Overview of time-dependent CP violation in B meson decays

Second Italian Workshop on the Physics at High Intensity

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Jakub Kandra

(INFN Padova)

on behalf of Belle II collaboration

Time-dependent CP violation in B mesons

- Belle II detector at SuperKEKB and LHCb detector at LHC
- Experimental methods
- Time-dependent CP violation
- Flavor taggers in experiments
- Time-dependent CP violation results
  - $\sin 2\varphi_1$ and $\sin 2\varphi_1^{eff}$ measurements
    - $J/\psi K^0_S$, $\eta' K^0_S$, φK^0_S, $\pi^0 K^0_S$ and $K^0_S K^0_S K^0_S$ analyses
  - φ_s, $\varphi_s^{s\bar{s}s}$, Γ_s and φ_3 analyses
- Systematic uncertainties limitations
- Perspective for future measurements
- Conclusion

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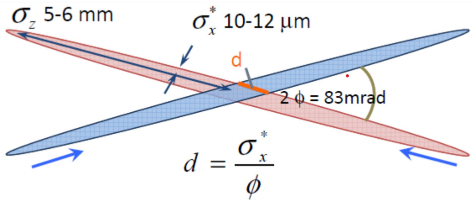
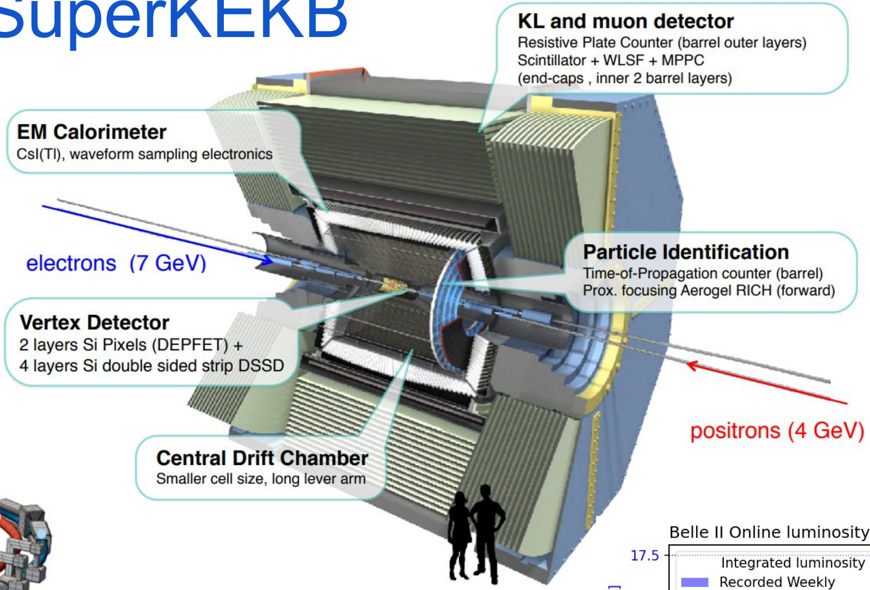
Belle II detector at SuperKEKB

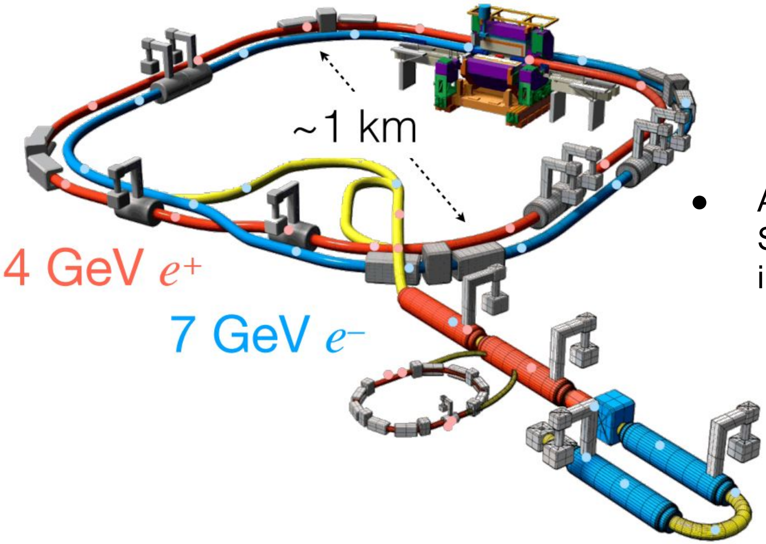
Nano-Beam scheme



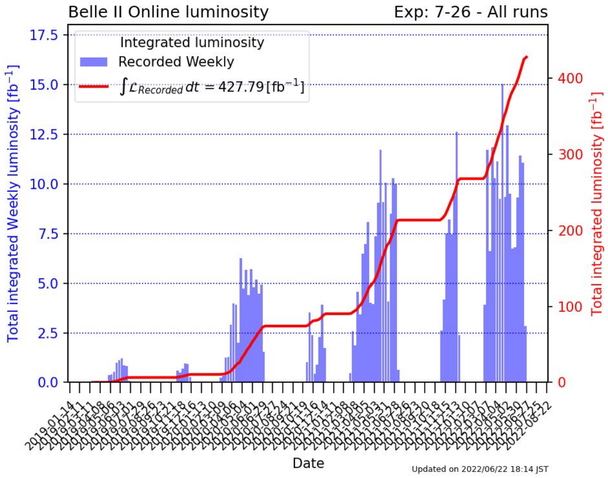


- Excellent vertex resolution
- Efficient neutrals reconstruction (π^0, K_S)
- K/π separation

Belle II detector and its luminosity

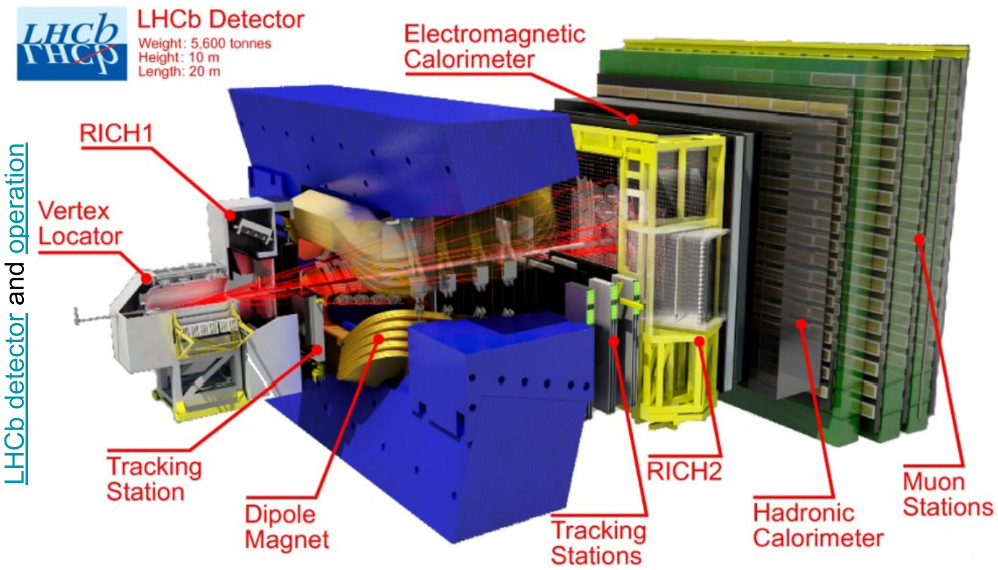


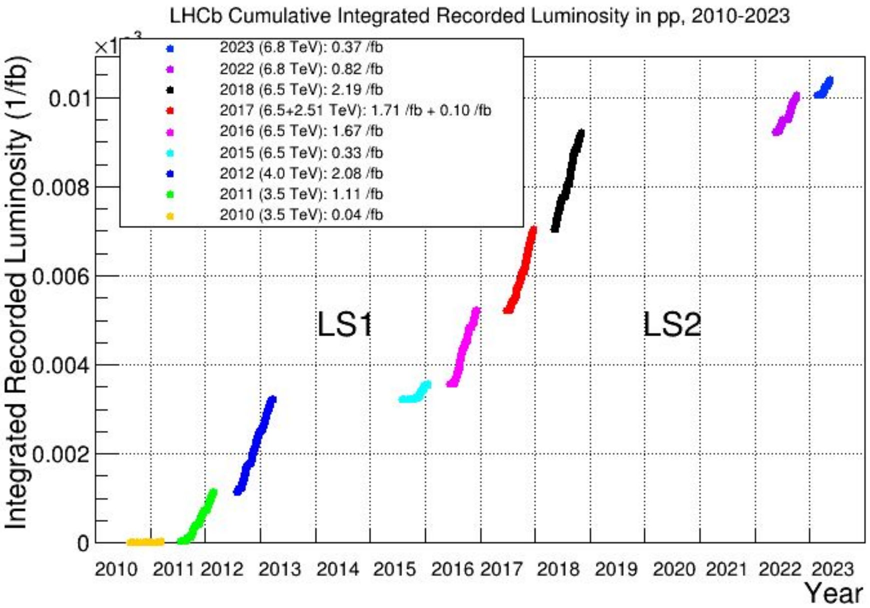
- Asymmetric e^+e^- collisions at the SuperKEKB accelerator complex in Japan
  - Recorded world's highest instantaneous luminosity (4.7×10^{34} $cm^{-2}s^{-1}$)
  - Collected 362 fb^{-1} dataset at the Υ(4S) in 2019-22, corresponding to 387M $B\bar{B}$ pairs



LHCb detector at LHC

LHCb detector and operation





- Single armed forward spectrometer
- Large sample of semileptonic decays
- All b-hadron species accessible
- Decay time resolution ~ 45 ps
- $\Delta p/p$ = 0.5 - 1.0 %
- eff(kaonID) ~ 95 %
- eff(muonID) ~ 97 %
- Pion mis-ID fraction ~ 10 %

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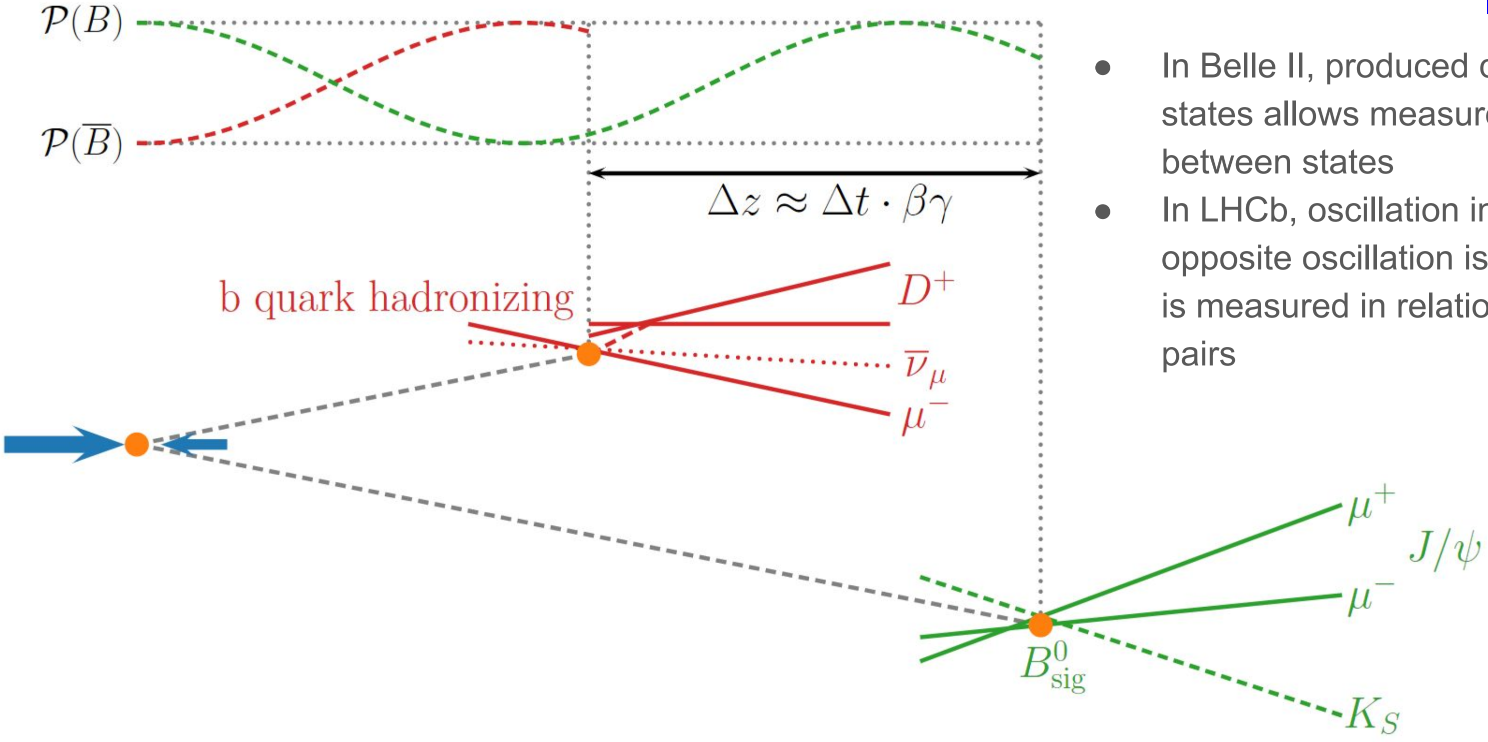
Experimental methods

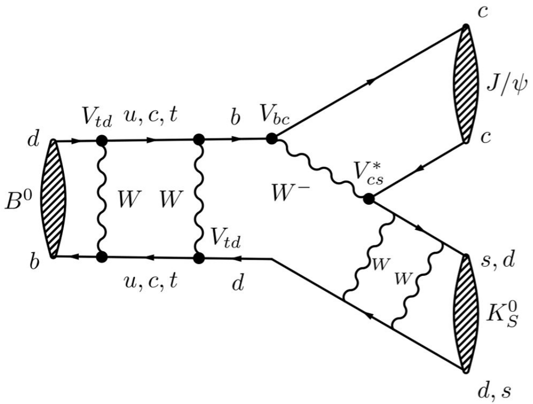


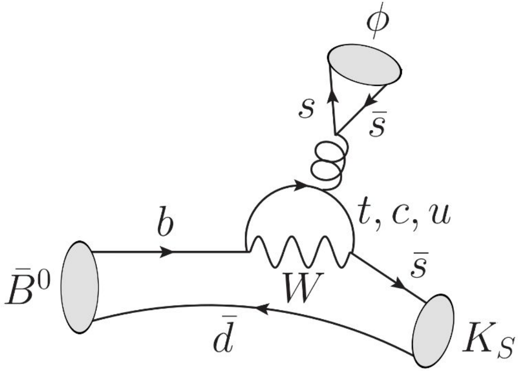
- In Belle II, produced quantum entangled states allows measurement time difference between states
- In LHCb, oscillation in signal side and opposite oscillation is not guaranteed, time is measured in relation to production of $B\overline{B}$ pairs

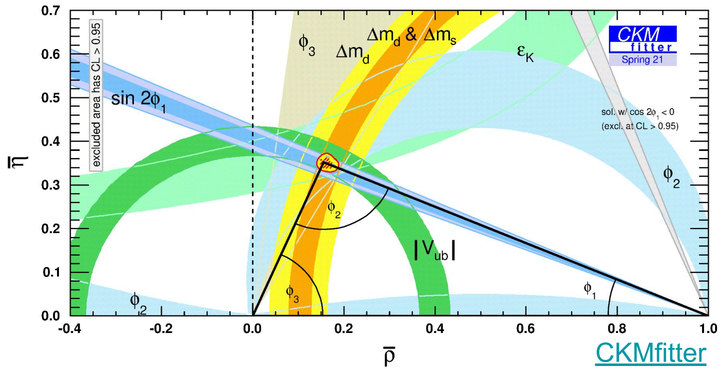
- To measure time-dependent asymmetry in B mesons we need to know:
  - Flavor of the other b quark
  - Proper decay time (difference)

Time-dependent CP violation

- The measurements of $\varphi_1 = \beta$ can be performed either at:
  - Tree dominated in $c\bar{c}s$ transition using $J/\psi K^0$ channel
  - Loop dominated in $q\bar{q}s$ transition using e.g. φK^0 channel







CKMfitter

$$\mathcal{A}_{\rm CP}(\Delta t) = \frac{\Gamma(\overline{B}^0 \to f) - \Gamma(B^0 \to f)}{\Gamma(\overline{B}^0 \to f) + \Gamma(B^0 \to f)}$$
$$= S_f \sin(\Delta m_d \Delta t) - C_f \cos(\Delta m_d \Delta t)$$

Mixing-induced CP asymmetry: $S_f \sim \sin(2\phi_1) = \sin(2\beta)$

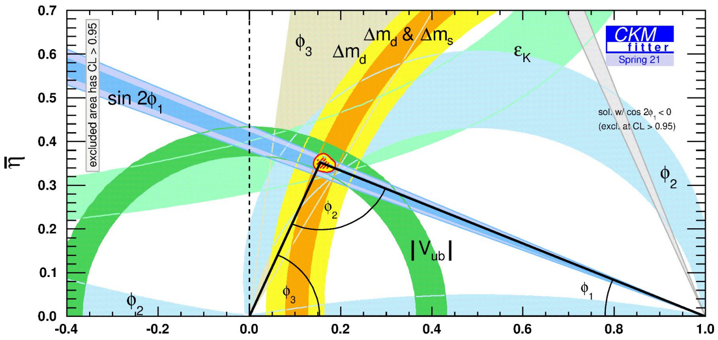
Direct CP asymmetry: C_f

- Six measurements done by Belle II
- One measurement done by LHCb

Time-dependent CP violation

- Another measurements in B^0_s meson sector (LHCb only):
  - For $B^0_s \rightarrow V\,V$ (vectors), angular analysis of φ_s, $\varphi_s^{s\bar{s}s}$:

$$\mathcal{A}_{\rm CP}(t) = \frac{\Gamma(\overline{B}^0_s \to f) - \Gamma(B^0_s \to f)}{\Gamma(\overline{B}^0_s \to f) + \Gamma(B^0_s \to f)} = \eta_f \cdot \sin\phi_s \cdot \sin \Delta m_s t$$



CKMfitter

  - Difference between decay widths of heavy and light mass eigenstates $\Delta\Gamma_s$
  - Asymmetry measurement of $\varphi_3 = \gamma$ angle

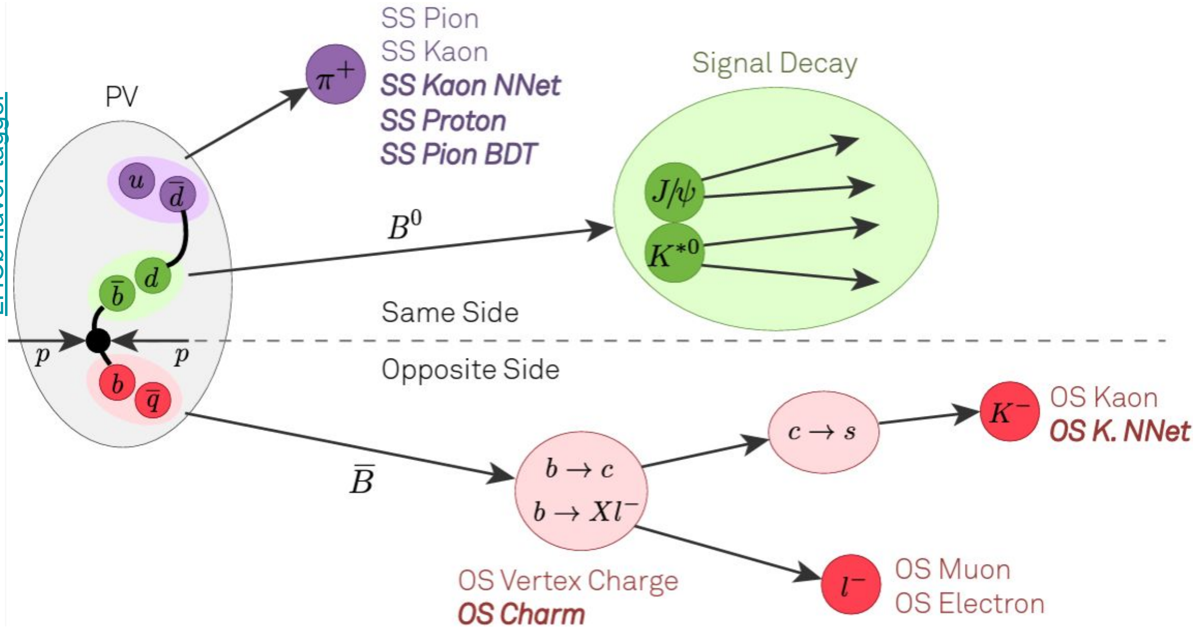
$$\Gamma(B^0_s(t) \to f/\overline{f}) \sim e^{-\Gamma_s t}\left(\cosh\left(\frac{\Delta\Gamma_s}{2}t\right) + C_{f/\overline{f}}\cos(\Delta m_s t) + A^{\Delta t}_{f/\overline{f}}\sinh\left(\frac{\Delta\Gamma_s}{2}t\right) - S_{f/\overline{f}}\sin(\Delta m_s t)\right)$$

$$C_f = C_{\overline{f}} = \frac{1 - r^2_{D_sK}}{1 + r^2_{D_sK}} \qquad A^{\Delta\Gamma}_f = \frac{-2r^2_{D_sK}\cos(\delta - (\gamma - 2\beta_s))}{1 + r^2_{D_sK}} \qquad S^{\Delta\Gamma}_f = \frac{2r^2_{D_sK}\sin(\delta - (\gamma - 2\beta_s))}{1 + r^2_{D_sK}}$$

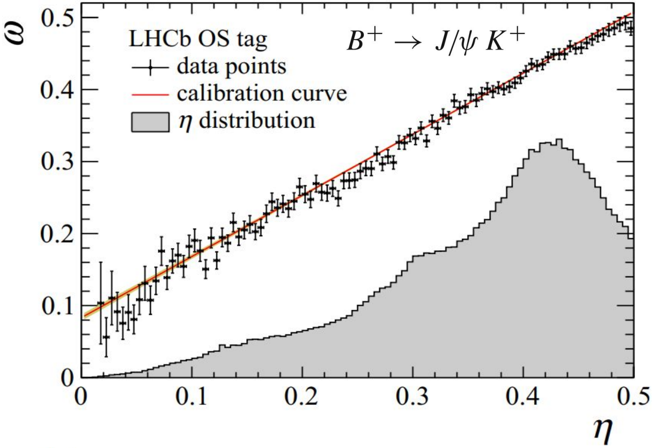
$$A^{\Delta\Gamma}_{\overline{f}} = \frac{-2r^2_{D_sK}\cos(\delta + (\gamma - 2\beta_s))}{1 + r^2_{D_sK}} \qquad S^{\Delta\Gamma}_{\overline{f}} = \frac{2r^2_{D_sK}\sin(\delta + (\gamma - 2\beta_s))}{1 + r^2_{D_sK}}$$

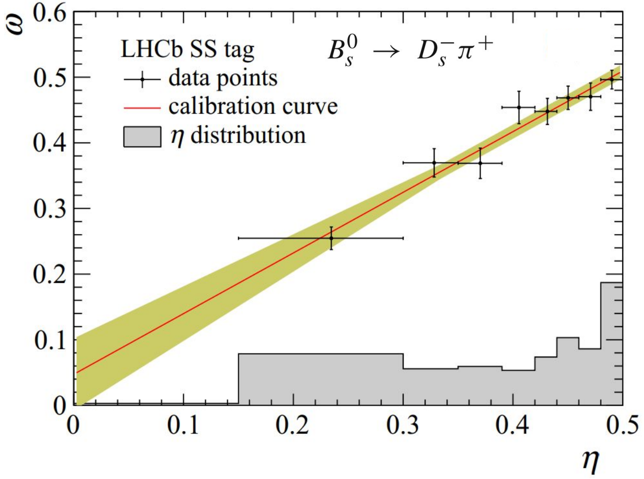
Flavor taggers at LHCb

LHCb flavor tagger



- Inputs of taggers are charge of daughter and granddaughters and they are output to qη
- Tagging power of combined OS and SS taggers:
  - 2015+2016: ε_{eff} = 4.18 ± 0.15 %
  - 2017: ε_{eff} = 4.22 ± 0.16 %
  - 2018: ε_{eff} = 4.36 ± 0.16 %

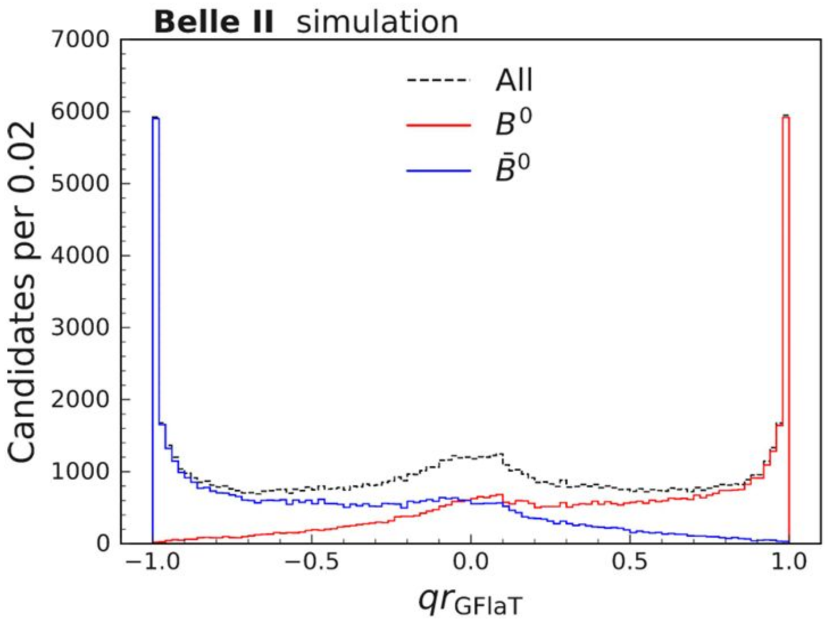




Eur. Phys. J. C 79, 706 (2019)

Flavor taggers at Belle II

- Traditional algorithm (Category based Flavor Tagger): exploit single particle's property (using e.g. charge of daughters, ...) outputted into qr
  - Typical flavor-specific decay modes are called categories and they are combined for output
  - Interrelations of particles are not fully exploited
- **G**raph-Neutral-Network based **Fla**vor **T**agger (GFlaT)
  - Pairs of particles are used as input information for the GFlaT
  - Single particle's information is used as well.
- Performance using Data:
  - ε_{eff} (Graph) = 37.39 ± 0.39 %
  - ε_{eff} (Category) = 31,68 ± 0.38 %
- GFlaT increase tagging efficiency about **18%** compared to category based flavor tagger
- Using GFlaT we are able reduce statistical uncertainty in TDCPV analysis about **8%**



EPS-HEP 2023 - TDCPV_BelleII

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Results of sin(2φ$_1$) at Belle II

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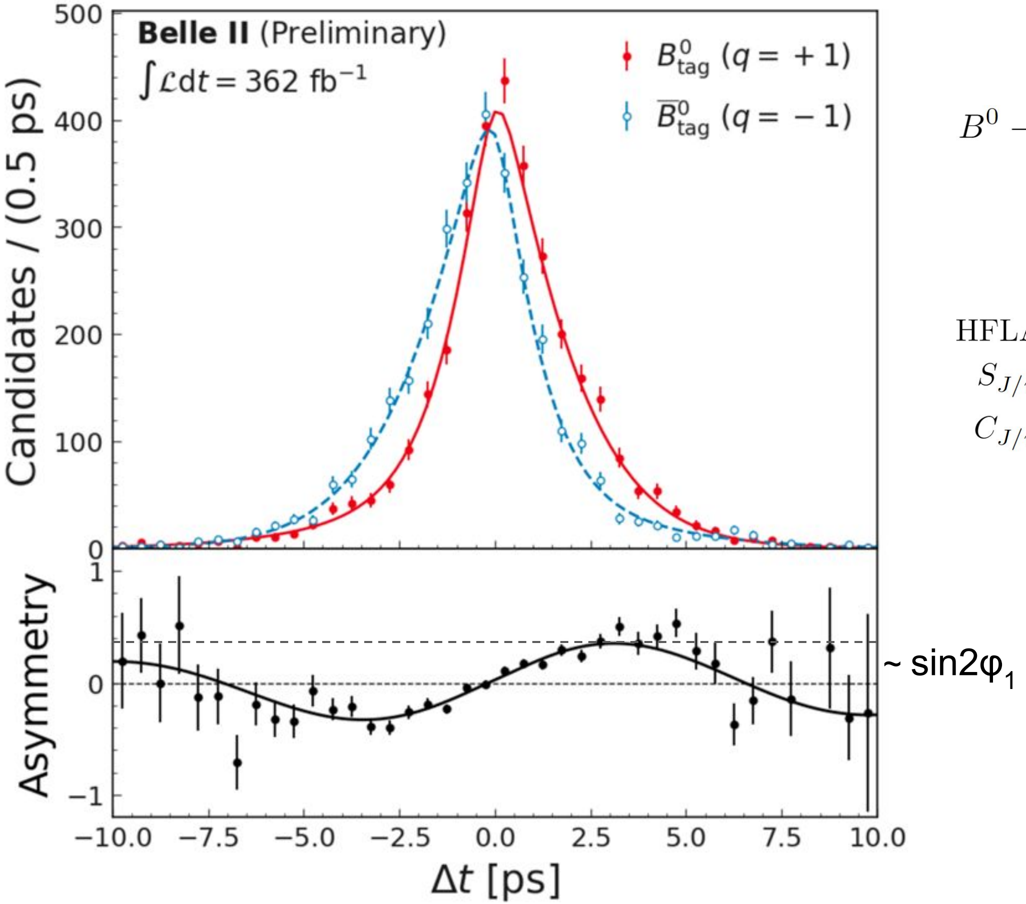


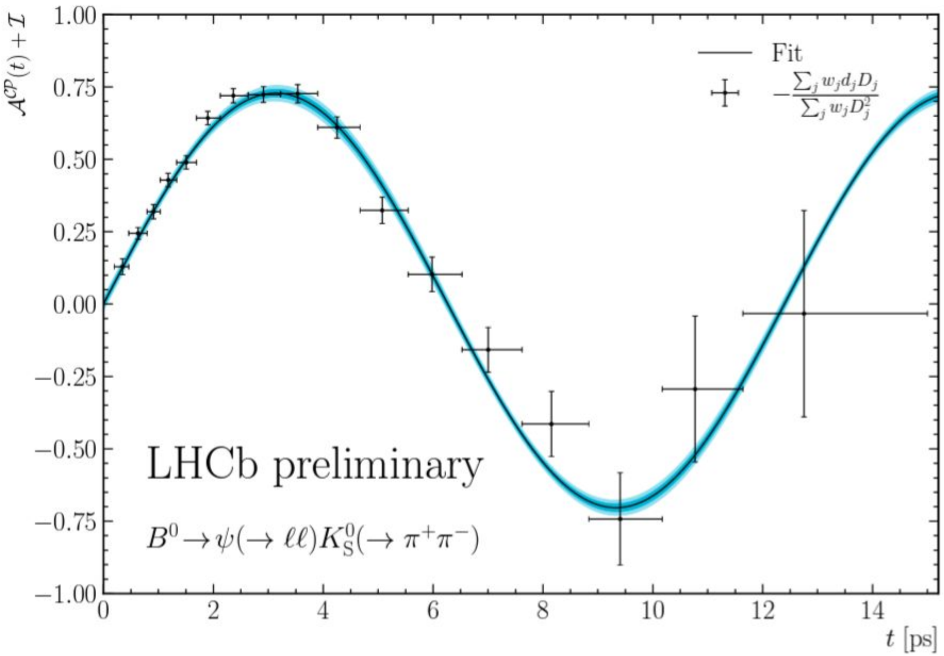
$B^0 \to J/\psi(\to \ell\ell)K^0_S(\to \pi^+\pi^-)$:

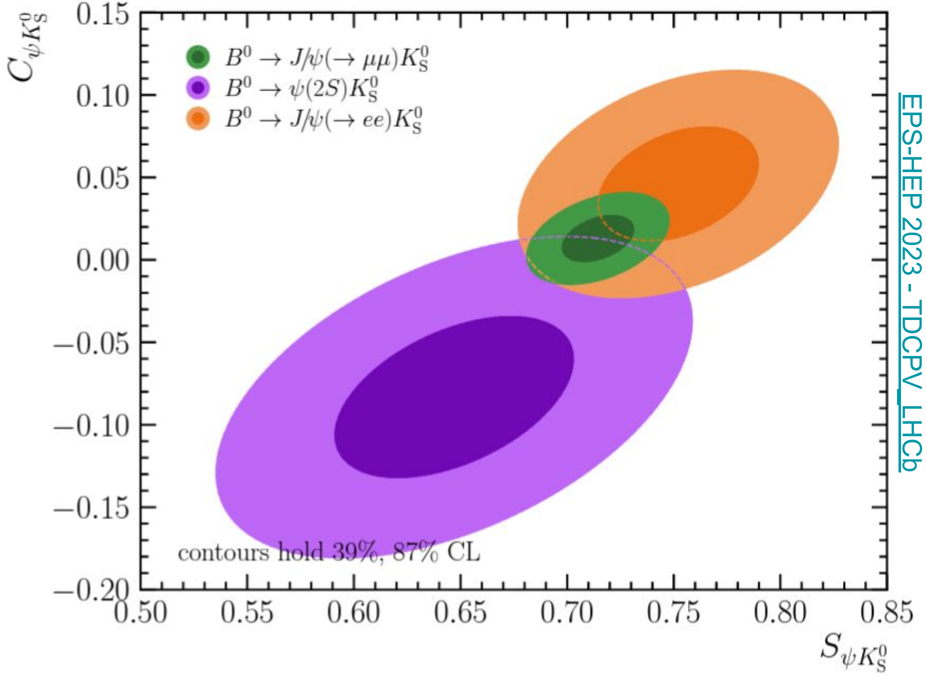
$$S_{J/\psi K^0_S} = \quad 0.724 \pm 0.035 \text{ (stat)} \pm 0.014 \text{ (syst)}$$
$$C_{J/\psi K^0_S} = -0.035 \pm 0.026 \text{ (stat)} \pm 0.012 \text{ (syst)}$$

HFLAV :

$$S_{J/\psi K^0_S} = 0.669 \pm 0.017$$
$$C_{J/\psi K^0_S} = 0.005 \pm 0.015$$

Result of $\sin(2\varphi_1)$ at LHCb





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$B^0 \to \{J/\psi(\to \ell\ell)\ \&\ \psi(2S)(\to \mu^+\mu^-)\}K^0_S(\to \pi^+\pi^-)$:

$$S^{\text{Run 1+2}}_{\psi K^0_S} = 0.716 \pm 0.013\ (\text{stat}) \pm 0.008\ (\text{syst})$$

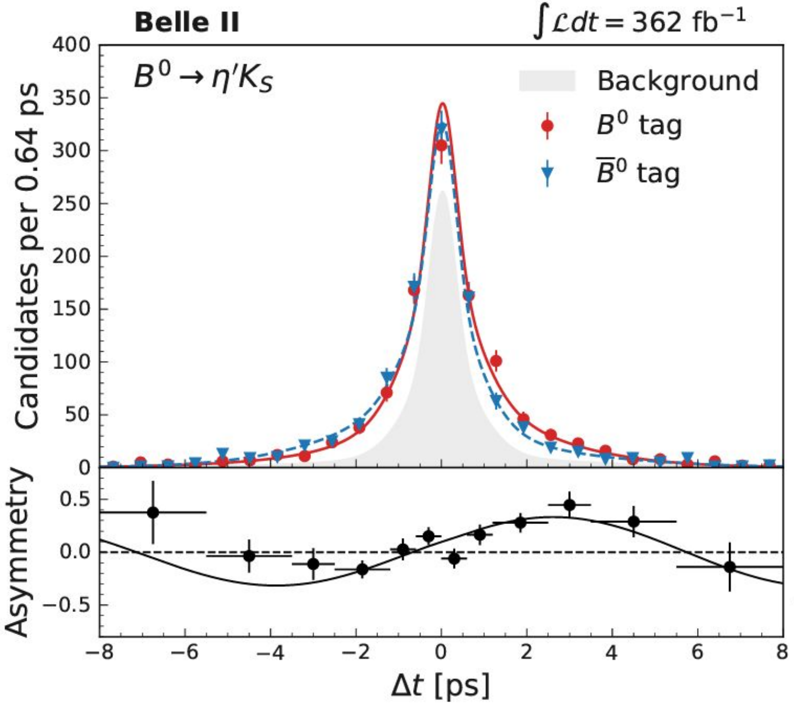
$$C^{\text{Run 1+2}}_{\psi K^0_S} = 0.012 \pm 0.012\ (\text{stat}) \pm 0.003\ (\text{syst})$$

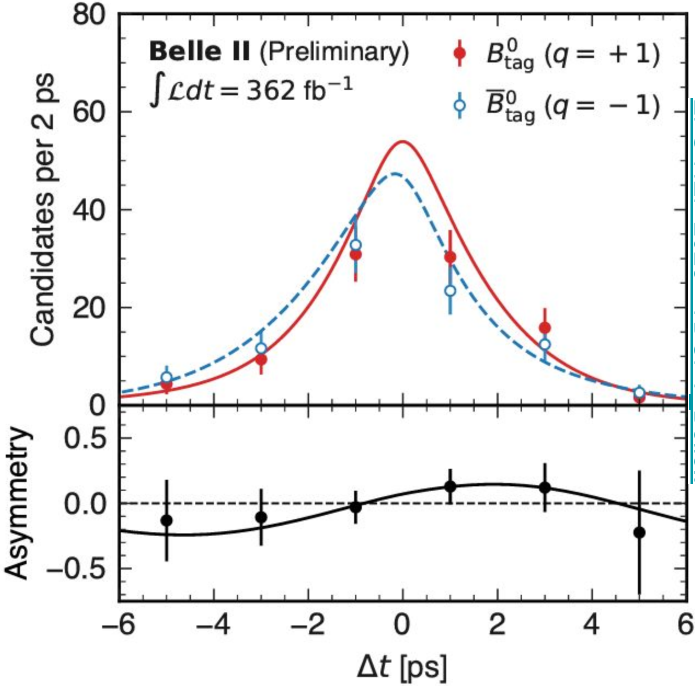
HFLAV :

$$S_{\psi K^0_S} = 0.669 \pm 0.017$$

$$C_{\psi K^0_S} = 0.005 \pm 0.015$$

Results of $\sin(2\varphi_1)^{\text{eff}}$ at Belle II





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HFLAV :

$$S_{\eta' K^0_S} = 0.63 \pm 0.06$$
$$C_{\eta' K^0_S} = -0.05 \pm 0.04$$
$$S_{\phi K^0_S} = 0.74^{+0.11}_{-0.13}$$
$$C_{\phi K^0_S} = 0.01 \pm 0.14$$

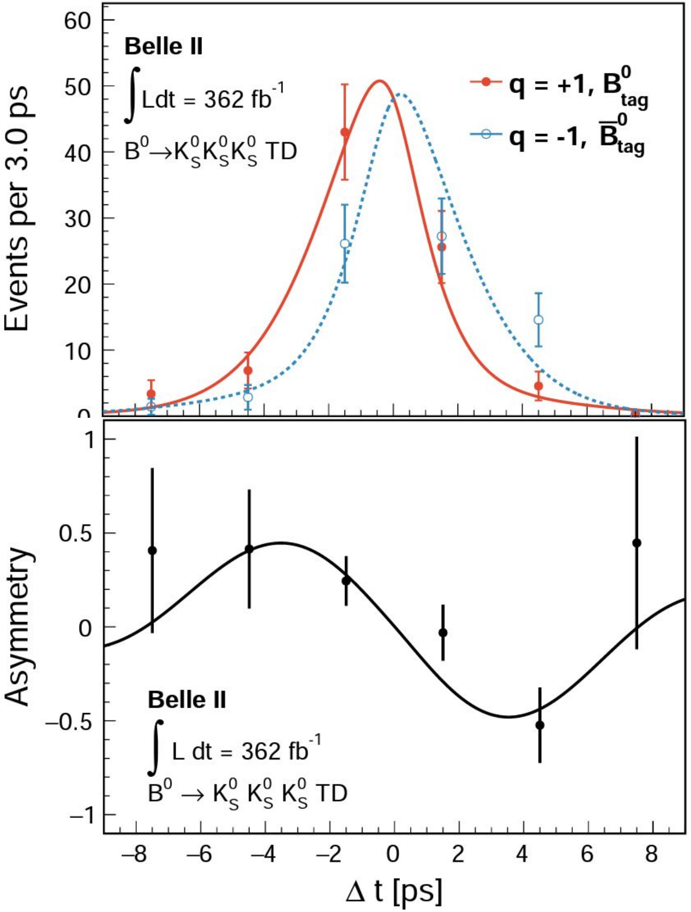
$B^0 \to \eta'(\to \{\rho\gamma\ \&\ \eta[\to \gamma\gamma]\pi^+\pi^-\})K^0_S(\to \pi^+\pi^-)$:

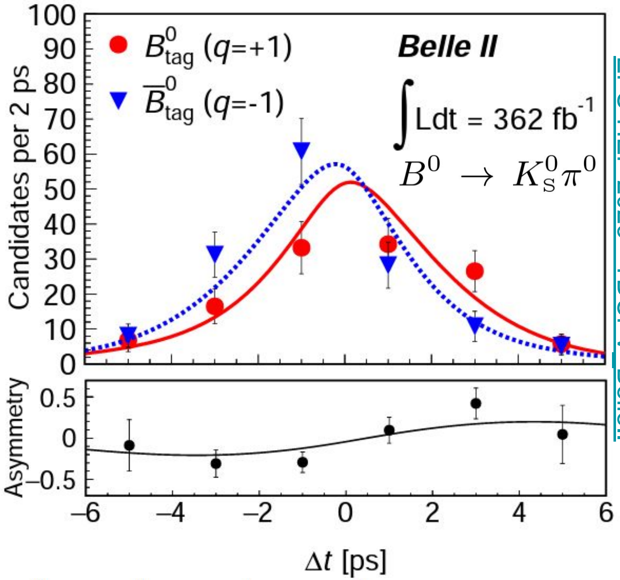
$$S_{\eta' K^0_S} = 0.67 \pm 0.10\ (\text{stat}) \pm 0.04\ (\text{syst})$$
$$C_{\eta' K^0_S} = -0.19 \pm 0.08\ (\text{stat}) \pm 0.03\ (\text{syst})$$

$B^0 \to \phi(\to K^+K^-)K^0_S(\to \pi^+\pi^-)$:

$$S_{\phi K^0_S} = 0.54 \pm 0.26\ (\text{stat})^{+0.06}_{-0.08}\ (\text{syst})$$
$$C_{\phi K^0_S} = -0.31 \pm 0.20\ (\text{stat}) \pm 0.05\ (\text{syst})$$

Results of $\sin(2\varphi_1)^{eff}$ at Belle II





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HFLAV :

$$S_{K_S^0\pi^0} = 0.57 \pm 0.17$$

$$C_{K_S^0\pi^0} = 0.01 \pm 0.10$$

$$S_{K_S^0K_S^0K_S^0} = -0.83 \pm 0.17$$

$$C_{K_S^0K_S^0K_S^0} = -0.15 \pm 0.12$$

$B^0 \to K_S^0(\to \pi^+\pi^-)\pi^0$:

$$S_{K_S^0\pi^0} = 0.75\ ^{+0.20}_{-0.20}\ (\text{stat}) \pm 0.04\ (\text{syst})$$

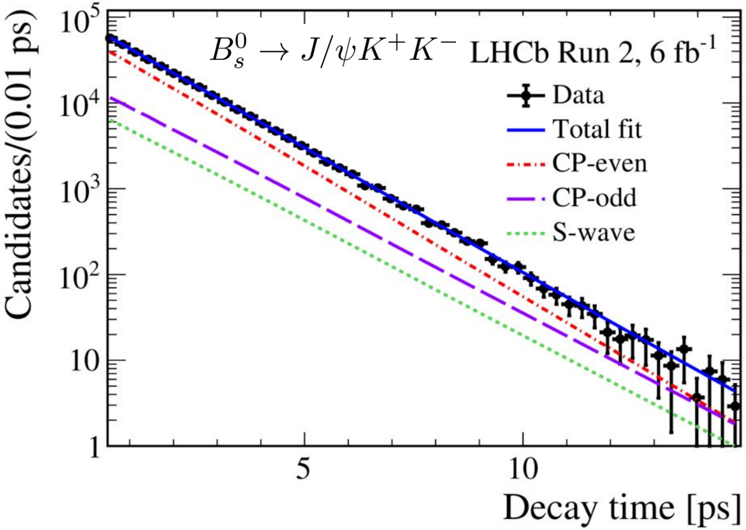
$$C_{K_S^0\pi^0} = 0.04\ ^{+0.14}_{-0.15}\ (\text{stat}) \pm 0.05\ (\text{syst})$$

$B^0 \to K_S^0(\to \pi^+\pi^-)K_S^0(\to \pi^+\pi^-)K_S^0(\to \pi^+\pi^-)$:

$$S_{K_S^0K_S^0K_S^0} = -1.75\ ^{+0.35}_{-0.45}\ (\text{stat}) \pm 0.03\ (\text{syst})$$

$$C_{K_S^0K_S^0K_S^0} = -0.07 \pm 0.20\ (\text{stat}) \pm 0.05\ (\text{syst})$$

Results of φ_s, $\varphi_s^{s\bar{s}s}$ by LHCb

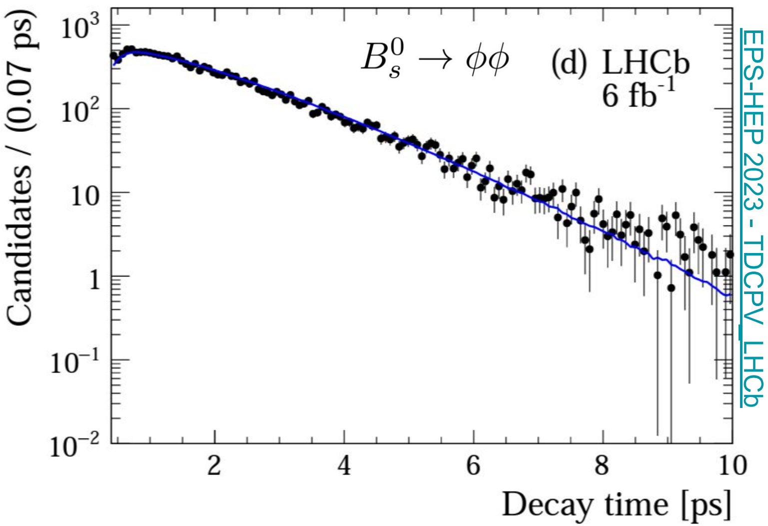


parameter	value ± stat ± syst
ϕ_s [rad]	-0.039 ± 0.022 ± 0.006

$$\text{Run } 1+2 : \phi_s = -0.044 \pm 0.020 \text{ rad}$$

HFLAV :

$$\phi_s = -0.039 \pm 0.016 \text{ rad}$$



parameter	value ± stat ± syst
$\phi_s^{s\bar{s}s}$ [rad]	-0.042 ± 0.075 ± 0.009

$$\text{Run } 1+2 : \phi_s^{s\bar{s}s} = -0.074 \pm 0.069 \text{ rad}$$

As expected CP violation is very small in these channels

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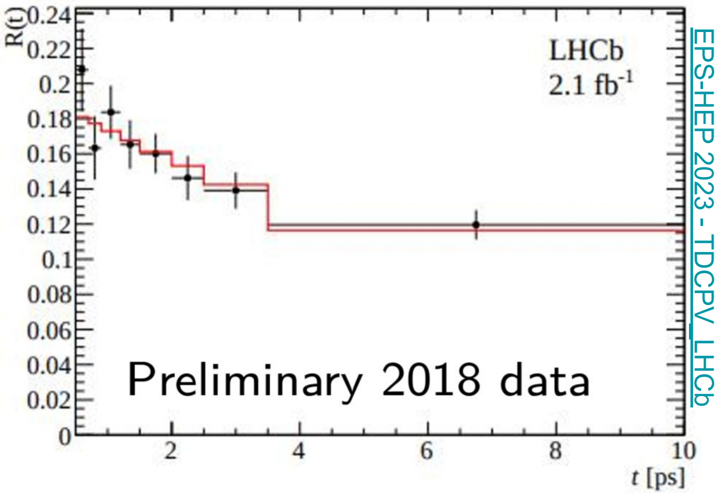
Results of $\Delta\Gamma_s$, γ by LHCb

$$\mathcal{R}(t) = \frac{N_L}{N_H} \propto \frac{[e^{-\Gamma_s t(1+y)}]_{t_1}^{t_2}}{[e^{-\Gamma_s t(1+y)}]_{t_1}^{t_2}} \cdot \frac{1-y}{1+y}$$



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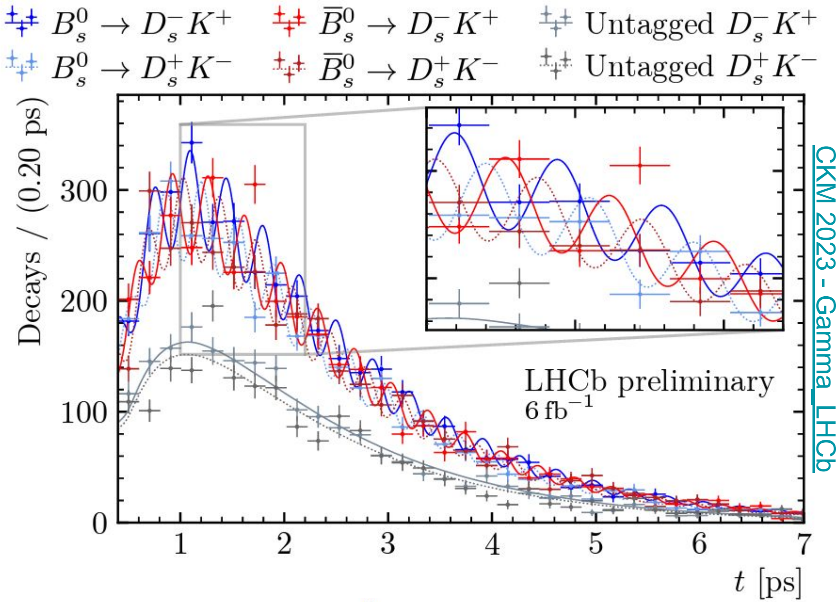

CKM 2023 - Gamma_LHCb

From $B_s^0 \to J/\psi\eta'$ and $B_s^0 \to J/\psi\pi^+\pi^-$:

$$\Delta\Gamma_s = 0.087 \pm 0.012\ (\text{stat}) \pm 0.009\ (\text{syst})\ \text{ps}^{-1}$$

HFLAV :

$$\Delta\Gamma_s = 0.074 \pm 0.006\ \text{ps}^{-1}$$

$$\gamma = 74 \pm 11^\circ$$

HFLAV :

$$\gamma = 65.9\ ^{+3.3}_{-3.5}\ {}^\circ$$

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Uncertainties and limitations for $B^0 \rightarrow J/\psi K^0_S$

LHCb

$$S^{\text{Run 1+2}}_{\psi K^0_S} = 0.716 \pm 0.013\ (\text{stat}) \pm 0.008\ (\text{syst})$$
$$C^{\text{Run 1+2}}_{\psi K^0_S} = 0.012 \pm 0.012\ (\text{stat}) \pm 0.003\ (\text{syst})$$

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

EPS-HEP 2023 - TDCPV_LHCb

Dominant

Scaled to statistics

Belle II

$$S_{J/\psi K^0_S} = 0.724 \pm 0.035\ (\text{stat}) \pm 0.014\ (\text{syst})$$
$$C_{J/\psi K^0_S} = -0.035 \pm 0.026\ (\text{stat}) \pm 0.012\ (\text{syst})$$

Source	$\sigma(\varepsilon_{\text{tag}})$ [%]	$\sigma(S_{CP})$	$\sigma(C_{CP})$
$B^0 \to D^{(*)-}\pi^+$ sample size	0.43	0.004	0.007
$B^0 \to J/\psi K^0_S$ sample size		0.035	0.026
Fit model			
Analysis bias	0.02	0.002	0.005
Fixed resolution parameters	0.07	0.004	0.004
τ & Δm_d	0.06	0.001	0.000
$\sigma_{\Delta t}$ binning	0.04	0.000	0.000
Δt measurement			
Alignment	0.06	0.005	0.003
Beam spot	0.16	0.002	0.002
CMS Energy	0.03	0.000	0.001
Backgrounds			
$B^0 \to D^{(*)-}\pi^+$ sWeight bias	0.24	0.001	0.001
$B^0 \to D^{(*)-}\pi^+ \Delta E$ background	0.11	0.001	0.001
Signal ΔE shape	0.08	0.002	0.000
Tag-side interference	—	0.010	0.007
Total systematic	0.34	0.014	0.012

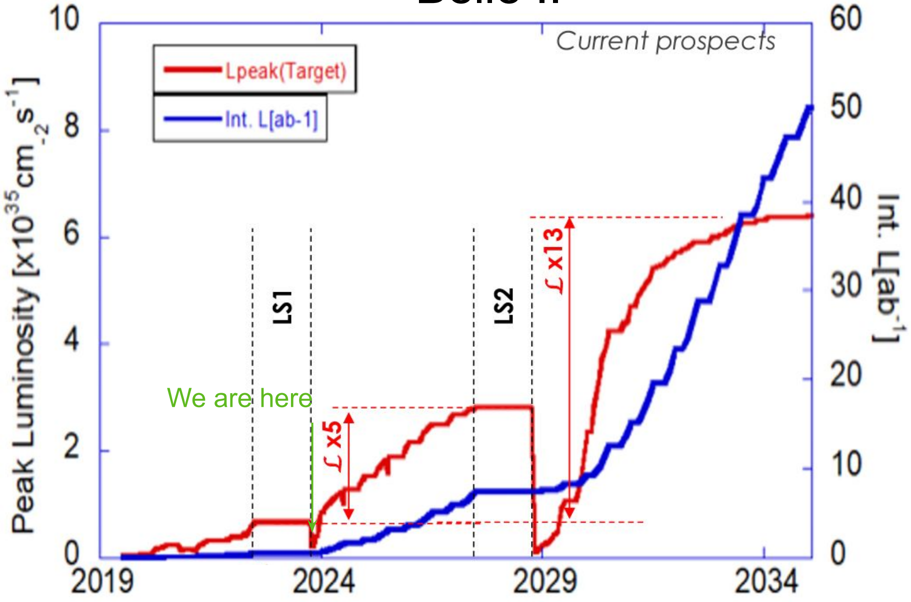
Future prospects

EPS-HEP 2023 - Highlights LHCb

LHCb

We are here

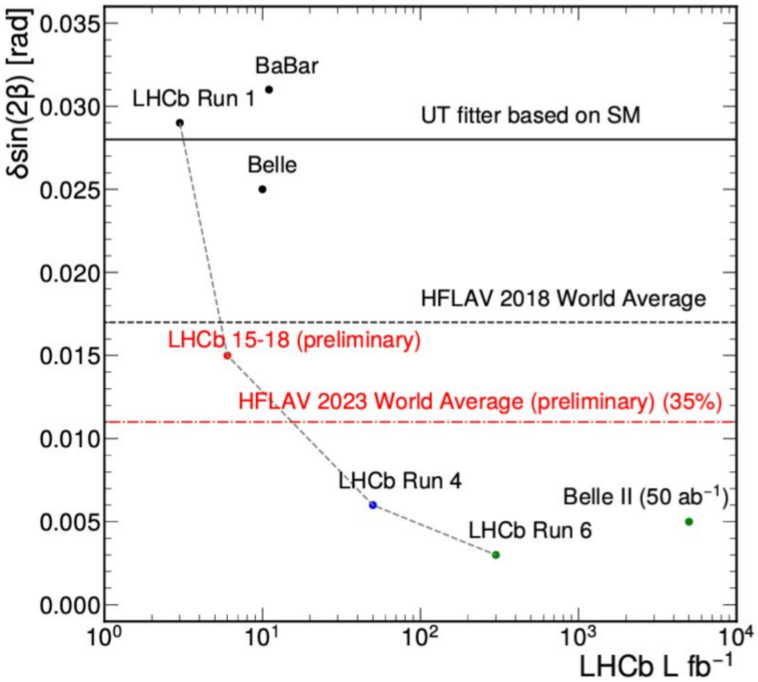
Belle II

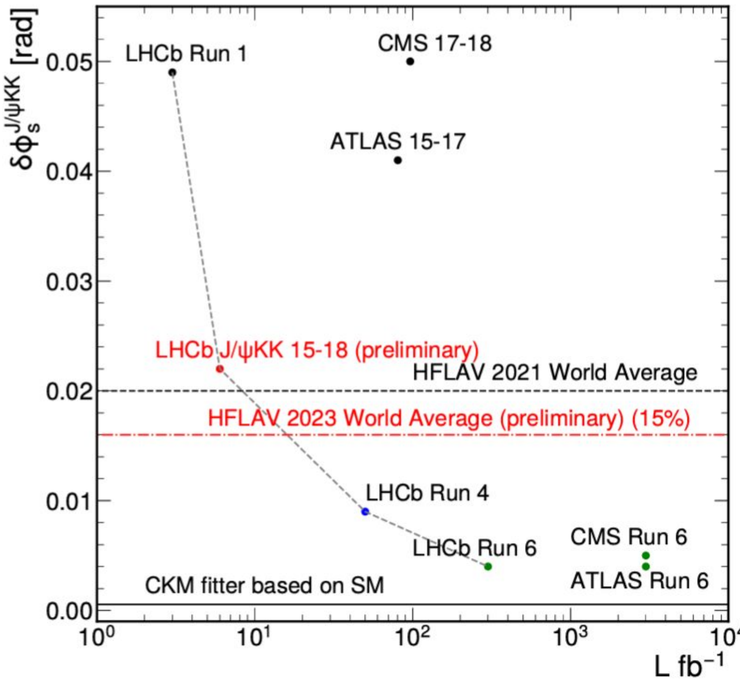


FPCP 2023 - BelleII

- Current status:
  - Belle II: ~ 428 fb^{-1} (~ 1% $\int L_{total}$)
  - LHCb: ~ 9 fb^{-1} (~ 3% $\int L_{total}$)
- Next runs:
  - Belle II: ~ 5 ab^{-1} (~ 10% $\int L_{total}$)
  - LHCb: ~ 50 fb^{-1} (~ 16% $\int L_{total}$)

Future prospects - statistical uncertainty





EPS-HEP 2023 - TDCPV_LHCb

$\delta\sin(2\varphi_1)$ using $B^0 \to \eta' K^0$

L (ab^{-1})	stat. (10^{-2})	syst. (10^{-2})	total (10^{-2})
5	2.7	2.1 (1.7)	3.4 (3.2)
50	0.85	1.8 (1.3)	2.0 (1.5)

B2TiP

Conclusions and outlook

- Time-dependent CP violation measurements in B meson decays were introduced
- Flavor taggers used in Belle II and LHCb experiments were explained
- Results for several time-dependent CP violation analyses have been shown:
  - $\sin(2\varphi_1)$ measurements using $J/\psi K^0_S$
  - $\sin(2\varphi_1)^{eff}$ measurements using $\eta' K^0_S$, $\pi^0 K^0_S$, φK^0_S and $K^0_S K^0_S K^0_S$
  - φ_s, φ_s^{sss}, Γ_s and γ analyses
- Uncertainties of measurements with dominated factors were discussed
- In future, LHCb and Belle II will deliver more precise measurements:

Year	Luminosity $[\mathrm{fb}^{-1}]$ LHCb	Luminosity $[\mathrm{fb}^{-1}]$ Belle II	$\delta(\sin(2\phi_1/2\beta))$
2018	3	0	0.017
2023	9	362	0.011
2032	50	5 000	0.006
2041	300	50 000	0.004

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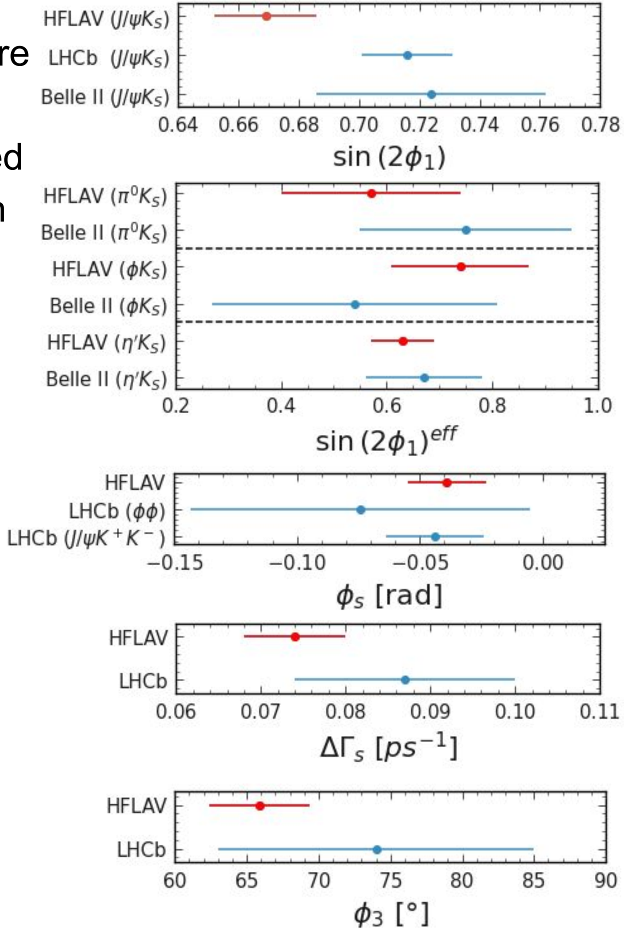
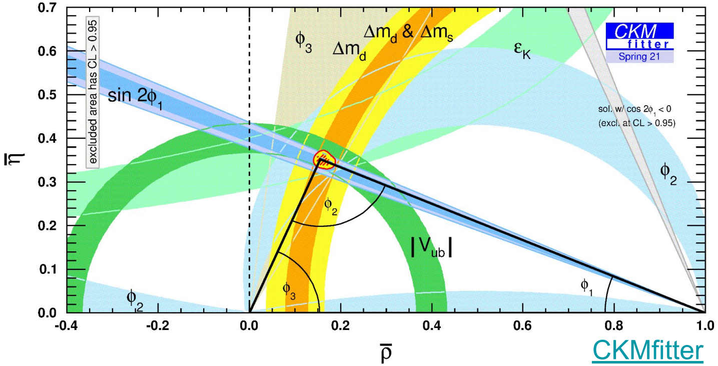


Backup

Time-dependent CP violation

- Another measurements in B^0_s meson sector (LHCb only):
  - Angular analysis of φ_s, φ_s^{sss},

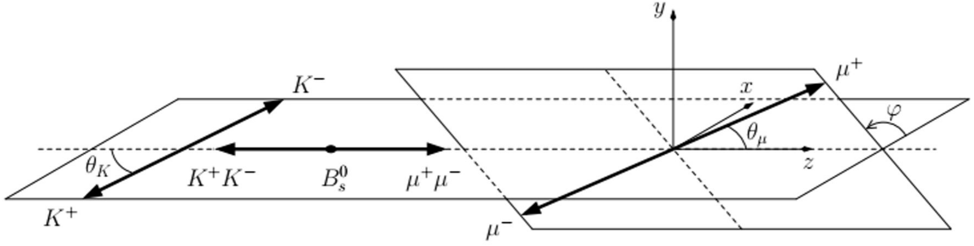
$$\mathcal{A}_{\rm CP}(\Delta t) = \frac{\Gamma(\overline{B}^0_s \to f) - \Gamma(B^0_s \to f)}{\Gamma(\overline{B}^0_s \to f) + \Gamma(B^0_s \to f)} = \eta_f \cdot \sin\phi_s \cdot \sin\Delta m_s t$$



CKMfitter

  - Yield ratio $\Delta\Gamma_s$

$$\mathcal{R}(t) = \frac{N_L}{N_H} \propto \frac{[e^{-\Gamma_s t(1+y)}]^{t_2}_{t_1}}{[e^{-\Gamma_s t(1+y)}]^{t_2}_{t_1}} \cdot \frac{1-y}{1+y}$$



  - Asymmetry measurement of $\varphi_3 = \gamma$ angle

$$\Gamma(B^0_s(t) \to f/\overline{f}) \sim e^{-\Gamma_s t}(\cosh(\frac{\Delta\Gamma_s}{2}t) + C_{f/\overline{f}}\cos(\Delta m_s t) + A^{\Delta t}_{f/\overline{f}}\sinh(\frac{\Delta\Gamma_s}{2}t) - S_{f/\overline{f}}\sin(\Delta m_s t))$$

$$C_f = C_{\overline{f}} = \frac{1-r^2_{D_sK}}{1+r^2_{D_sK}} \qquad A^{\Delta\Gamma}_f = \frac{-2r^2_{D_sK}\cos(\delta-(\gamma-2\beta_s))}{1+r^2_{D_sK}} \qquad S^{\Delta\Gamma}_f = \frac{2r^2_{D_sK}\sin(\delta-(\gamma-2\beta_s))}{1+r^2_{D_sK}}$$

$$A^{\Delta\Gamma}_{\overline{f}} = \frac{-2r^2_{D_sK}\cos(\delta+(\gamma-2\beta_s))}{1+r^2_{D_sK}} \qquad S^{\Delta\Gamma}_{\overline{f}} = \frac{2r^2_{D_sK}\sin(\delta+(\gamma-2\beta_s))}{1+r^2_{D_sK}}$$

Results of $\sin(2\varphi_1/2\beta)^{eff}$ at Belle II

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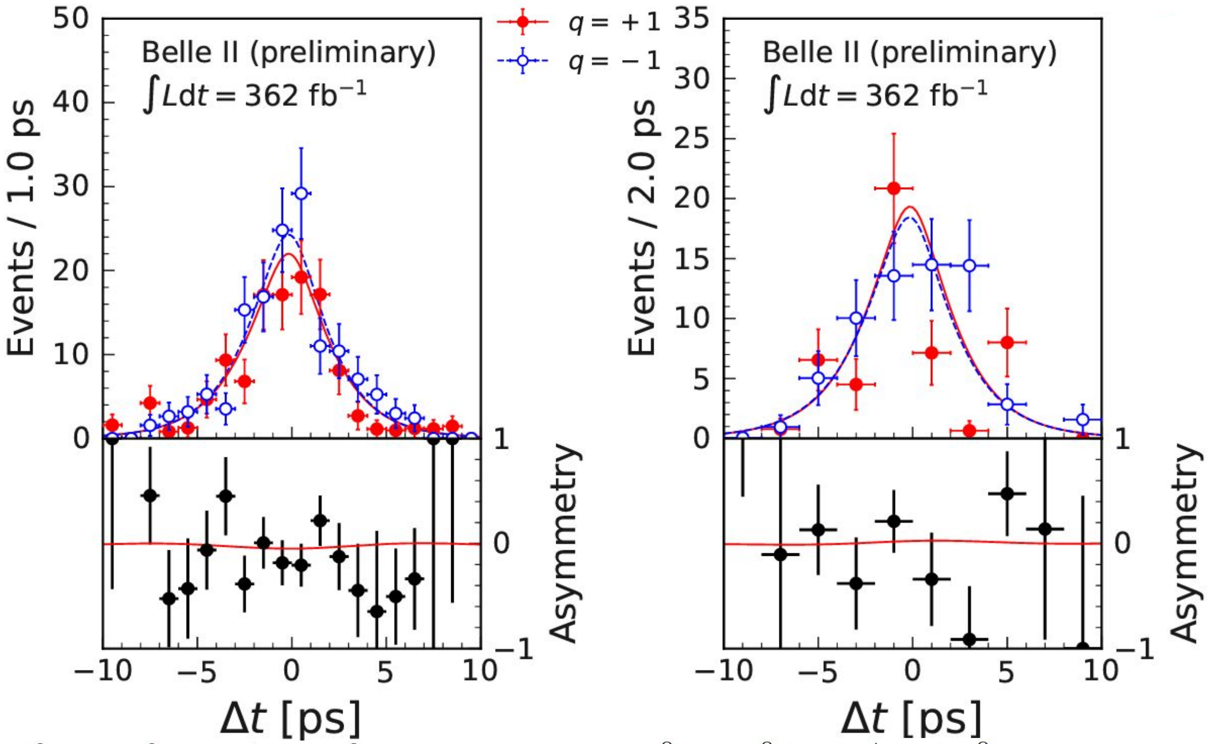


Due to polarization of photon $\sin(2\varphi_1/2\beta)^{eff} \sim 0$.

HFLAV :

$$S_{K^{*0}\gamma} = -0.16 \pm 0.22$$
$$C_{K^{*0}\gamma} = -0.04 \pm 0.14$$
$$S_{K^0_S\pi^0\gamma} = 0.50 \pm 0.68$$
$$C_{K^0_S\pi^0\gamma} = 0.20 \pm 0.39$$

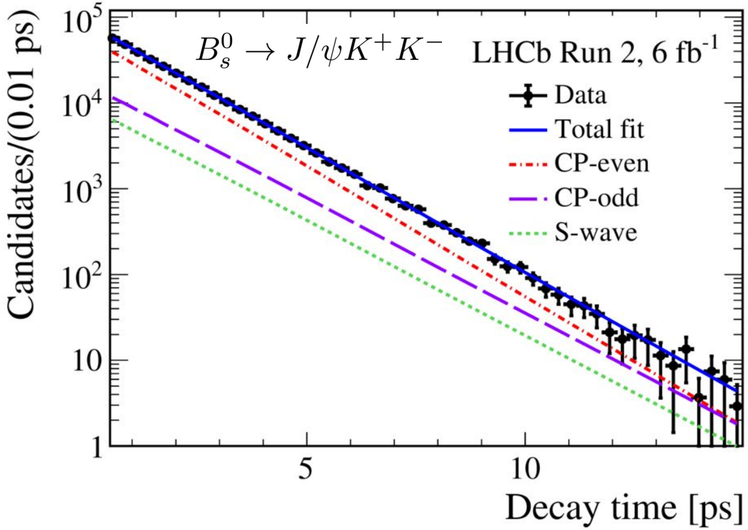
$B^0 \to K^{*0}(\to K^0_S[\to \pi^+\pi^-]\pi^0)\gamma$:

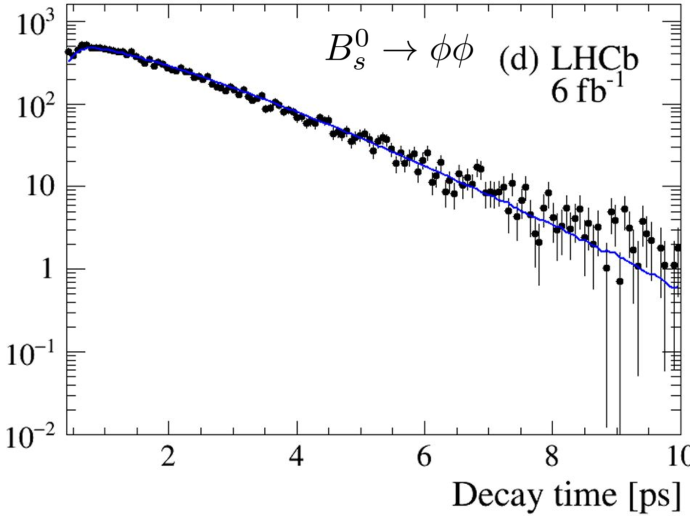
$$S_{K^{*0}\gamma} = 0.00\ ^{+0.27}_{-0.26}\ (\text{stat})\ ^{+0.03}_{-0.04}\ (\text{syst})$$
$$C_{K^{*0}\gamma} = 0.10 \pm 0.13\ (\text{stat}) \pm 0.03\ (\text{syst})$$

$B^0 \to K^0_S(\to \pi^+\pi^-)\pi^0\gamma$:

$$S_{K^0_S\pi^0\gamma} = 0.04\ ^{+0.45}_{-0.44}\ (\text{stat}) \pm 0.10\ (\text{syst})$$
$$C_{K^0_S\pi^0\gamma} = -0.06 \pm 0.25\ (\text{stat}) \pm 0.07\ (\text{syst})$$

Results of φ_s, $\varphi_s^{s\bar{s}s}$ by LHCb





EPS-HEP 2023 - TDCPV_LHCb

parameter	value ± stat ± syst
ϕ_s [rad]	-0.039 ± 0.022 ± 0.006
$\lvert\lambda\rvert$	1.001 ± 0.011 ± 0.005
$\lvert A_\perp\rvert^2$	0.2463 ± 0.0023 ± 0.0024
$\lvert A_0\rvert^2$	0.5179 ± 0.0017 ± 0.0032
$\delta_\perp - \delta_0$ [rad]	2.903 ± 0.0075 ± 0.048
$\delta_\parallel - \delta_0$ [rad]	3.146 ± 0.061 ± 0.052

$$\text{Run } 1+2: \phi_s = -0.044 \pm 0.020 \text{ rad}$$

$$\text{Run } 1+2: |\lambda| = 0.990 \pm 0.010$$

parameter	value ± stat ± syst
$\phi_s^{s\bar{s}s}$ [rad]	-0.042 ± 0.075 ± 0.009
$\lvert\lambda\rvert$	1.004 ± 0.030 ± 0.009
$\lvert A_\perp\rvert^2$	0.384 ± 0.007 ± 0.003
$\lvert A_0\rvert^2$	0.310 ± 0.006 ± 0.003
$\delta_\perp - \delta_0$ [rad]	2.463 ± 0.029 ± 0.009
$\delta_\parallel - \delta_0$ [rad]	2.769 ± 0.105 ± 0.011

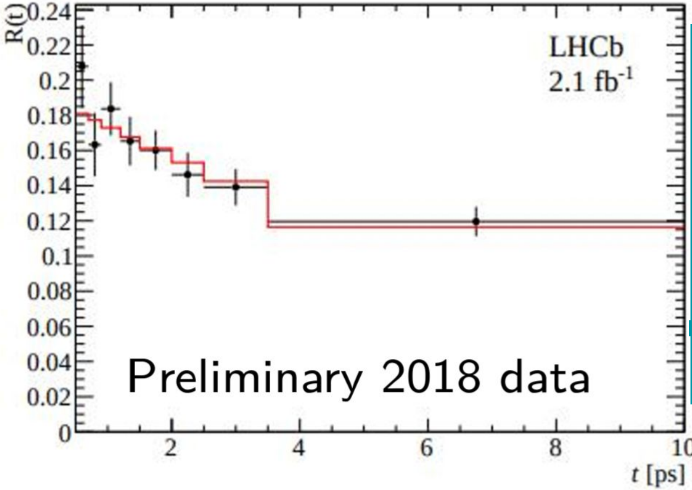
$$\text{Run } 1+2: \phi_s^{s\bar{s}s} = -0.074 \pm 0.069 \text{ rad}$$

$$\text{Run } 1+2: |\lambda| = 1.009 \pm 0.07 \pm 0.030$$

$$\phi_{s,0} = -0.18 \pm 0.09 \text{ rad}$$
$$\phi_\parallel - \phi_{s,0} = 0.12 \pm 0.09 \text{ rad}$$
$$\phi_\perp - \phi_{s,0} = 0.17 \pm 0.09 \text{ rad}$$
$$|\lambda_0| = 1.02 \pm 0.17$$
$$|\lambda_\perp/\lambda_0| = 0.97 \pm 0.22$$
$$|\lambda_\parallel/\lambda_0| = 0.78 \pm 0.21$$

Results of $\Delta\Gamma_s$, γ by LHCb

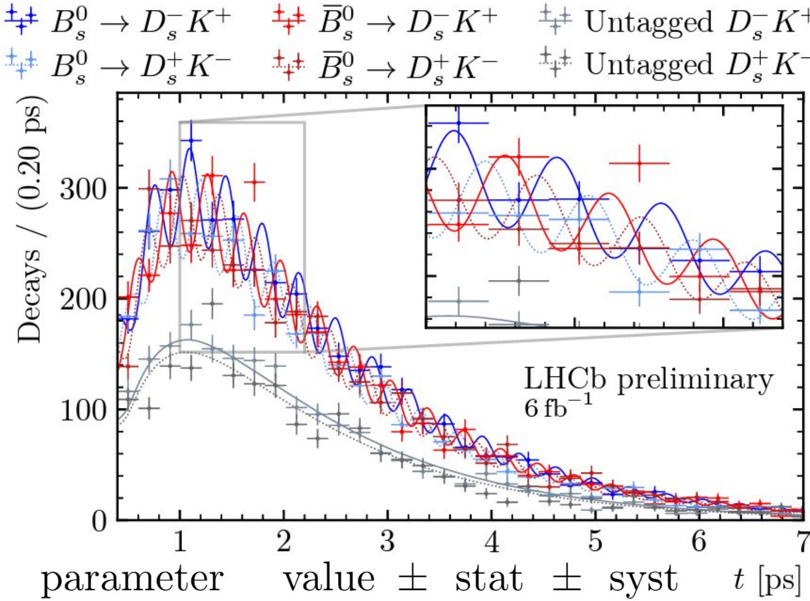
$$\mathcal{R}(t) = \frac{N_L}{N_H} \propto \frac{[e^{-\Gamma_s t(1+y)}]_{t_1}^{t_2}}{[e^{-\Gamma_s t(1+y)}]_{t_1}^{t_2}} \cdot \frac{1-y}{1+y}$$



EPS-HEP 2023 - TDCPV_LHCb

From $B_s^0 \to J/\psi\eta'$ and $B_s^0 \to J/\psi\pi^+\pi^-$:

$$\Delta\Gamma_s = 0.0087 \pm 0.0012\ \text{(stat)} \pm 0.0009\ \text{(syst)}\ \text{ps}^{-1}$$



CKM 2023 - Gamma_LHCb

parameter	value ± stat ± syst
C_f	0.791 ± 0.061 ± 0.022
$A_f^{\Delta\Gamma}$	0.051 ± 0.134 ± 0.037
S_f	-0.071 ± 0.084 ± 0.023
$A_{\bar{f}}^{\Delta\Gamma}$	0.303 ± 0.125 ± 0.036
$S_{\bar{f}}$	-0.503 ± 0.084 ± 0.025
γ [°]	74 ± 11

Systematic uncertainties $B^0 \to \eta' K^0_S$, $B^0 \to \phi K^0_S$

Source	$C_{\eta' K^0_S}$	$S_{\eta' K^0_S}$
Signal and continuum yields	< 0.001	0.002
SxF and $B\bar{B}$ yields	< 0.001	0.006
C_{BDT} mismodeling	0.004	0.010
Signal and background modelling	0.020	0.014
Observable correlation	0.008	0.001
Δt resolution fixed parameters	0.005	0.009
Δt resolution model	0.004	0.019
Flavor tagging	0.007	0.004
τ_{B^0} and Δm_d	< 0.001	0.002
Fit bias	0.003	0.002
Tracker misalignment	0.004	0.006
Momentum scale	0.001	0.001
Beam spot	0.002	0.002
B-meson motion in $\Upsilon(4S)$ frame	< 0.001	0.017
Tag-side interference	0.005	0.011
$B\bar{B}$ background asymmetry	0.008	0.006
Candidate selection	0.007	0.009
Total	0.027	0.037

Source	$\sigma(A)$	$\sigma(S)$
Calibration with $B^0 \to D^{(*)-}\pi^+$ decays		
Calibration sample size	± 0.010	± 0.009
Calibration sample systematic	± 0.010	± 0.012
Sample dependence	-0.005	$+0.021$
Fit model		
Fit bias	$^{+0.017}_{-0.028}$	$^{+0.033}_{-0.062}$
$B^0 \to K^+K^-K^0_S$ backgrounds	-0.020	-0.011
Fixed fit shapes	± 0.009	± 0.022
τ_{B^0} and Δm_d uncertainties	± 0.006	± 0.022
$A_{K^+K^-K^0_S}$ and $S_{K^+K^-K^0_S}$	± 0.014	± 0.013
$B\bar{B}$ backgrounds	$^{+0.030}_{-0.019}$	$^{+0.017}_{-0.031}$
Tag-side interference	< 0.001	$+0.012$
Multiple candidates	$+0.032$	-0.002
Δt measurement		
Detector misalignment	$+0.002$	-0.002
Momentum scale	± 0.001	± 0.001
Beam spot	± 0.002	± 0.002
Δt approximation	< 0.001	-0.018
Total systematic	$^{+0.052}_{-0.046}$	$^{+0.058}_{-0.082}$
Statistical	± 0.201	± 0.256

arXiv:2307.02802

Systematic uncertainties $B^0 \to K^0_S \pi^0 \gamma$

	$K^{*0}\gamma$		$K^0_S\pi^0\gamma$	
Source	S	C	S	C
E and p scales	± 0.017	± 0.015	± 0.083	± 0.047
Vertex measurement	± 0.021	± 0.009	± 0.023	± 0.036
Flavor tagging	± 0.005	$^{+0.012}_{-0.009}$	± 0.008	$^{+0.013}_{-0.009}$
Event-by-event fractions	± 0.003	$^{+0.004}_{-0.003}$	± 0.032	± 0.013
Resolution functions	± 0.014	± 0.009	± 0.032	± 0.013
Physics parameters	< 0.001	< 0.001	± 0.003	< 0.001
$B\overline{B}$ asymmetries	$^{+0.010}_{-0.021}$	± 0.022	$^{+0.023}_{-0.015}$	$^{+0.032}_{-0.033}$
Tag-side interference	< 0.001	-0.002	$+0.001$	$+0.001$
Total	$^{+0.033}_{-0.037}$	$^{+0.032}_{-0.031}$	$^{+0.100}_{-0.098}$	$^{+0.071}_{-0.070}$

Systematic uncertainties $B^0 \to K^0_S \pi^0$, $B^0 \to K^0_S K^0_S K^0_S$

Belle II INFN

$B^0 \to K_S^0 \pi^0$

Source	δC	δS
Flavor tagging	0.013	0.011
Resolution function	0.014	0.022
$B\overline{B}$ background asymmetry	0.030	0.018
$q\bar{q}$ background asymmetry	0.028	< 0.001
Signal modeling	0.004	0.003
Background modeling	0.006	0.018
Fit bias	0.005	0.011
Best candidate selection	0.005	0.010
τ_{B^0} and Δm_d	< 0.001	< 0.001
Tag-side interference	0.006	0.011
VXD misalignment	0.004	0.005
Total	0.047	0.040

$B^0 \to K^0_S K^0_S K^0_S$

Source	S	C
τ_{B^0}, τ_{B^+}, and Δm_d	0.009	0.000
Signal modeling	0.014	0.008
Δt resolution function	0.013	0.008
Background Δt modeling	0.004	0.002
Flavor tagging	0.013	0.012
Fit bias	0.014	0.004
Tag-side interference	0.011	0.006
Vertex reconstruction	0.011	0.004
Tracker misalignment	0.008	0.007
Total	0.032	0.020

arXiv:2305.07555

Systematic uncertainties $B_s^0 \to J/\psi K^+K^-$

* Uncertainties (×0.01) Dominant sys. Sub-dominant sys. Stat. limited

Source	$\lvert A_0\rvert^2$	$\lvert A_\perp\rvert^2$	ϕ_s [rad]	$\lvert\lambda\rvert$	$\delta_\perp - \delta_0$ [rad]	$\delta_\parallel - \delta_0$ [rad]	$\Gamma_s - \Gamma_d$ [ps^{-1}]	$\Delta\Gamma_s$ [ps^{-1}]	Δm_s [ps^{-1}]
Mass parametrization	0.04	0.03	0.03	0.02	0.15	0.12	0.02	0.04	0.03
Mass: shape statistical	0.04	0.04	0.05	0.09	0.62	0.33	0.02	0.01	0.11
Mass factorization	0.11	0.10	0.42	0.19	0.54	0.60	0.12	0.16	0.18
B_c^+ contamination *	0.04	0.05	—	0.02	—	0.17	(0.07)	(0.03)	—
D–wave component	0.04	0.04	0.02	—	0.07	0.13	0.01	0.03	0.02
Ghost tracks	0.07	0.04	0.02	0.10	0.18	0.18	0.02	—	0.01
Multiple candidates	0.01	—	0.27	0.22	0.90	0.41	0.01	0.01	0.24
Particle identification	0.06	0.09	0.27	0.27	1.31	0.51	0.05	0.15	0.46
C_{SP} factors	—	0.01	0.01	0.03	0.73	0.41	—	0.01	0.04
DTR model portability	—	—	0.08	0.03	0.26	0.09	—	—	0.09
DTR calibration	—	—	0.03	0.02	0.11	0.07	—	—	0.05
Time bias correction	0.04	0.05	0.06	0.05	0.77	0.11	0.03	0.05	0.44
Angular efficiency	0.05	0.14	0.25	0.32	0.42	0.44	0.01	0.02	0.13
Angular resolution	0.01	0.01	0.02	0.01	0.02	0.08	—	0.01	0.02
Kinematic weighting	0.24	0.09	0.01	0.01	0.98	0.86	0.02	0.03	0.31
Momentum uncertainty	0.08	0.04	0.04	—	0.07	0.11	0.01	—	0.13
Longitudinal scale	0.07	0.04	0.04	—	0.10	0.09	0.02	—	0.31
Neglected correlations	—	—	—	—	4.20	4.96	—	—	—
Total sys. unc.	0.32	0.24	0.6	0.5	4.8	5.2	0.14	0.24	0.9
Stat. unc.	0.17	0.23	2.2	1.1	7.5	6.0	0.14	0.44	3.3

*The uncertainty of the B_c^+ contamination for $\Delta\Gamma_d^s$ and $\Delta\Gamma_s$ is included in the fit to data and does not contribute to the quoted total systematic uncertainty.

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Systematic uncertainties $B_s^0 \to \phi\phi$

Source	$\phi_s^{s\bar{s}s}$	$\lvert\lambda\rvert$	$\lvert A_0\rvert^2$	$\lvert A_\perp\rvert^2$	$\delta_\parallel - \delta_0$	$\delta_\perp - \delta_0$
Time resolution	4.9	2.6	0.8	0.8	0.1	3.4
Flavor tagging	4.8	4.7	0.9	1.3	1.2	9.7
Angular acceptance	3.9	4.9	1.4	1.7	4.7	1.2
Time acceptance	2.3	1.7	0.1	0.1	5.6	0.7
Mass fit & factorization	2.2	4.4	1.9	2.3	2.3	2.5
MC truth match	1.1	0.2	0.1	0.1	0.2	0.3
Fit bias	0.8	0.7	0.9	0.3	3.6	0.7
Candidate multiplicity	0.3	0.2	0.1	0.8	0.2	0.1
Total	8.8	8.6	2.7	3.3	8.5	10.7

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Systematic uncertainties $B_s^0 \to J/\psi\eta'/\pi\pi$, γ

Belle II INFN

$B_s^0 \to J/\psi\eta'$ / $B_s^0 \to J/\psi\pi\pi$

Source	Value [ns^{-1}]
Simulation sample size	4.6
Acceptance Model	3.0
Bin centre method	0.3
CP violation	0.1
Γ_s	0.1
$J/\psi\eta'$ background model	6.9
$J/\psi\pi^+\pi^-$ background model	0.8
Total	9.0

$B_s^0 \to D_s^+K^-$

Source	C_f	$A_f^{\Delta\Gamma}$	$A_{\bar{f}}^{\Delta\Gamma}$	S_f	$S_{\bar{f}}$
Δm_s	0.007	0.004	0.004	0.108	0.103
Detection asymmetry	—	0.079	0.083	0.006	0.007
Multivariate fit	0.045	0.095	0.121	0.088	0.112
Flavour tagging	0.256	0.026	0.028	0.012	0.070
Decay-time resolution model	0.195	0.002	0.003	0.058	0.167
Decay-time bias	0.062	0.027	0.046	0.188	0.167
Decay-time acceptance, Γ_s, $\Delta\Gamma_s$	0.006	0.225	0.231	0.003	0.003
Decay-time acceptance ratios	0.001	0.018	0.018	—	—
Neglecting correlations	0.137	0.081	0.054	0.135	0.043
Total	0.358	0.273	0.285	0.278	0.294

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