  - $B_s^0 \rightarrow J/\psi\, \phi$: **T + P + E +PA**

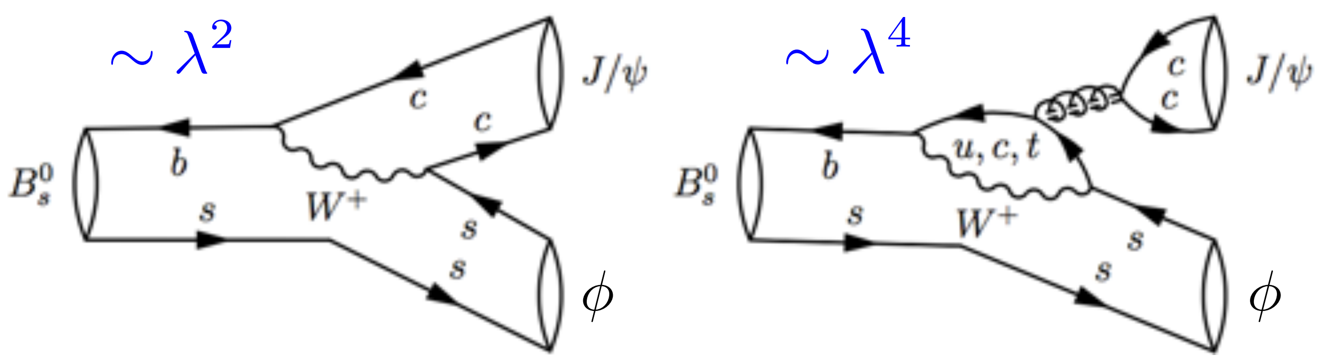
- **Assumptions**:
  - Given the current experimental sensitivities, exchange and annihilation topologies can be ignored (control channels to cross-check this assumption : $B_s^0 \rightarrow J/\psi\, \pi^0$, $B_s^0 \rightarrow J/\psi \rho^0$)
  - Up to now, only penguin contributions are being studied from analyses involving SU(3) counterparts where T ~ P: $B_s^0 \rightarrow J/\psi\, K_S^0$ , $B^0 \rightarrow J/\psi \rho^0$, $B_s^0 \rightarrow J/\psi\, \overline{K}^{*0}$
  - Ignore non-factorisable SU(3) breaking

# The penguin shift $\Delta\phi_s$

- $B_s^0 \to J/\psi\,\phi$:

$$A\left(B_s^0 \to (J/\psi\phi)_i\right) = \left(1 - \frac{\lambda^2}{2}\right)\mathcal{A}_i'\left[1 + \epsilon a_i' e^{i\theta_i'} e^{i\gamma}\right] \qquad \epsilon \equiv \lambda^2/(1-\lambda^2) = 0.0536$$

« tree » « penguin »




- $a_i'$ and $\theta_i'$: magnitude and phase of the penguin contributions
- Amplitudes are polarisation dependent: $i \in \{0, \parallel, \perp\}$
- Penguin contributions are doubly Cabbibo-suppressed
- Will ignore Exchange and Penguin-Annihilation contributions
- Differences in hadronisation dynamics: $\Delta\phi_s$ can be polarisation dependent (but so far no indication of that in the data)

# The penguin shift $\Delta\phi_s$

- **<u>Partner 1</u>: $B_s^0 \to J/\psi\, \overline{K}^{*0}$**

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

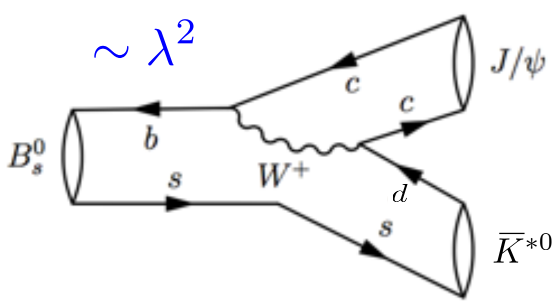
  - Reconstructed using flavor specific final state, only access to direct *CP* violation, $A_{CP}^{\mathrm{dir}}$
  - Need additional information from branching fractions

- **<u>Partner 2</u>: $B^0 \to J/\psi \rho^0$**

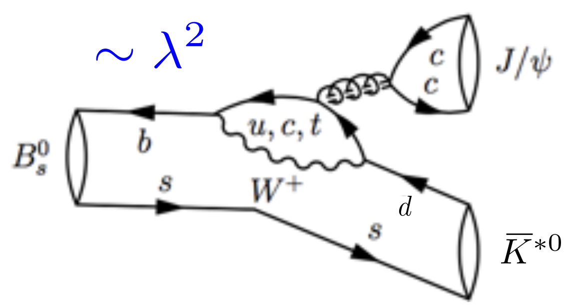
$$A\left(B_s^0 \to J/\psi \rho^0\right) = -\lambda \mathcal{A}_i \left[1 - \tilde{a}_i e^{i\tilde{\theta}_i} e^{i\gamma}\right]$$

  - Access to both $A_{CP}^{\mathrm{dir}}$ and mixing induced *CP* violation $A_{CP}^{\mathrm{mix}}$
  - Branching fraction information is optional

« tree »




« penguin »



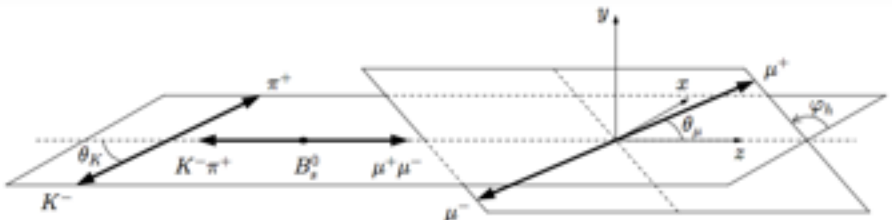

(similar picture for $B^0 \to J/\psi \rho^0$)

- **Ignoring non-factorisable SU(3) breaking:**
  - There is one universal set of $a$ and $\theta$: $a_i = \tilde{a}_i = a'_i$; $\theta_i = \tilde{\theta}_i = \theta'_i$
  - The penguin shift can be expressed in terms of the penguin parameters:

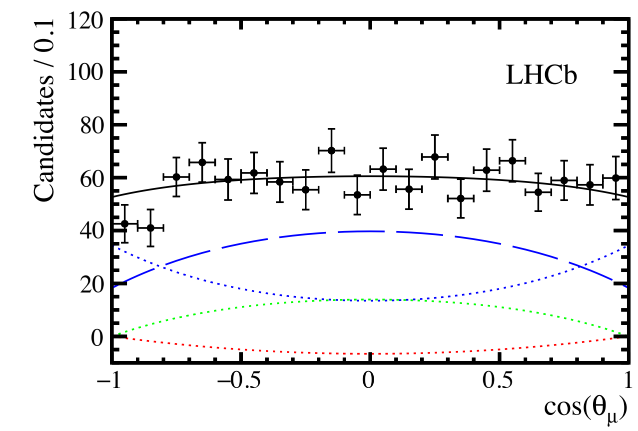
$$\tan(\Delta\phi_{s,i}) = \frac{2\epsilon a_i \cos\theta_i \sin\gamma + \epsilon^2 a_i^2 \sin(2\gamma)}{1 + 2\epsilon a_i \cos\theta_i \cos\gamma + \epsilon^2 a_i^2 \cos(2\gamma)}$$

# Analysis of $B_s^0 \to J/\psi\, \overline{K}^{*0}$ decays

[JHEP 11 (2015) 082]



- **Analysis overview:**
  - Perform an **angular analysis** using full Run-I data sample and measure the **polarisation dependent fractions $f_i$, the direct *CP* asymmetries, and the branching fraction**

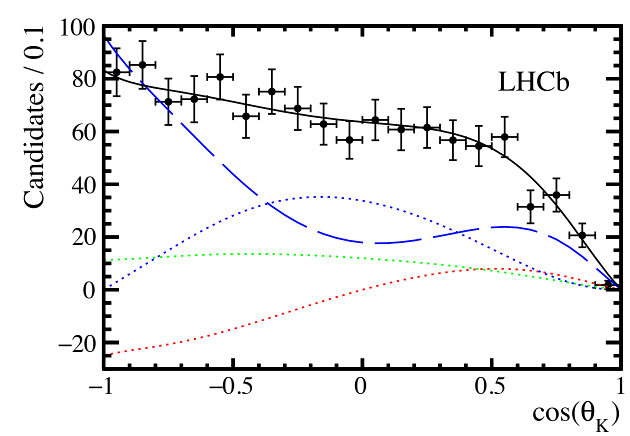


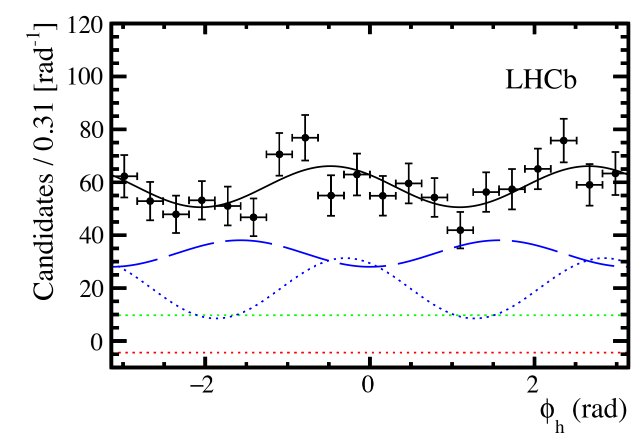

- **Results:**

$$\mathcal{B}(B_s^0 \to J/\psi \overline{K}^{*0}) = \left(4.13 \pm 0.16\,(\mathrm{stat}) \pm 0.25\,(\mathrm{syst}) \pm 0.24\,(\frac{f_d}{f_s})\right) \times 10^{-5}$$

$$\begin{aligned} f_0 &= 0.497 \pm 0.025\ (\mathrm{stat}) \pm 0.025\ (\mathrm{syst}) \\ f_\parallel &= 0.179 \pm 0.027\ (\mathrm{stat}) \pm 0.013\ (\mathrm{syst}) \end{aligned}$$

$$\begin{aligned} A_0^{CP}(B_s^0 \to J/\psi \overline{K}^{*0}) &= -0.048 \pm 0.057\ (\mathrm{stat}) \pm 0.020\ (\mathrm{syst}) \\ A_\parallel^{CP}(B_s^0 \to J/\psi \overline{K}^{*0}) &= 0.171 \pm 0.152\ (\mathrm{stat}) \pm 0.028\ (\mathrm{syst}) \\ A_\perp^{CP}(B_s^0 \to J/\psi \overline{K}^{*0}) &= -0.049 \pm 0.096\ (\mathrm{stat}) \pm 0.025\ (\mathrm{syst}) \end{aligned}$$



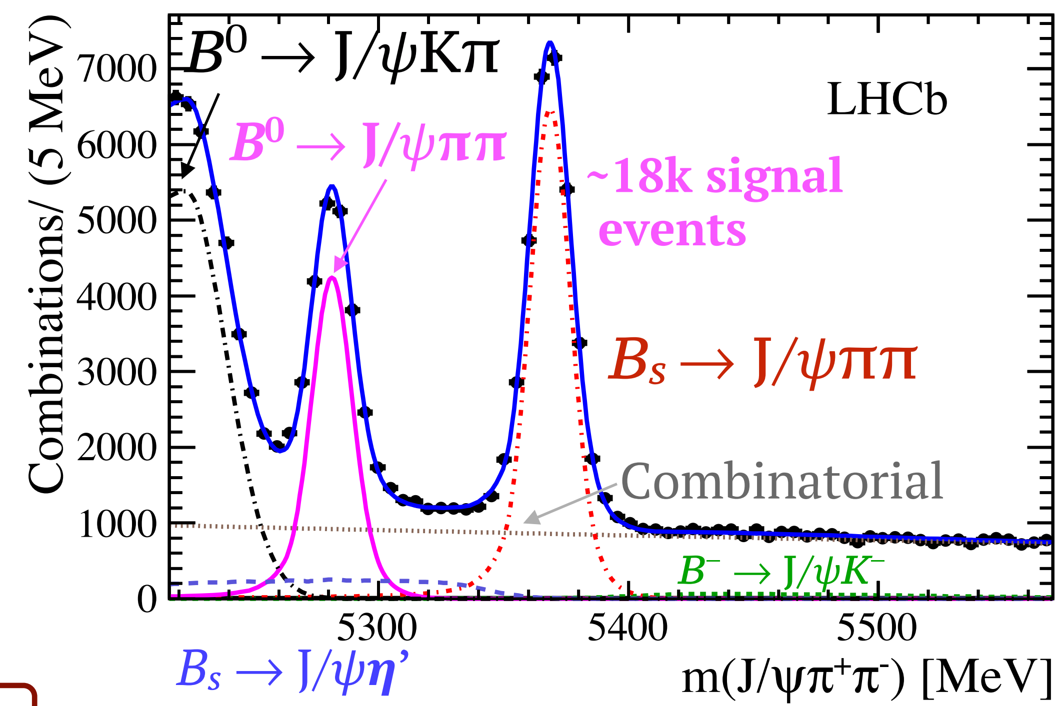

- **Accessing penguin parameters:**
  - $$A_i^{CP} = \frac{\Gamma\left(\overline{B}_s^0 \to J/\psi(K^+\pi^-)_i\right) - \Gamma\left(B_s^0 \to J/\psi(K^-\pi^+)_i\right)}{\Gamma\left(\overline{B}_s^0 \to J/\psi(K^+\pi^-)_i\right) + \Gamma\left(B_s^0 \to J/\psi(K^-\pi^+)_i\right)} = -\frac{2a_i \sin\theta_i \sin\gamma}{1 - 2a_i \cos\theta_i \cos\gamma + a_i{}^2}$$
  - $$H_i \propto \frac{1}{\epsilon}\boxed{\left|\frac{\mathcal{A}_i'}{\mathcal{A}_i}\right|^2} \frac{\mathcal{B}(B_s^0 \to J/\psi \overline{K}^{*0})}{\mathcal{B}(B_s^0 \to J/\psi \phi)} \frac{f_i}{f_i'} = \frac{1 - 2a_i \cos\theta_i \cos\gamma + a_i{}^2}{1 + 2\epsilon a_i' \cos\theta_i' \cos\gamma + \epsilon^2 a_i'^2}$$

Ratio of hadronic amplitudes calculated using latest results from QCD LCSR [arXiv:1503.05534]

# Analysis of $B^0 \rightarrow J/\psi\ \pi^+\pi^-$ decays

[Phys. Lett. B742 (2015) 38]

- **Analysis overview:**
  - Perform a **time-dependent flavor-tagged angular analysis** using full Run-I data sample and measure the **direct and mixing-induced *CP* violation parameters**
  - $\rho^0$ disentangled from the $\pi^+\pi^-$ spectrum using technique from [Phys. Lett. B719 (2013) 383]




- **Results:** (using $\rho^0$ events)

$$2\beta^{\text{eff}}(B^0 \to J/\psi\rho^0) = (41.7 \pm 9.6(\text{stat})^{+2.8}_{-6.3}(\text{syst}))^\circ$$

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

$$\alpha_{CP} = \frac{1-|\lambda_f|}{1+|\lambda_f|}$$

- **Accessing penguin parameters:**

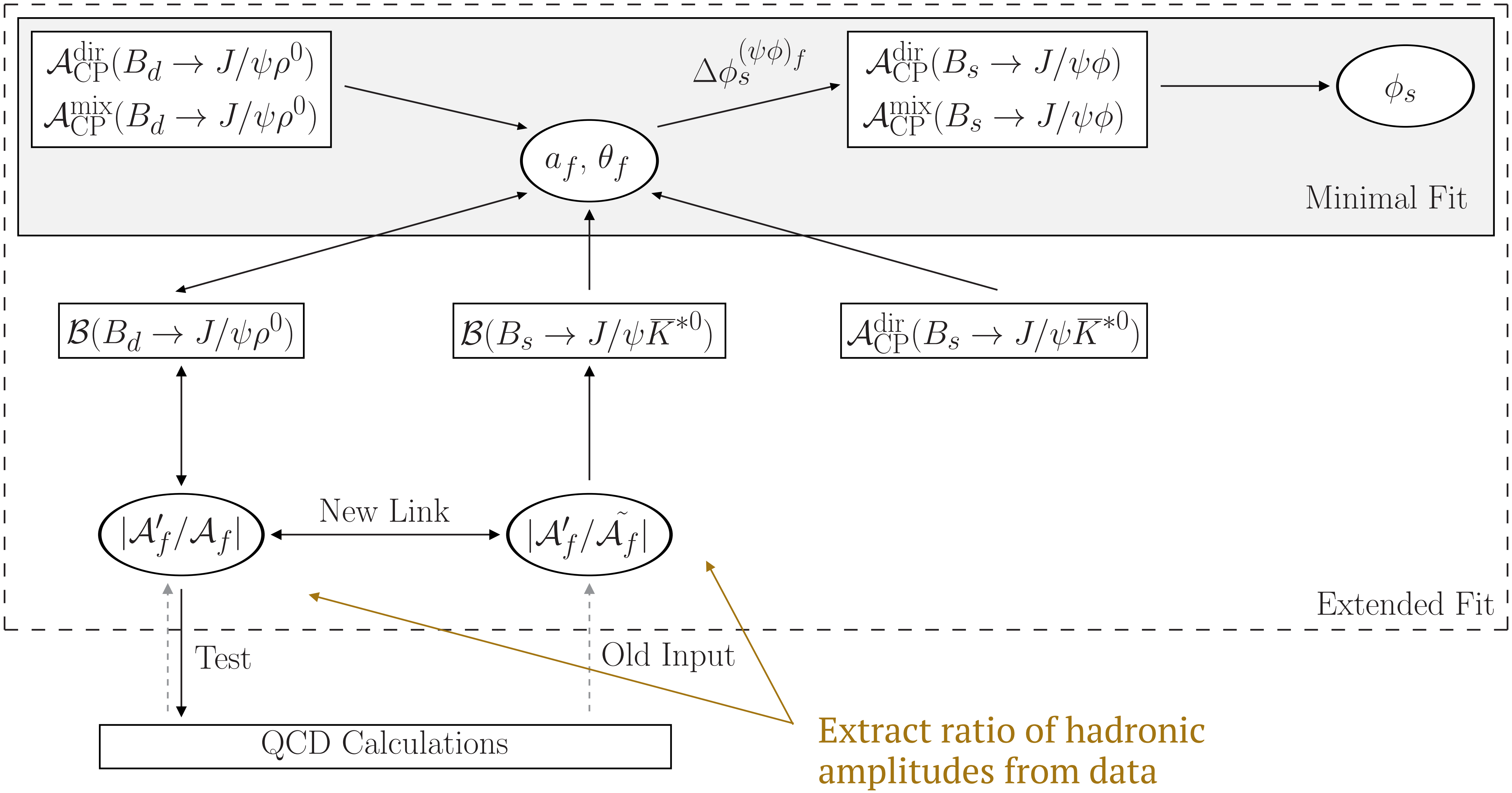
$$\Delta\phi_s = -\arg\left(\frac{(\lambda'_f e^{2i\gamma} - 1) + \epsilon(\lambda'_f - 1)}{(\lambda'_f e^{2i\gamma} - 1) + \epsilon(\lambda'_f - 1)e^{2i\gamma}}\right) \qquad \lambda'_f \equiv |\lambda_f| e^{-i\Delta 2\beta}$$

$$\Delta 2\beta = \left(2\beta^{J/\psi\rho} - 2\beta^{J/\psi K^0_S}\right) = (-0.9 \pm 9.7(\text{stat})^{+2.8}_{-6.3}(\text{syst}))^\circ$$

# Combining $B_s^0 \rightarrow J/\psi \overline{K}^{*0}$ & $B^0 \rightarrow J/\psi \rho^0$

[JHEP 11 (2015) 082]

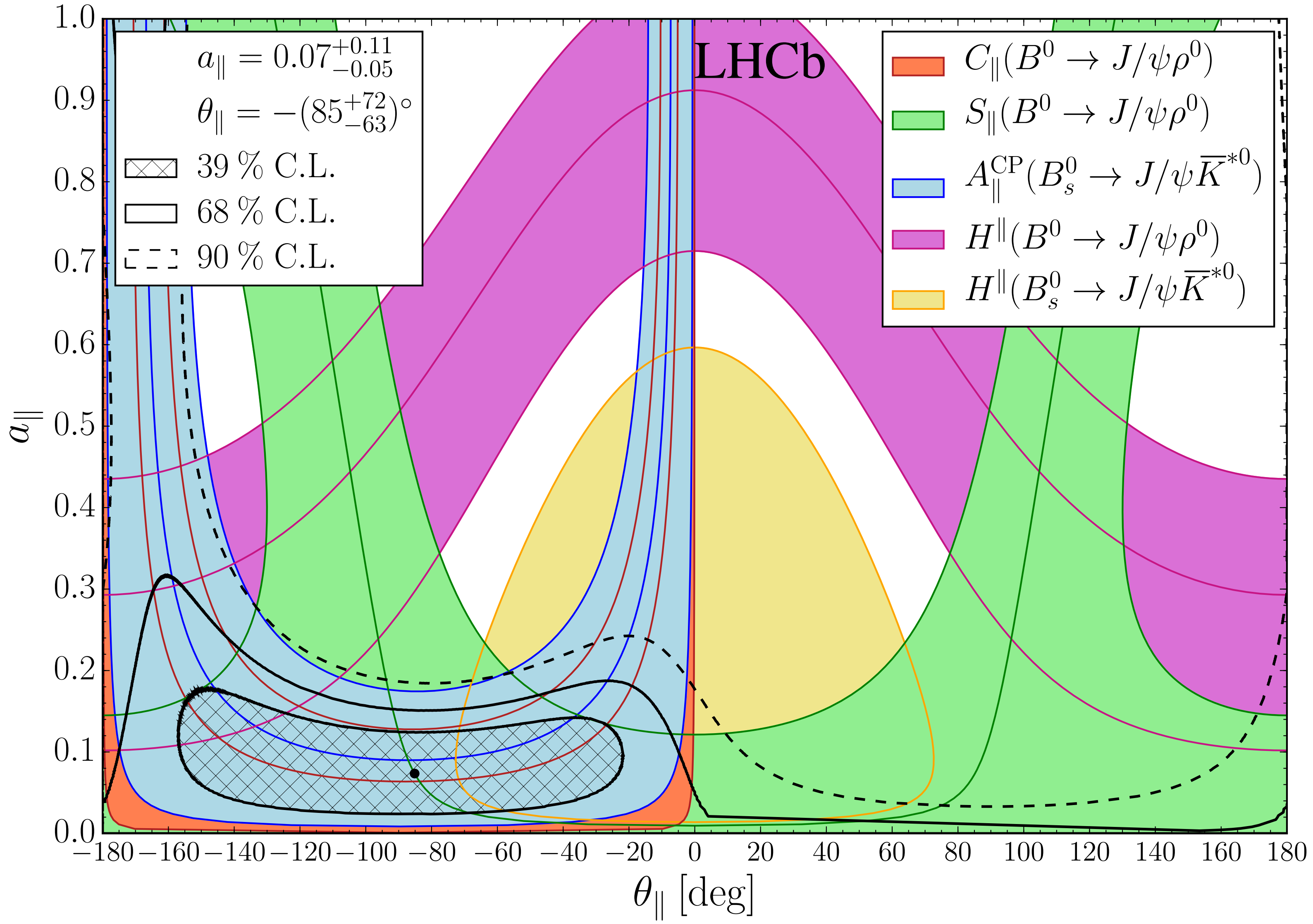
- **<u>Using the extended fit method proposed in</u>:** [JHEP 1503 (2015) 145]



# Combining $B_s^0 \to J/\psi\, \overline{K}^{*0}$ & $B^0 \to J/\psi \rho^0$

[JHEP 11 (2015) 082]

- **Using the extended fit method proposed in:** [JHEP 1503 (2015) 145]
  - Assuming: $\left|\frac{\mathcal{A}'_i(B_s^0 \to J/\psi\phi)}{\mathcal{A}_i(B_s^0 \to J/\psi \overline{K}^{*0})}\right| = \left|\frac{\mathcal{A}'_i(B_s^0 \to J/\psi\phi)}{\mathcal{A}_i(B^0 \to J/\psi \rho^0)}\right|$

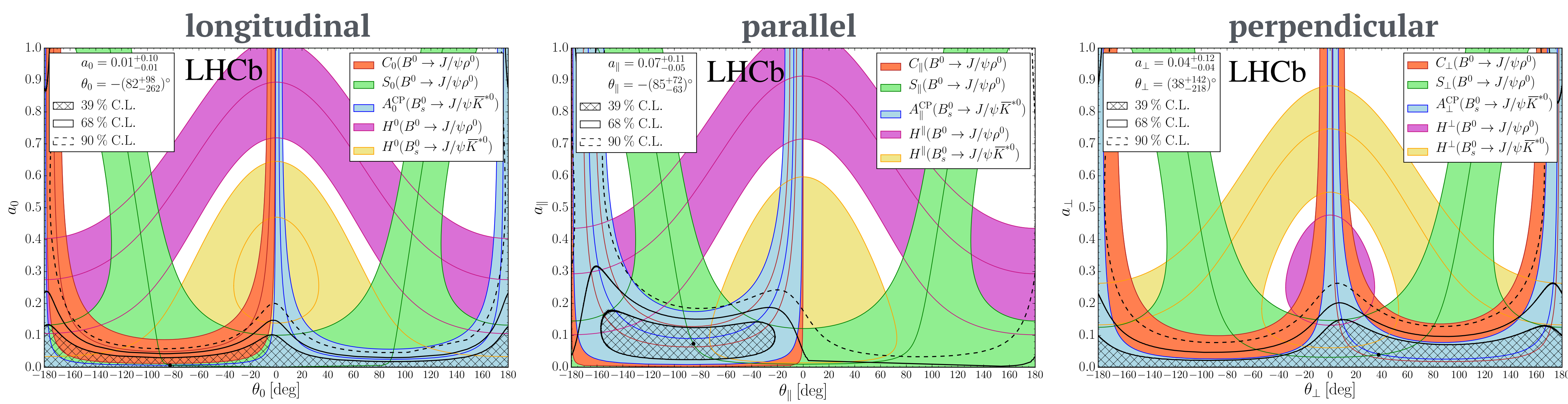



Complete set of results on following slide

# Combining $B_s^0 \to J/\psi \overline{K}^{*0}$ & $B^0 \to J/\psi \rho^0$

[JHEP 11 (2015) 082]

- **Using the extended fit method proposed in:** [JHEP 1503 (2015) 145]
  - Assuming: $\left|\frac{\mathcal{A}'_i(B_s^0 \to J/\psi\phi)}{\mathcal{A}_i(B_s^0 \to J/\psi \overline{K}^{*0})}\right| = \left|\frac{\mathcal{A}'_i(B_s^0 \to J/\psi\phi)}{\mathcal{A}_i(B^0 \to J/\psi \rho^0)}\right|$




$$a_0 = 0.01^{+0.10}_{-0.01} \qquad \theta_0 = -\left(82^{+98}_{-262}\right)^\circ$$
$$a_\parallel = 0.07^{+0.11}_{-0.05} \qquad \theta_\parallel = -\left(85^{+71}_{-63}\right)^\circ$$
$$a_\perp = 0.04^{+0.12}_{-0.04} \qquad \theta_\perp = \left(38^{+142}_{-218}\right)^\circ$$

$$\Delta\phi_{s,0}^{J/\psi\phi} = 0.000^{+0.009}_{-0.011}\,(\text{stat})^{+0.004}_{-0.009}\,(\text{syst})$$
$$\Delta\phi_{s,\parallel}^{J/\psi\phi} = 0.001^{+0.010}_{-0.014}\,(\text{stat})^{+0.007}_{-0.008}\,(\text{syst})$$
$$\Delta\phi_{s,\perp}^{J/\psi\phi} = 0.003^{+0.010}_{-0.014}\,(\text{stat})^{+0.007}_{-0.008}\,(\text{syst})$$

**Penguin effects in $B_s^0$ mixing are under control!**

# Combining $B_s^0 \to J/\psi\,\overline{K}^{*0}$ & $B^0 \to J/\psi\rho^0$

[JHEP 11 (2015) 082]

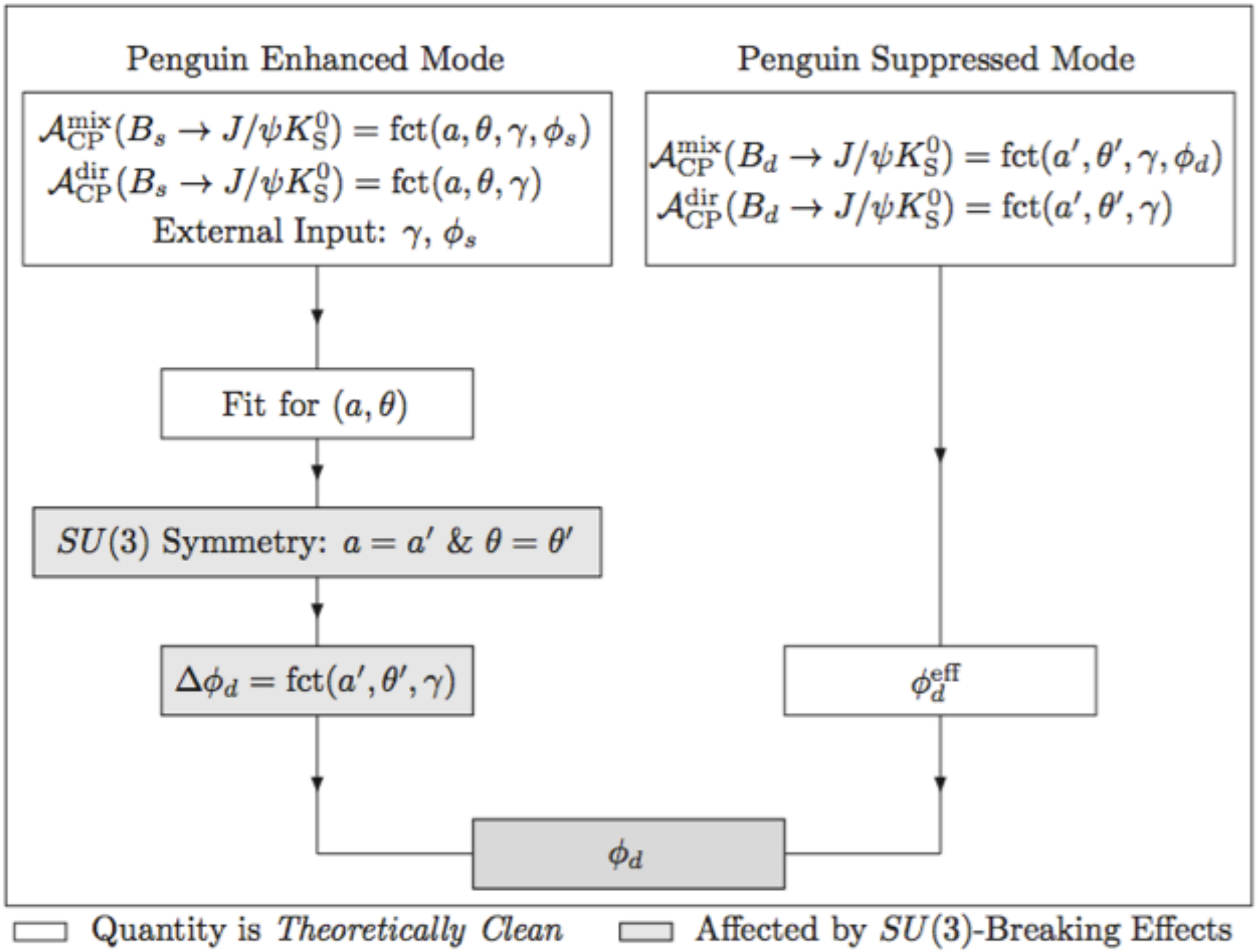
- **Accessing Hadronic Parameters :**
  - Using the branching ratio information and solutions for $(a_i\,,\theta_i)$ as inputs
  - Get information on hadronic amplitudes as a nice byproduct of the fit:

| | Fact./LCSR | LHCb Fit |
|---|---|---|
| $\left\lvert\frac{\mathcal{A}'_0(B_s \to J/\psi\,\phi)}{\mathcal{A}_0(B_d \to J/\psi\,\rho^0)}\right\rvert$ | $1.15 \pm 0.15$ | $1.195^{+0.074}_{-0.056}$ |
| $\left\lvert\frac{\mathcal{A}'_\parallel(B_s \to J/\psi\,\phi)}{\mathcal{A}_\parallel(B_d \to J/\psi\,\rho^0)}\right\rvert$ | $1.25 \pm 0.15$ | $1.238^{+0.104}_{-0.080}$ |
| $\left\lvert\frac{\mathcal{A}'_\perp(B_s \to J/\psi\,\phi)}{\mathcal{A}_\perp(B_d \to J/\psi\,\rho^0)}\right\rvert$ | $1.13 \pm 0.10$ | $1.042^{+0.081}_{-0.063}$ |

[JHEP 08 (2016) 098] [JHEP 11 (2015) 082]

# The penguin shift $\Delta\phi_d$

- **Strategy:**
  - Similarly as for $\Delta\phi_s$, the decay mode $B_s^0 \to J/\psi\, K_S^0$ can be used to control $\Delta\phi_d$



# Analysis of $B_s^0 \rightarrow J/\psi\, K_S^0$ decays

[JHEP 06 (2015) 131]

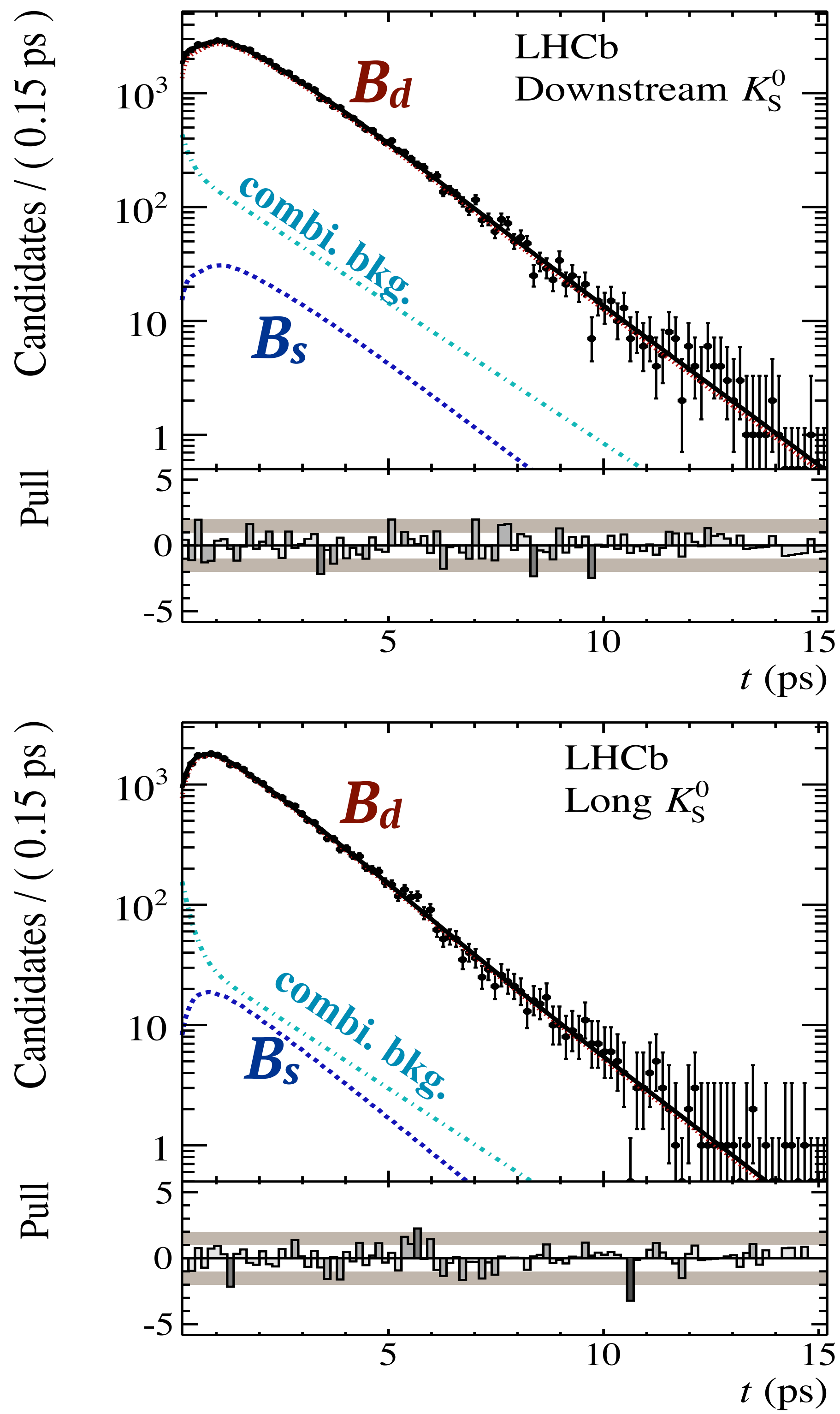
- **Analysis overview:**
  - First **flavor-tagged time-dependent** analysis of $B_s^0 \rightarrow J/\psi\, K_S^0$ decays

| Yield | Long $K_S^0$ | Downstream $K_S^0$ |
|---|---|---|
| $B^0 \rightarrow J/\psi K_S^0$ | $27\,801 \pm 168$ | $51\,351 \pm 231$ |
| $B_s^0 \rightarrow J/\psi K_S^0$ | $307 \pm 20$ | $601 \pm 30$ |
| Combinatorial background | $658 \pm 37$ | $2\,852 \pm 74$ |

- **Results:**

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

- **Successful proof of concept waiting for more statistics**
- **Can be used to estimate the penguin shift $\Delta\phi_d$**



*Nature Methods 11,1242–1244 (2014)*

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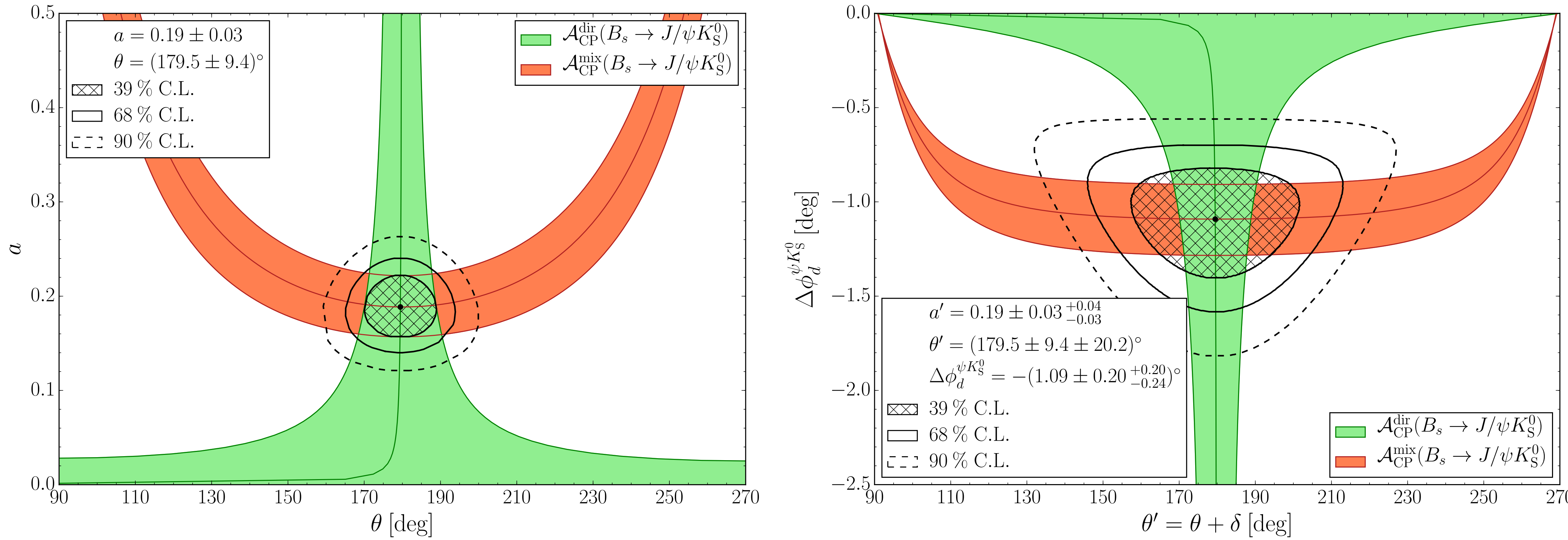
# Prospects and summary

# Prospects on penguin shift $\Delta\phi_d$

- **Illustration the era of the LHCb Upgrade:**
  - Results from [JHEP 1503 (2015) 145] using the following extrapolated inputs:

$$\mathcal{A}_{CP}^{\mathrm{dir}}(B_s \to J/\psi\, K_S^0) = 0.004 \pm 0.065\,, \qquad \gamma = (73.2 \pm 1.0)^\circ$$

$$\mathcal{A}_{CP}^{\mathrm{mix}}(B_s \to J/\psi\, K_S^0) = -0.274 \pm 0.065\,, \qquad \phi_s = -(2.1 \pm 0.5|_{\mathrm{exp}} \pm 0.3|_{\mathrm{theo}})^\circ$$

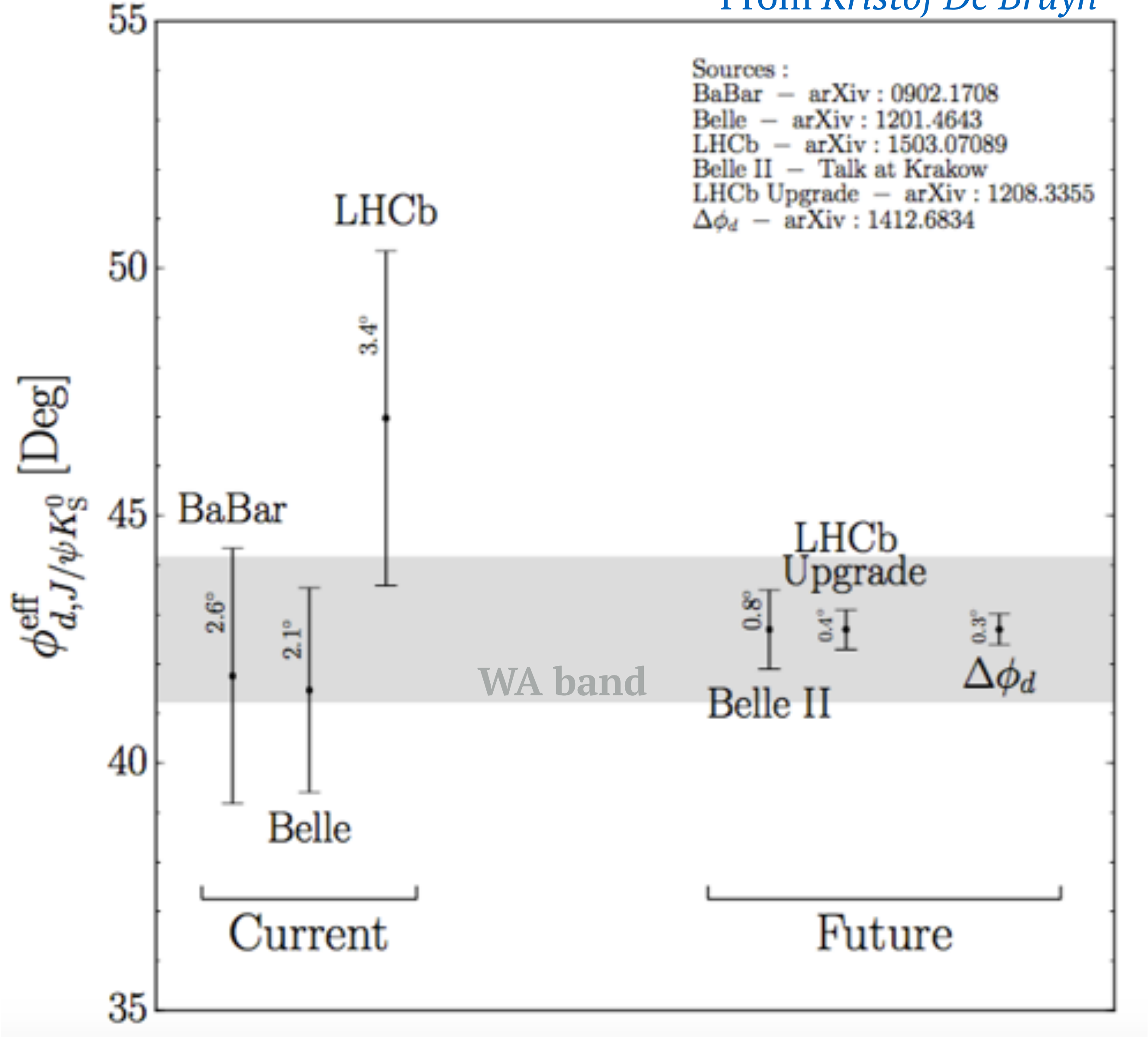



$$\Delta\phi_d = -(1.02 \pm 0.24(\mathrm{stat})^{+0.17}_{-0.24}(\mathrm{SU}(3)))^\circ$$

# Prospects on penguin shift $\Delta\phi_d$

- **Illustration the era of the LHCb Upgrade:**

From *Kristof De Bruyn*




**We will be able to control the penguin effects in $B^0$ mixing!**

# Prospects on penguin pollution measurements

- **<u>Modes to be investigated in the future</u>:**

  – 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) **Search for** $B_s^0 \to J/\psi \rho^0$ **and/or** $B^0 \to J/\psi \phi$: Control contribution from E + PA

  (3) **High precision CP analysis of** $B_s^0 \to J/\psi \overline{K}^{*0}$: Cross-check

  – 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

  (3) **Search for** $B_s^0 \to J/\psi \pi^0$: Control contributions from E + PA in $B^0 \to J/\psi \pi^0$

# Summary

- **We entered in the era of high-precision for the measurement of the $B^0$—$\overline{B}^0$ and $B_s^0$—$\overline{B}_s^0$ mixing phases**

| Observable | Mode | Run 1 (2010-12) $3\,\mathrm{fb}^{-1}$ | Run 2 (2015-18) $8\,\mathrm{fb}^{-1}$ | Upgrade 1 (2020-30) $50\,\mathrm{fb}^{-1}$ | Upgrade 2 (2031-34) $300\,\mathrm{fb}^{-1}$ | CKMFitter (2015) |
|---|---|---|---|---|---|---|
| $\phi_d$ [°] | $B^0 \to J/\psi K_S^0$ | 2.2 | 1.2 | 0.4 | $\sim 0.2$ | $\sim 2.6$ |
| $\phi_s$ [rad] | $B_s^0 \to J/\psi K^+K^-$ | 0.049 | 0.025 | 0.008 | $\sim 0.004$ | $\sim 0.001$ |
| | $B_s^0 \to J/\psi \pi^+\pi^-$ | 0.068 | 0.035 | 0.012 | $\sim 0.005$ | |
| | Combination | 0.039 | 0.020 | 0.007 | $\sim 0.003$ | |

- **Controlling higher order corrections to $\phi_d$ and $\phi_s$ becomes mandatory**
- **Demonstrated that we can control the penguin effects sufficiently well for the Upgrade Era:**

$$\boxed{\Delta\phi_s \sim 0.001 \pm 0.020\ \mathrm{rad} \qquad \phi_{s,c\bar{c}s}^{\mathrm{eff}} = -0.030 \pm 0.033\,\mathrm{rad}}$$

- **…but more work might still be needed for a 300 fb$^{-1}$ Upgrade**

# Additional material

# SU(3) assumption

- **$\omega$-$\phi$ mixing:**
  - **Octet and Singlet Contributions:**
    - $\phi$ being a pure $s\bar{s}$ state, hence an admixture of octet and singlet state
    - In the current framework, only the octet contribution is considered:
      - Only needed for the H observable to relate the form factors of $B_s^0 \to \phi$ and $B_s^0 \to \bar{K}^{*0}$ or $B^0 \to \rho^0$ (+ E & PA contributions are ignored)
  - **Mixing:**
    - Can mix with the orthogonal $\omega$ state: parametrised by mixing angle $\delta$
    - Relation between branching ratios: [*Phys. Lett. B666 (2008) 185*]

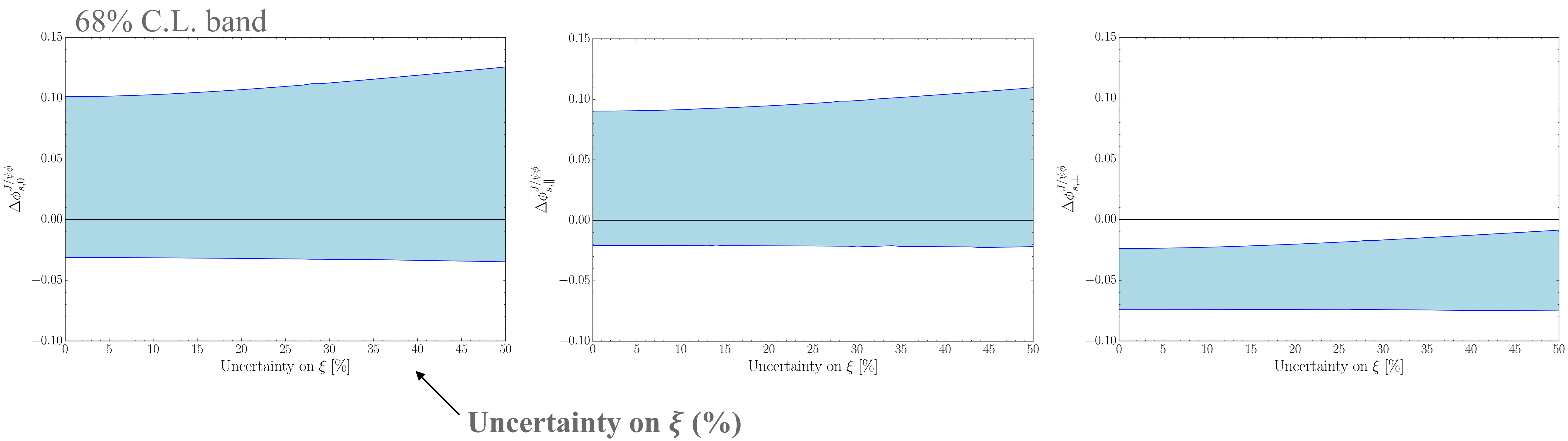
$$\mathcal{B}(B_s^0 \to J/\psi\,\omega) = \tan^2\delta \times \mathcal{B}(B_s^0 \to J/\psi\,\phi)$$

    - **Challenging**, but LHCb should be able to perform a measurement of this branching fraction allowing to get insight on the mixing angle $\delta$

# SU(3) assumption

- **Penguin pollution in $\phi_s$ with $B_s^0 \to J/\psi \overline{K}^{*0}$**

  Allowing for SU(3) flavor symmetry breaking: $a_i' = \xi \times a_i$ , $\theta_i' = \theta_i + \delta$

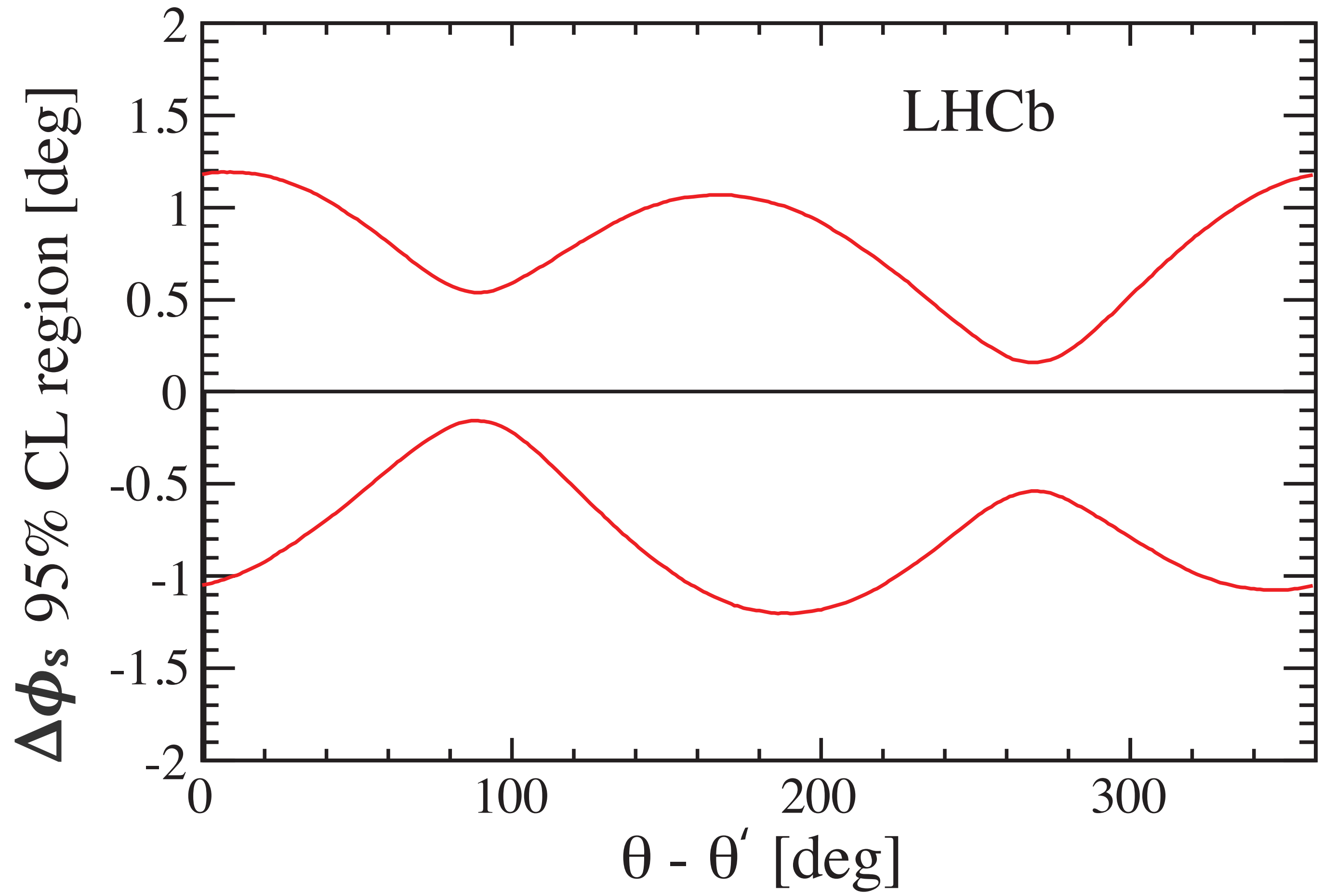


# SU(3) assumption

[Phys. Lett. B742 (2015) 38]

- **Penguin pollution in $\phi_s$ with $B^0 \to J/\psi\rho^0$**

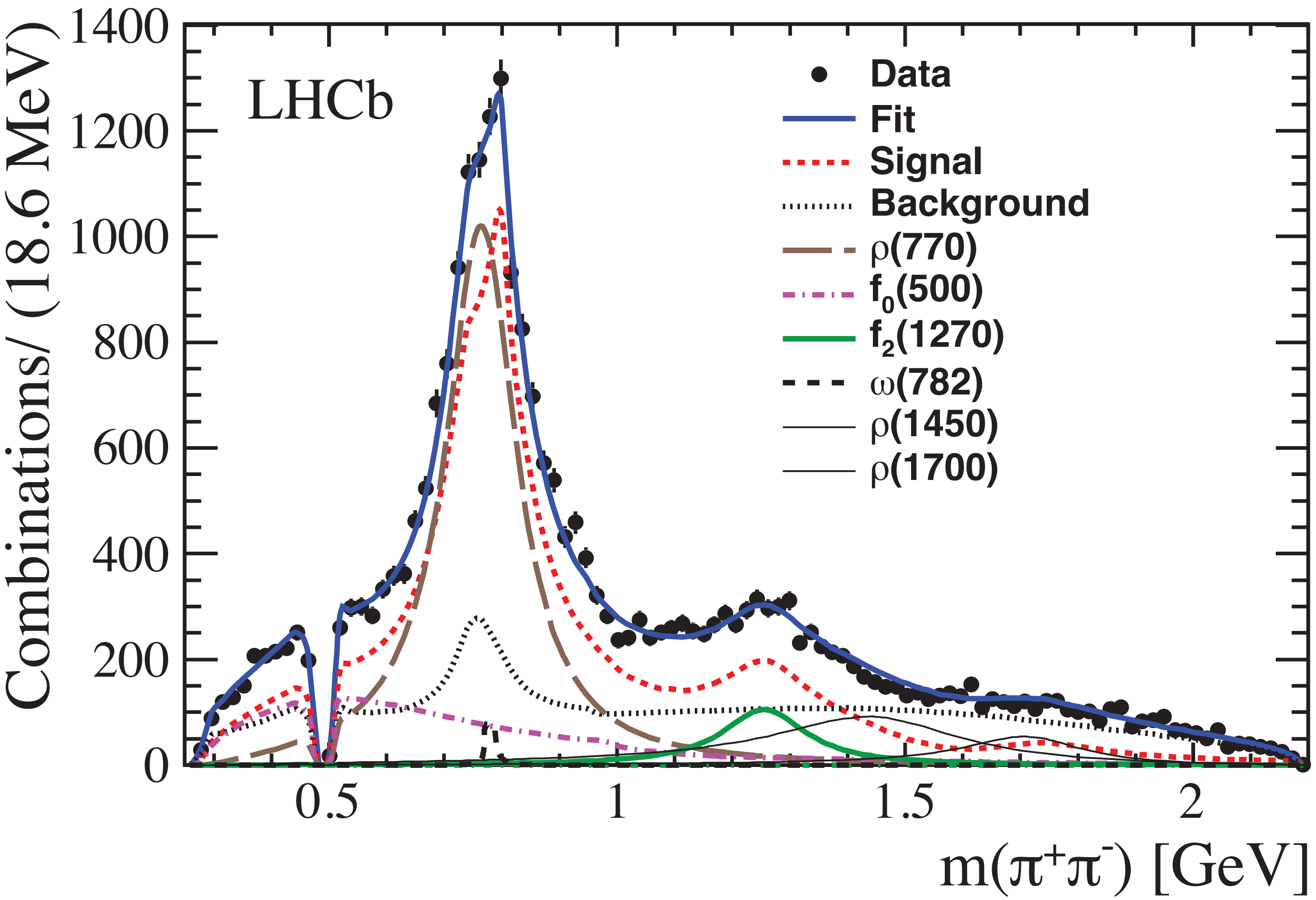
  Allowing for SU(3) flavor symmetry breaking:



# $B^0 \to J/\psi\pi^+\pi^-$: Resonance contant

[Phys. Lett. B742 (2015) 38]

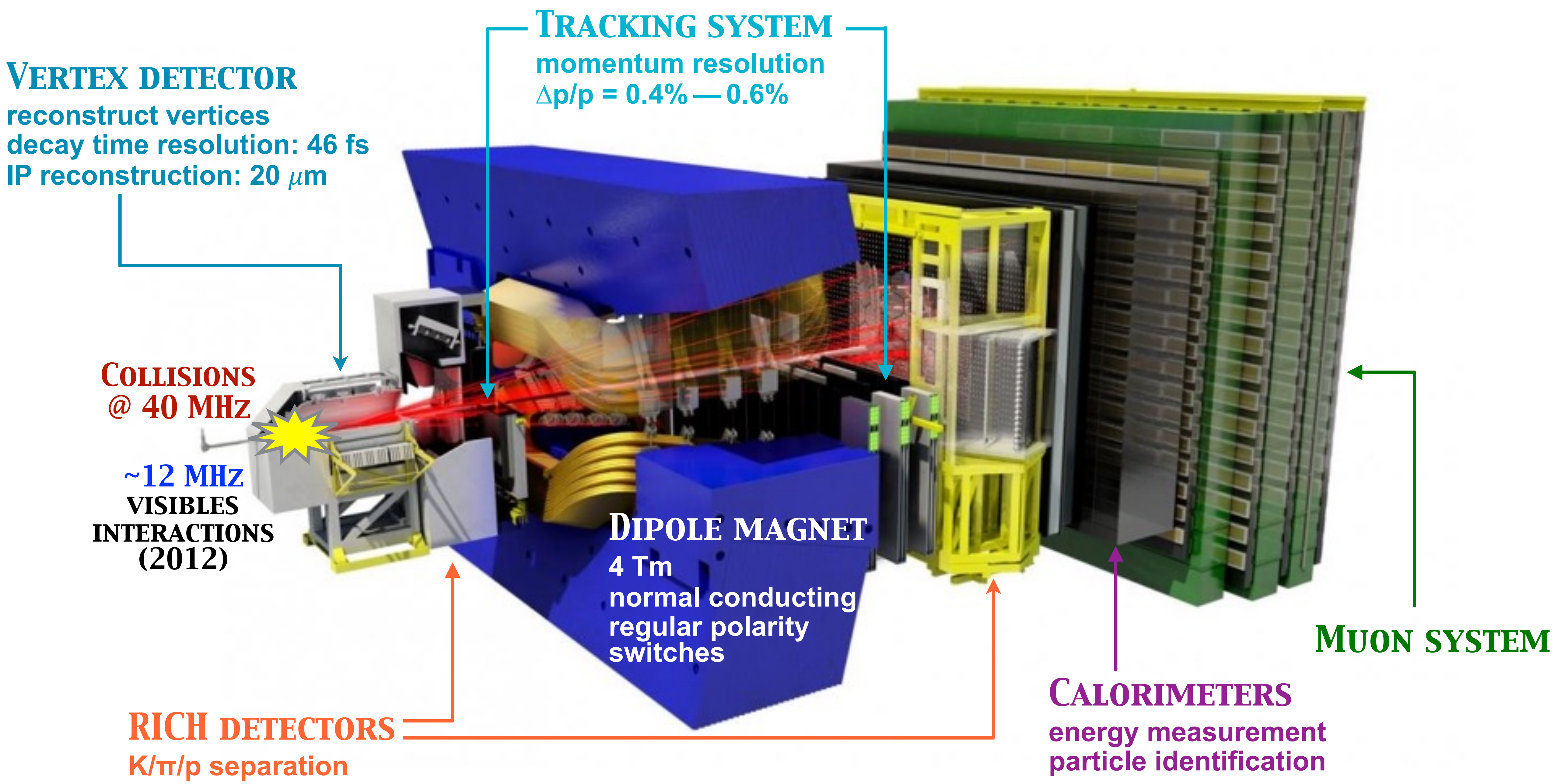
- **$\pi^+\pi^-$ invariant-mass spectrum:**




| Component | Fit fraction (%) |
|---|---|
| $\rho(770)$ | $65.6 \pm 1.9$ |
| $f_0(500)$ | $20.1 \pm 0.7$ |
| $f_2(1270)$ | $7.8 \pm 0.6$ |
| $\omega(782)$ | $0.64^{+0.19}_{-0.13}$ |
| $\rho(1450)$ | $9.0 \pm 1.8$ |
| $\rho(1700)$ | $3.1 \pm 0.7$ |

# The LHCb experiment

- Forward General-Purpose Detector at the LHC
- ~30 % of heavy quark production cross-section with just 4% of solid angle



# Measurement ingredients

- **Time-dependent *CP* asymmetry:**

$$\mathcal{A}_{CP}(t) = \frac{\Gamma\left(\overline{B}^0_q(t)\to f\right) - \Gamma\left(B^0_q(t)\to f\right)}{\Gamma\left(\overline{B}^0_q(t)\to f\right) + \Gamma\left(B^0_q(t)\to f\right)} = \frac{\mathcal{S}_f \sin\left(\Delta m t\right) - \mathcal{C}_f \cos\left(\Delta m t\right)}{\cosh\left(\frac{\Delta\Gamma t}{2}\right) + \mathcal{A}_{\Delta\Gamma}\sinh\left(\frac{\Delta\Gamma t}{2}\right)}$$

- Mixing parameters:

$$\Delta m = m_{\mathrm{H}} - m_{\mathrm{L}} \qquad \Delta\Gamma = \Gamma_{\mathrm{L}} - \Gamma_{\mathrm{H}}$$

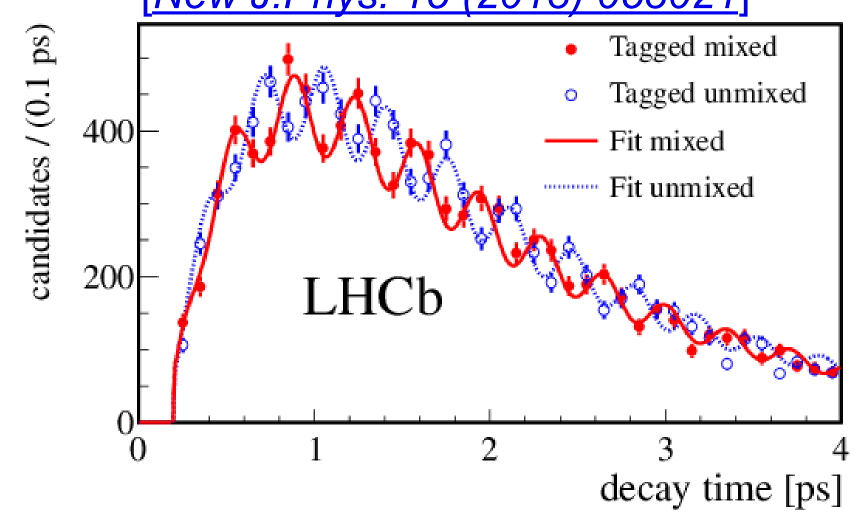
- CP observables:

$$\mathcal{S}_f = \frac{2\Im(\lambda_f)}{1+|\lambda_f|^2}\,, \quad \mathcal{C}_f = \frac{1-|\lambda_f|^2}{1+|\lambda_f|^2}\,, \quad \mathcal{A}_{\Delta\Gamma} = -\frac{2\Re(\lambda_f)}{1+|\lambda_f|^2}$$

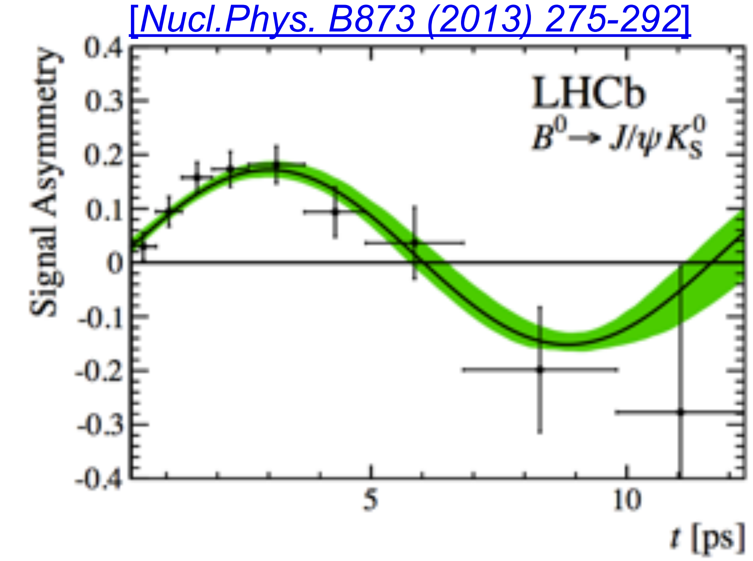
$$\lambda_f = \eta_f \frac{q}{p}\frac{A(\overline{B}^0_q(t)\to f)}{A(B^0_q(t)\to f)} = \eta_f|\lambda_f|e^{i\phi_q}$$

$$\boxed{\mathcal{S}_f = -\eta_f\frac{2|\lambda_f|\sin(\phi_s)}{1+|\lambda_f|^2}\,, \quad \mathcal{A}_{\Delta\Gamma} = \eta_f\frac{2|\lambda_f|\cos(\phi_s)}{1+|\lambda_f|^2}}$$

[New J.Phys. 15 (2013) 053021]




[Nucl.Phys. B873 (2013) 275-292]



# Measurement ingredients

- **Tagging, resolution and other nuisance effects:**

$$\mathcal{A}_{\text{meas}}(t) = \mathcal{A}_{CP}(t) \times D_{\text{res}} \times D_{\text{tag}} \pm \mathcal{A}_{\text{det/prod}}$$

- **Decay time resolution (~45 fs):**

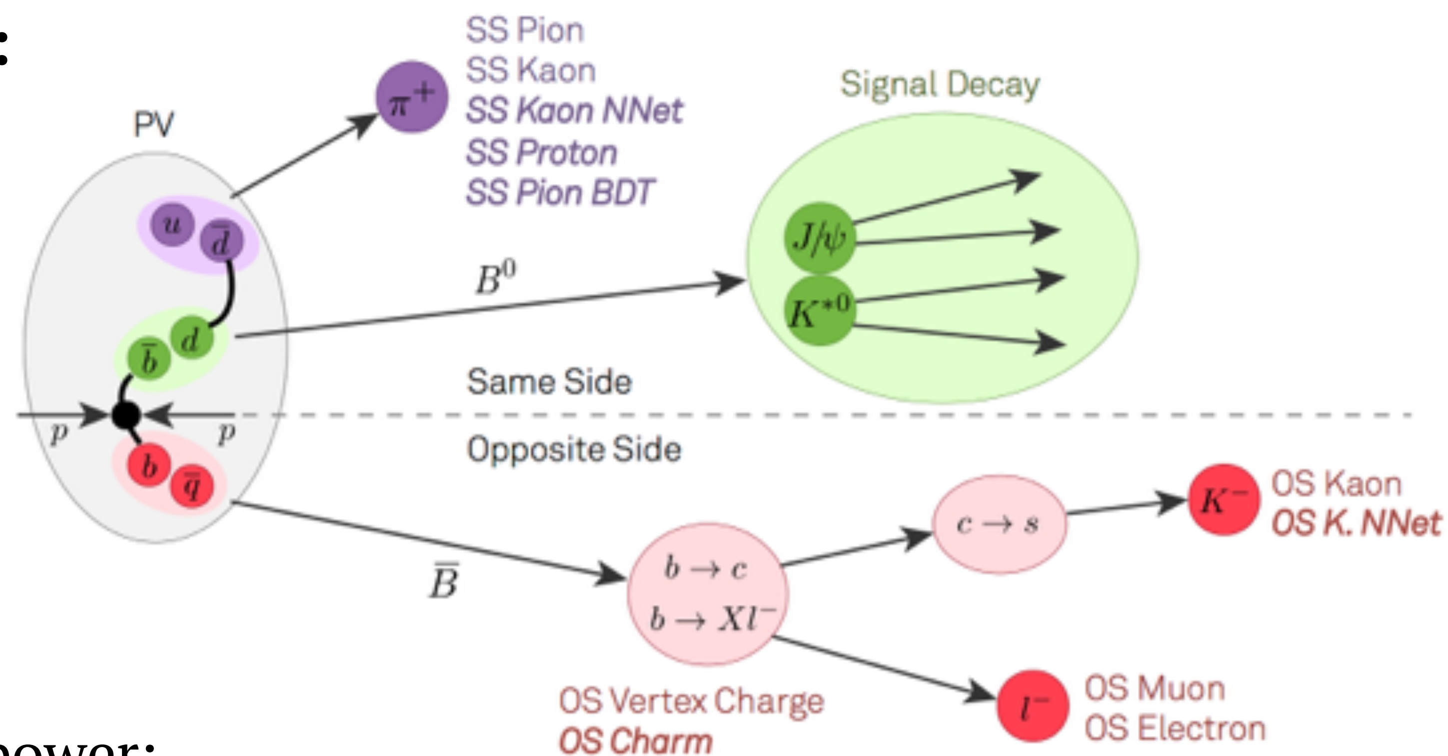
$$D_{\text{res}} = e^{-\frac{\Delta m^2 \sigma_t^2}{2}}$$

- **Tagging dilution:**

$$D_{\text{tag}} = (1 - 2\omega)$$

  - Initial B flavor efficiency: $\epsilon_{\text{tag}}$
  - Wrong tag rate: $\omega$
  - Effective reduction in statistical power:

$$\epsilon_{\text{eff}} = \epsilon_{\text{tag}}(1 - 2\omega)^2 \sim \mathcal{O}(\%) \qquad \sigma^{\text{stat}}(\phi_s) \propto \frac{1}{\sqrt{\epsilon_{\text{eff}} \text{N}}}$$




- Also need to account for detection/production asymmetries, acceptance effects on time and angular variables (P → VV), …