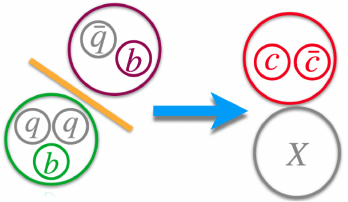
Beauty to charmonium decays at LHCb

Luis Miguel Garcia Martin
on behalf of the LHCb collaboration

Physics goals

- Mainly tree-level $b \to Xc\bar{c}$ decays
  - High $\mathcal{B} \sim (10^{-3} - 10^{-5})$
  - Negligible penguin pollutions
- Charmonium resonances (J/ψ, $\psi(2S)$):
  - Clean exp. signature ($\psi \to \mu^+\mu^-$)
- Stringent tests for SM
- Focus on measurements of $\mathcal{B}$ and CP quantities
  - Observables: $\mathcal{A}_{CP}$, lifetime, helicity angles



LHCb recent results

- Measurement of the branching fraction of $B^0 \to J/\psi\pi^0$
- A measurement of $\Delta\Gamma_s$
- Measurement of CP violation in $B^0 \to \psi(\to \ell^+\ell^-)K^0_S(\to \pi^+\pi^-)$ decays
- Measurement of CP violation in $B^0_s \to J/\psi K^+K^-$ decays near $\phi(1020)$

Measurement of the $\mathcal{B}(B^0 \to J/\psi\,\pi^0)$ [JHEP2405(2024)065]

Physics interest:

- Help to determine penguin pollution to β
  - $J/\psi\,K^0_\mathrm{S}$ $(b \to c\bar{c}s)$: Precision to β
  - $J/\psi\,\pi^0$ $(b \to c\bar{c}d)$: Precision to phase shift
- Evidence of indirect CP violation in $B^0 \to J/\psi\pi^0$, [BaBar] and [Belle]
- Connection to η/η' mixing
- Probe for final-state interaction effects

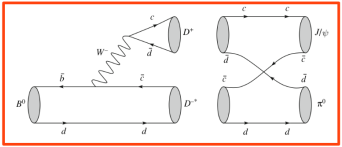
[EPJC71(2011)1798]

$$R_d \equiv \frac{\mathrm{BR}(B_d^0 \to J/\psi\eta')}{\mathrm{BR}(B_d^0 \to J/\psi\eta)}\left(\frac{\Phi_d^{\eta}}{\Phi_d^{\eta'}}\right)^3 = \cos^2\phi_G\,\tan^2\phi_P$$

$$R_s \equiv \frac{\mathrm{BR}(B_s^0 \to J/\psi\eta')}{\mathrm{BR}(B_s^0 \to J/\psi\eta)}\left(\frac{\Phi_s^{\eta}}{\Phi_s^{\eta'}}\right)^3 = \frac{\cos^2\phi_G}{\tan^2\phi_P}$$

$$R_0 \equiv \frac{\mathrm{BR}(B_d^0 \to J/\psi\eta)}{\mathrm{BR}(B_d^0 \to J/\psi\pi^0)}\left(\frac{\Phi_d^{\pi^0}}{\Phi_d^{\eta}}\right)^3 = \cos^2\phi_P.$$

[PAN77(2014)1483–1490]



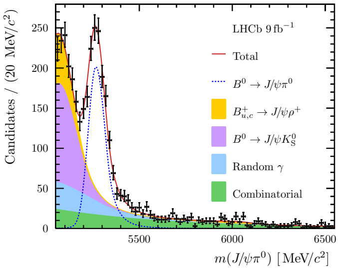
Analysis strategy:

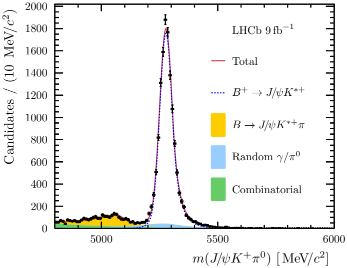
- Goal: Measure $\mathcal{B}(B^0 \to J/\psi\pi^0)$
- Use $B^+ \to J/\psi\,K^{*+}$ as normalization channel with $K^{*+} \to K^+\pi^0$
- Run 1 (2011-2012) + Run 2 (2015-2018) $=$ 9 fb^{-1}

Measurement of the $\mathcal{B}(B^0 \to J/\psi\,\pi^0)$ [JHEP2405(2024)065]

Measured value with 6.3% precision:

$$\frac{\mathcal{B}(B^0 \to J/\psi\,\pi^0)}{\mathcal{B}(B^+ \to J/\psi\,K^{*+})} = (1.153 \pm 0.053(\text{stats.}) \pm 0.048(\text{syst.})) \times 10^{-2}$$





$N(B^0 \to J/\psi\,\pi^0)_{\text{signal}} = 1232 \pm 55$ $N(B^+ \to J/\psi\,K^+\pi^0)_{\text{norm.}} = 13052 \pm 115$

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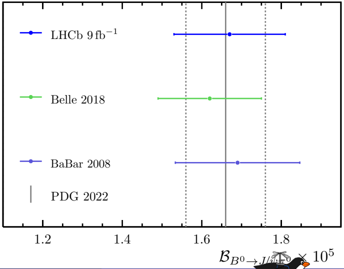
Using $\mathcal{B}\ (B^+ \to J/\psi\,K^{*+})$ from PDG

Branching fraction:

$$\mathcal{B}(B^0 \to J/\psi\,\pi^0) = (1.670 \pm 0.077(\text{stats.}) \pm 0.069(\text{syst.}) \pm 0.095(\text{ext.})) \times 10^{-5}$$

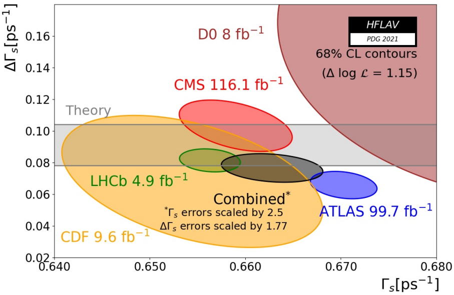


Results compatible with previous measurements

A measurement of $\Delta\Gamma_s$ [JHEP05(2024)253]

Physics interest:

- Sizable decay width difference $\Delta\Gamma_s = \Gamma_L - \Gamma_H$
- Measured by B_s^0-$\overline{B}_s^0$ mixing:
  - Golden mode: $B_s^0 \to J/\psi\,\phi$
  - Requires flavor tagging angular analysis
- Tension in LHC results



Analysis strategy:

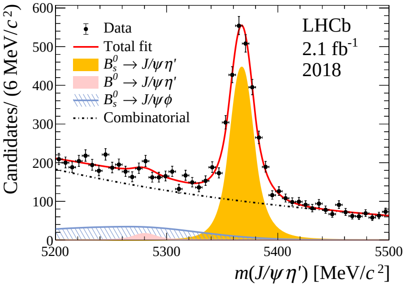
- Innovative method: measure $\tau_{\text{eff}} = 1/\Gamma_{L/H}$ using
  - Pure CP-even $B_s^0 \to J/\psi\,\eta'$ ($\tau_{\text{eff}} = 1/\Gamma_L$)
  - Pure CP-odd $B_s^0 \to J/\psi\, f_0(980)$ ($\tau_{\text{eff}} = 1/\Gamma_H$)
- Neither angular analysis flavor tagging is needed
- Using Run 1 + Run 2 ($9\,\text{fb}^{-1}$)

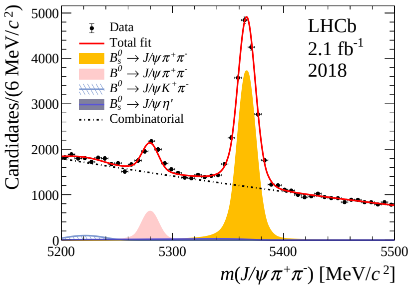
A measurement of $\Delta\Gamma_s$ [JHEP05(2024)253]

- Yields are extracted in bins of decay time

$$R_i = \frac{N_H^{\text{odd}}}{N_L^{\text{even}}} \propto A_r(t) \frac{\left[e^{-\Gamma_s t(1+y)}\right]_{t1}^{t2}}{\left[e^{-\Gamma_s t(1-y)}\right]_{t1}^{t2}} \frac{1-y}{1+y}, \quad y = \frac{\Delta\Gamma_s}{2\Gamma_s}$$

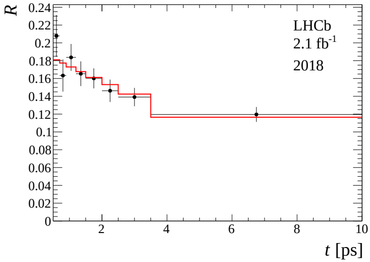
- Corrected with time-dependent relative acceptance ($A_r(t)$)
- Measurement split in years:

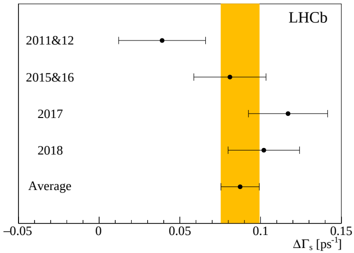




A measurement of $\Delta\Gamma_s$ [JHEP05(2024)253]

Number of bins and ranges from simulation: optimize the sensitivity on $\Delta\Gamma_s$





Combined result:

$$\Delta\Gamma_s = 0.084 \pm 0.011 \pm 0.009\,\text{ps}^{-1}$$

Combined value within 1σ $\Delta\Gamma_s^{\text{HFLAV}} = 0.082 \pm 0.005\,\text{ps}^{-1}$

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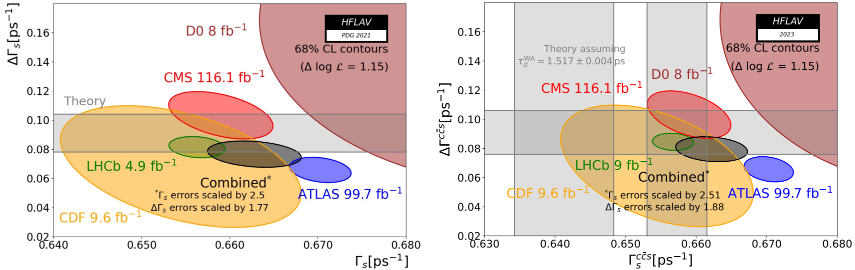
HFLAV 2021 | HFLAV 2023: New LHCb result



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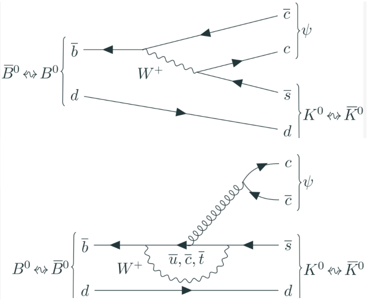
CP violation in $B^0 \to \psi K^0_{\mathrm{S}}$ [PRL132(2024)021801]

Physics interest:

- Measurement of CPV parameters of $S_{(d)}$ and $C_{(d)}$
- Golden modes:
  - $B^0 \to J/\psi(\to \mu^+\mu^-, e^+e^-)K^0_{\mathrm{S}}(\to \pi^+\pi^-)$
  - $B^0 \to \psi(2S)(\to \mu^+\mu^-)K^0_{\mathrm{S}}(\to \pi^+\pi^-)$
- $S = \sin(2\beta + \Delta\phi + \Delta\phi^{\mathrm{NP}})$
- Penguin topologies suppressed ($\Delta\phi \simeq 0$)



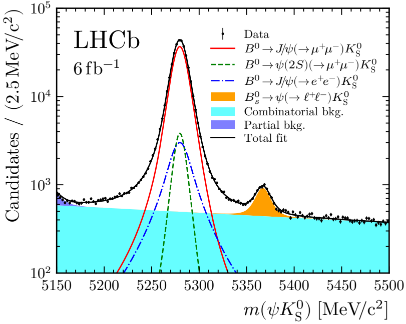
- Assuming $\Delta\Gamma_d \simeq 0$:
  - $\mathcal{A}_{CP} = \frac{\Gamma(\bar{B}^0(t)\to f) - \Gamma(B^0(t)\to f)}{\Gamma(\bar{B}^0(t)\to f) + \Gamma(B^0(t)\to f)} \simeq \sin(2\beta)\sin(\Delta m_d t)$

Analysis strategy:

- Goal: Update measurements with Run 2 data ($6\,\mathrm{fb}^{-1}$)
  - Previous measurements using Run 1 data ($3\,\mathrm{fb}^{-1}$) [PRL115(2015)031601] [JHEP11(2017)170]
- Combined, time-dependent measurement of the CP violation parameters

CP violation in $B^0 \to \psi K^0_S$ [PRL132(2024)021801]

Mass fit to tagged (flavor identified) candidates:



- Signal yields:
  - 306090 ± 570 $B^0 \to J/\psi(\to \mu^+\mu^-)K^0_S$
  - 42700 ± 220 $B^0 \to J/\psi(\to e^+e^-)K^0_S$
  - 23560 ± 160 $B^0 \to \psi(2S)(\to \mu^+\mu^-)K^0_S$
- Considering K^0_S reconstructed with partial tracker info (LD and UL)
  - Increase data size by 13%

Flavor tagging calibrated with:

- SS: $B^0 \to J/\psi K^*$
- OS: $B^+ \to J/\psi K^+$

Flavor tagging power $= \varepsilon_{\text{tag}} \times \mathcal{D}^2$

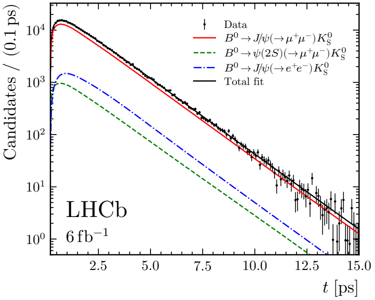
Channel	ϵ_{tag} [%]	$\mathcal{D}^2$ [%]
$B^0 \to J/\psi(\to \mu^+\mu^-)K^0_S$	85.34 ± 0.05	4.661 ± 0.013
$B^0 \to J/\psi(\to e^+e^-)K^0_S$	92.20 ± 0.08	6.462 ± 0.032
$B^0 \to \psi(2S)(\to \mu^+\mu^-)K^0_S$	84.81 ± 0.15	4.59 ± 0.04

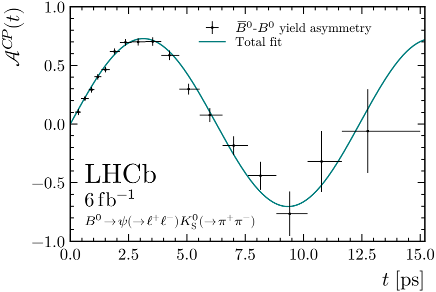
CP violation in $B^0 \to \psi K^0_S$ [PRL132(2024)021801]

CP fit from background-subtracted time-dependent decay rates:

$$\mathscr{P}(t,d,\eta) \propto e^{-\Gamma_d t/\hbar}\left(\left[1+d(1-2\omega^+(\eta))\right]P_{B^0}(t)+\left[1+d(1-2\omega^-(\eta))\right]P_{\overline{B}^0}(t)\right)$$

$$P_{B^0,\overline{B}^0}(t) \propto (1\mp\alpha)(1\mp\Delta\epsilon_{\text{tag}})\left[1\mp S\sin(\Delta m_d t)\pm C\cos(\Delta m_d t)\right]$$





- Estimated K^0_S regeneration and CPV

CP violation in $B^0 \to \psi K^0_S$ [PRL132(2024)021801]

Results per channel:

$$S_{J/\psi(\to\mu^+\mu^-)K^0_S} = 0.716 \pm 0.015\,(\text{stat}) \pm 0.007\,(\text{syst}),$$
$$C_{J/\psi(\to\mu^+\mu^-)K^0_S} = 0.010 \pm 0.014\,(\text{stat}) \pm 0.003\,(\text{syst}),$$
$$S_{\psi(2S)(\to\mu^+\mu^-)K^0_S} = 0.649 \pm 0.053\,(\text{stat}) \pm 0.018\,(\text{syst}),$$
$$C_{\psi(2S)(\to\mu^+\mu^-)K^0_S} = -0.087 \pm 0.048\,(\text{stat}) \pm 0.005\,(\text{syst}),$$
$$S_{J/\psi(\to e^+e^-)K^0_S} = 0.754 \pm 0.037\,(\text{stat}) \pm 0.008\,(\text{syst}),$$
$$C_{J/\psi(\to e^+e^-)K^0_S} = 0.042 \pm 0.034\,(\text{stat}) \pm 0.008\,(\text{syst}).$$

Combined result, more precise than the current HFLAV world average:

Simultaneous fit all channels

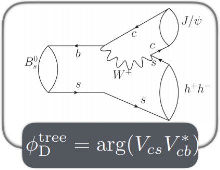
$$S_{\psi K^0_S} = 0.717 \pm 0.013\,(\text{stat}) \pm 0.008\,(\text{syst})$$
$$C_{\psi K^0_S} = 0.008 \pm 0.012\,(\text{stat}) \pm 0.003\,(\text{syst})$$

$$S_{\text{all}(c\bar{c})} = 0.699 \pm 0.017$$
$$C_{\text{all}(c\bar{c})} = -0.005 \pm 0.015$$

CPV in $B_s^0 \to J/\psi K^+K^-$ near $\phi(1020)$ [PRL132(2024)051802]

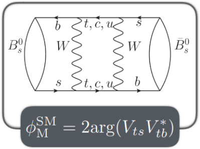
Physics interest:

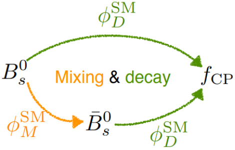
- B_s^0-$\overline{B}_s^0$ mixing induce CPV phase (ϕ_s)
  $\phi_s = -2\beta_s + \Delta\phi_s^{\text{SM}} + \Delta\phi_s^{\text{NP}}$
- Negligible penguin pollution ($\Delta\phi_s^{\text{SM}} \simeq 0$)
  - ϕ_s very sensitive to NP



Analysis strategy:

- Goal: Update measurement with Run 2 data ($6\,\text{fb}^{-1}$)
  - Previous measurement with 2015-2016 data ($1.9\,\text{fb}^{-1}$) [EPJC79(2019)706]
- $m(K^+K^-) \in (990, 1050)\,\text{MeV}/c^2$
- Also measure $\Delta\Gamma_s$, $\Gamma_s - \Gamma_d$, $\|\lambda\|$ and Δm_s
  - $\lambda = \eta_k(p/q)(A_k/\overline{A}_k)$
  - A_k polarization amplitudes
  - η_k: CP-eigenvalue of polarization k
  - p, q relate mass and flavor basis





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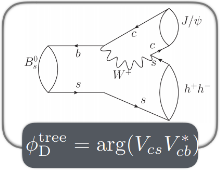

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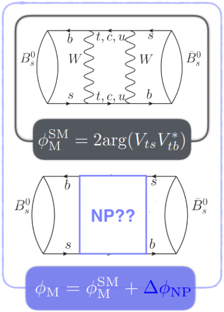
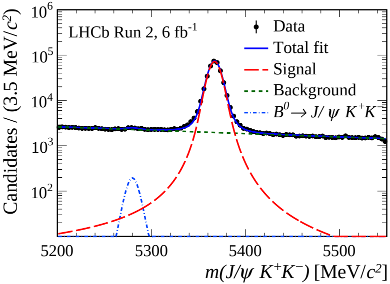


Mass fit for background subtraction

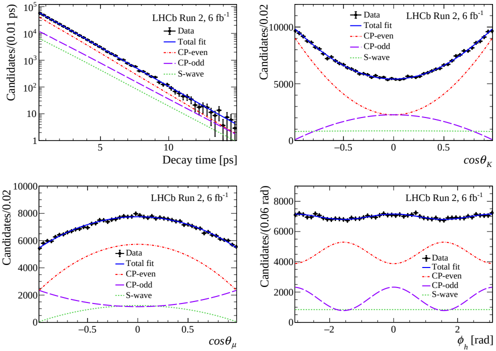


Using flavor tagging

- Calibration channels: $B^+ \to J/\psi K^+$ (OS) and $B_s^0 \to D_s^- \pi^+$ (SS)
- Tagging power: $(4.18 \pm 0.15)\%$,$(4.22 \pm 0.16)\%$, $(4.36 \pm 0.16)\%$

CPV in $B_s^0 \to J/\psi K^+K^-$ near $\phi(1020)$ [PRL132(2024)051802]

Time-angular dependent decay rates



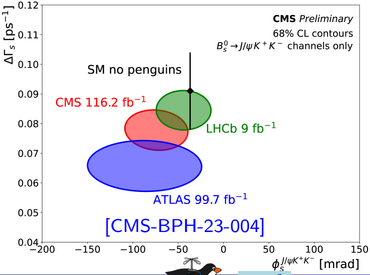
- Angular resolution and decay time acceptance and resolution
- Consider four polarization:
  - J/ψ-ϕ (P-wave): 2 CP-even + 1 CP-odd
  - K^+-K^- (S-wave): 1 CP-odd

CPV in $B_s^0 \to J/\psi K^+ K^-$ near $\phi(1020)$ [PRL132(2024)051802]

Run 2 results:

$$\phi_s^{c\bar{c}s} = -0.039 \pm 0.022 \pm 0.006\,\text{rad}$$
$$|\lambda| = 1.001 \pm 0.011 \pm 0.005$$
$$\Delta\Gamma_s = 0.0848^{+0.0044}_{-0.0045} \pm 0.0024\,\text{ps}^{-1}$$
$$\Gamma_s - \Gamma_d = -0.0059^{+0.0014}_{-0.0013} \pm 0.0014\,\text{ps}^{-1}$$
$$\Delta m_s = 17.743 \pm 0.033 \pm 0.009\,\text{ps}^{-1}$$

- Most precise/competitive with CMS: ϕ_s, $\Delta\Gamma_s$ and $\Gamma_s - \Gamma_d$
- No evidence for CPV
- Compatible with SM prediction
  - $\phi_s^{\text{SM}} = -0.0368^{+0.0009}_{-0.0006}$ [PRD91(2015)073007]
- No polarization dependency is observed
- Consistent with 2015-2016 measurement



Summary

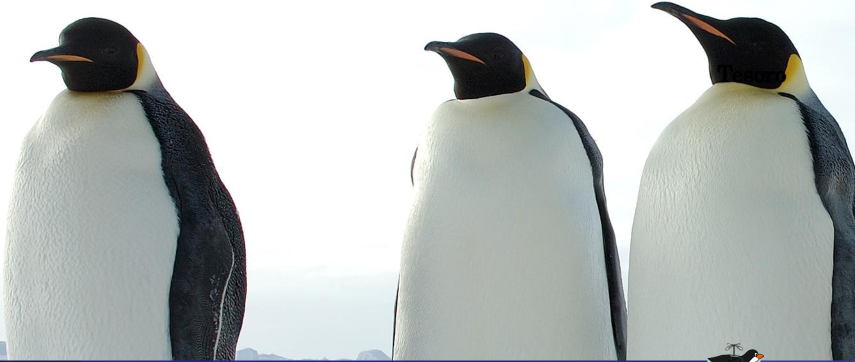
Branching ratios:

- Measurement of $\mathcal{B}\,(B^0 \to J/\psi\,\pi^0)$ with $9\,\text{fb}^{-1}$ compatible with BaBar and Belle

CP parameters:

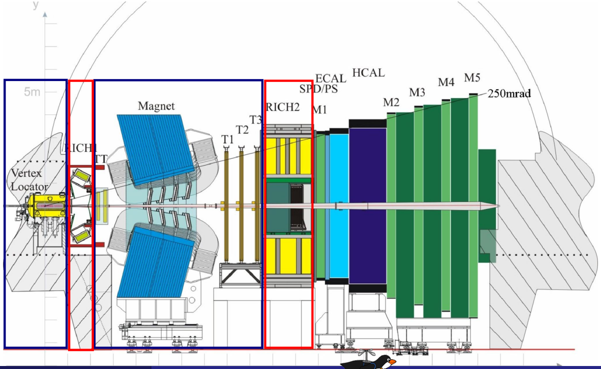
- **Time-dependent:** Updated $\Delta\Gamma_s$ measurement in $B_s^0 \to J/\psi\,\eta'/\phi$ with $9\,\text{fb}^{-1}$ compatible with world average
- **Time-dependent $\mathcal{A}_{CP}$:** Update S_d and C_d measurement in $B^0 \to \psi K_\text{S}^0$ with $6\,\text{fb}^{-1}$ more precise than current world average
- **Angular-Time dependent:** Update ϕ_s, $\Delta\Gamma_s$, $\Gamma_s - \Gamma_d$, $\|\lambda\|$ and Δm_s measurement in $B_s^0 \to J/\psi\,K^+K^-$ with $6\,\text{fb}^{-1}$

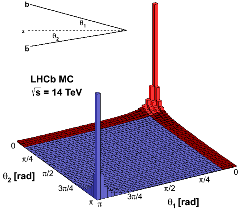
Thanks for your attention



The LHCb experiment

- The LHCb idea: to build a single-arm forward spectrometer:
  - $\sim$4% of the solid angle ($2 < \eta < 5$)
  - $\sim$30% of the b hadron production
- **Excellent PID** via Two Ring Imaging CHerenkov (RICH) detectors
- **Precise tracking and IP**: VErtex LOcator (VELO) and tracking stations





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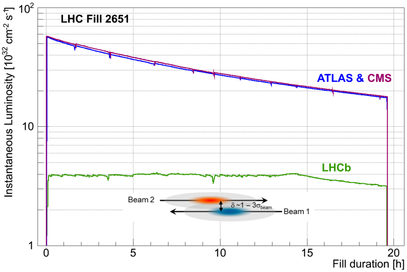
- Designed to run at lower instantaneous luminosity



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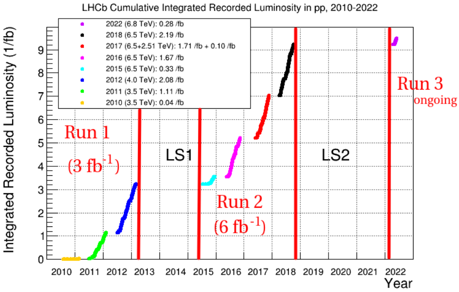
- Largest sample of heavy flavour decays



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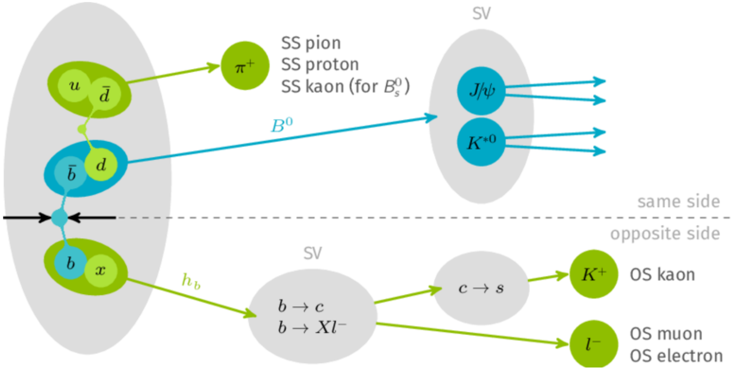
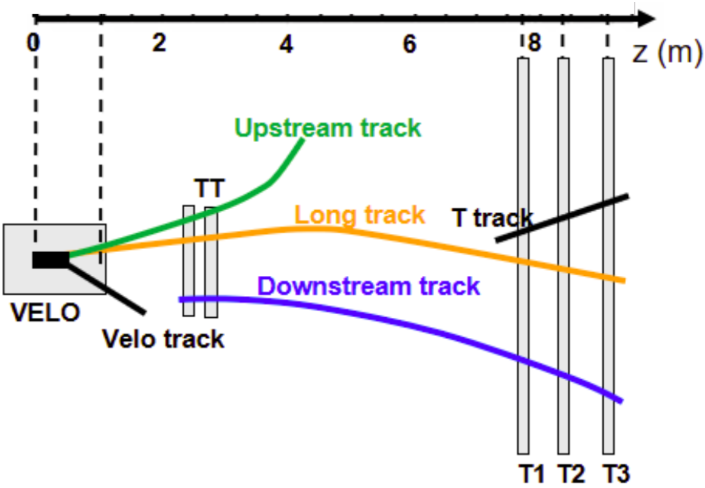
- **Precise tracking and IP**: VErtex LOcator (VELO) and tracking stations
- Designed to run at lower instantaneous luminosity
- Largest sample of heavy flavour decays
- Highly complementary to e^+e^- "B-factory" experiments:
  - Produce all types of b,c-mesons and baryons
  - Huge cross-section

Flavor tagging



Track types


0
2
4
6
8
z (m)
Upstream track
TT
Long track
T track
Downstream track
VELO
Velo track
T1
T2
T3