Measurement of sin2β at LHCb

10th International Workshop on the CKM Unitarity Triangle

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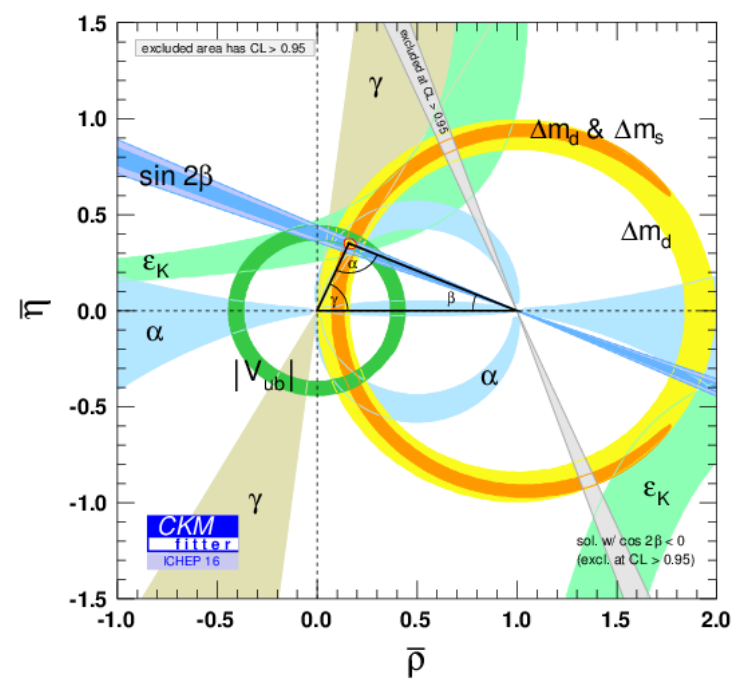
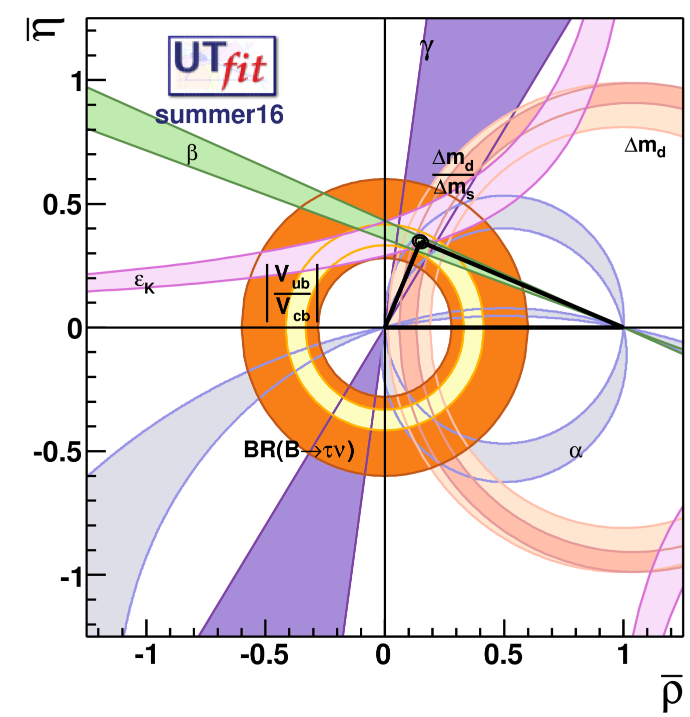
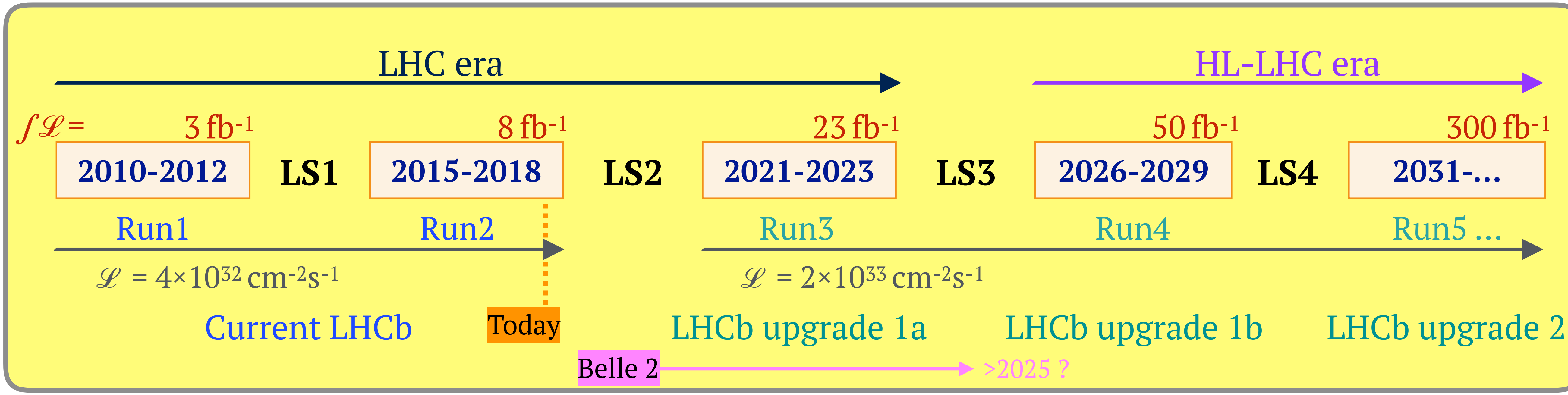
Time-dependent *CP* violation

- **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





Experimental context

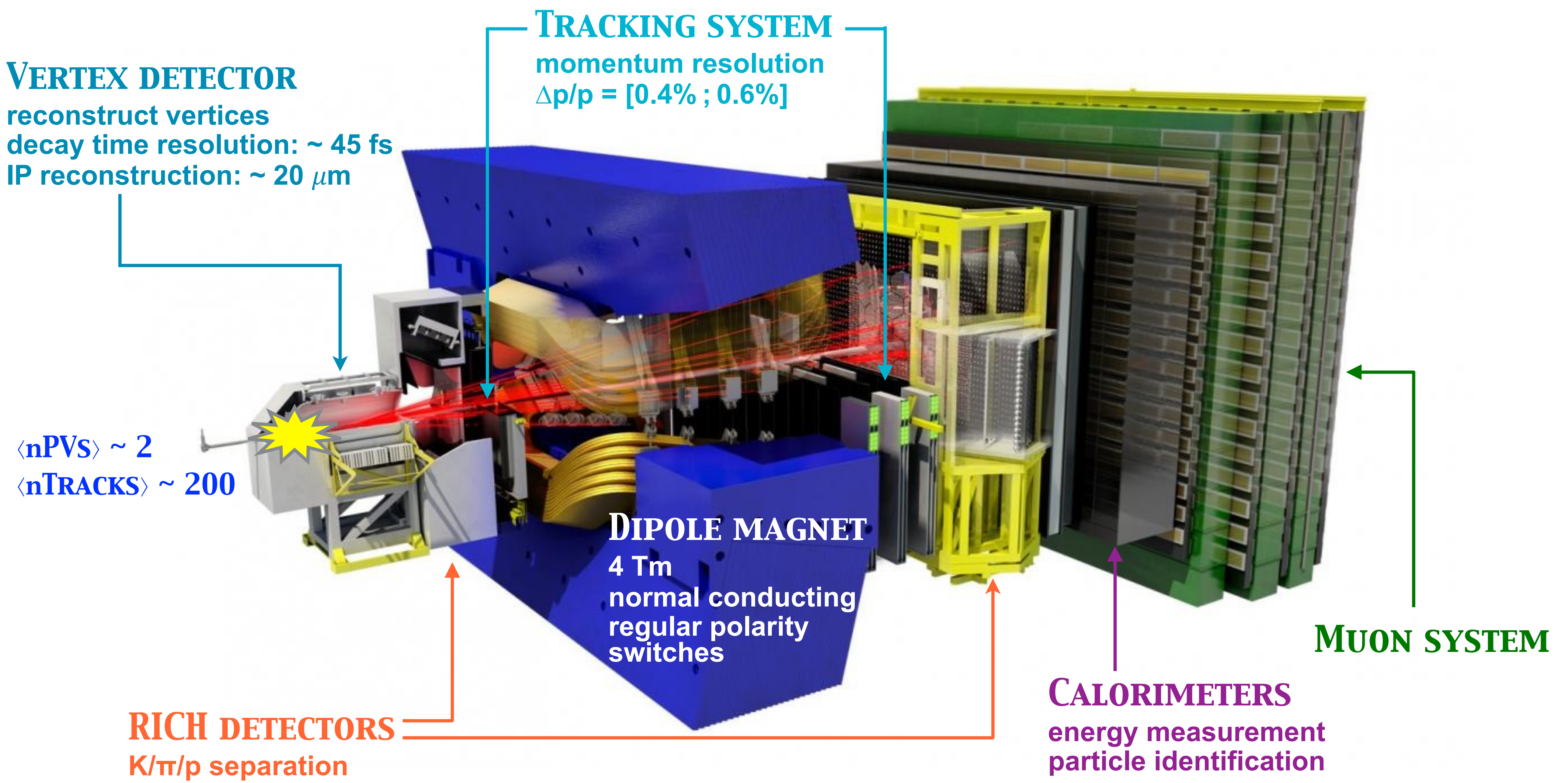


- **LHCb is currently the main actor in flavour physics**
- **Belle 2 is entering the game**
- **LHCb may be the only large-scale flavour physics experiment operating in the HL-LHC era**

LHCb apparatus

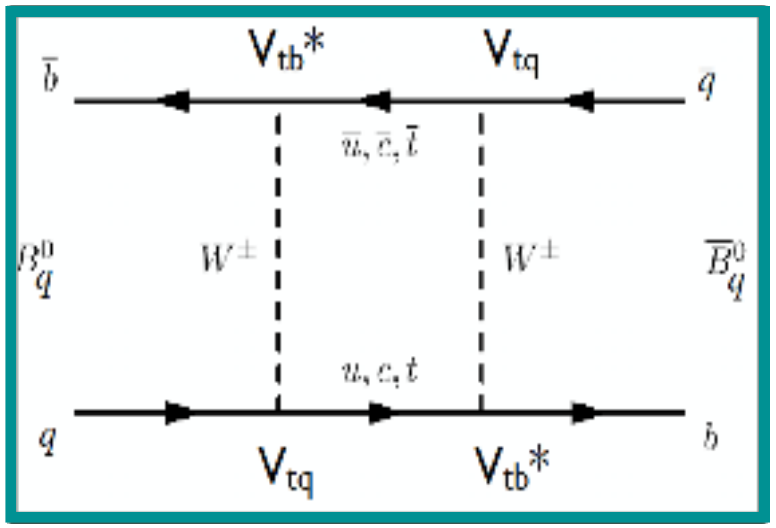
[JINST 3 (2008) S08005]

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



Time-dependent *CP* violation

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



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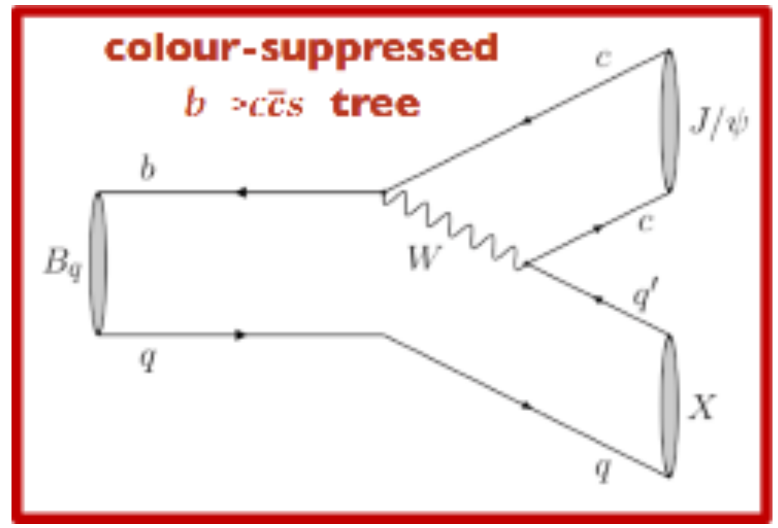

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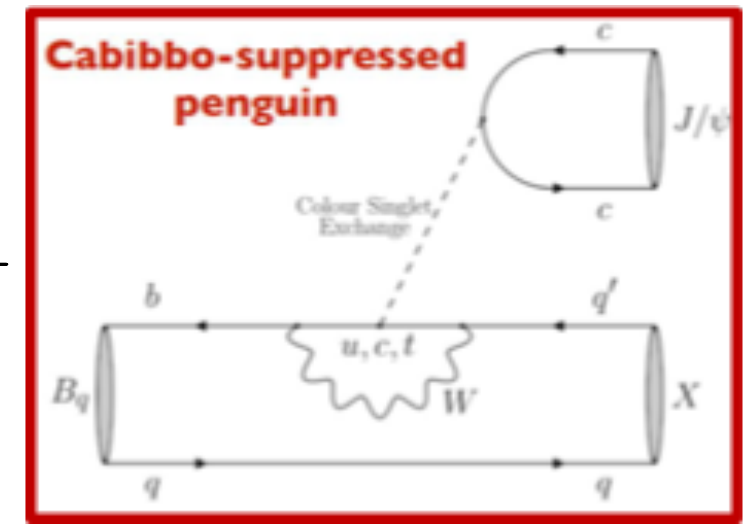
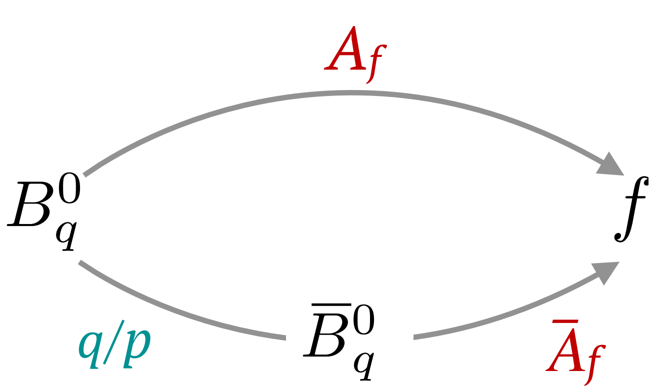


$B_{H,L} = pB_{(s)} \pm q\bar{B}_{(s)}$

+ smaller weak exchange (E) and penguin annihilation (PA) diagrams

Measurable CPV if



$$\arg(\lambda_f) = \arg\left(\frac{q}{p}\frac{\bar{A}_f}{A_f}\right) \neq 0$$

$$\arg(\lambda_{J/\psi K_S^0}) = 2\beta + \Delta\beta^{\text{peng}} + \Delta\beta^{\text{NP}}$$

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

$$2\beta^{\text{eff}} = \left(47.48^{+2.26}_{-1.96}\right)^\circ$$

SM prediction from global fit

[CKMFitter]

Time-dependent *CP* violation

- **Measurement ingredients:**

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

- **Mixing parameters:**

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

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

- **CP observables:**

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

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

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

Time-dependent *CP* violation

- **Measurement ingredients:**

For $B^0 \to J/\psi K^0_S$

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

($\cosh \to 1$, $\sinh \to 0$)

- **Mixing parameters:**

$$\Delta m = m_\mathrm{H} - m_\mathrm{L} = 0.5065 \pm 0.0019\,\mathrm{ps}^{-1}$$

$$\Delta\Gamma = \Gamma_\mathrm{L} - \Gamma_\mathrm{H} \propto (-0.002 \pm 0.010) \times \Gamma_d$$

[HFLAV]

- **CP observables:**

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

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

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

Time-dependent CP violation

- **Measurement ingredients**:

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

Time-dependent *CP* violation

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

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

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

Time-dependent *CP* violation

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

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

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

- **Tagging dilution:**

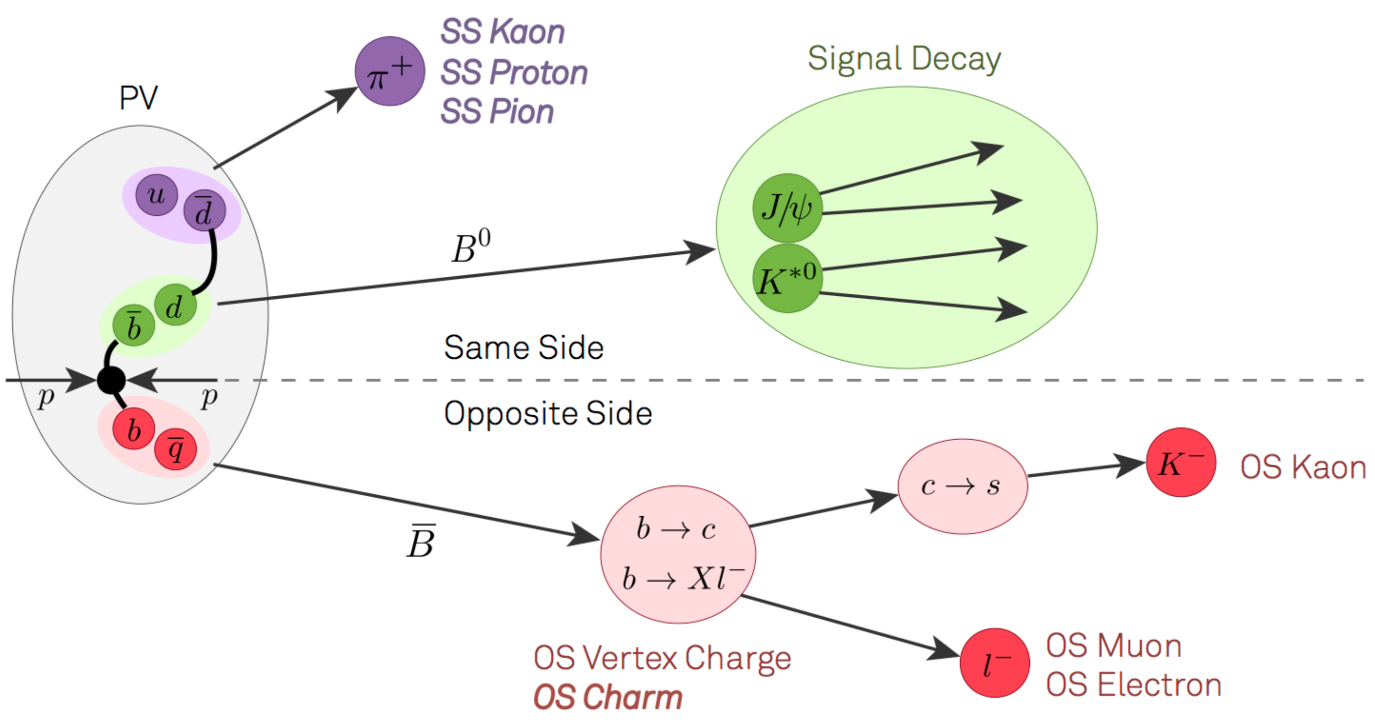
$$D_{\rm tag} = (1 - 2\omega)$$

  - Initial B flavor efficiency: $\epsilon_{\rm tag}$
  - Wrong tag rate: ω
  - Effective tagging power:

$$\epsilon_{\rm eff} = \epsilon_{\rm tag}(1 - 2\omega)^2$$

$$\sigma^{\rm stat}(CPV) \propto \frac{1}{\sqrt{\varepsilon_{\rm eff} N}}$$

Same side (SS): exploit the charge of the **fragmentation particles**



Opposite side (OS): exploit the charge of the particles produced from the **other *b*-hadron**

Time-dependent *CP* violation

- **Measurement ingredients:**

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

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

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

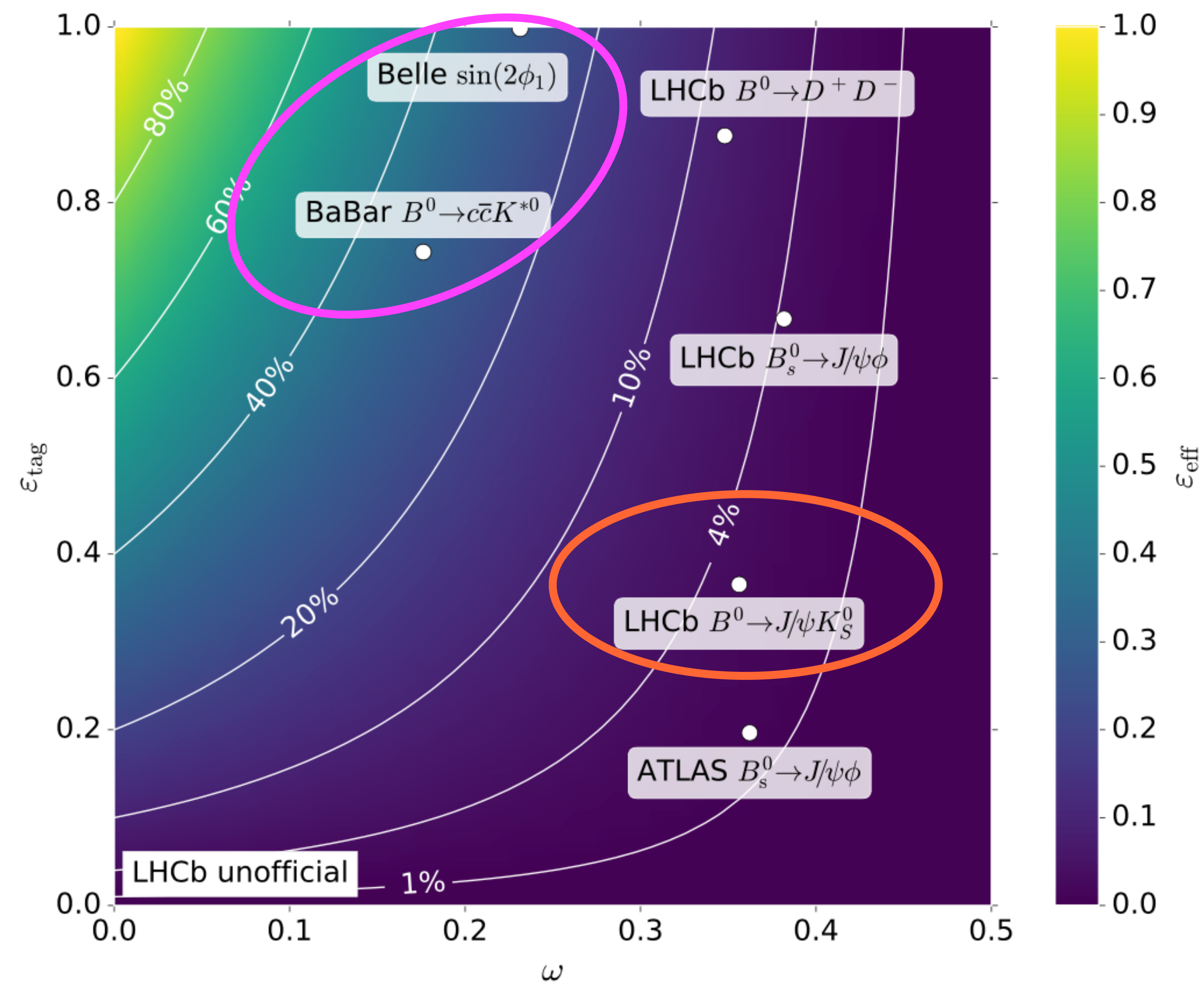
- **Tagging dilution:**

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

  - Initial B flavor efficiency: ϵ_{tag}
  - Wrong tag rate: ω
  - Effective tagging power:

$$\epsilon_{\text{eff}} = \epsilon_{\text{tag}}(1-2\omega)^2$$ **~O(%) @ LHCb**

$$\sigma^{\text{stat}}(CPV) \propto \frac{1}{\sqrt{\varepsilon_{\text{eff}} N}}$$



[CERN-THESIS-2016-152]

Time-dependent *CP* violation

- **Measurement ingredients**:

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

- **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: ϵ_{tag}
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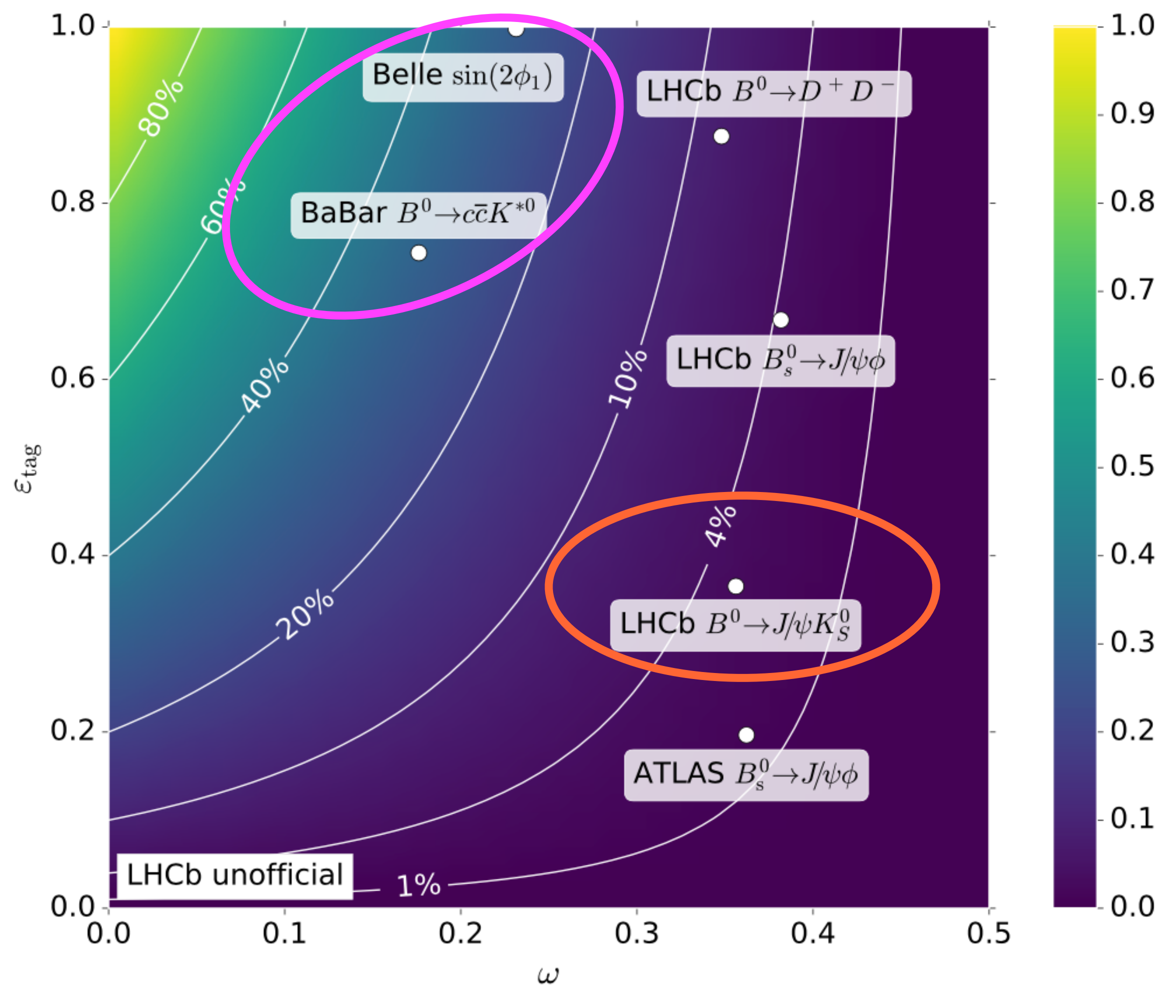
  - Effective tagging power:

$$\epsilon_{\text{eff}} = \epsilon_{\text{tag}}(1-2\omega)^2$$ **~O(%) @ LHCb**

$$\sigma^{\text{stat}}(CPV) \propto \frac{1}{\sqrt{\varepsilon_{\text{eff}} N}}$$

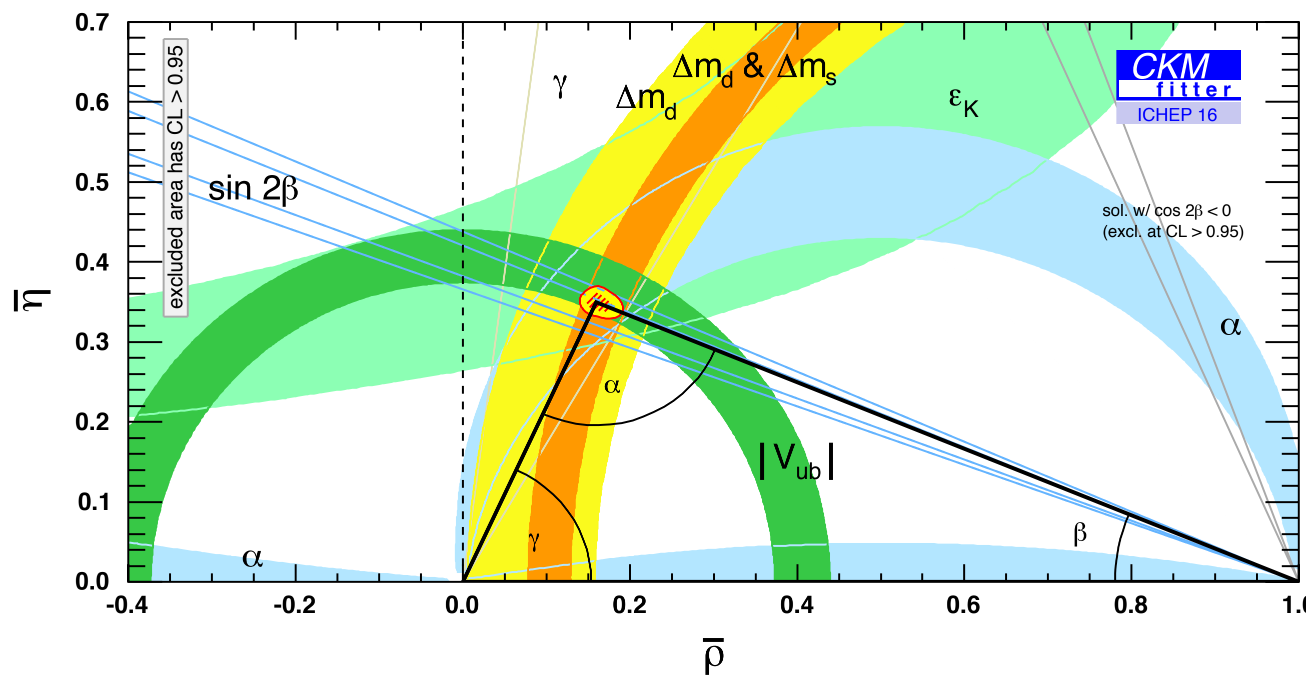


[CERN-THESIS-2016-152]

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

Measurement of β - Status @ CKM16

- ***β* is the most precisely measured angle of the Unitarity triangle**
- **CPV measurement in time-dependent decay rates of $b \to c\bar{c}s$ transitions**



$$\mathcal{A}_{CP}(t) \overset{\Delta\Gamma\approx 0}{\approx} \mathcal{S}_{c\bar{c}s}\sin(\Delta m_d\, t) - \mathcal{C}_{c\bar{c}s}\cos(\Delta m_d\, t)$$

$S_{c\bar{c}s} \approx \sin(2\beta)$ if no direct CPV and neglecting higher order contributions

$C_{c\bar{c}s} \approx 0$ if no direct CPV (good enough approx. given current precision)

$$\sin(2\beta^{\mathrm{SM}}_{c\bar{c}s}) = 0.740^{+0.020}_{-0.025}$$ [CKMFitter]

$$\sin(2\beta^{\mathrm{SM}}_{c\bar{c}s}) = 0.724 \pm 0.028$$ [UTFit]

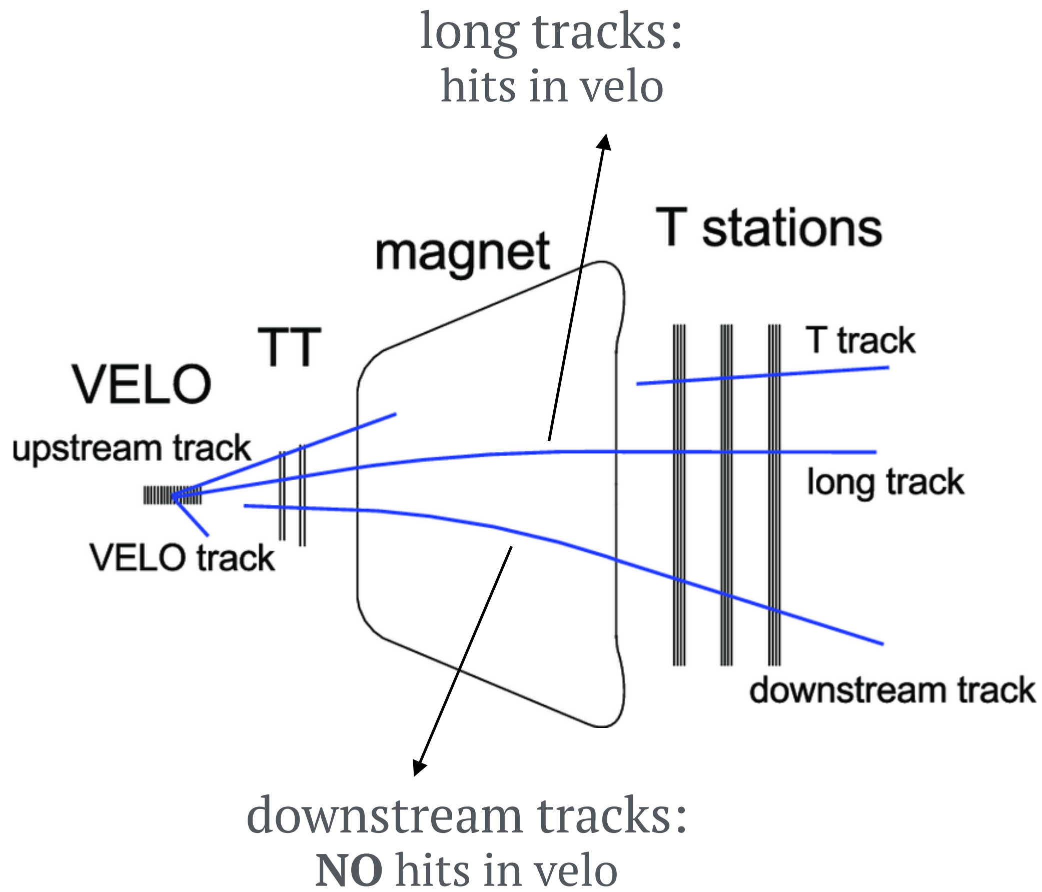
$$\sin(2\beta_{c\bar{c}s}) = 0.691 \pm 0.017$$ [HFLAV]

- **New physics contributions, if present, will be small!**
- **Controlling contributions from penguin topologies becomes mandatory**

Measurement of β @ LHCb

[PRL 115, 031601 (2015)]

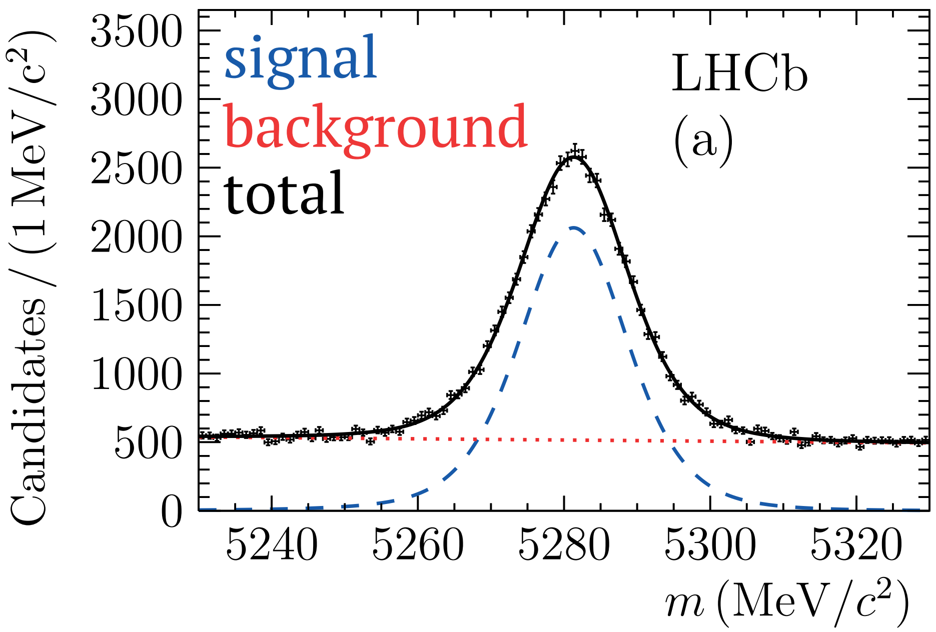
- $B^0 \to J/\psi\ [\mu^+\mu^-]\ K^0_S$: (golden mode)
  - **Using 2011+2012 (3 fb^{-1}) data**
  - **Cut-based selection**
  - **DD & LL reconstructed $K^0_S \to \pi^+\pi^-$**
    - $\langle\sigma(t)_{DD}\rangle > \langle\sigma(t)_{LL}\rangle$
  - **OS and SSπ taggers: ε_{eff} ~ 3%**
  - **~42000 tagged candidates**

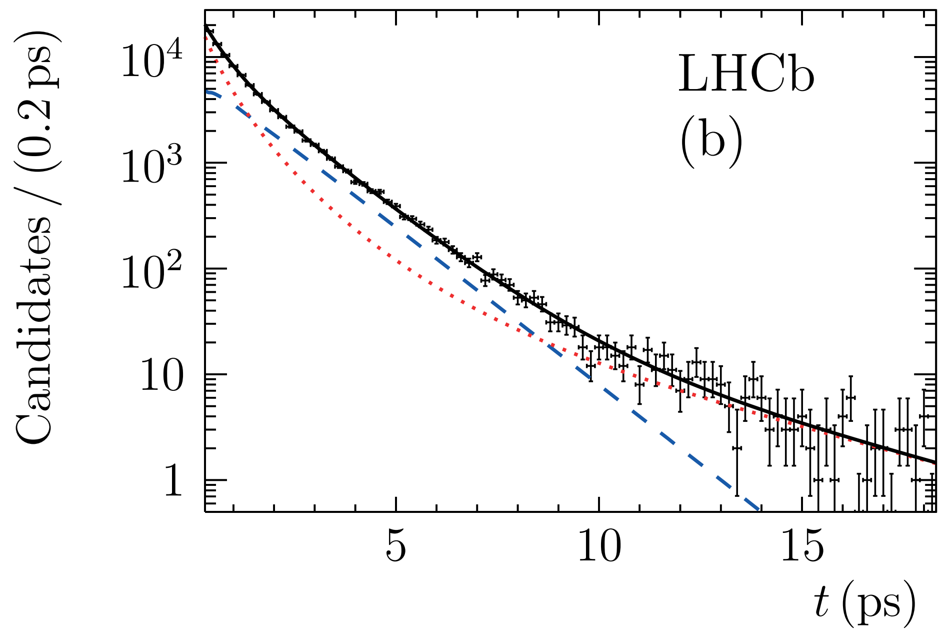


- **Simultaneous fit in 24 categories:**
  - (2011,2012) x (SSπ,OS,OS&SSπ) x (DD,LL) x (AU,EB)
  - signal & background components
  - *CP* parameters S and C free
  - Δm constraint to 0.5100 ± 0.0030 ps

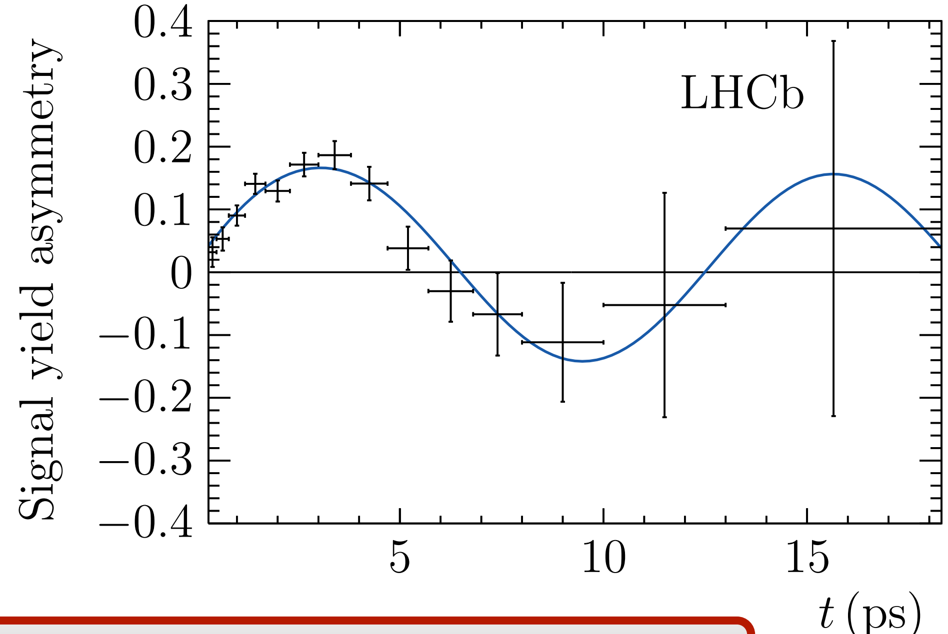
[PRL 115, 031601 (2015)]

- $B^0 \rightarrow J/\psi\,[\mu^+\mu^-]\,K^0_S$: (golden mode)
  - **Fit results:**





$$S = 0.731 \pm 0.035(\text{stat}) \pm 0.020(\text{syst})$$
$$C = -0.038 \pm 0.032(\text{stat}) \pm 0.005(\text{syst})$$
$$\rho(S, C) = 0.483$$



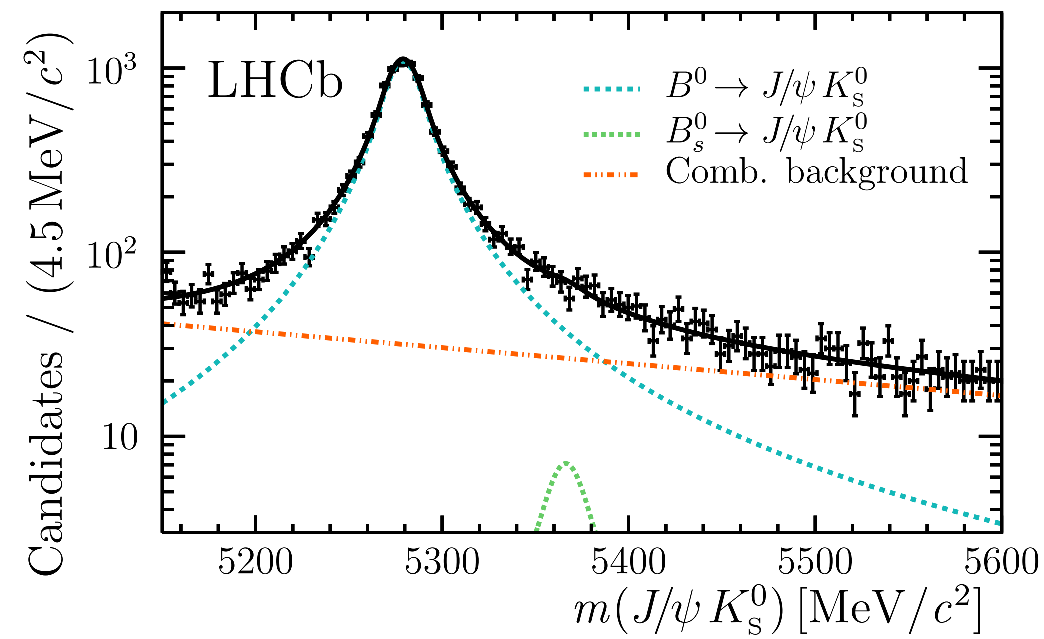
  - **Main systematics:**
    - ***S***: Background Tagging Asymmetry
      → expect to scale with more data
    - ***C***: *Δm*

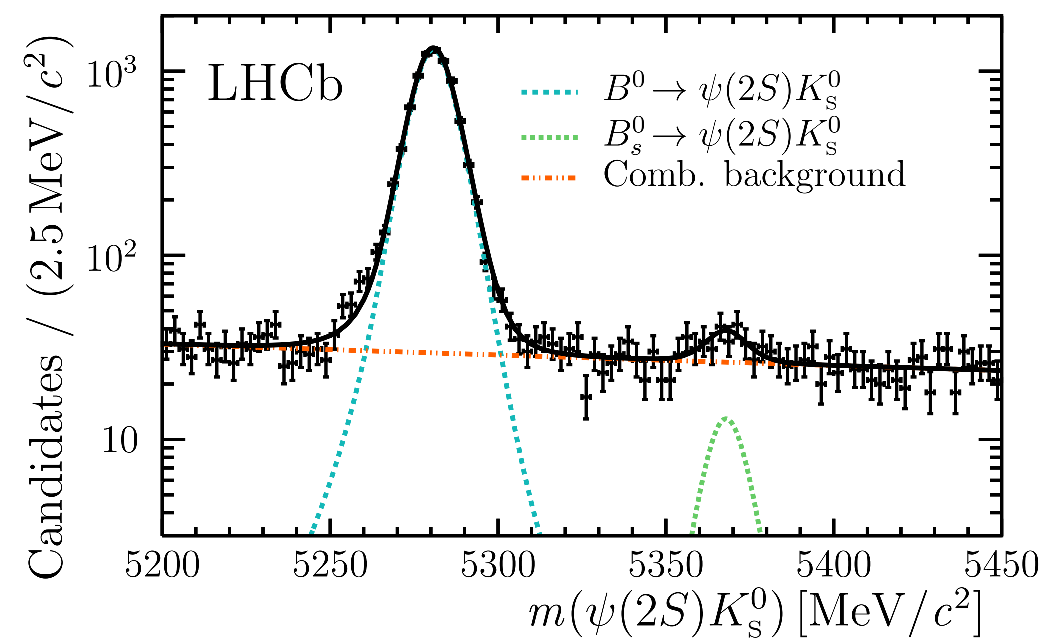
Close to precision of *B*-Factories and statistically limited

Measurement of β @ LHCb

[JHEP 11 (2017) 170]

- $B^0 \to J/\psi\,[e^+e^-]\,K^0_S$ & $B^0 \to \psi(2S)\,[\mu^+\mu^-]\,K^0_S$:
  - Using 2011+2012 (3 fb^{-1}) data
  - BDT in selection
  - DD & LL reconstructed K^0_S
  - OS and SSπBDT + SS*p* taggers:
    - ε_{eff} ~ 6% ($B^0 \to J/\psi\,[e^+e^-]\,K^0_S$)
    - ε_{eff} ~ 3.4% ($B^0 \to \psi(2S)\,[\mu^+\mu^-]\,K^0_S$)
  - ~10600 + 8000 tagged candidates
  - Fit strategy:
    - first fit invariant mass (obtain sWeights)
    - simultaneously fit decay time of both samples (next slide)
    - *CP* parameters S and C + acceptance parameters free





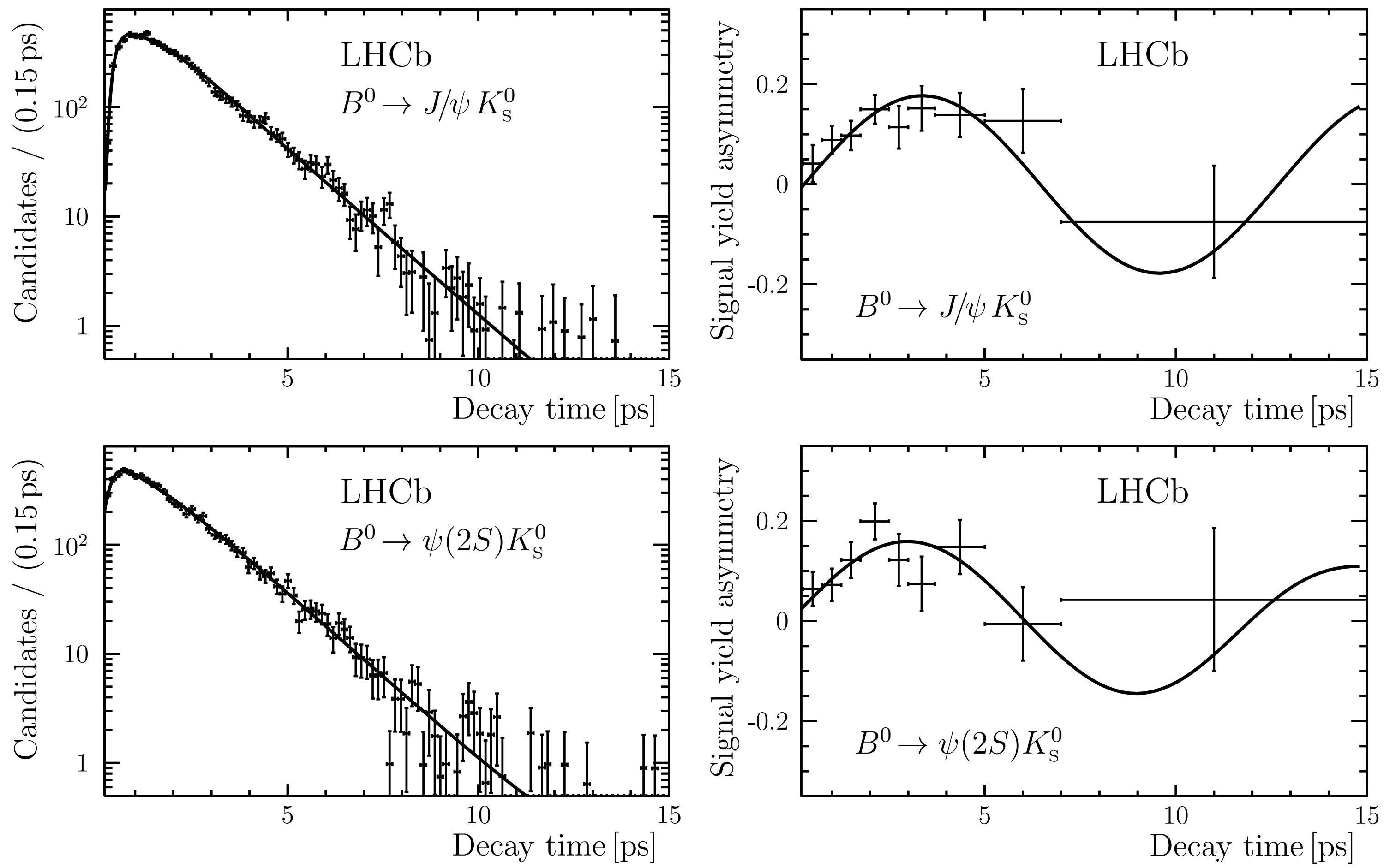
Measurement of β @ LHCb

[JHEP 11 (2017) 170]

- **$B^0 \to J/\psi\,[e^+e^-]\,K^0_S$ & $B^0 \to \psi(2S)\,[\mu^+\mu^-]\,K^0_S$:**
  - **Decay-time fit results**

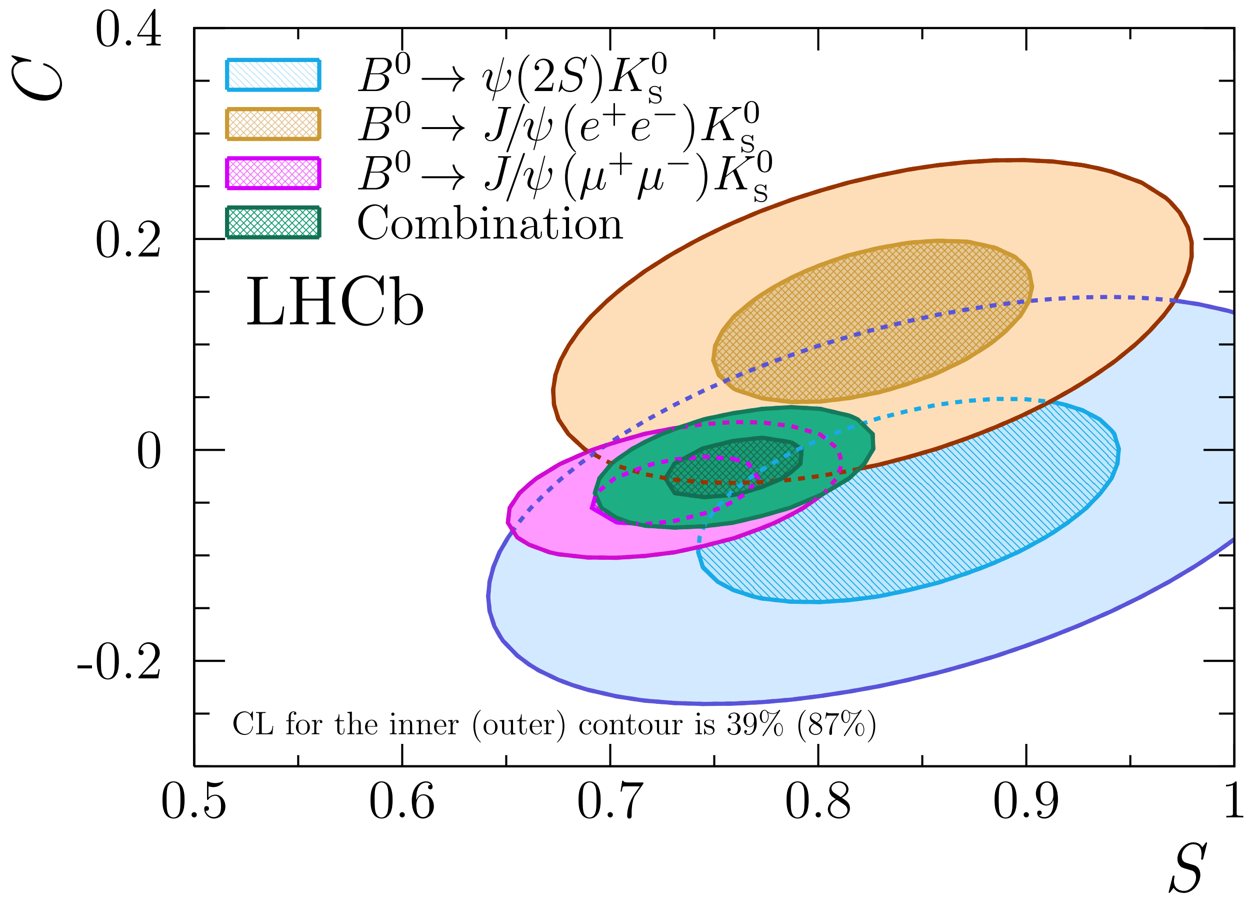
$$S_{J/\psi K^0_S} = 0.83 \pm 0.08(\text{stat}) \pm 0.01(\text{syst})$$
$$C_{J/\psi K^0_S} = 0.12 \pm 0.07(\text{stat}) \pm 0.02(\text{syst})$$
$$\rho(S,C)_{J/\psi K^0_S} = 0.46$$

$$S_{\psi(2S) K^0_S} = 0.84 \pm 0.10(\text{stat}) \pm 0.01(\text{syst})$$
$$C_{\psi(2S) K^0_S} = -0.05 \pm 0.10(\text{stat}) \pm 0.01(\text{syst})$$
$$\rho(S,C)_{\psi(2S) K^0_S} = 0.48$$



Measurement of β @ LHCb

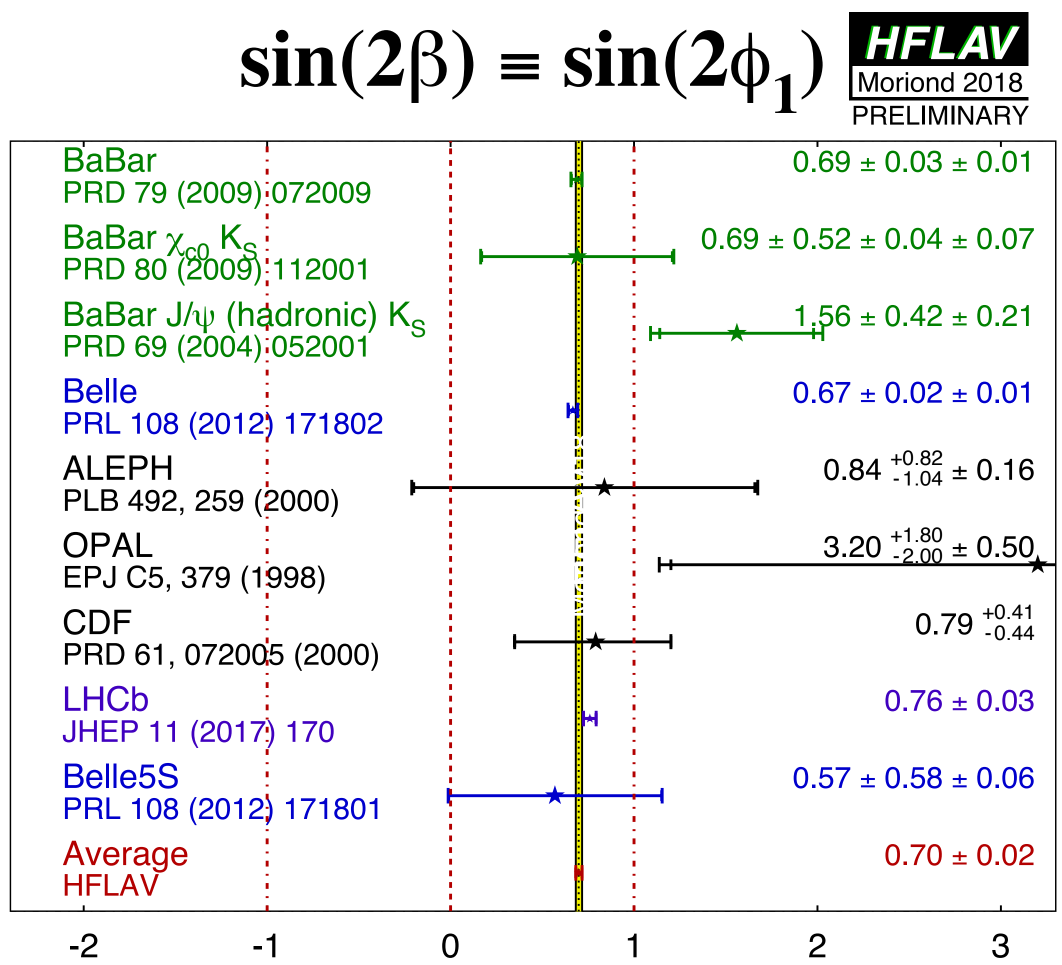
- $B^0 \to J/\psi\,[e^+e^-]\,K^0_S$ & $B^0 \to \psi(2S)\,[\mu^+\mu^-]\,K^0_S$:
  - **Combination + golden mode ($B^0 \to J/\psi\,[\mu^+\mu^-]\,K^0_S$) results**



$$S_{[c\bar{c}]K^0_S} = 0.760 \pm 0.034$$
$$C_{[c\bar{c}]K^0_S} = -0.017 \pm 0.029$$

J/ψ [e⁺e⁻] & $\psi(2S)$ [$\mu^+\mu^-$] modes provide additional ~15% on the overall LHCb precision

Measurement of β - Status & prospects

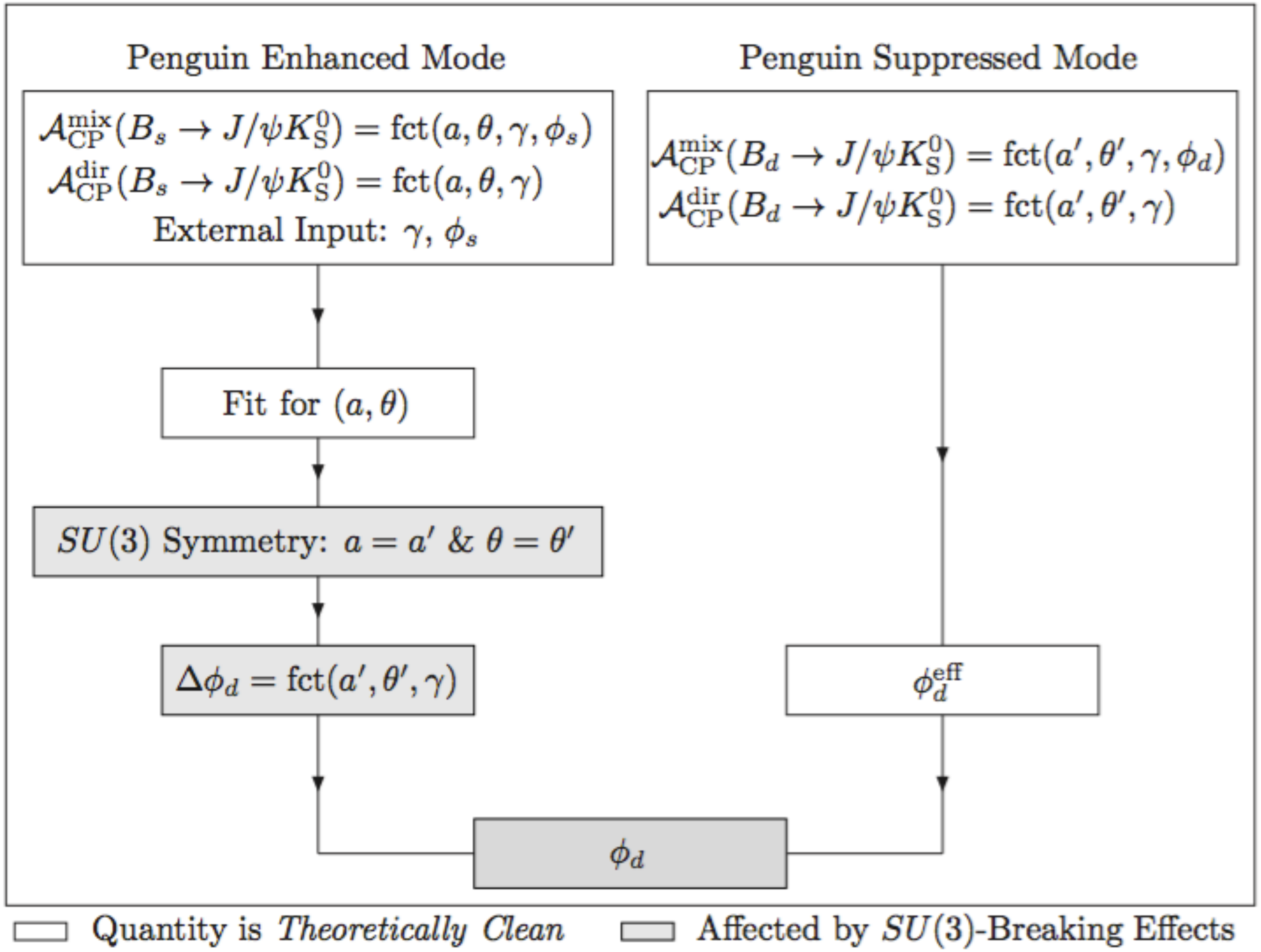


$\sigma_{stat}(\mathcal{S}(J/\psi K^0_S))$	now	50 ab^{-1}	
Belle/II	0.029	0.005	
	now	50 fb^{-1}	300 fb^{-1}
LHCb	0.035	0.006	0.003

- **LHCb achieves similar precision wrt *B*-Factories**
- **Belle 2 and LHCb Upgrades target significantly improved sensitivities with mostly uncorrelated systematics**
  → mandatory to control penguin pollution!

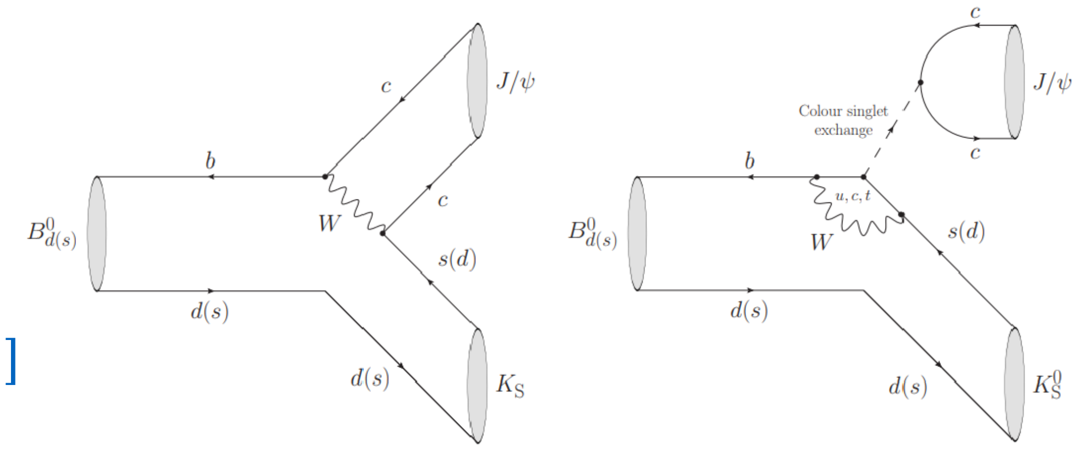
Controlling penguin topologies for β

- **Strategy:**
  - use U-spin and SU(3) related modes, where penguin not suppressed
    [S. Faller, R. Fleischer, M. Jung, T. Mannel, PRD79:014030,2009]
  - the decay mode $B_s^0 \to J/\psi\, K_S^0$ can be used to control $\Delta\phi_d \propto \Delta\beta^{\text{peng}}$:



Controlling penguin topologies for β

- $B_s^0 \to J/\psi\, K_S^0$:
  - same topology as $B^0 \to J/\psi\, K_S^0$
  - LHCb performed first **flavor-tagged time-dependent** analysis: [LHCb, *JHEP 06 (2015) 131*]



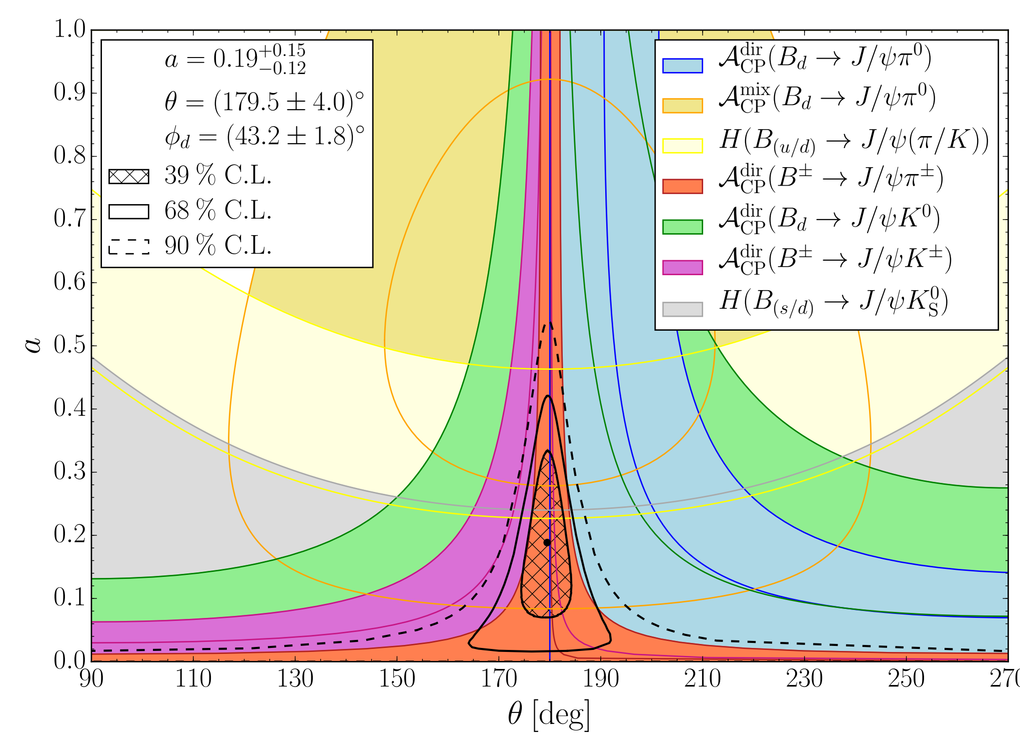
$$\mathcal{A}_{\Delta\Gamma}(B_s^0 \to J/\psi K_S^0) = +0.49^{+0.77}_{-0.65}(\text{stat}) \pm 0.06(\text{syst})$$
$$\mathcal{C}(B_s^0 \to J/\psi K_S^0) = -0.28 \pm 0.41(\text{stat}) \pm 0.08(\text{syst})$$
$$\mathcal{S}(B_s^0 \to J/\psi K_S^0) = -0.08 \pm 0.40(\text{stat}) \pm 0.08(\text{syst})$$

$\Rightarrow$ Successful proof of concept waiting for more statistics

  - Using information from $B^0 \to J/\psi\, \pi^0$ [Belle, PRL 93, 261801] together with inputs from $B^+ \to J/\psi\, K^+$ and $B^+ \to J/\psi\, \pi^+$ [LHCb JHEP 03 (2017) 036] [LHCb, PRD 95 (2017) 052005] translates into penguin shift on β:

$$\Delta\beta^{\text{peng}} = (-1.10^{+0.70}_{-0.85})^\circ$$

same order of uncertainties on 2β
$\Rightarrow$ needs to be improved with more data!



[De Bruyn, Fleischer, JHEP 1503 (2015) 145]

Summary & prospects

- β is and will remain the most precisely measured angle of the unitarity triangle
- Controlling higher order corrections becomes mandatory:
  - penguin pollution to be determined with increased precision in U-spin and SU(3)-related modes both by LHCb and Belle II
- For the future:
  - Measurements statistically dominated
    → look forward to Run-2 updates (and LHCb-upgrade)

Additional material

Measurement of β @ LHCb

[JHEP 11 (2017) 170]

- $B^0 \to J/\psi\,[e^+e^-]\,K^0_S$ & $B^0 \to \psi(2S)\,[\mu^+\mu^-]\,K^0_S$:
  - **Systematics**

	$B^0 \to J/\psi K^0_S$		$B^0 \to \psi(2S) K^0_S$	
Source	σ_S	σ_C	σ_S	σ_C
$\Delta\Gamma$	0.003	0.007	0.007	0.003
Δm	0.004	0.004	0.004	0.004
Production asymmetry	0.004	0.009	0.007	0.005
Tagging calibration	0.002	0.005	0.005	0.002
Decay-time bias	0.006	0.006	0.006	0.004
σ_t scaling	0.003	0.005	0.002	0.002
Decay-time efficiency	0.006	0.004	0.006	0.004
Total	0.011	0.016	0.014	0.010

$$S_{J/\psi K^0_S} = 0.83 \pm 0.08(\text{stat}) \pm 0.01(\text{syst})$$
$$C_{J/\psi K^0_S} = 0.12 \pm 0.07(\text{stat}) \pm 0.02(\text{syst})$$
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$$S_{\psi(2S) K^0_S} = 0.84 \pm 0.10(\text{stat}) \pm 0.01(\text{syst})$$
$$C_{\psi(2S) K^0_S} = -0.05 \pm 0.10(\text{stat}) \pm 0.01(\text{syst})$$
$$\rho(S,C)_{\psi(2S) K^0_S} = 0.48$$

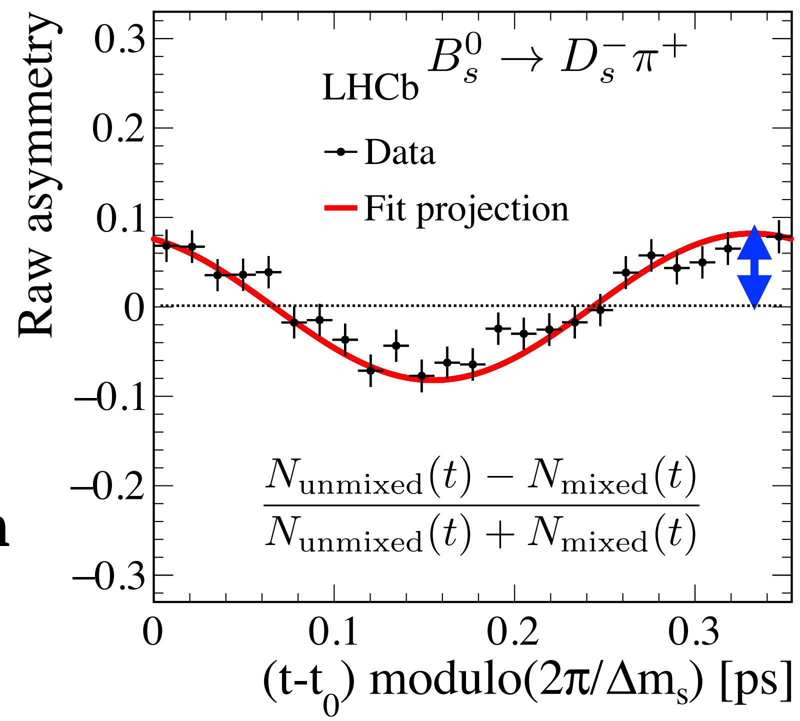
Flavour tagging definitions

[Journal of Instrumentation 11 (2016) P05010]

- **Tagging Efficiency: fraction of tagged events**

$$\varepsilon_{\text{tag}} = \frac{N_{\text{wrong}} + N_{\text{correct}}}{N_{\text{wrong}} + N_{\text{correct}} + N_{\text{untagged}}}$$

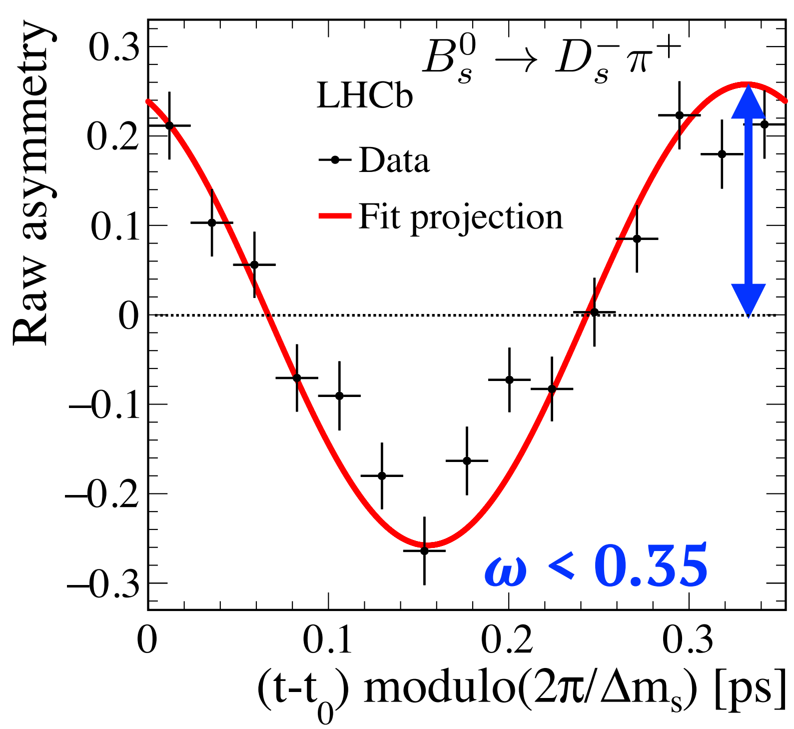
  - Correlated with the transverse momentum of the signal B



- **Mistag fraction: fraction of events with wrong tag decision**

$$\omega = \frac{N_{\text{wrong}}}{N_{\text{wrong}} + N_{\text{correct}}}$$

  - ***Dilution: D* = (1-2*ω*)** of asymmetries and decay rates.
  - Predicted mistag, η, computed by taggers needs calibration $\omega(\eta)$ to provide unbiased estimate of ω



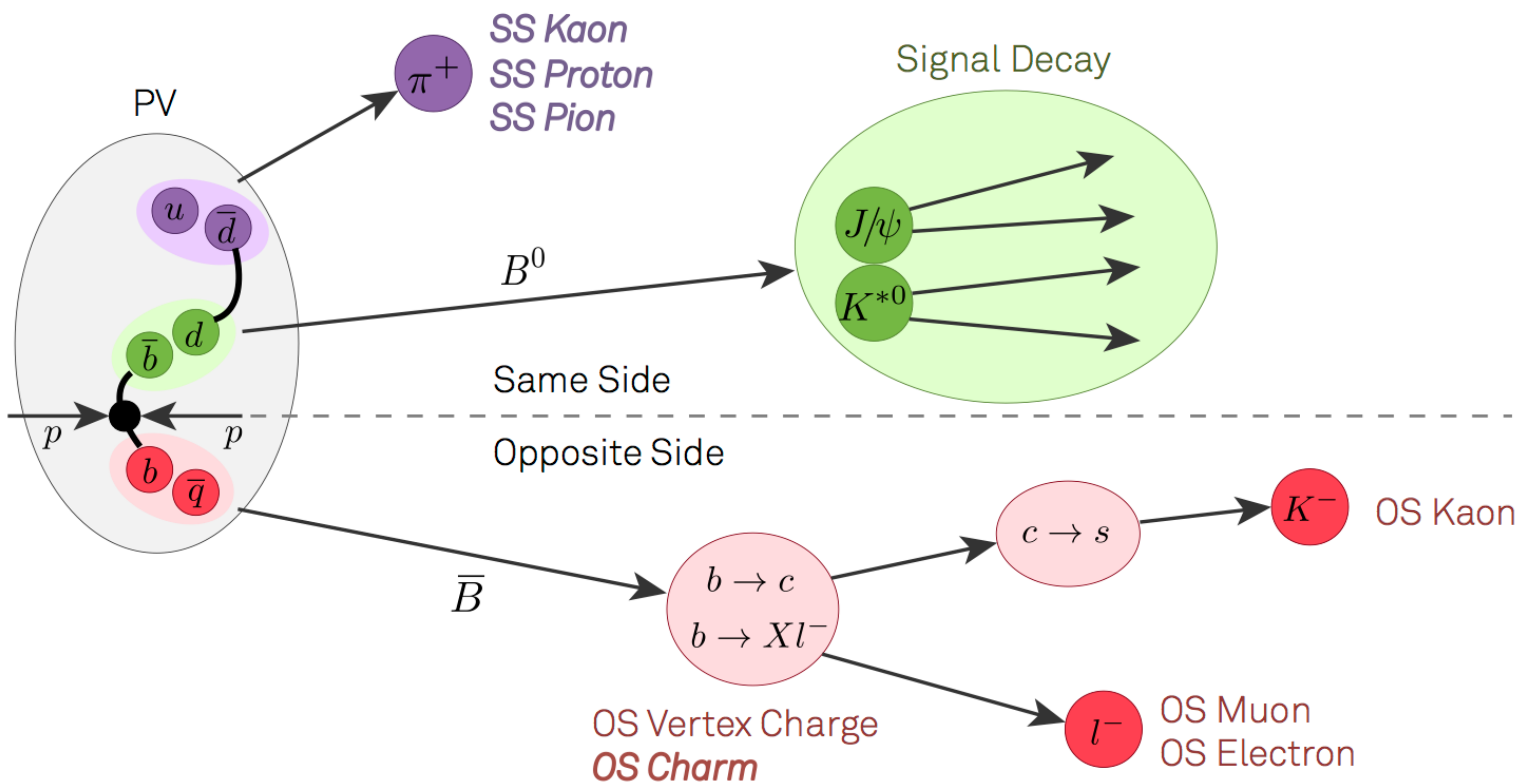
- **Tagging power: statistical degradation of *CP* asym.**

$$\varepsilon_{\text{eff}} = \varepsilon_{\text{tag}} D^2 = \varepsilon_{\text{tag}} \left\langle (1-2\omega)^2 \right\rangle$$

$$\sigma^{\text{stat}}(CP\text{ asym}) \propto \frac{1}{\sqrt{\varepsilon_{\text{eff}} N}}$$

Flavour tagging algorithms

Same side (SS): exploit the charge of the **fragmentation particle** (pion, kaon, proton) produced next to the signal *b*-hadron in the hadronisation process to infer its initial flavour (t=0)

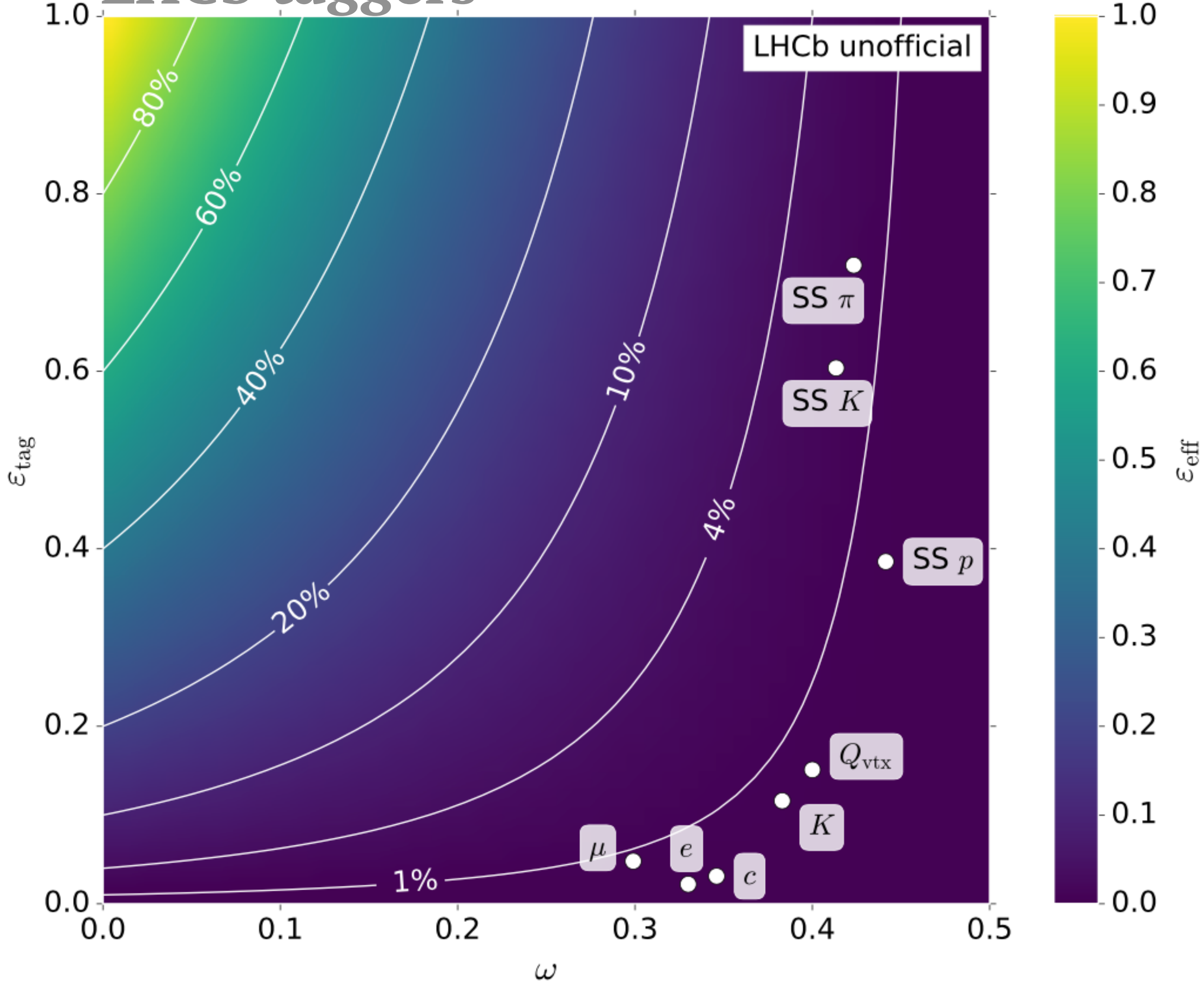


Opposite side (OS): exploit the charge of the particle (lepton, kaon, charm decays) or of the **reconstructed secondary vertex produced from the other *b*-hadron** in the event to infer signal *b*-hadron initial flavour (t=0)

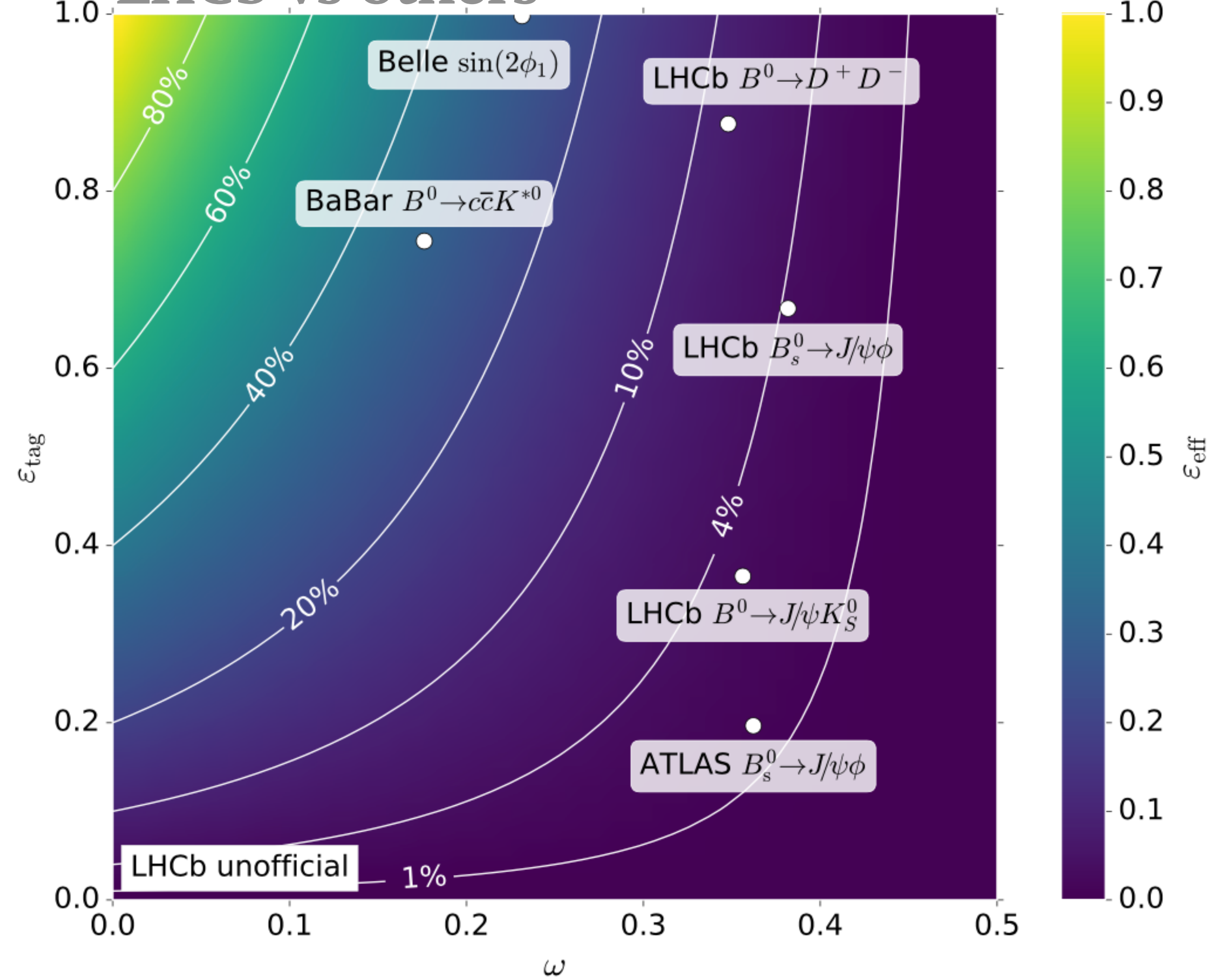
Typical performances

[CERN-THESIS-2016-152]

LHCb taggers



LHCb vs others

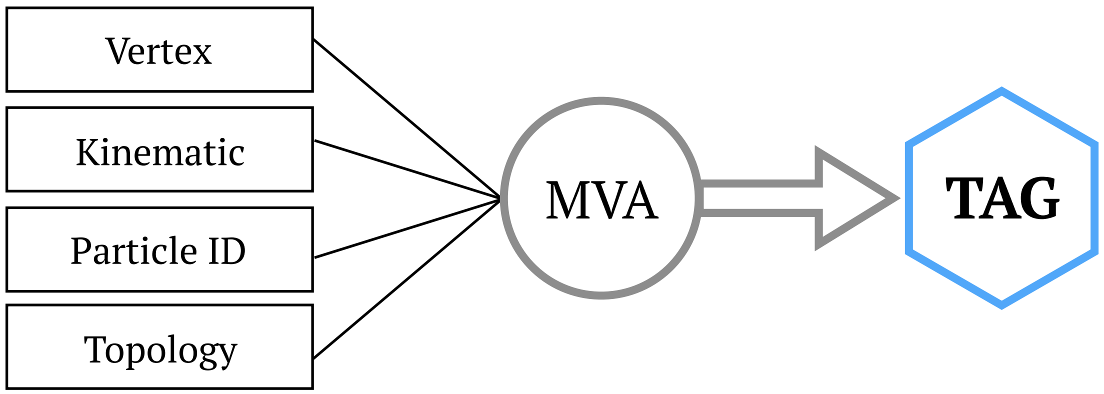


- **OS taggers: good mistag but low decision rate**
- **SS taggers: modest mistag but high decision rate**
- **Tagging performances are channel dependent**

$$\sigma^{\rm stat}(CP\ \text{asym}) \propto \frac{1}{\sqrt{\varepsilon_{\rm eff} N}}$$

Developing FT algorithms

- **Tagging tracks identification**
  - *pp* collisions harsh environment
  - few tracks among $O(10^2)$
  - FT algorithms based on MVA classifiers designed to isolate specific physical process (SS tracks, OS tracks divided by categories)



- **Taggers calibration**

$$\omega = p_0 + p_1(\eta - \langle\eta\rangle)$$

measured ev-by-ev mistag (ω); estimated ev-by-ev mistag (η); estimated mean mistag ($\langle\eta\rangle$)

  - Calibration performed on control channels:
    - Charged modes: $B^+ \to J/\psi K^+$, $B^+ \to D^0 \pi^+$
      No oscillation, large samples
    - Neutral B^0 modes: $B^0 \to J/\psi K^*$, $B^0 \to D^- \pi^+$
      large samples
    - Neutral B_s^0 modes: $B_s^0 \to D_s^- \pi^+$
      only control decay for data SSK, statistically limited

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