Time-dependent *CP* Violation and Flavour Tagging at LHCb

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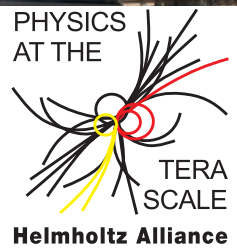

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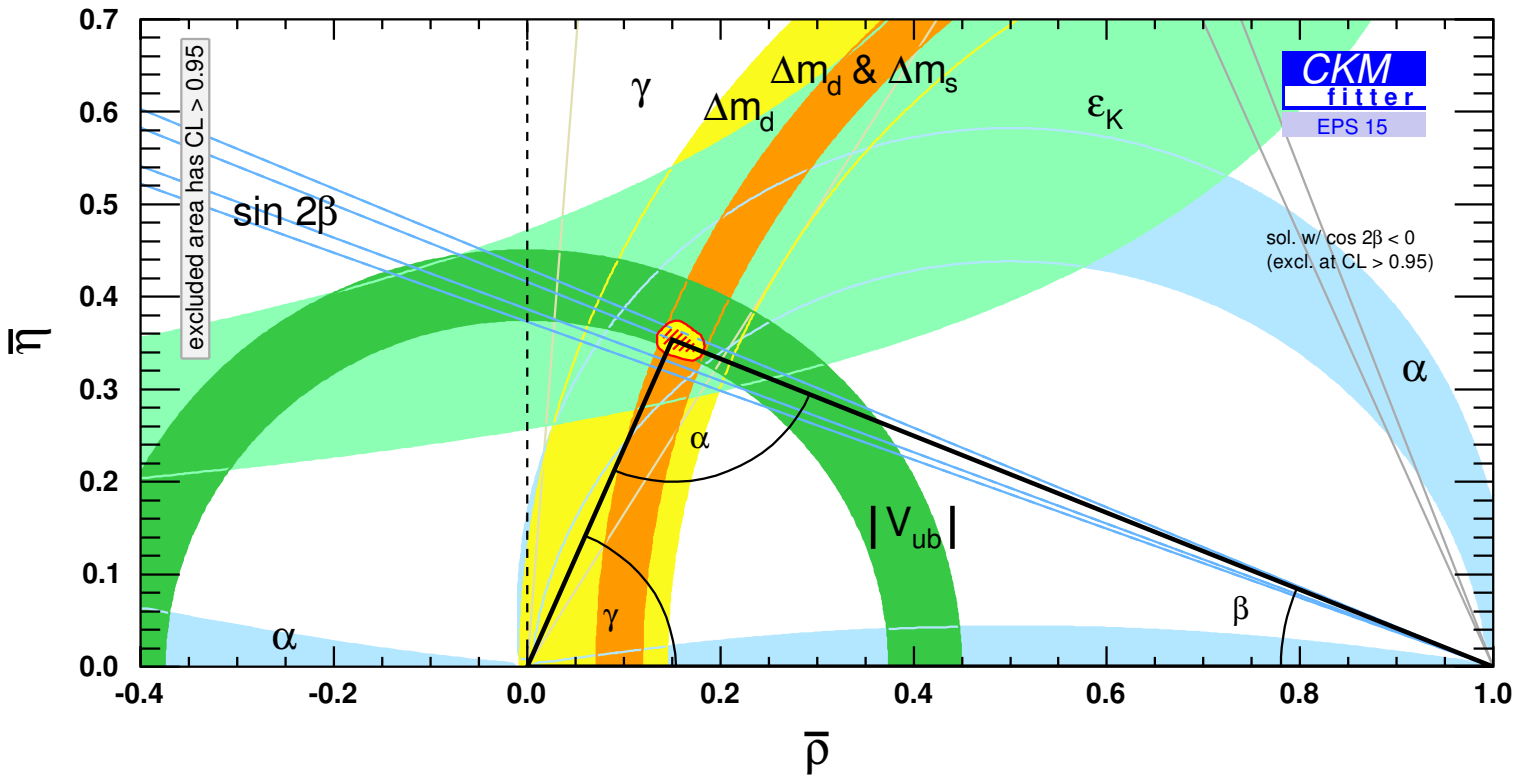
CP Violation in the SM Quark Sector

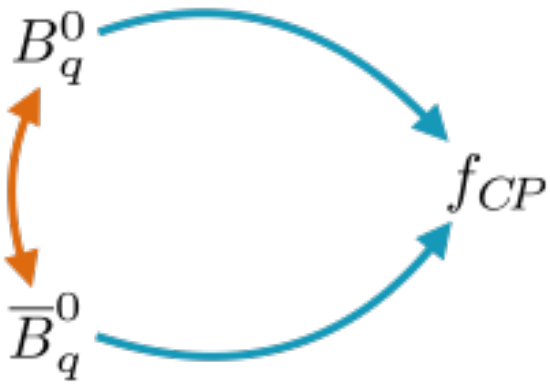
$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = V_{\text{CKM}} \begin{pmatrix} d \\ s \\ b \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

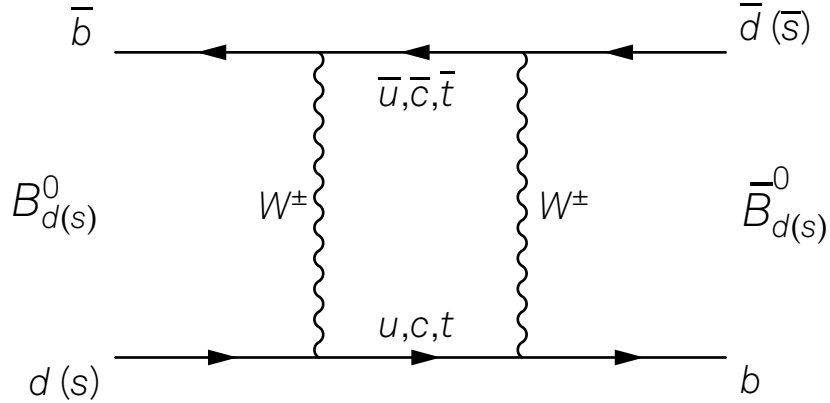
$$V_{ud}V_{ub}^{*} + V_{cd}V_{cb}^{*} + V_{td}V_{tb}^{*} = 0$$



Time-dependent *CP* Asymmetry

- *CP* violation in the interference between direct decay and decay after mixing

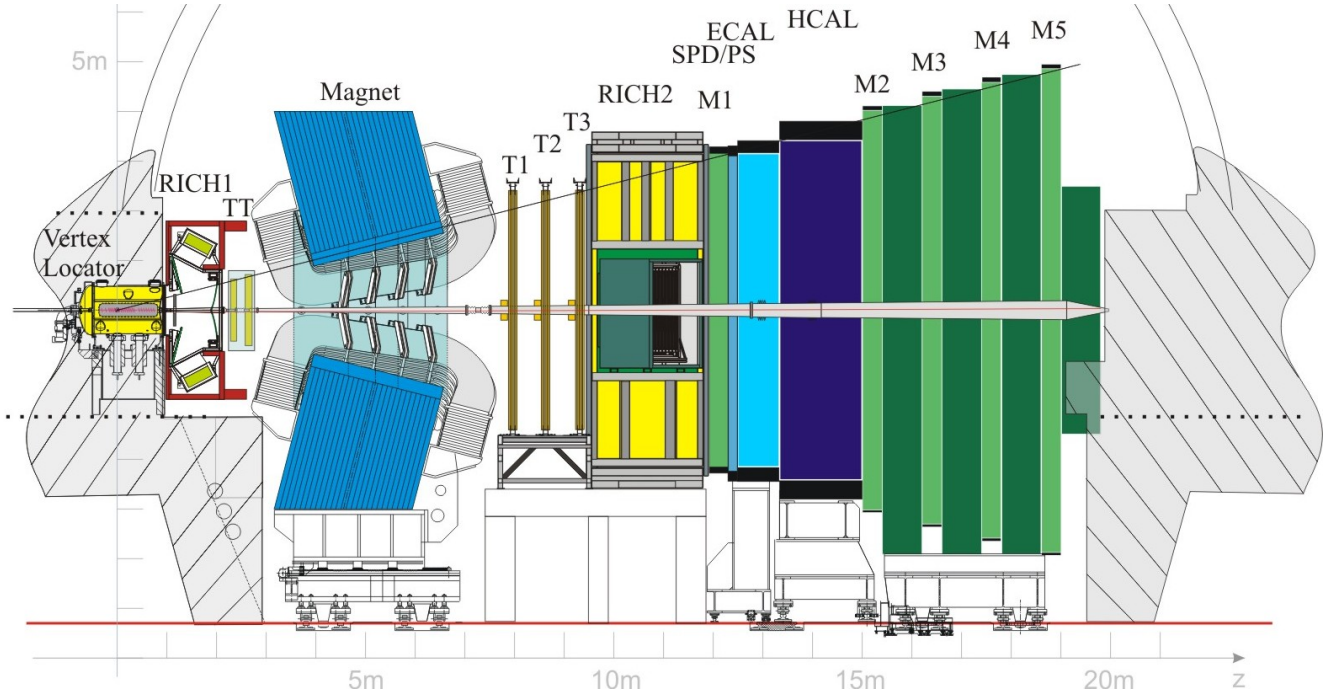




$$\mathcal{A}(t) \equiv \frac{\Gamma(\bar{B}(t) \to f_{CP}) - \Gamma(B(t) \to f_{CP})}{\Gamma(\bar{B}(t) \to f_{CP}) + \Gamma(B(t) \to f_{CP})} = \frac{S \sin(\Delta m\, t) - C \cos(\Delta m\, t)}{\cosh(\Delta\Gamma\, t/2) + A_{\Delta\Gamma} \sinh(\Delta\Gamma\, t/2)}$$

- initial flavour → flavour tagging
- *CP* observables → parameters of interest
- mixing parameters → to be constrained

LHCb Detector

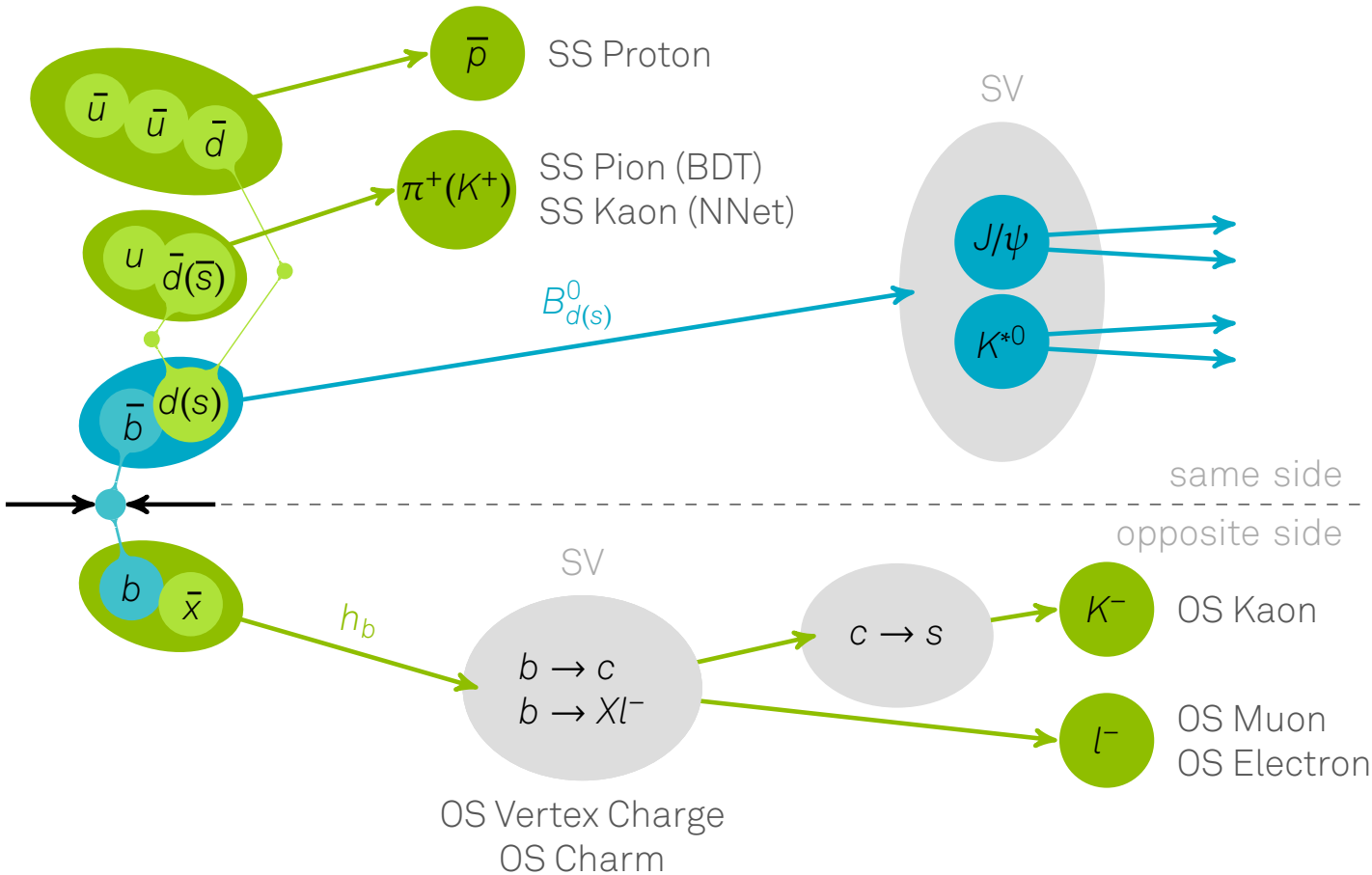


$$\mathcal{A}(t) \equiv \frac{\Gamma(\bar{B}(t) \to f_{CP}) - \Gamma(B(t) \to f_{CP})}{\Gamma(\bar{B}(t) \to f_{CP}) + \Gamma(B(t) \to f_{CP})}$$

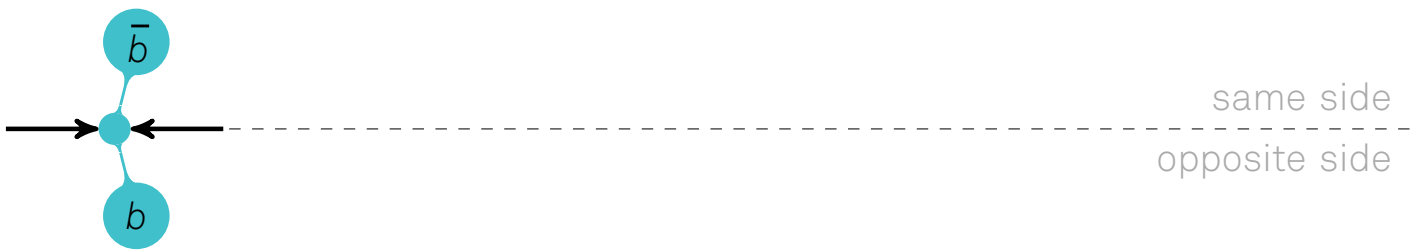
- reconstruction of final state
  - RICH1 + RICH2: distinction of π, K, p
  - identification of μ in M1 - M5
- determination of decay time

  VELO + tracking stations
  - decay time resolution ~ 45 fs
  - momentum resolution $\Delta p/p = 0.4\,\% - 0.6\,\%$
  - IP resolution ~ 20 μm

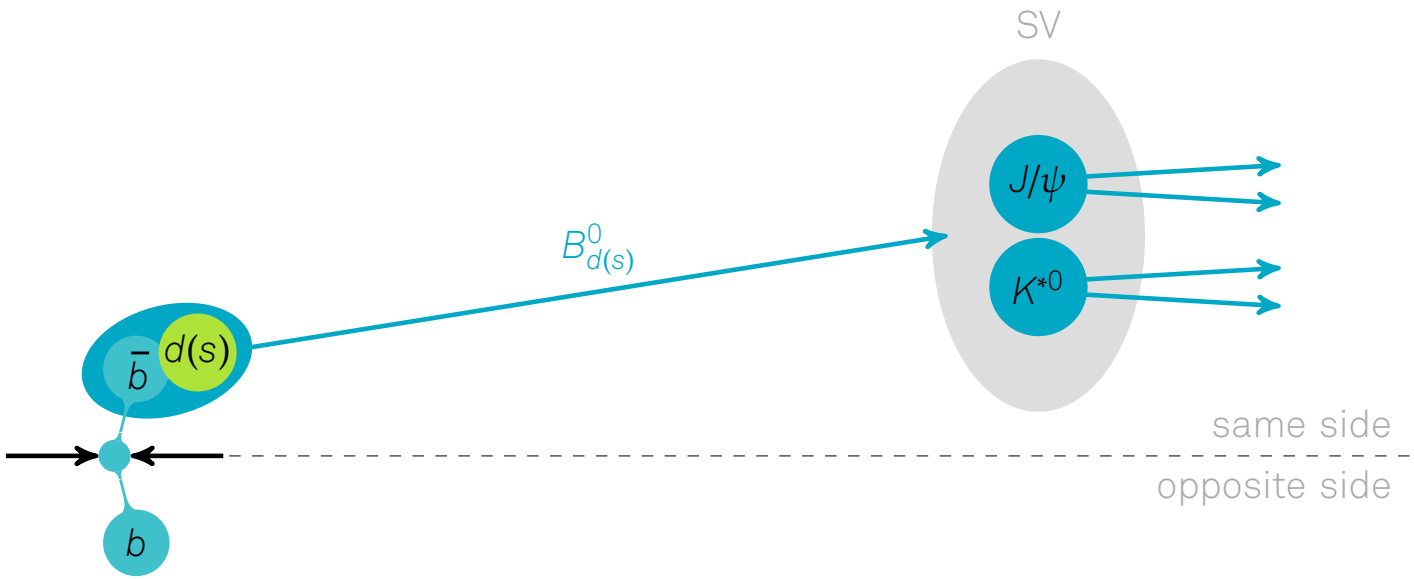
Flavour Tagging Scheme



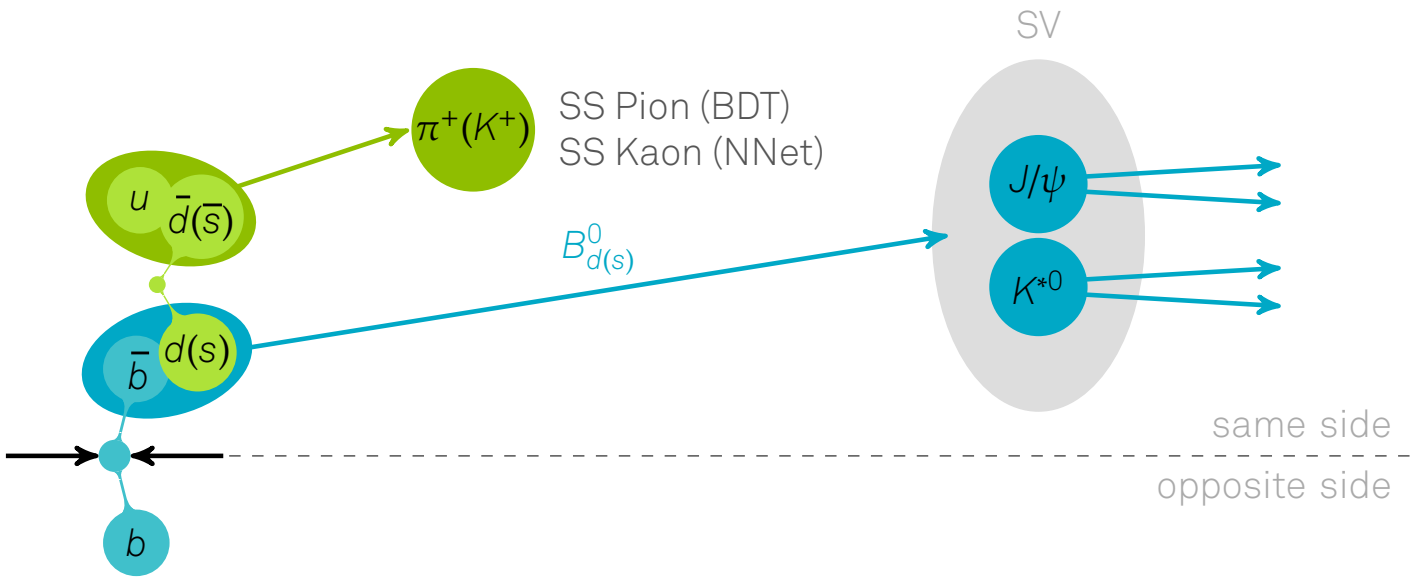
Flavour Tagging Scheme



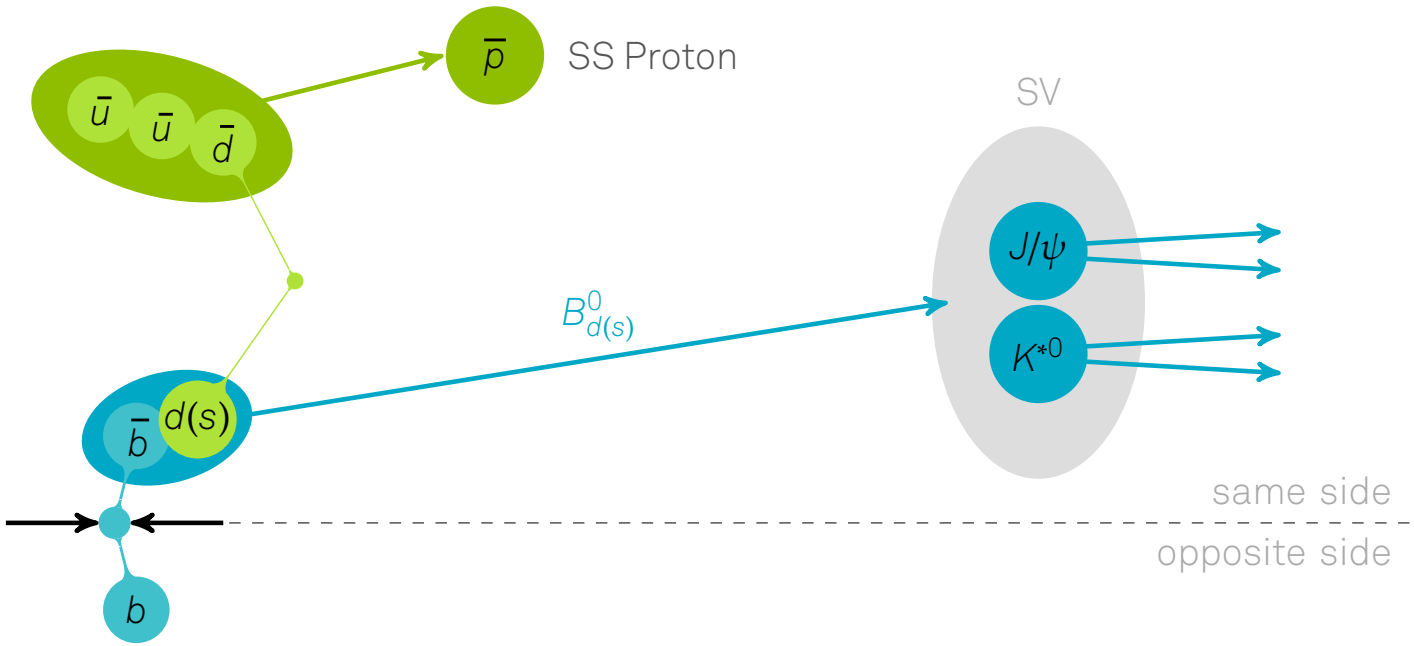
Flavour Tagging Scheme



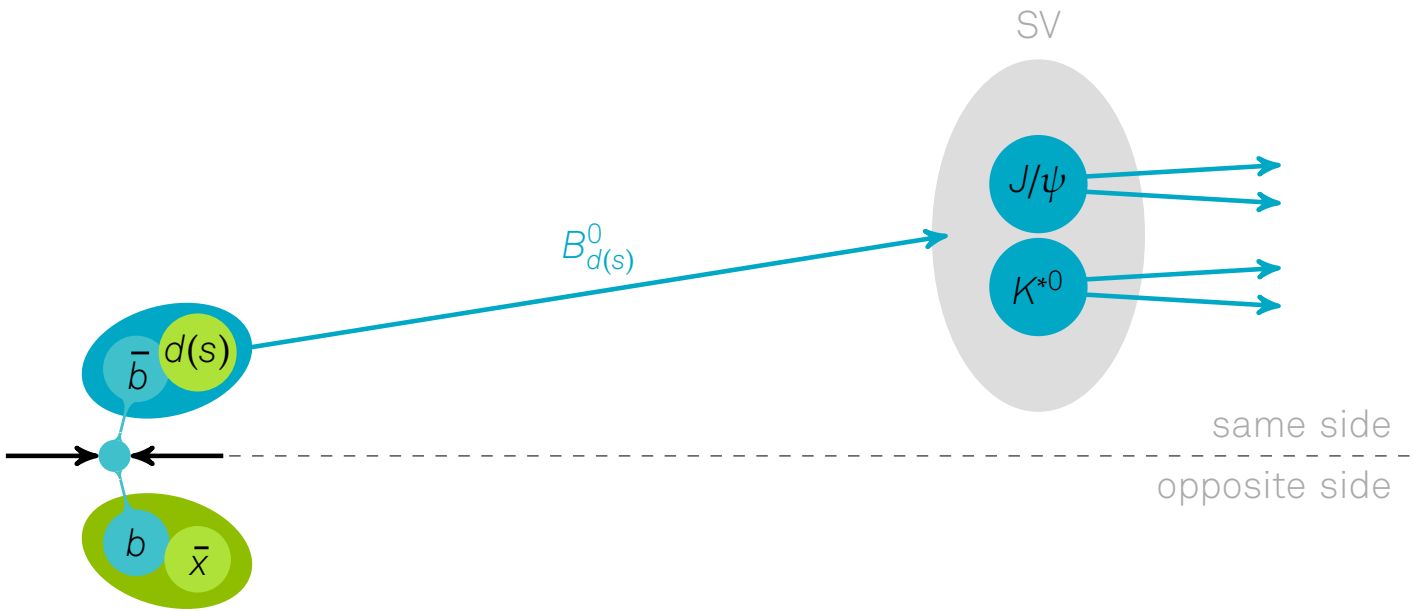
Flavour Tagging Scheme



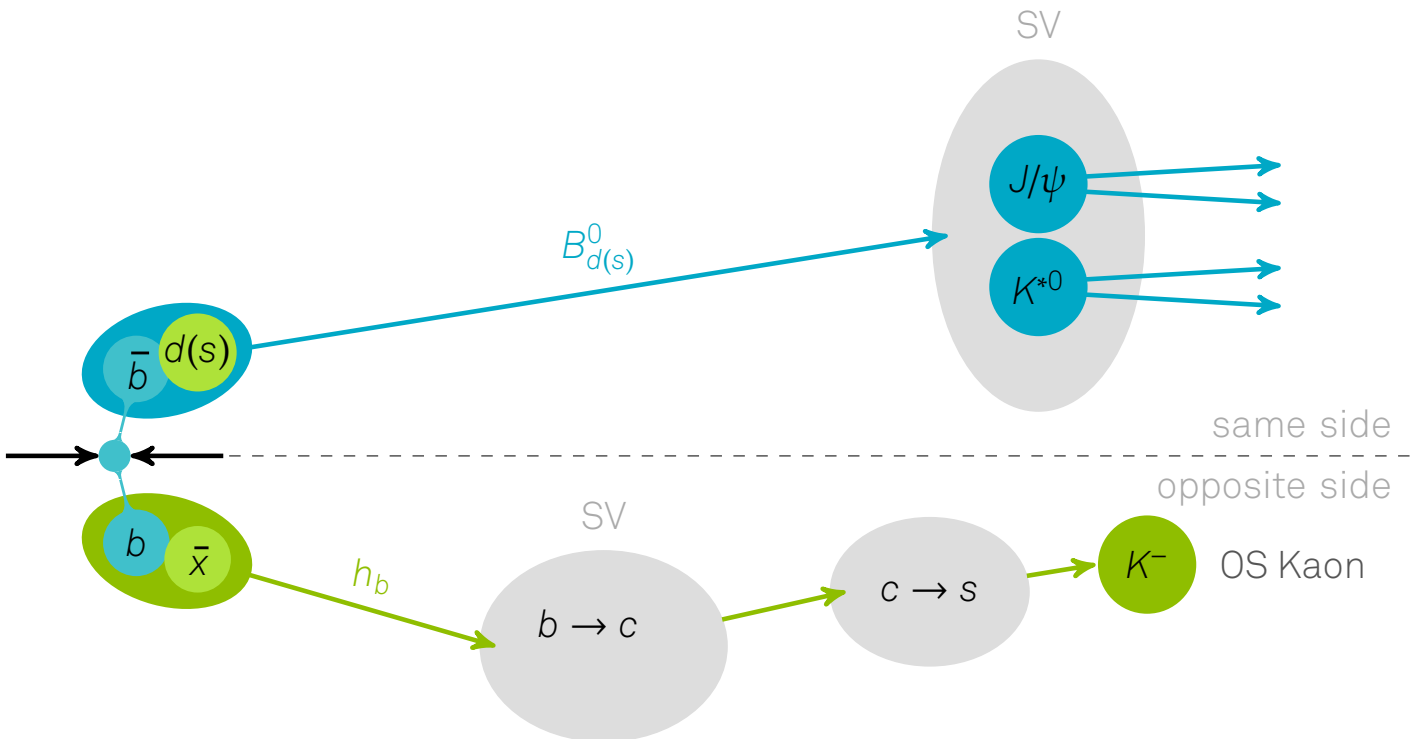
Flavour Tagging Scheme



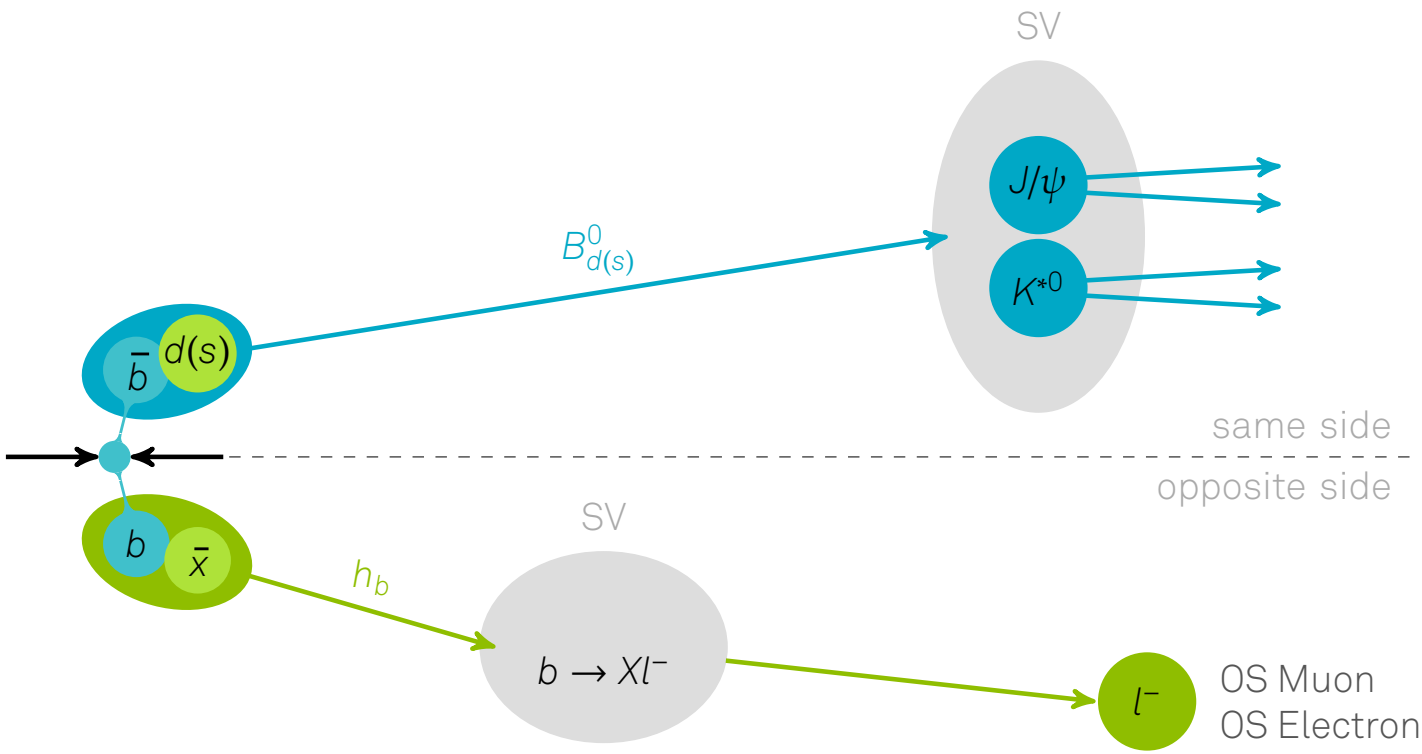
Flavour Tagging Scheme



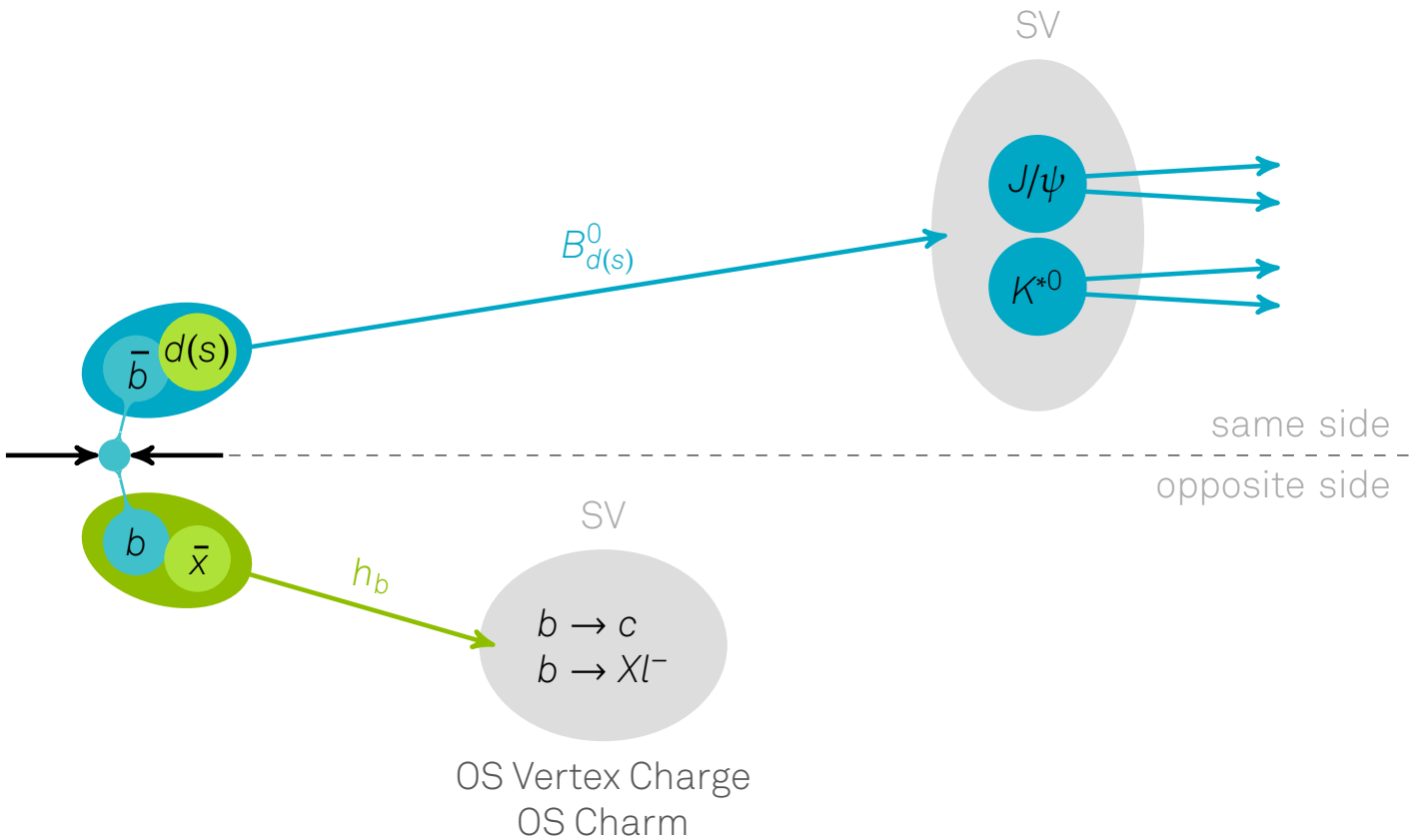
Flavour Tagging Scheme



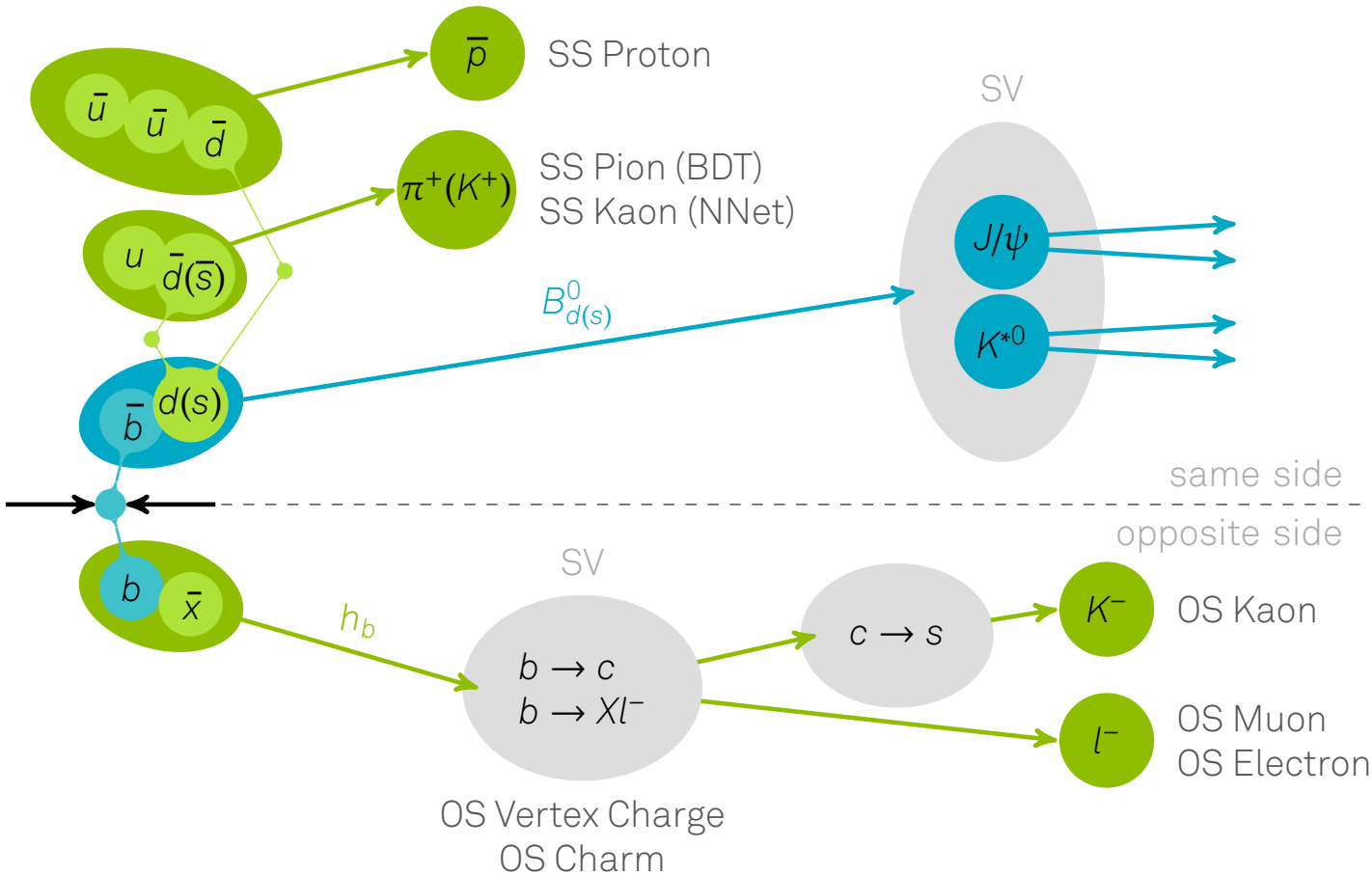
Flavour Tagging Scheme



Flavour Tagging Scheme



Flavour Tagging Scheme



FT algorithms provide

- tag decision d
- mistag prediction η

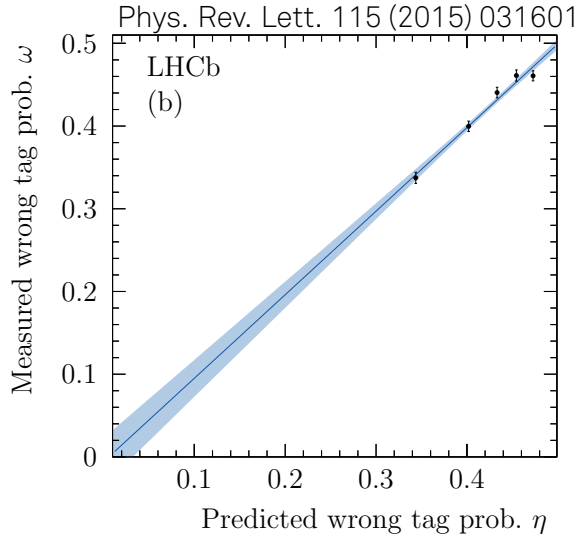
Flavour Tagging Calibration

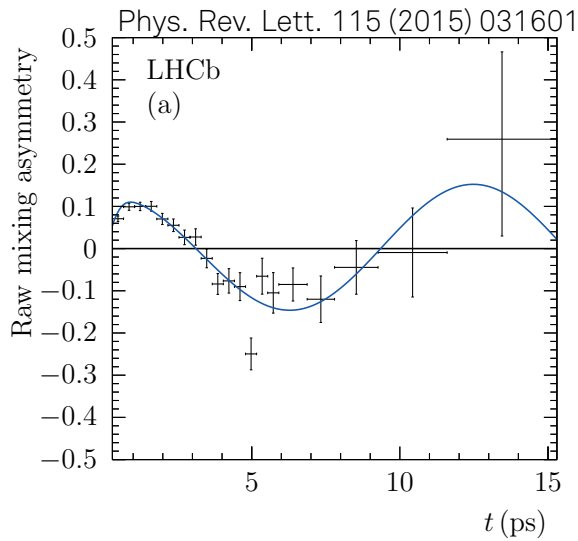
- comparison of true and predicted mistag $\omega(\eta)$

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

- consider mistag asymmetries
- self-tagging (charged) modes like $B^+ \to J/\psi K^+$
  - count wrong tag fraction
- flavour-specific decay channels like $B^0 \to J/\psi K^{*0}$
  - measure amplitude of mixing asymmetry

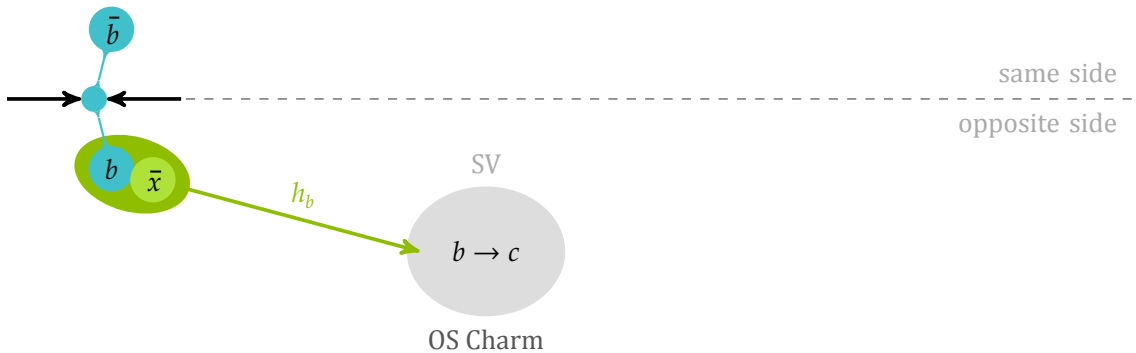
$$\mathcal{A}_{\text{mix}}(t) = \frac{N_{\text{unmixed}}(t) - N_{\text{mixed}}(t)}{N_{\text{unmixed}}(t) + N_{\text{mixed}}(t)} = (1 - 2\omega)\cos(\Delta m\, t)$$



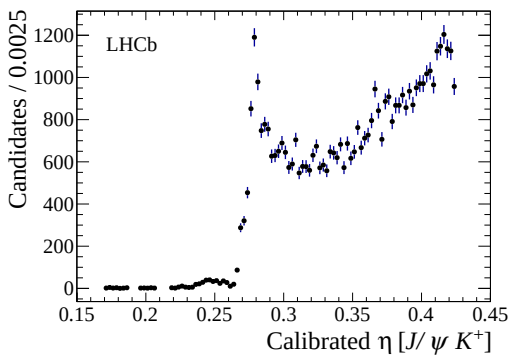


New Flavour Tagging Algorithm: OS Charm

J. Instrum. 10 (2015) P10005



- reconstruction of charm hadron in various
  - fully/partially reconstructed hadronic modes
  - partially reconstructed semileptonic modes
- individual training of multivariate algorithm for each mode
- low mistag tagger
- irreducible mistag probability due to
  - B^0- $\bar{B}^0$ oscillation
  - wrong sign charm hadrons from $b \to c\bar{c}q$ decays

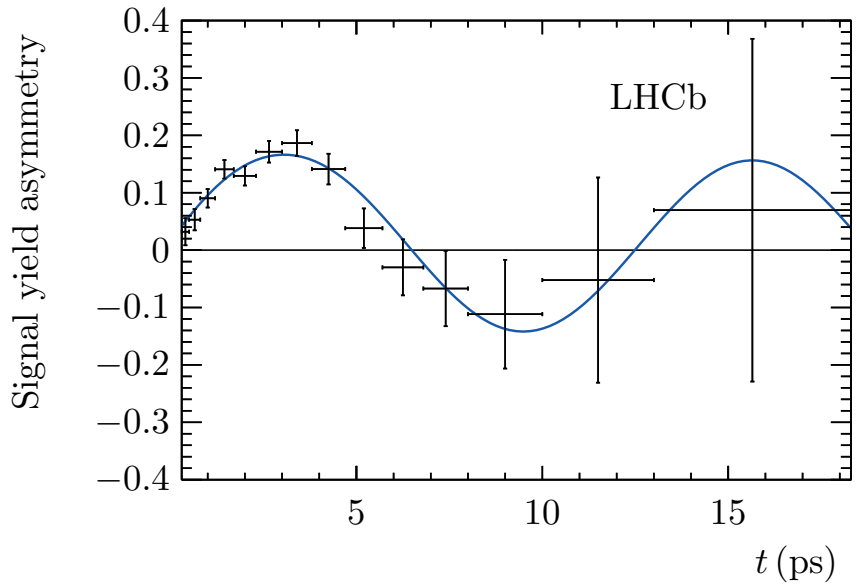


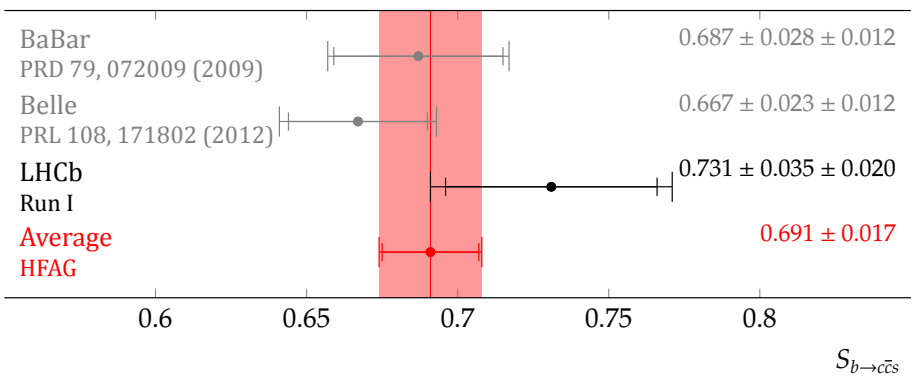
$\Rightarrow$ single effective tagging efficiency: 0.3 %

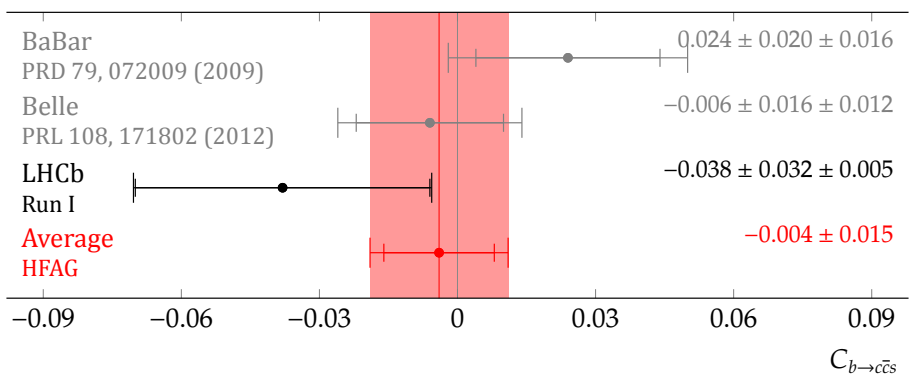
$\sin 2\beta$ from $B^0 \to J/\psi K^0_S$

Phys. Rev. Lett. 115 (2015) 031601

- $\beta = \arg\left(-\frac{V_{cd}V^*_{cb}}{V_{td}V^*_{tb}}\right)$
- 41 500 tagged signal candidates
- FT algorithms: OS + SSπ
- tagging power 3 %
- largest systematic related to flavour tagging







Constraining Penguin Corrections to sin 2β

J. High Energy Phys. 06 (2015) 131

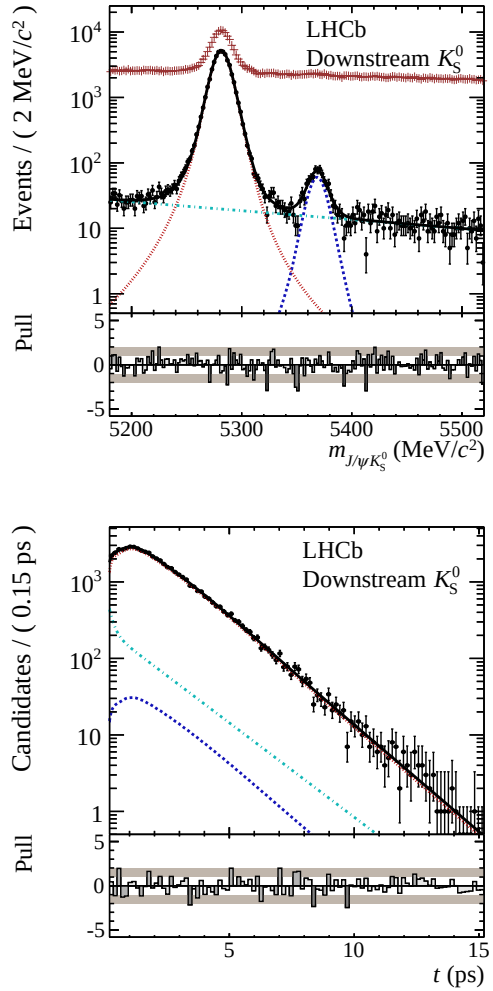
- $B_s^0 \to J/\psi K_S^0$ related to $B^0 \to J/\psi K_S^0$ via U-spin symmetry (exchange of d- and s-quarks)
- 100 x fewer B_s^0 than B^0 candidates
- simultaneous fit to B^0 and B_s^0 component
- FT algorithms: OS + SSK

$$A_{\Delta\Gamma}\left(B_s^0 \to J/\psi K_S^0\right) = \quad 0.49 \pm {}^{0.77}_{0.65}\ \text{(stat)} \pm 0.06\ \text{(syst)}$$

$$S\left(B_s^0 \to J/\psi K_S^0\right) = -0.08 \pm 0.40\ \text{(stat)} \pm 0.08\ \text{(syst)}$$

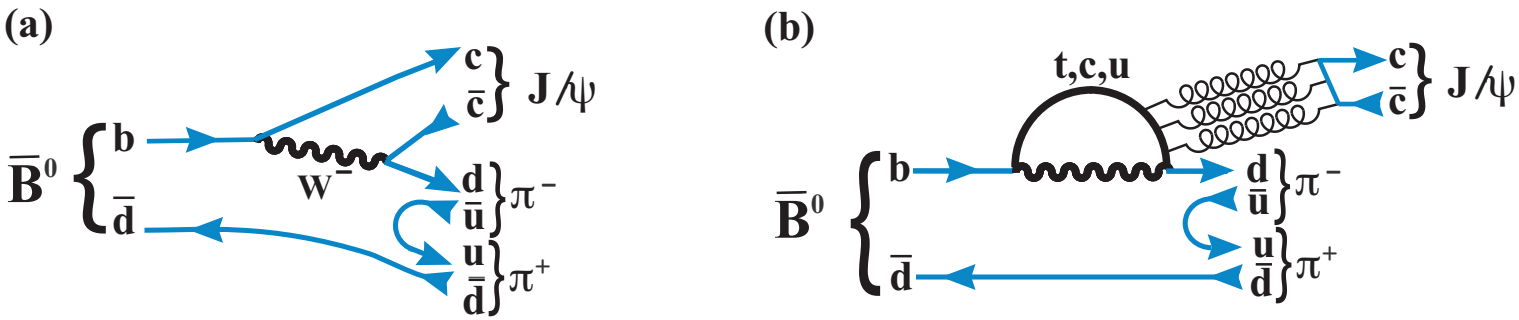
$$C\left(B_s^0 \to J/\psi K_S^0\right) = -0.28 \pm 0.41\ \text{(stat)} \pm 0.08\ \text{(syst)}$$

- first measurement of these parameters



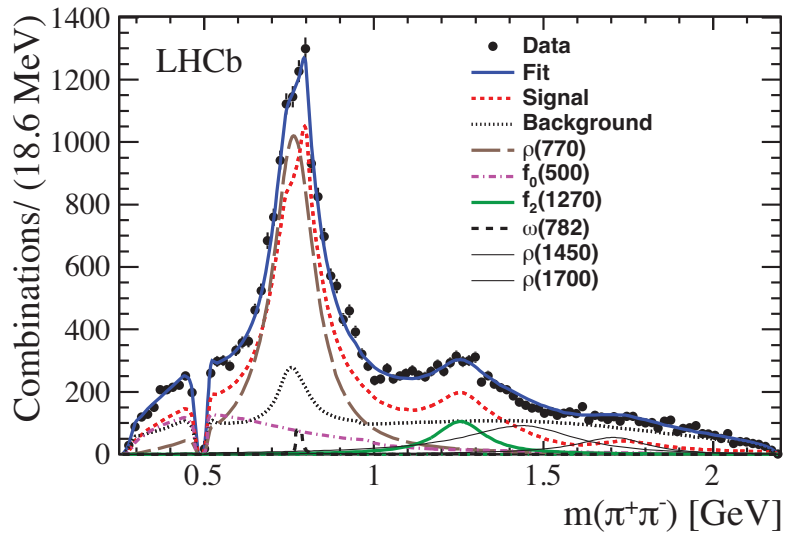
Measurement of *CP* Violation in $B^0 \to J/\psi\pi^+\pi^-$

Phys. Lett. B742 (2015) 38-49



- various $\pi^+\pi^-$ resonances studied
  - K^0_S vetoed
  - separation of angular momenta
- largest rate for $B^0 \to J/\psi\rho^0(770)$

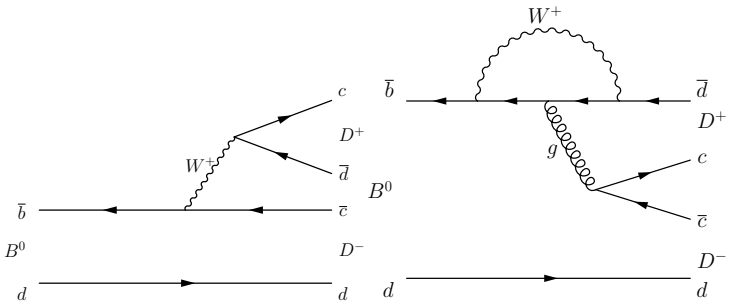
$$2\,\beta^{\text{eff}} = \left(41.7 \pm 9.6^{+2.8}_{-6.3}\right)^\circ$$



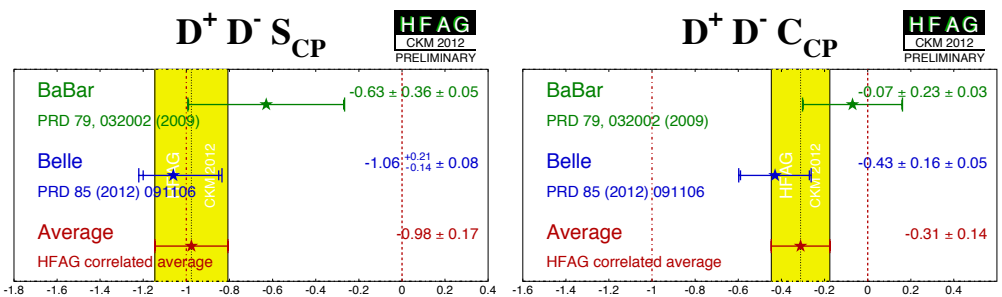
- limit on size of penguin amplitude contributions to *CPV* measurements

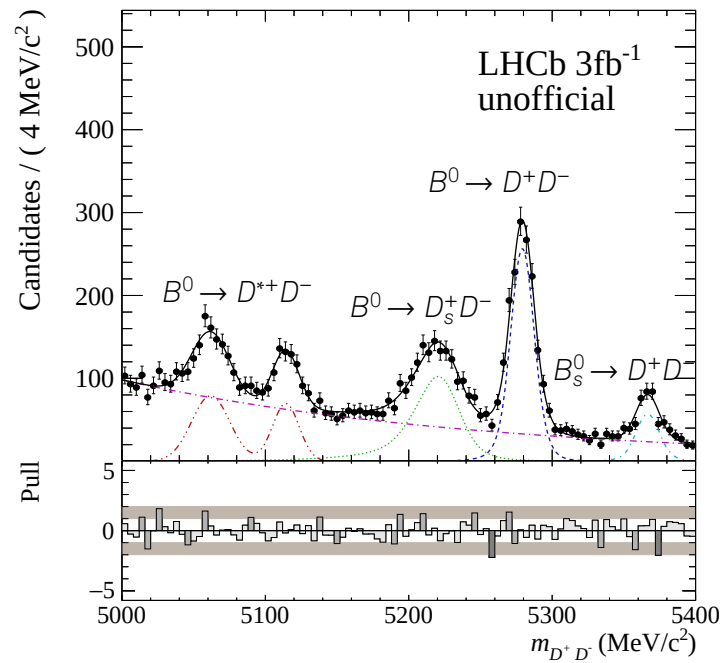
Measurement of sin 2β with $B^0 \to D^+D^-$

- $b \to c\bar{c}d$ transition
- access to other Feynman diagrams



- ~ 1400 untagged signal candidates
- tagging power: 4.3 % (OS only)
- expected sensitivity: ≤ ±0.25

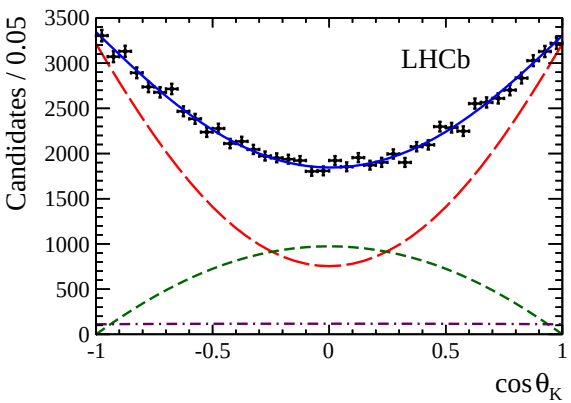


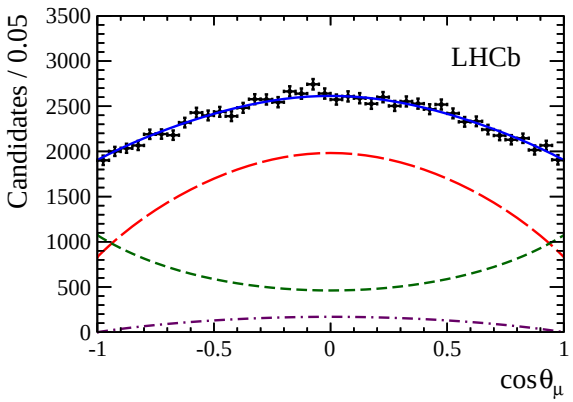


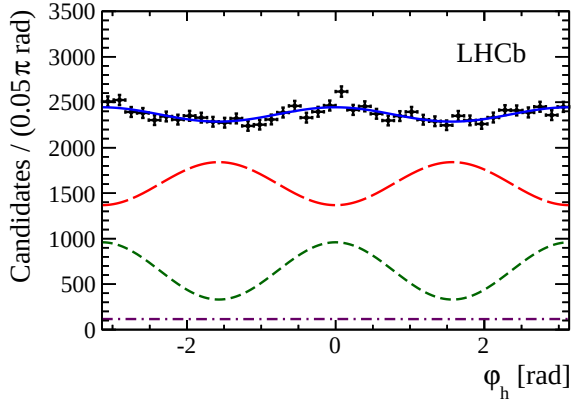
Measurement of ϕ_s using $B_s^0 \to J/\psi K^+K^-$

Phys. Rev. Lett. 114 (2015) 041801

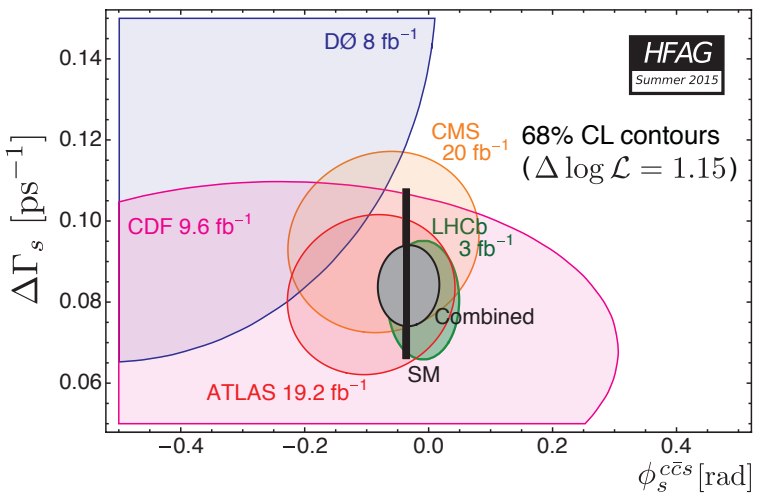
- $\phi_s = -2\beta_s + \Delta\phi_{\mathrm{NP}}$ with $\beta_s = \arg\left(-\frac{V_{ts}V_{tb}^*}{V_{cs}V_{cb}^*}\right)$
- angular analysis required to disentangle *CP*-even and *CP*-odd states







- $\phi_s = -0.058 \pm 0.049\,(\mathrm{stat}) \pm 0.006\,(\mathrm{syst})$ rad
- no evidence for polarisation dependence found



Indirect *CP* Asymmetries in $D^0 \to h^-h^+$

J. High Energy Phys. 04 (2015) 043

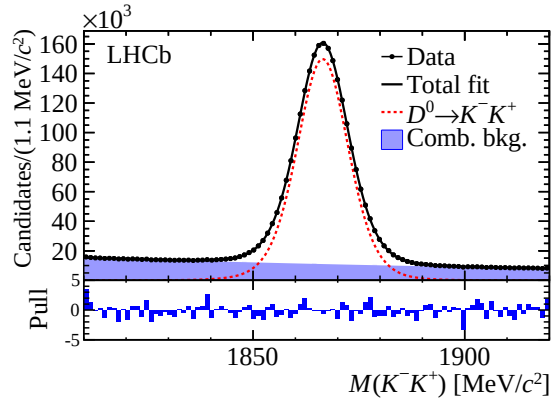
$$A_{CP}(t) \equiv \frac{\Gamma(D^0(t) \to f) - \Gamma(\bar{D}^0(t) \to f)}{\Gamma(D^0(t) \to f) + \Gamma(\bar{D}^0(t) \to f)} \approx A_{CP}^{\text{dir}} - A_\Gamma \frac{t}{\tau}$$

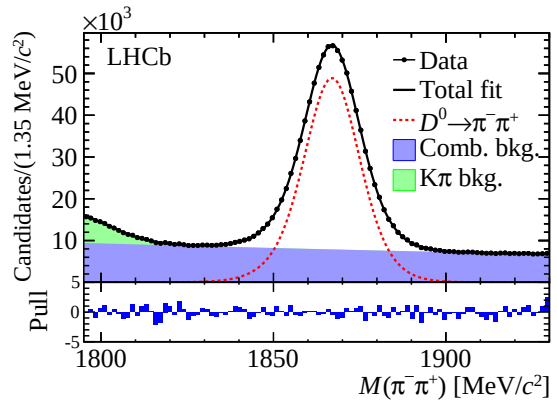
$$A_\Gamma \equiv \frac{\widehat{\Gamma}_{D^0} - \widehat{\Gamma}_{\bar{D}^0}}{\widehat{\Gamma}_{D^0} + \widehat{\Gamma}_{\bar{D}^0}} \approx \left(A_{CP}^{\text{mix}}/2 - A_{CP}^{\text{dir}}\right) y \cos\phi - x \sin\phi$$

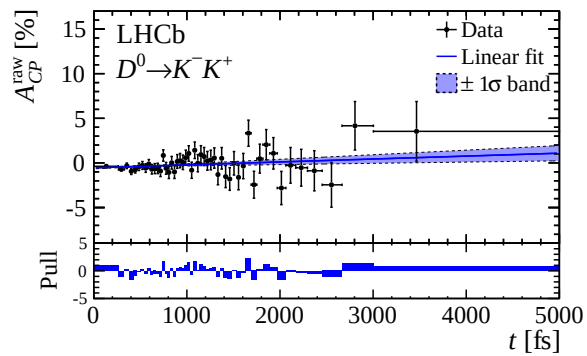
- D^0 mesons from semileptonic b-hadron decays
  - flavour determined by charge of μ
- simultaneous mass fit of D^0 and $\bar{D}^0$ yield in 50 bins of decay time
- χ^2-fit to $A_{CP}(t)$

$$A_\Gamma(K^+K^-) = \left(-0.134 \pm 0.077\ (\text{stat}) \pm {}^{0.026}_{0.034}\ (\text{syst})\right)\%$$

$$A_\Gamma(\pi^+\pi^-) = \left(-0.092 \pm 0.145\ (\text{stat}) \pm {}^{0.025}_{0.033}\ (\text{syst})\right)\%$$







Conclusion and Prospects

- world's largest sample of B- and D-hadrons
- Flavour Tagging essential for measurements of time-dependent CP violation
- new/improved Flavour Tagging algorithms
- extension of CPV physics program through
  - analysis of higher charmonium modes
    - $B_s^0 \to \psi(2S)\phi$, $B^0 \to \psi(2S)K_S^0$, ...
  - reconstruction involving electrons
    - $J/\psi \to e^+e^-$
- stay tuned for Run II data

Backup

Indirect *CP* Asymmetries in $D^0 \to h^-h^+$

J. High Energy Phys. 04 (2015) 043