Measurements of $\sin(2\beta)$ at LHCb

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(on behalf of the LHCb Collaboration)

18th September 2023

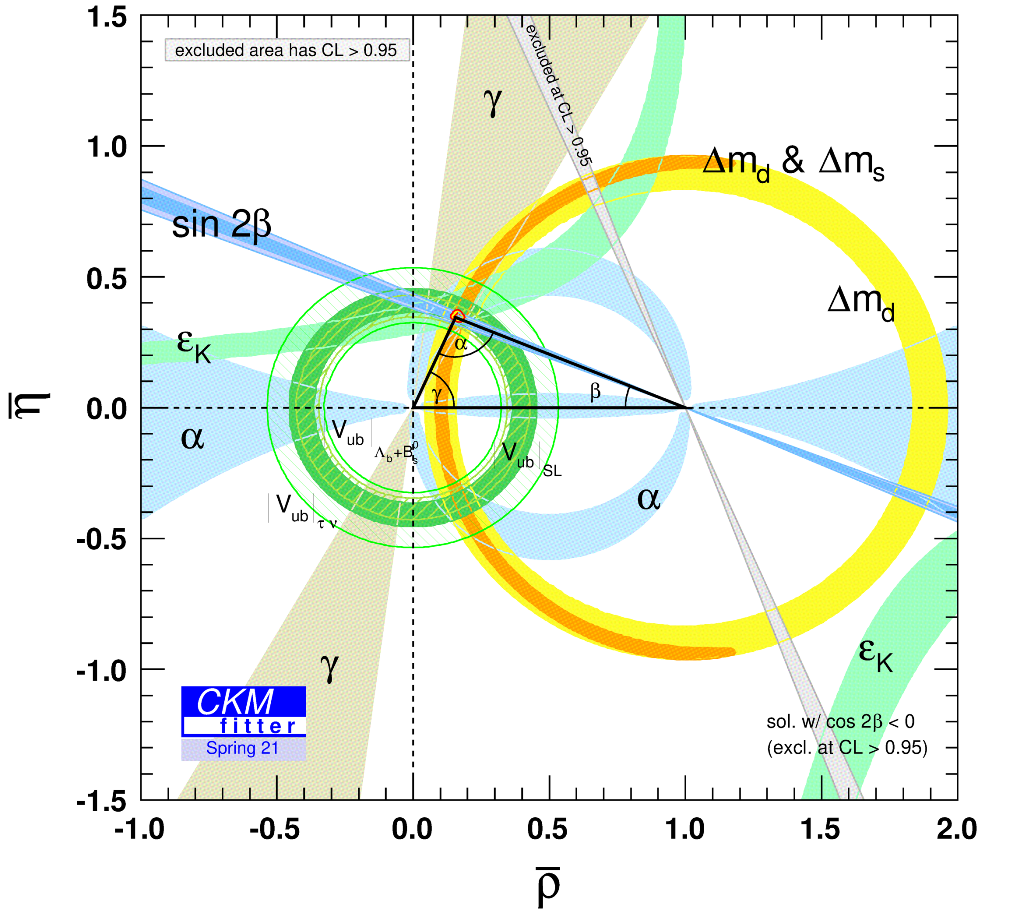
12th International Workshop on the CKM Unitarity Triangle

Overview

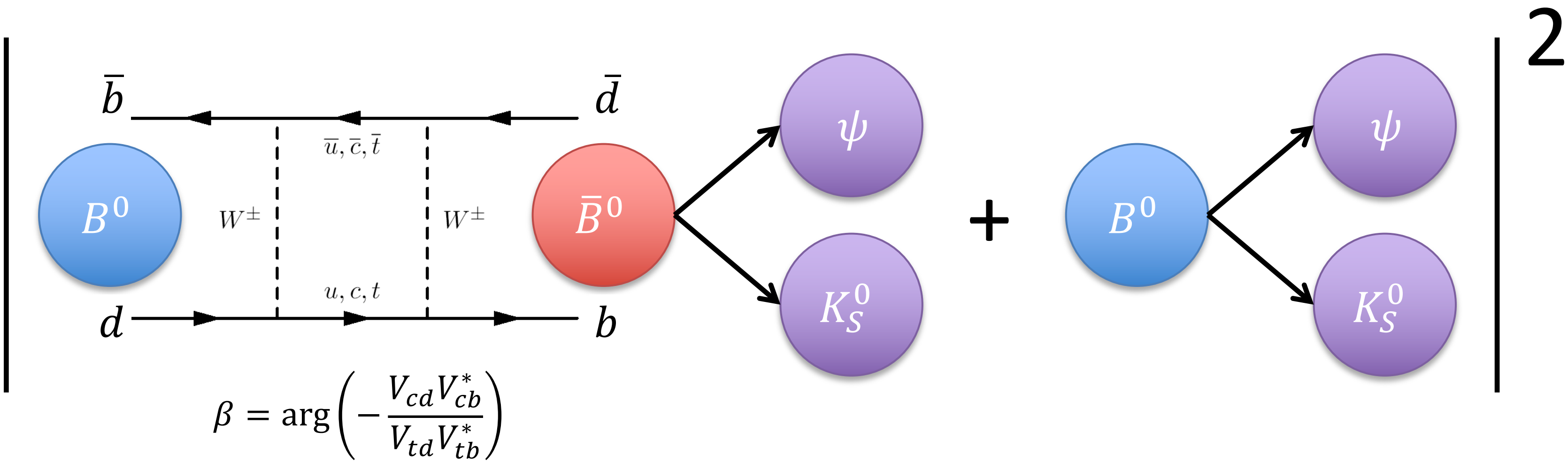
- Introduction
- Recent results from LHCb
  - Measurement of *CP* violation in $B^0 \to \psi(\to l^+l^-)\, K_S^0(\to \pi^+\pi^-)$ decays
    - LHCb-PAPER-2023-013 (in preparation)
- Concluding remarks

CKM mechanism and CP violation

- CKM mechanism agrees well with experiment
- But still room for new physics contributions
- Vital to make precision measurements of CP violating observables in as many different decay processes as possible
- Look for disagreements



$B^0 \sim \bar{B}^0$ mixing



- B^0 decays to *CP* eigenstates allow to probe the mixing phase, β, through the interference between decays with and without mixing

Time-dependent asymmetries

Assumes $\Delta\Gamma_d \approx 0$

- The time-dependent CP asymmetry is given by:

$$A_{CP}(t) = \frac{\Gamma[\bar{B}^0(t) \to f] - \Gamma[B^0(t) \to f]}{\Gamma[\bar{B}^0(t) \to f] + \Gamma[B^0(t) \to f]} = S_f \sin(\Delta m_d\, t) - C_f \cos(\Delta m_d\, t)$$

  - $\lambda_f = \frac{q}{p}\frac{\bar{A}_f}{A_f}$
  - $\frac{\bar{A}_f}{A_f}$ is the ratio of decay amplitudes
  - $\frac{q}{p}$ is related to neutral B mixing

$$S_f = \frac{2\mathrm{Im}\lambda_f}{1 + |\lambda_f|^2}$$

$$C_f = \frac{1 - |\lambda_f|^2}{1 + |\lambda_f|^2}$$

- B^0 decays via $b \to c\bar{c}s$ transitions, e.g., $B^0 \to \psi K_S^0$, give a theoretically clean determination of $\sin(2\beta)$

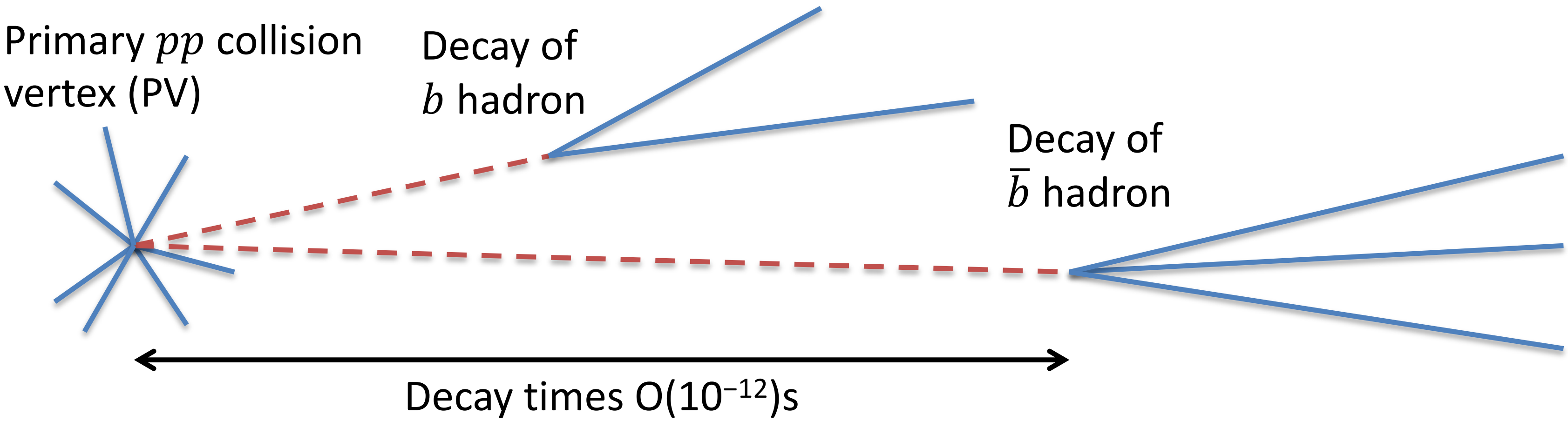
$$S_{\psi K_S^0} = \sin\left(2\beta + \Delta^{\mathrm{peng}} + \Delta^{\mathrm{NP}}\right)$$

$$C_{\psi K_S^0} \approx 0$$

$\Delta^{\mathrm{peng}} \approx 0.5°$

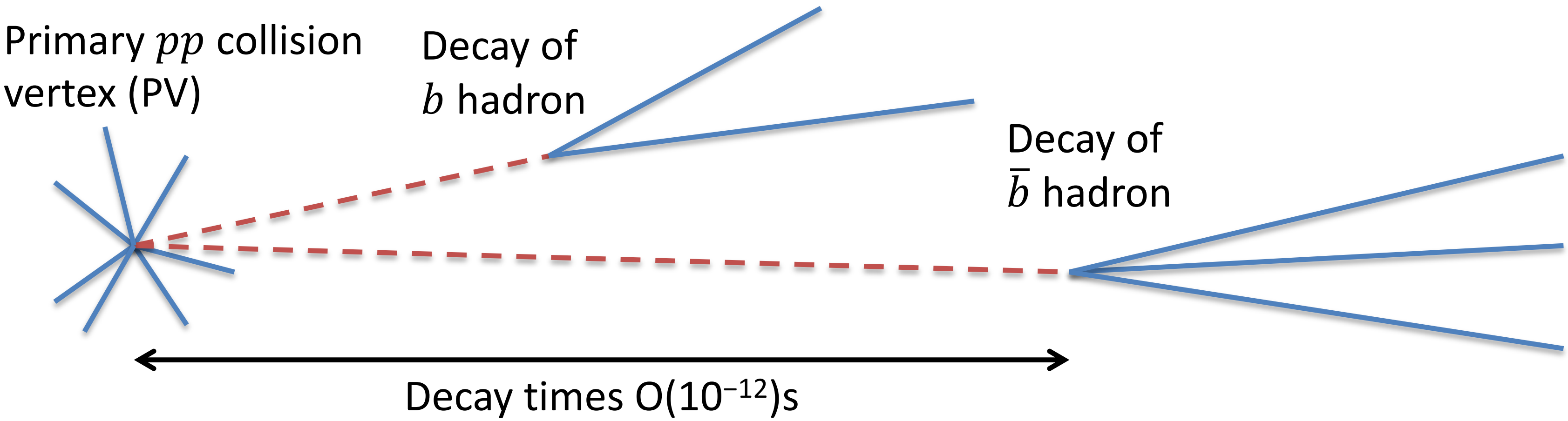
See, e.g.
J.Phys.G 48(2021) 065002
and references therein

Time dependent analysis



- Vertex measurements by LHCb VELO allow decay times of particles to be precisely determined
- Need also to tag the flavour of the signal at production
  - Using information from PV and/or the other b-hadron
- Putting these two pieces of information together, can measure decay rates as a function of the decay time
- Hence allows mixing-induced CPV to be probed

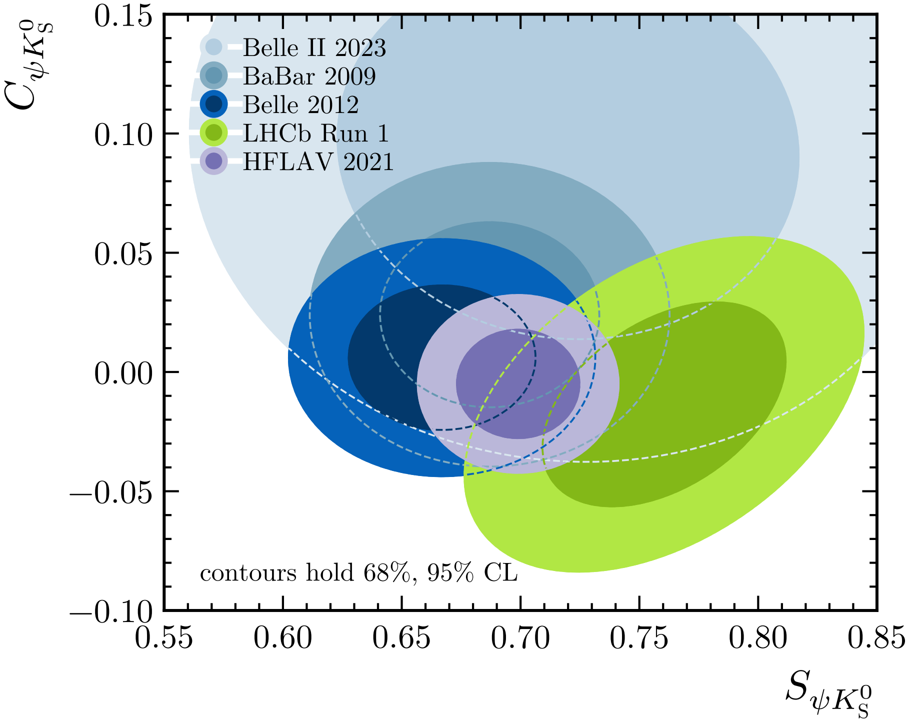
Time dependent analysis



- Need also to account for experimental effects, e.g.:
  - Rate of mis-tagging the B flavour at production
  - Decay time acceptance (from trigger & selection requirements)
  - Experimental resolution on the measurement of the decay time

Previous experimental status

- Previous LHCb results use Run 1 data (3 fb^{-1})
- Measurements of both $S_{\psi K^0}$ and $C_{\psi K^0}$ in good agreement between B-factories and LHCb
- World averages (HFLAV 2021)
  - $S_{\psi K^0} = \quad 0.699 \pm 0.017$
  - $C_{\psi K^0} = -0.005 \pm 0.015$



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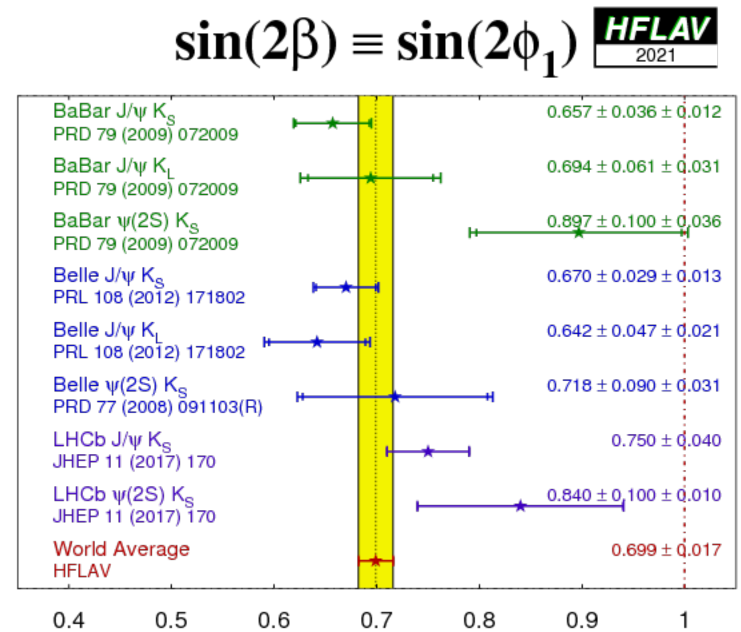
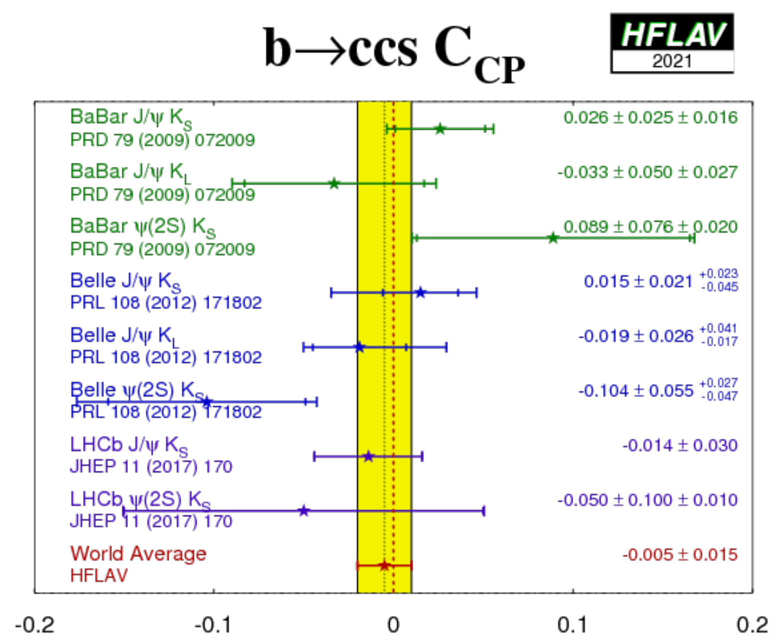
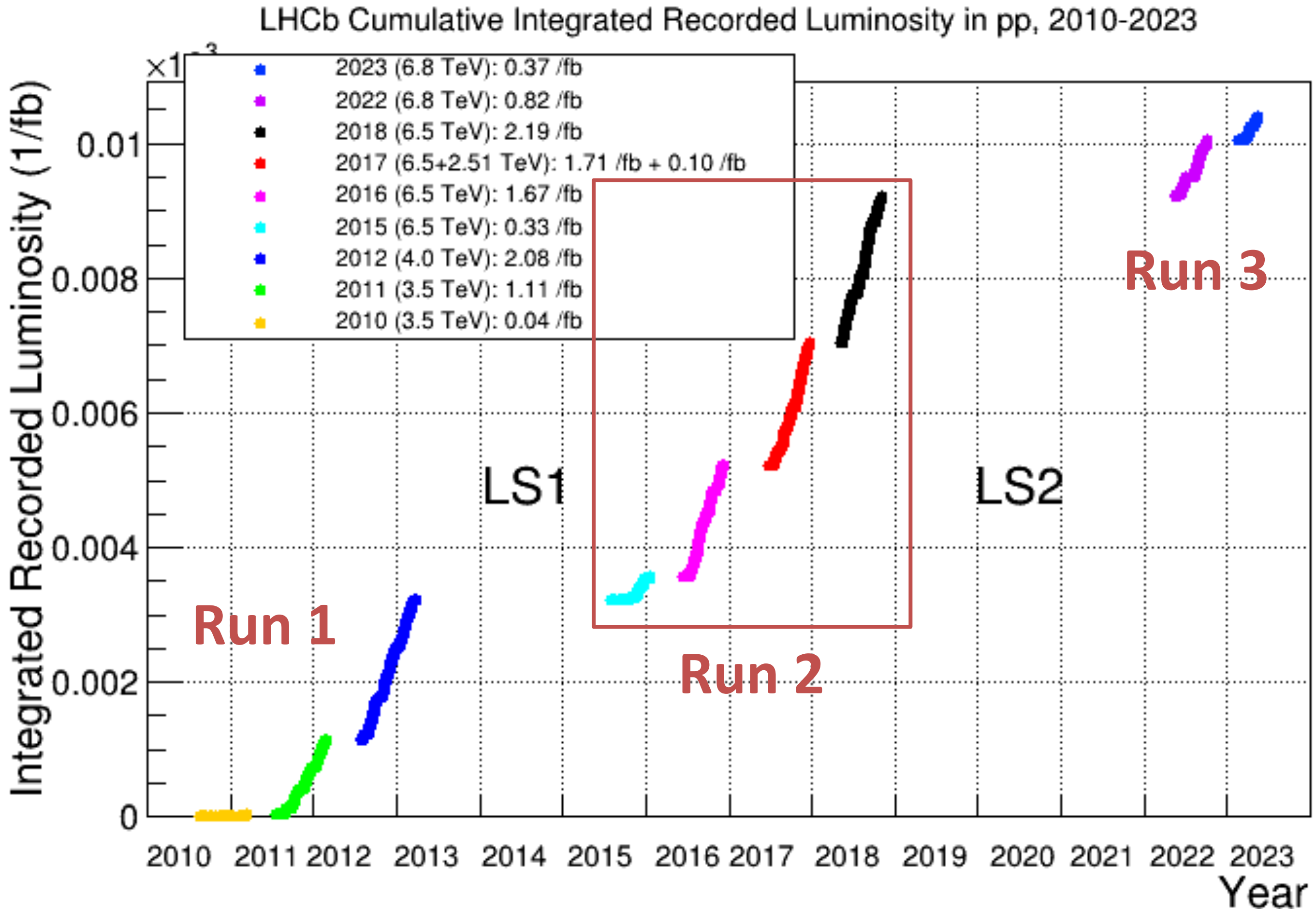




data sample



Run 2 data set (6 fb^{-1}) used in analysis presented today

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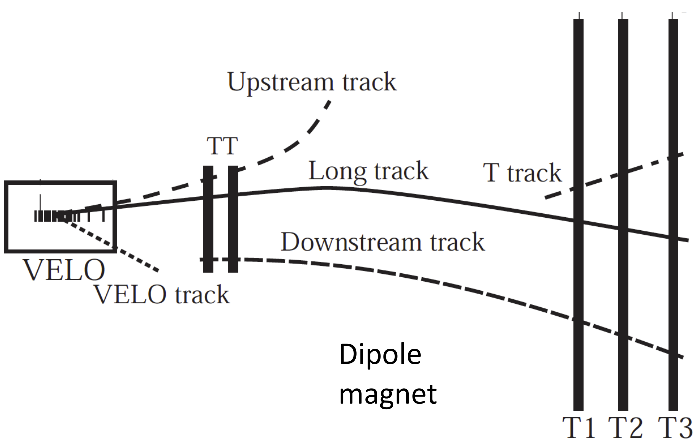
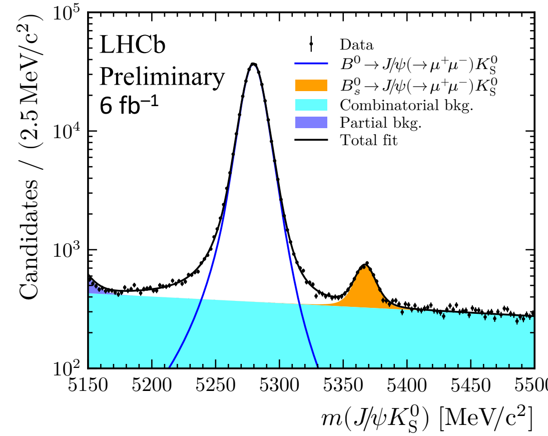
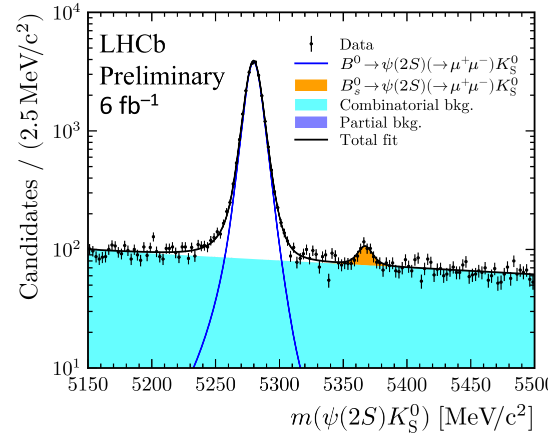
Signal reconstruction

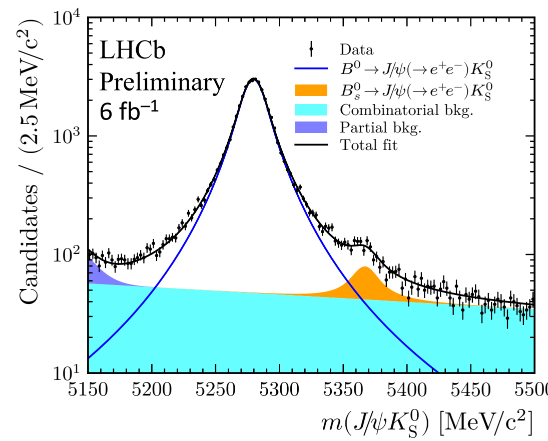
- Use three decay modes
  - $B^0 \to J/\psi(\to \mu^+\mu^-)\, K_S^0$ ~306k signal decays
  - $B^0 \to \psi(2S)(\to \mu^+\mu^-)\, K_S^0$ ~23k signal decays
  - $B^0 \to J/\psi(\to e^+e^-)\, K_S^0$ ~43k signal decays

- In all cases, reconstruct $K_S^0 \to \pi^+\pi^-$
  - For first time in CPV analysis, include “Upstream” tracks
  - Include also combinations of “Long” + “Downstream” tracks
  - Together, these boost signal yields by ~13%









Experimental decay rates

$$P(t,d,\eta) \propto \left[1 + d\left(1 - 2\omega^{+}(\eta)\right)\right]P_{B^0}(t) + \left[1 + d\left(1 - 2\omega^{-}(\eta)\right)\right]P_{\bar{B}^0}(t)$$

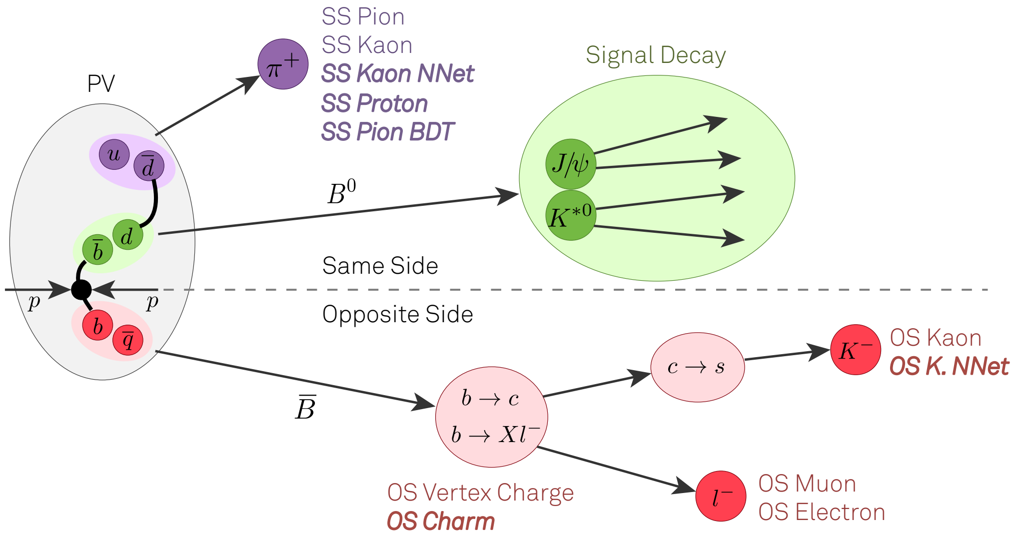
$$P_{B^0(\bar{B}^0)}(t) \propto \left\{(1 \mp A_P)(1 \mp \Delta\epsilon_{tag})e^{-\Gamma_d t'}(1 \mp S\sin(\Delta m_d t') \pm C\cos(\Delta m_d t'))\right\} \otimes R(t - t') \cdot \epsilon(t)$$

- Crucial experimental ingredients
  - Determination of any production asymmetry
  - Determination of the flavour of signal B at production (flavour tagging)
  - Determination of the decay time resolution and acceptance

- CP violation coefficients determined from weighted maximum likelihood fits
  - Fit variables:
    - Decay time, t
    - Flavour tag decision, d : $(+1 = B^0, -1 = \bar{B}^0)$
    - Predicted mis-tag probability, η
  - Simultaneous fit to 3 decay modes

Flavour tagging

- Use **Opposite Side** (OS) and **Same Side** (SS) taggers, which provide for each candidate:
  - Flavour tag decision, d:
    $+1 = B^0 \quad -1 = \bar{B}^0$
  - Predicted mis-tag probability, η



- Calibration
  - Use control modes in data $B^+ \to J/\psi\, K^+$ & $B^0 \to J/\psi\, K^{*0}$ to determine OS and SS calibration parameters:

$$\omega^{\pm} = p_0^{\pm} + p_1^{\pm}(\eta - \hat{\eta})$$

- Production asymmetry, A_P, & tagging asymmetry, $\Delta\epsilon_{tag}$, determined in same time-dependent fit to $B^0 \to J/\psi\, K^{*0}$ control mode
- Full covariance matrix used to constrain parameters in signal fit

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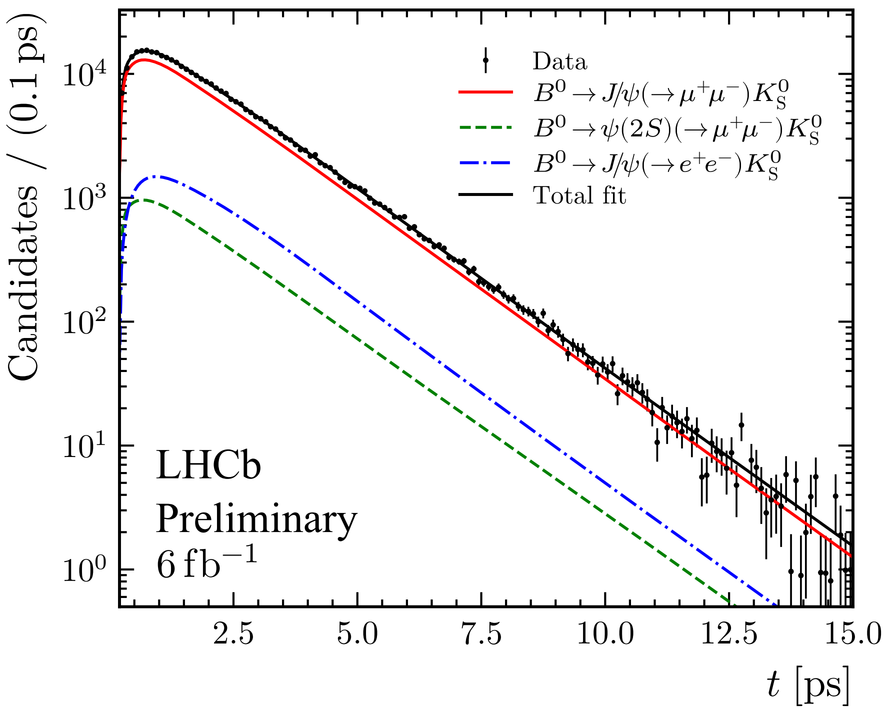
Decay time acceptance

$$P_{B^0(\bar{B}^0)}(t) \propto \{(1 \mp A_P)(1 \mp \Delta\epsilon_{tag})e^{-\Gamma_d t'}(1 \mp S\sin(\Delta m_d t') \pm C\cos(\Delta m_d t'))\} \otimes R(t-t') \cdot \epsilon(t)$$

- $\epsilon(t)$ is the decay time acceptance
  - Introduced by selection/trigger requirements
  - Parameterised using cubic splines
    - Number of spline components optimised using simulation
    - Parameters floated in fit to data

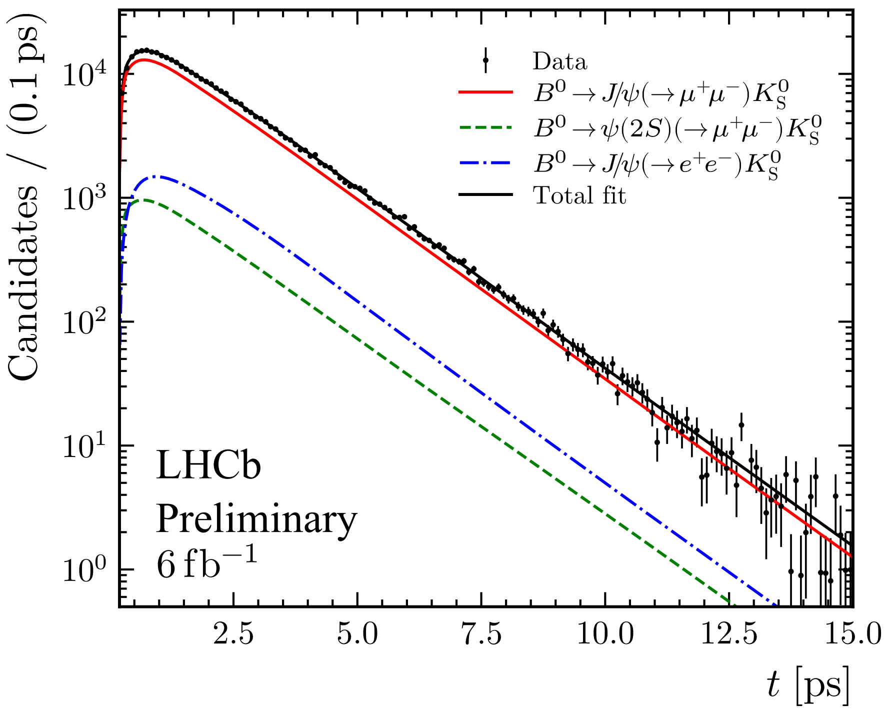


Decay time resolution and bias

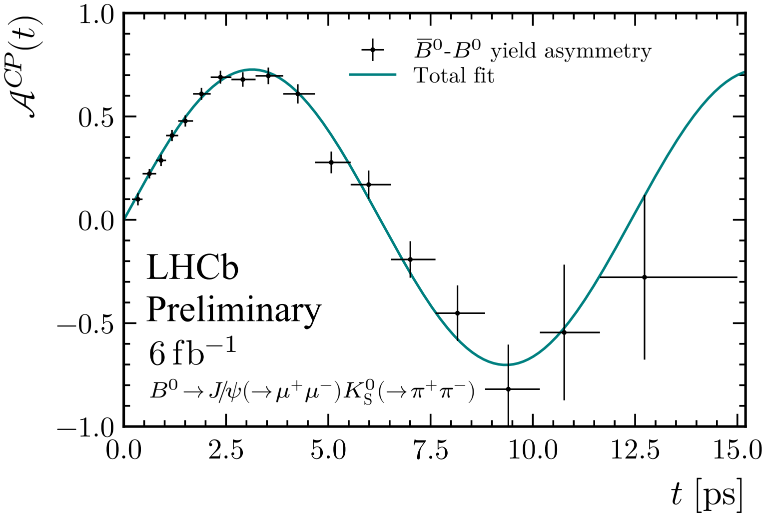
$$P_{B^0(\bar{B}^0)}(t) \propto \{(1 \mp A_P)(1 \mp \Delta\epsilon_{tag})e^{-\Gamma_d t'}(1 \mp S\sin(\Delta m_d t') \pm C\cos(\Delta m_d t'))\} \otimes R(t-t') \cdot \epsilon(t)$$

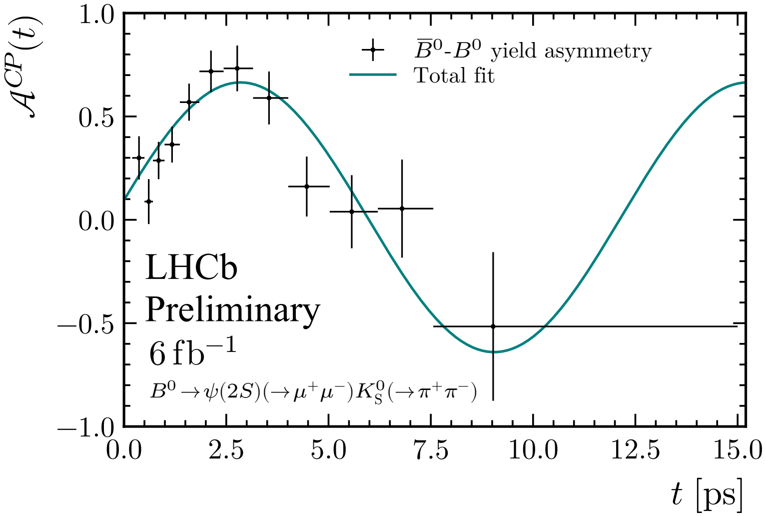
- $R(t-t')$ is the decay time resolution function
  - Modelled as sum of Gaussian functions
    - Centred at zero
    - Widths are linear functions of per-event decay time error
  - Effective resolution is ~60 fs
  - Thanks to the relatively long B^0 oscillation period, the resolution has a very small effect – at level of 0.5% – on oscillation amplitude

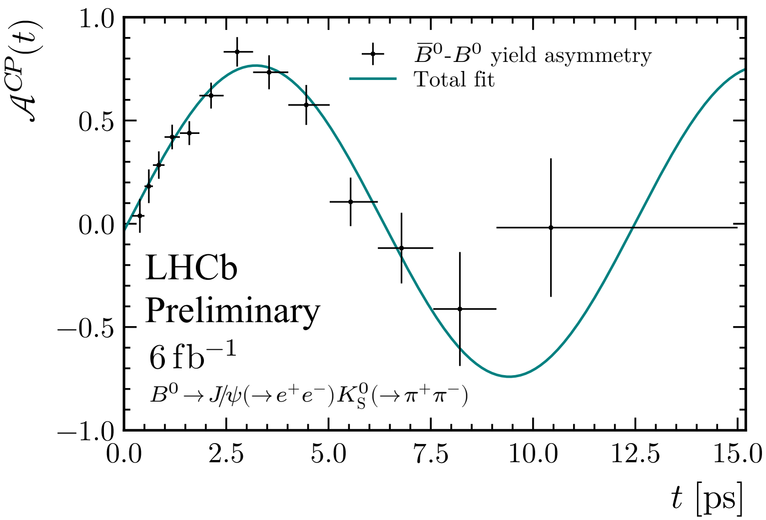
- Possible bias on the decay time measurement, from VELO misalignment, is calibrated with prompt data



Result of the simultaneous fit





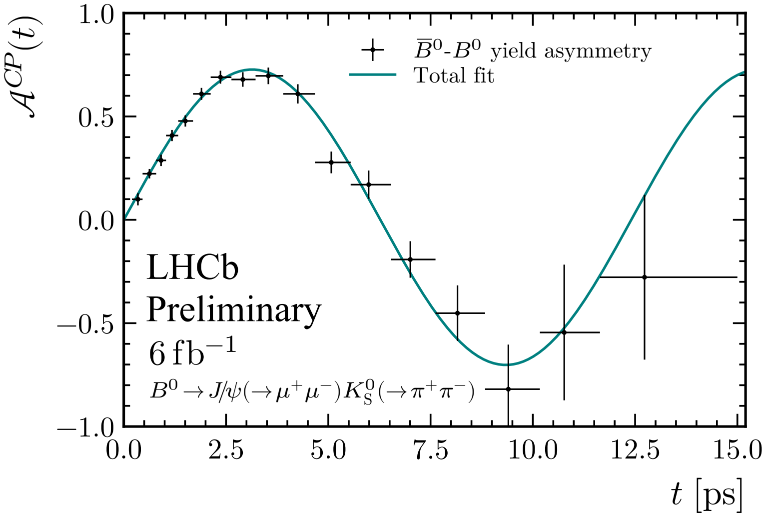


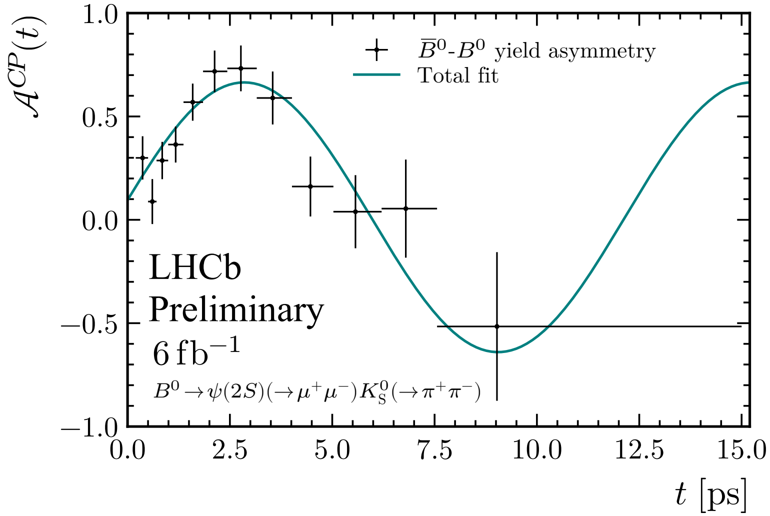
- Data points show the maximum likelihood estimator of the CP asymmetry integrated over the bin:

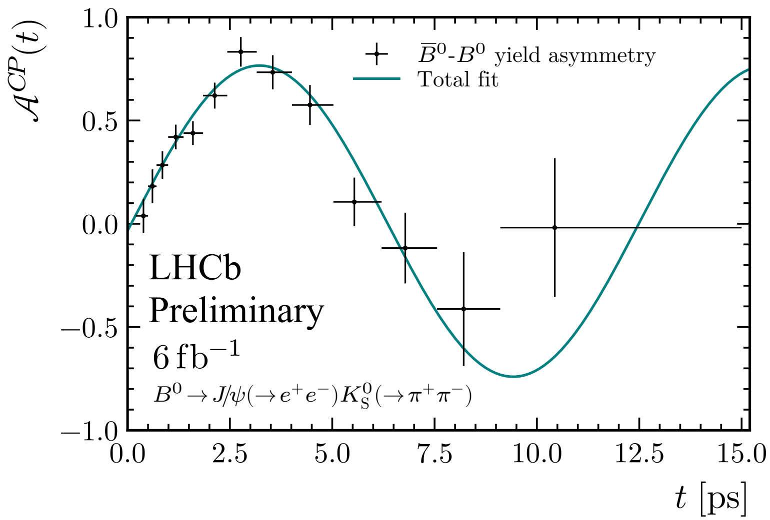
$$\mathcal{A}^{CP} = \frac{-\sum_j^N \kappa_j d_j D_j}{\sum_j^N \kappa_j D_j^2}$$

  - κ_j is the signal sWeight
  - d_j is the flavour tagging decision
  - $D_j = 1 - \omega_j^+ - \omega_j^-$ is the flavour tagging dilution

Result of the simultaneous fit







- Corrections applied to CPV coefficients to account for
  - Kaon regeneration
  - CPV in kaon system
- Corrections:
  - $\delta S = +0.0016$
  - $\delta C = -0.0035$

Systematic uncertainties

- All systematic uncertainties evaluated using pseudoexperiments
- Variations of sources of systematic uncertainty used to generate samples

Source	$\sigma(S)$	$\sigma(C)$
Fitter validation	0.0004	0.0006
Decay-time bias model	0.0007	0.0013
FT $\Delta\epsilon_{\rm tag}$ portability	0.0014	0.0017
FT calibration portability	0.0053	0.0001
$\Delta\Gamma_d$ uncertainty	0.0055	0.0017

- Fitter validation
  - Nominal model used for generation
- Decay-time bias model
  - Variation of bias model parameters
- FT $\Delta\epsilon_{tag}$ portability
  - Variation from difference in asymmetry between simulated samples of calibration channels and signal channels
- FT calibration portability
  - Variation from difference between calibration parameters obtained from MC-truth information in calibration channels and signal channels
- $\Delta\Gamma_d$ uncertainty
  - Vary by HFLAV uncertainty

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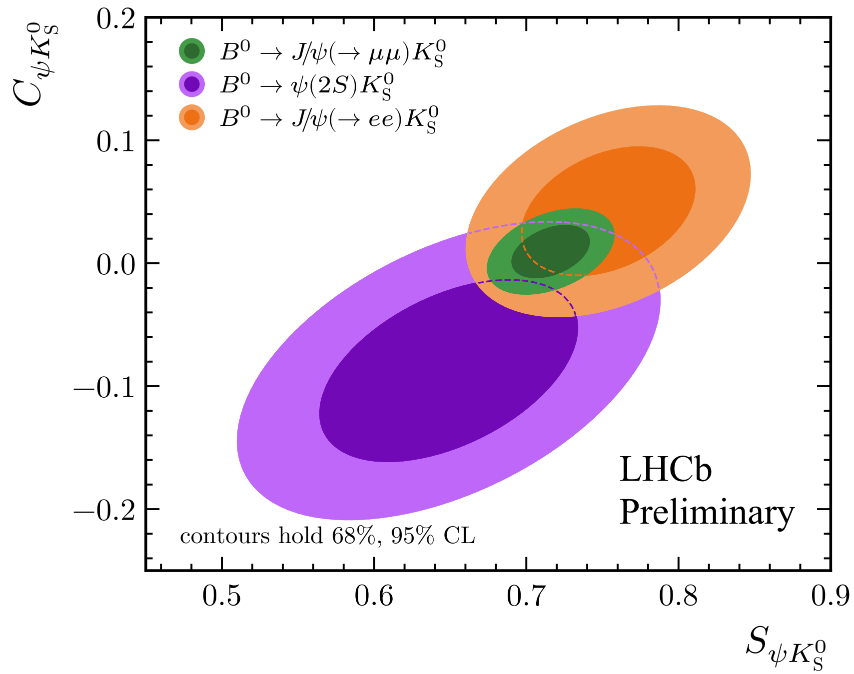
Results

LHCb Preliminary

Mode	S	C	ρ
$J/\psi(\to \mu^+\mu^-)\,K_S^0$	$0.716 \pm 0.015 \pm 0.007$	$+0.010 \pm 0.014 \pm 0.003$	0.446
$\psi(2S)(\to \mu^+\mu^-)\,K_S^0$	$0.649 \pm 0.053 \pm 0.018$	$-0.087 \pm 0.048 \pm 0.005$	0.503
$J/\psi(\to e^+e^-)\,K_S^0$	$0.754 \pm 0.037 \pm 0.008$	$+0.042 \pm 0.034 \pm 0.008$	0.374



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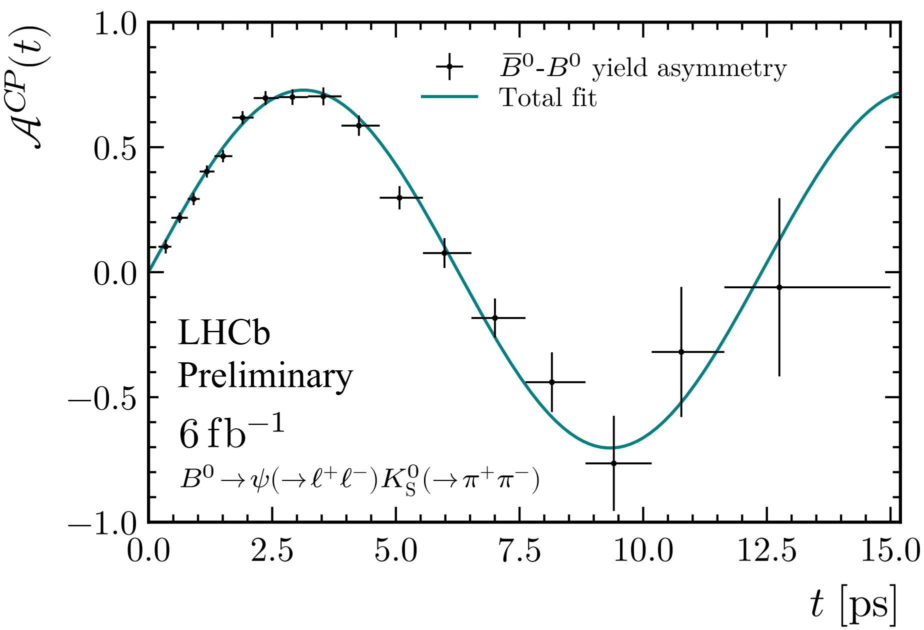


Combination from simultaneous fit of the three decay modes:

$$S_{\psi K_S^0} = 0.717 \pm 0.013 \pm 0.008$$

$$C_{\psi K_S^0} = 0.008 \pm 0.012 \pm 0.003$$

$$\rho = 0.441$$

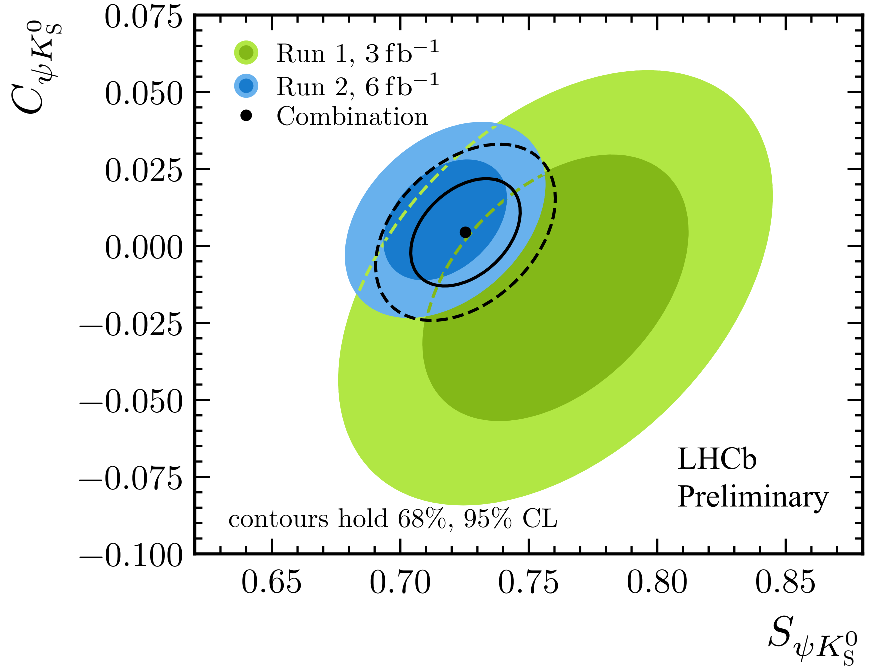
Combination with Run 1

- Combination with the previous Run 1 results
  - Assumes sources of systematic uncertainties from external parameters Δm_d, $\Delta\Gamma_d$, A_P are fully correlated

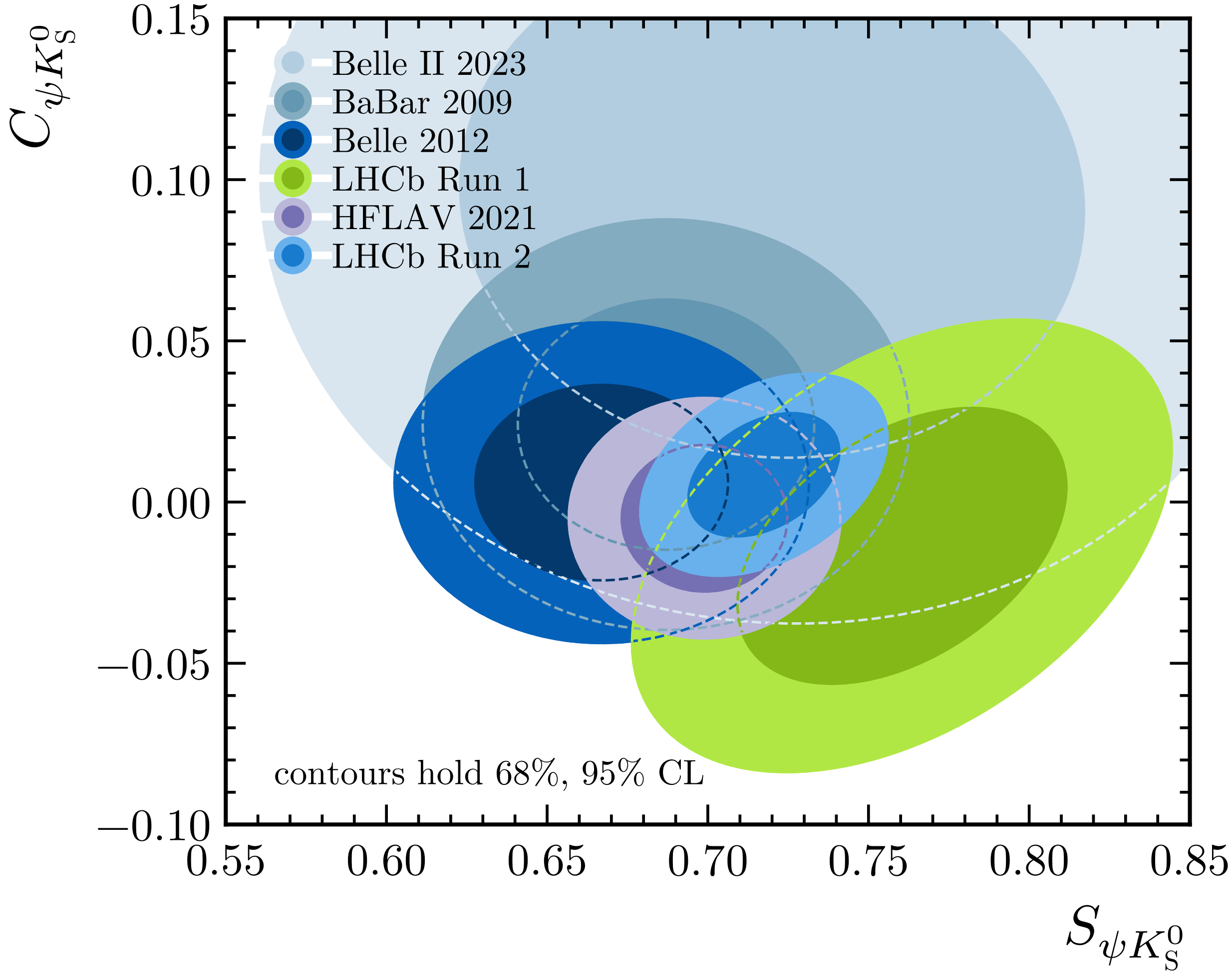
$$S_{\psi K_S^0} = 0.724 \pm 0.014$$

$$C_{\psi K_S^0} = 0.004 \pm 0.012$$

$$\rho = 0.40$$



Comparison with other experiments

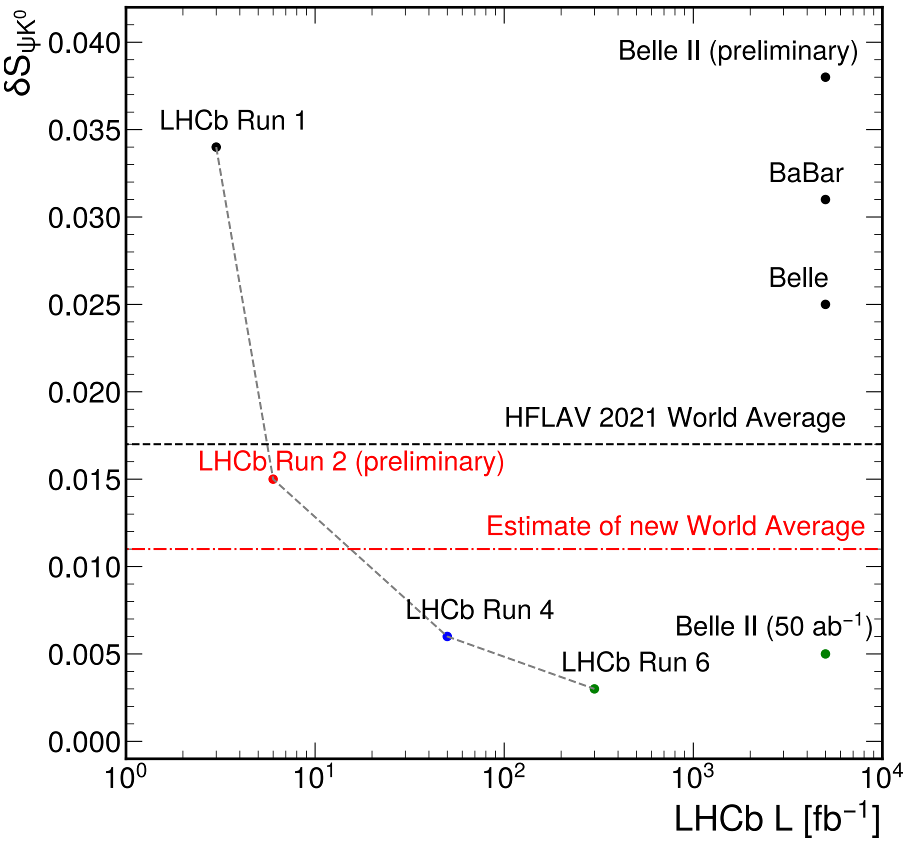


Does not include latest result from Belle II

Concluding remarks

- To date, most precise single measurement of $\sin(2\beta)$
- Should improve precision of world average by $\sim 35\%$
- Still statistically limited

- Looking further forward, the LHCb upgrades will provide unprecedented samples of these decays
- Excellent prospects for making precision tests of the Standard Model explanation of CP violation



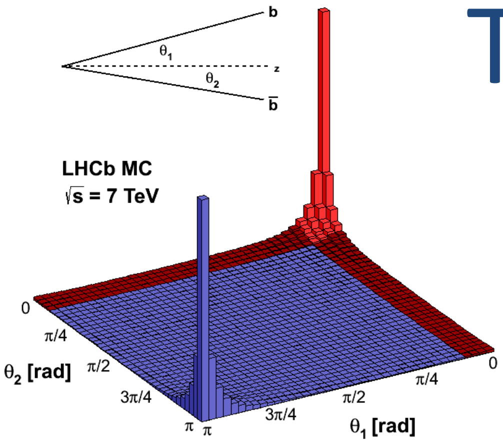
CERN-LHCC-2021-012
LHCb-PUB-2018-009
PoS(KMI2017)005

Concluding remarks

- However, not finished with Run 1 & 2 dataset just yet!
- Excellent prospects to make/update measurements of $\sin(2\beta)$ in several other quark-level transitions:
  - $b \to c\bar{c}d$, e.g., $B^0 \to J/\psi\, \pi^+\pi^-$ and $B^0 \to D^{(*)+}D^{(*)-}$ where LHCb had results from Run 1:
    PLB 742 (2015) 38 and PRL 117 (2016) 261801
  - $b \to c\bar{u}d$, e.g., $B^0 \to D_{CP}\pi^+\pi^-$ using method from
    JPhysG 36 (2009) 025006
  - $b \to q\bar{q}s$, e.g., $B^0 \to K_S^0 h^+h^-$, where LHCb has published a time-integrated amplitude analysis using Run 1 data:
    PRL 120 (2018) 261801
- Watch out for news on these and similar channels!

Backup Slides

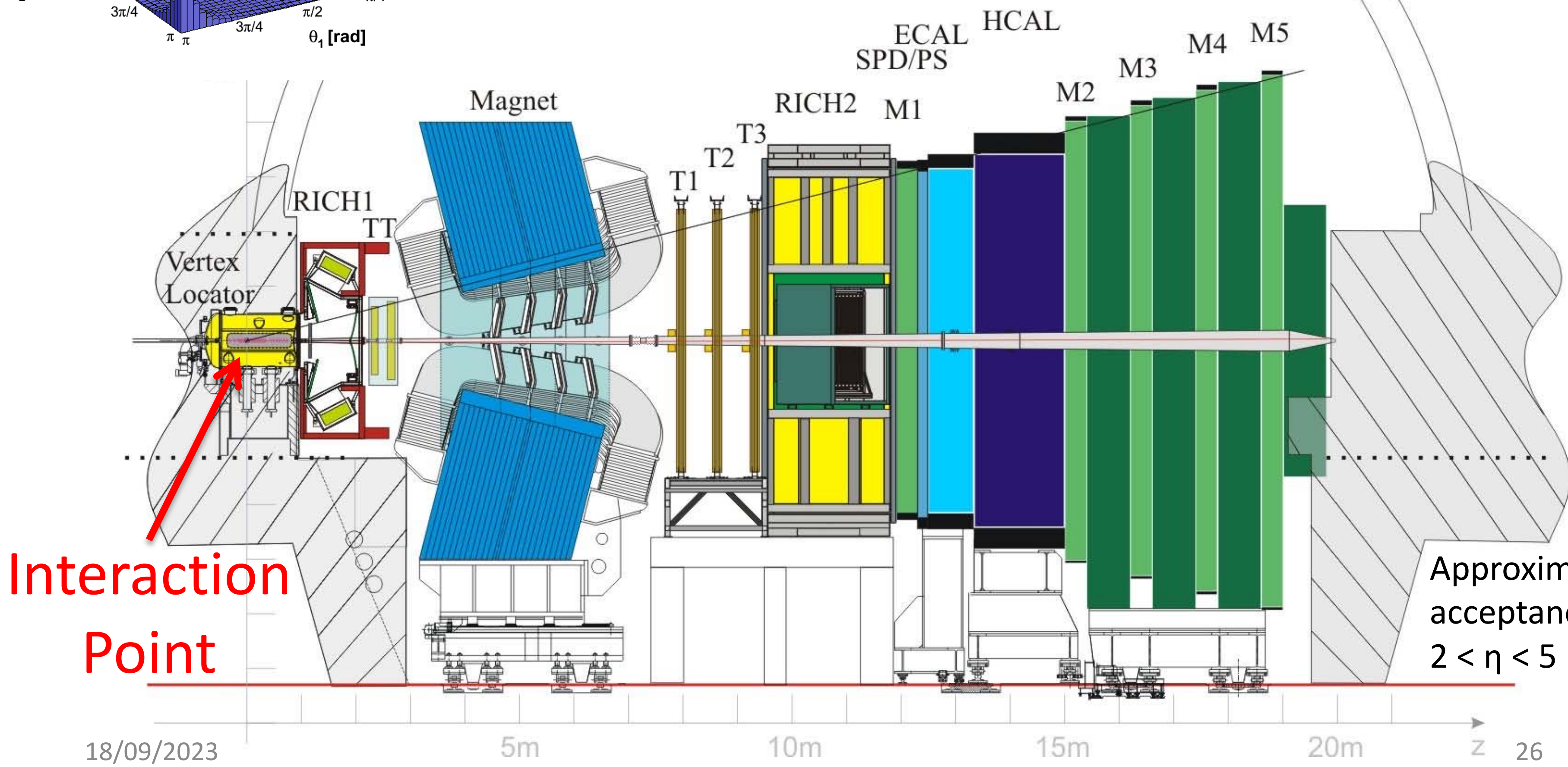
The LHCb detector



LHCb $\sigma(pp \rightarrow H_b X)$ @ 7 TeV = (72.0 ± 0.3 ± 6.8) μb

LHCb $\sigma(pp \rightarrow H_b X)$ @ 13 TeV = (154.3 ± 1.5 ± 14.3) μb

[Phys. Rev. Lett. 118 (2017) 052002]

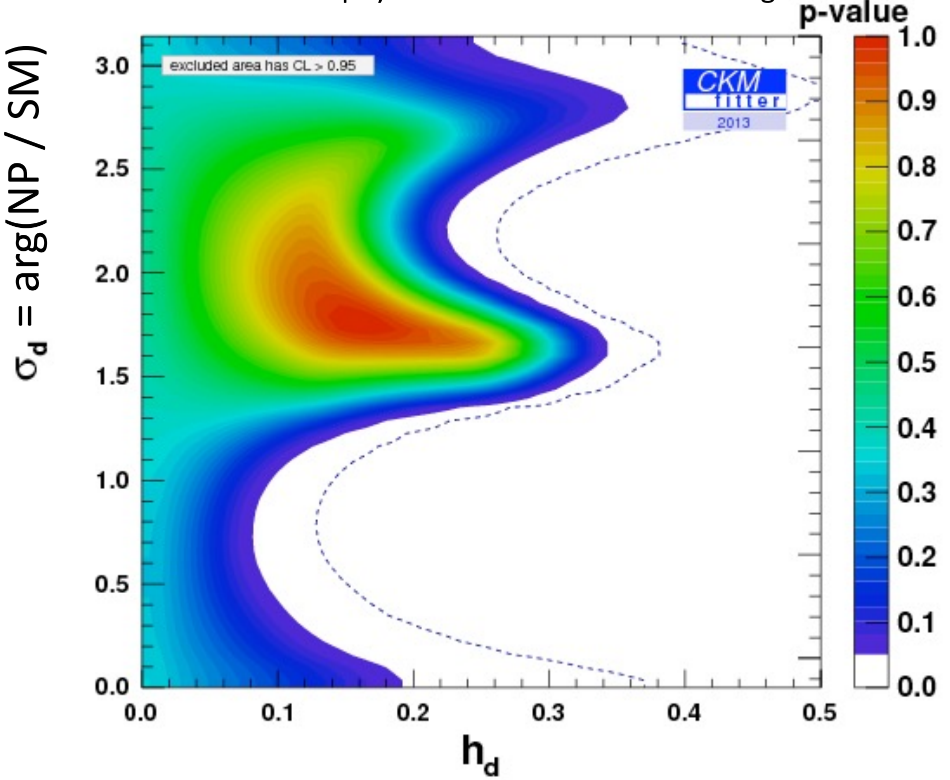


Approximate acceptance: $2 < \eta < 5$

CKM mechanism and CP violation

- CKM mechanism agrees well with experiment
- But still room for new physics contributions
- Vital to make precision measurements of CP violating observables in as many different decay processes as possible
- Look for disagreements

Allowed new physics contributions in B^0 mixing



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Controlling penguin contributions

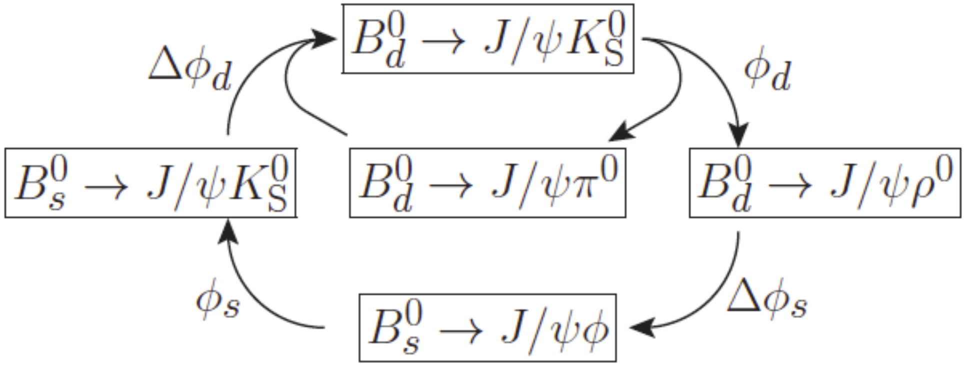


Figure 5: The cross-dependence between the determination of ϕ_d and ϕ_s and their hadronic penguin shifts, showing the interplay between the five $B_q^0 \to J/\psi X$ decays discussed in this paper.

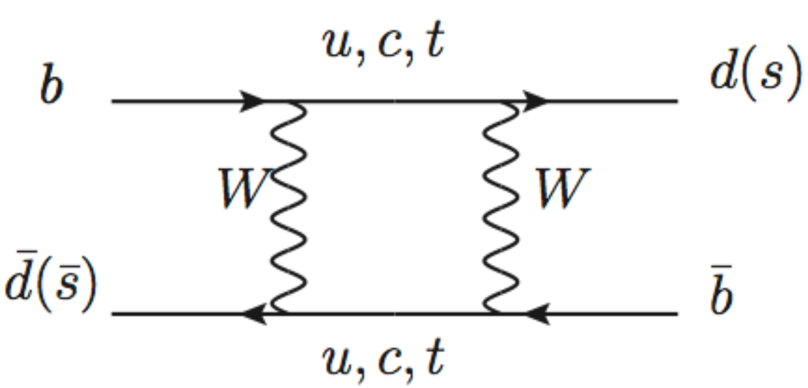
Manifestations of CPV

- **CPV in decay**
  - The ratio of the amplitudes for the decay of b and $\bar{b}$ hadrons to CP-conjugate final states is not of unit magnitude: $|\bar{A}_{\bar{f}}/A_f| \neq 1$
  - Only form of CPV possible for B^+ mesons and b-baryons

- **CPV in mixing**
  - The ratio of the mixing amplitudes is not of unit magnitude: $|q/p| \neq 1$
  - Expected to be very small for the B meson system

- **Mixing-induced CPV**
  - The ratio of the amplitudes for decays with and without mixing is not real: $\arg(\lambda_f) + \arg(\lambda_{\bar{f}}) \neq 0$
  - Occurs for both B^0 and B_s^0
  - Requires time-dependent analyses
  - The focus of this talk!

$$\lambda_f = \frac{q}{p}\frac{\bar{A}_f}{A_f}$$



Neutral B mesons exhibit mixing through box diagrams

Time-dependent decay rates

- For an initially pure flavour eigenstate, time evolution proceeds according to:

$$\frac{d\Gamma[B^0_{d,s}(t)\to f]}{dt} \propto e^{-\Gamma t}\Big[\left(|A_f|^2+|\bar{A}_f|^2\right)\cosh\left(\tfrac{\Delta\Gamma_{d,s}}{2}t\right)+\left(|A_f|^2-|\bar{A}_f|^2\right)\cos(\Delta m_{d,s}\,t) +2\mathrm{Re}\left(\tfrac{q}{p}A_f^*\bar{A}_f\right)\sinh\left(\tfrac{\Delta\Gamma_{d,s}}{2}t\right)-2\mathrm{Im}\left(\tfrac{q}{p}A_f^*\bar{A}_f\right)\sin(\Delta m_{d,s}\,t)\Big]$$

$$\frac{d\Gamma[\bar{B}^0_{d,s}(t)\to f]}{dt} \propto e^{-\Gamma t}\Big[\left(|A_f|^2+|\bar{A}_f|^2\right)\cosh\left(\tfrac{\Delta\Gamma_{d,s}}{2}t\right)-\left(|A_f|^2-|\bar{A}_f|^2\right)\cos(\Delta m_{d,s}\,t) +2\mathrm{Re}\left(\tfrac{q}{p}A_f^*\bar{A}_f\right)\sinh\left(\tfrac{\Delta\Gamma_{d,s}}{2}t\right)+2\mathrm{Im}\left(\tfrac{q}{p}A_f^*\bar{A}_f\right)\sin(\Delta m_{d,s}\,t)\Big]$$

- The time-dependent CP asymmetry is therefore:

$$A_{CP}(t)=\frac{\Gamma[\bar{B}^0_{d,s}(t)\to f]-\Gamma[B^0_{d,s}(t)\to f]}{\Gamma[\bar{B}^0_{d,s}(t)\to f]+\Gamma[B^0_{d,s}(t)\to f]}=\frac{S_f\sin(\Delta m_{d,s}\,t)-C_f\cos(\Delta m_{d,s}\,t)}{\cosh\left(\frac{\Delta\Gamma_{d,s}}{2}t\right)+A_f^{\Delta\Gamma_{d,s}}\sinh\left(\frac{\Delta\Gamma_{d,s}}{2}t\right)}$$

$$S_f=\frac{2\mathrm{Im}\lambda_f}{1+|\lambda_f|^2}\qquad C_f=\frac{1-|\lambda_f|^2}{1+|\lambda_f|^2}\qquad \lambda_f=\frac{q}{p}\frac{\bar{A}_f}{A_f}$$

$$A_f^{\Delta\Gamma_{d,s}}=\frac{2\mathrm{Re}\lambda_f}{1+|\lambda_f|^2}$$

- $|C_f|^2+|S_f|^2+|A_f^{\Delta\Gamma}|^2=1$
- $\frac{q}{p}$ is related to the neutral B mixing
- $\frac{\bar{A}_f}{A_f}$ is the ratio of decay amplitudes

Time-dependent asymmetries

- The time-dependent CP asymmetry is given by:

$$A_{CP}(t) = \frac{\Gamma[\bar{B}^0(t) \to f] - \Gamma[B^0(t) \to f]}{\Gamma[\bar{B}^0(t) \to f] + \Gamma[B^0(t) \to f]} = \frac{S_f \sin(\Delta m_d\, t) - C_f \cos(\Delta m_d\, t)}{\cosh\left(\frac{\Delta\Gamma_d}{2} t\right) + A_f^{\Delta\Gamma_d} \sinh\left(\frac{\Delta\Gamma_d}{2} t\right)}$$

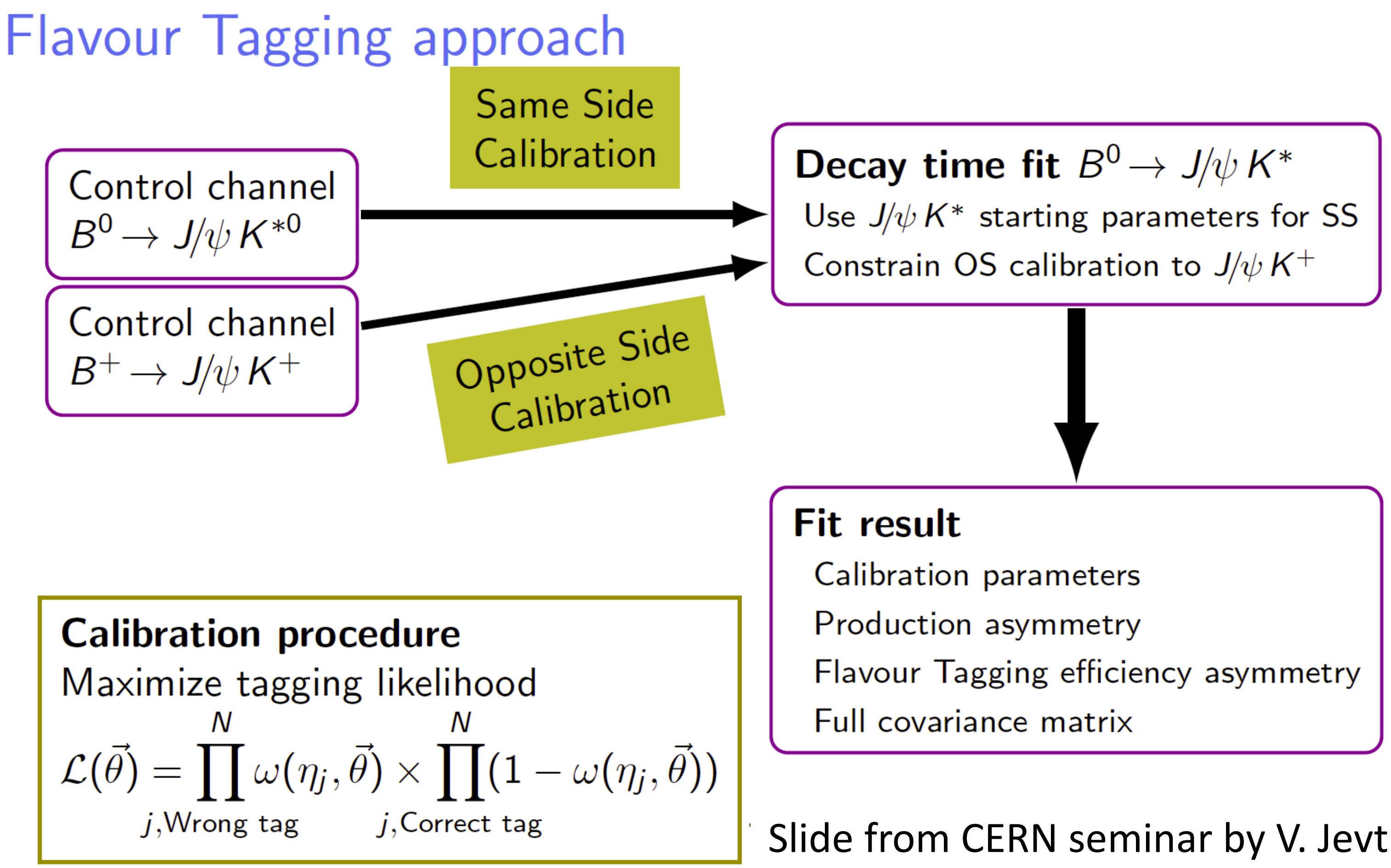
$$S_f = \frac{2\mathrm{Im}\lambda_f}{1 + |\lambda_f|^2} \qquad C_f = \frac{1 - |\lambda_f|^2}{1 + |\lambda_f|^2} \qquad A_f^{\Delta\Gamma_d} = \frac{2\mathrm{Re}\lambda_f}{1 + |\lambda_f|^2}$$

$$|S_f|^2 + |C_f|^2 + |A_f^{\Delta\Gamma}|^2 = 1$$

$$\lambda_f = \frac{q}{p}\frac{\bar{A}_f}{A_f}$$

- $\frac{\bar{A}_f}{A_f}$ is the ratio of decay amplitudes
- $\frac{q}{p}$ is related to the neutral B mixing

Flavour Tagging Approach



Slide from CERN seminar by V. Jevtic & P. Li
https://indico.cern.ch/event/1281612/

Flavour Tagging Performance

Table 1: Flavour Tagging efficiency and mean squared dilution of each decay channel.

Channel	ϵ_{tag} [%]	$\mathcal{D}^2$ [%]	$Q = \epsilon_{tag}\mathcal{D}^2$ [%]
$B^0 \to J/\psi(\to \mu^+\mu^-)K^0_S$	85.34 ± 0.05	4.661 ± 0.013	3.98
$B^0 \to J/\psi(\to e^+e^-)K^0_S$	92.20 ± 0.08	6.462 ± 0.032	5.96
$B^0 \to \psi(2S)(\to \mu^+\mu^-)K^0_S$	84.81 ± 0.15	4.59 ± 0.04	3.89