# Opportunities to probe CP violation in rare B decays at LHCb Upgrades

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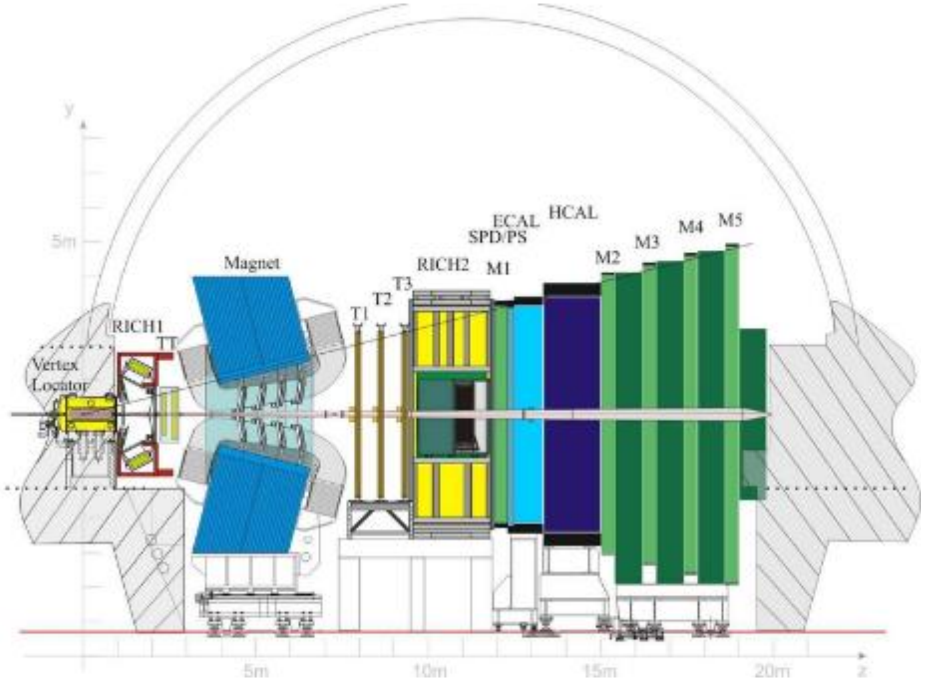
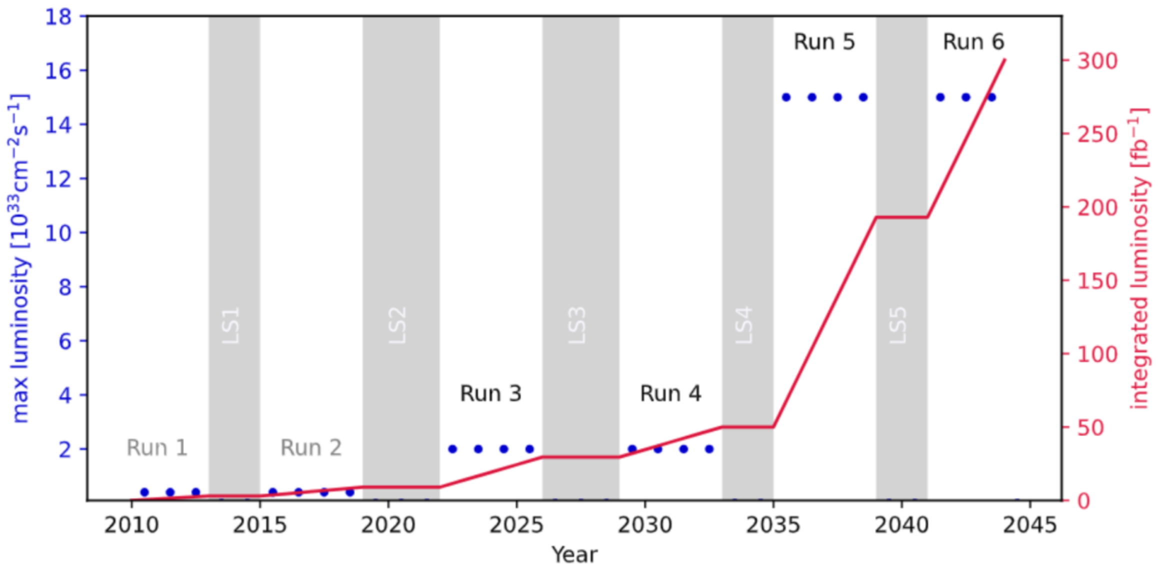
第三届强子与重味物理理论与实验联合研讨会

武汉， 2024年4月6-9日

# LHCb Upgrades



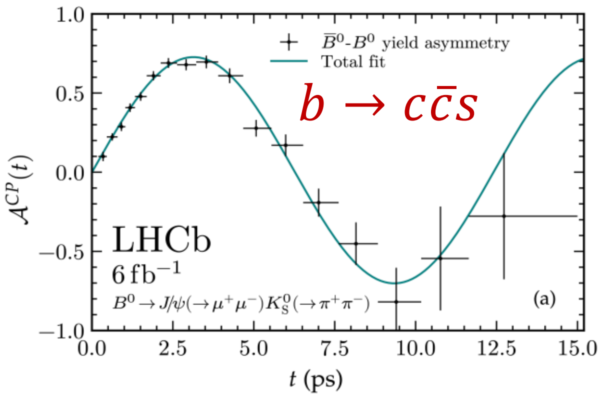




- 理解正反物质不对称（CP破坏）
- 间接寻找新物理效应（稀有衰变、轻子普适性）
- 理解强相互作用机制（强子性质、QCD）
- 前向区域的物理研究（电弱物理、重离子物理）

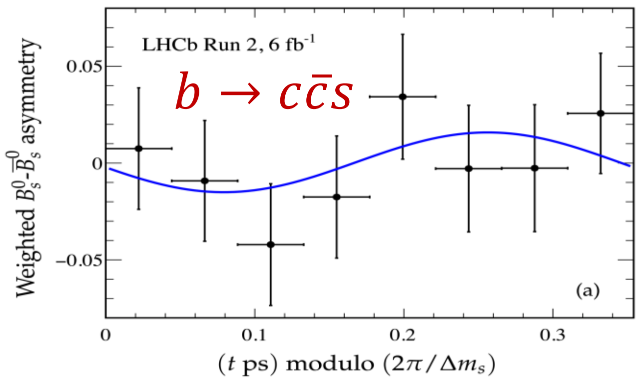
- Run 1+2：9 $\text{fb}^{-1}$
- After Run 3：达到 23 $\text{fb}^{-1}$
- Upgrade I: 达到 50 $\text{fb}^{-1}$ (10年)
- Upgrade II: 达到 300 $\text{fb}^{-1}$（20年）

**两大主题：CP破坏与稀有衰变**

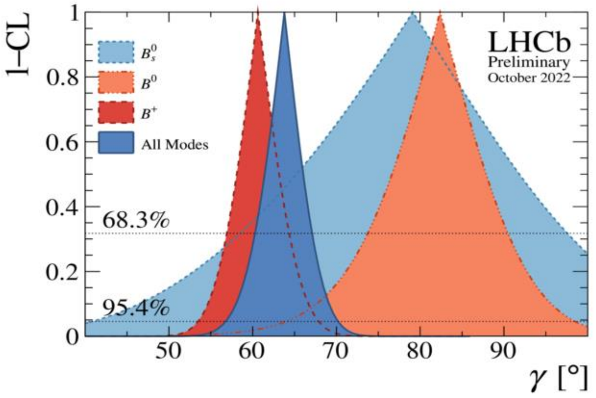
# State-of-the-art CP violation study



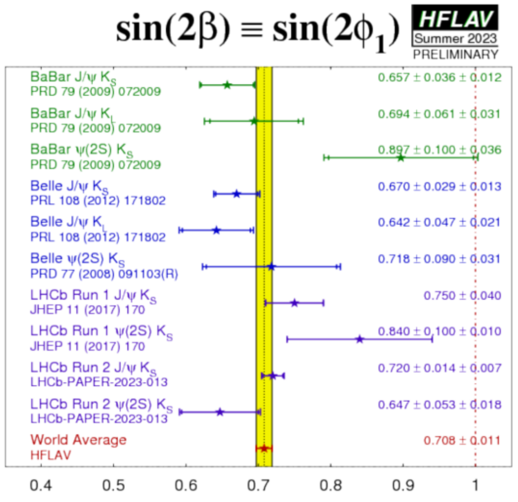

$b \to c\bar{c}s$

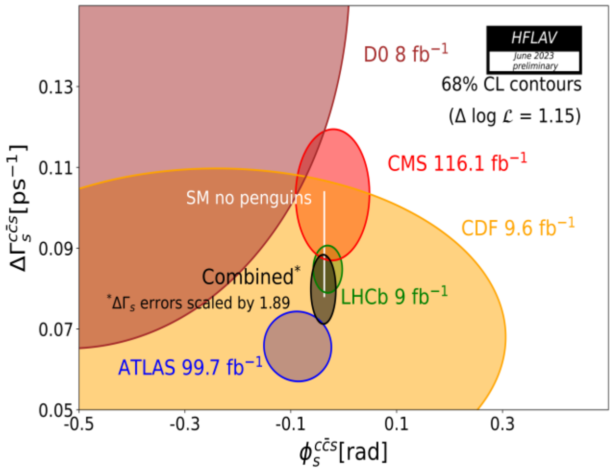


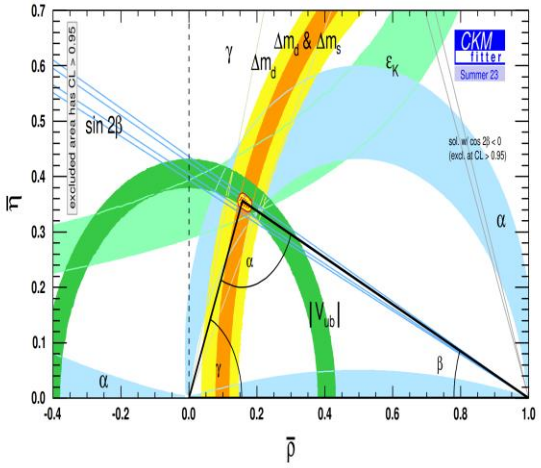

$b \to c\bar{c}s$




$b \to u$ &
$b \to c$




**CP violation has been precisely measured in tree-level hadron decays, which is very well described by the CKM mechanism.**

# Rare $B$ decays at LHCb

❑ **Focusing on FCNC decays**

- Dileptonic $b \to (s/d)l^+l^-$
- Radiative $b \to (s/d)\gamma$
- Hadronic $b \to (s/d)q\bar{q}$ $(q = s, d)$

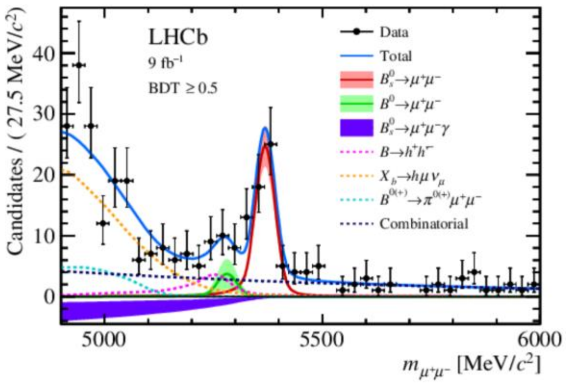
❑ **Major observables in FCNC decays**

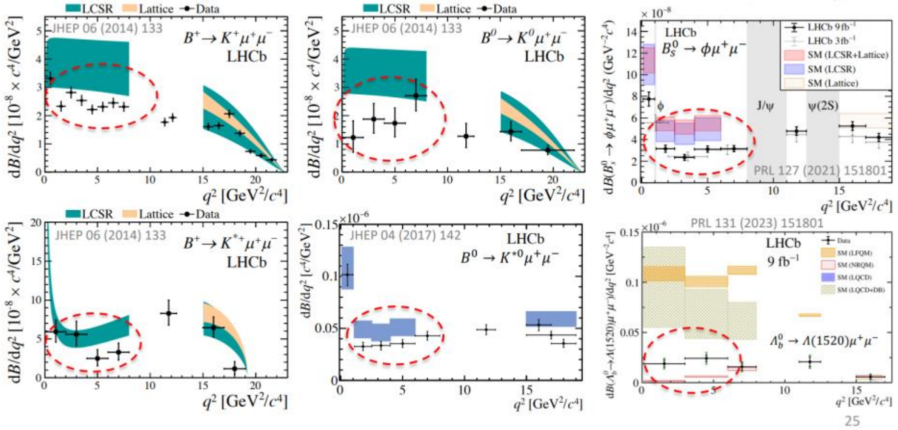
- Decay rates
- Angular correlations

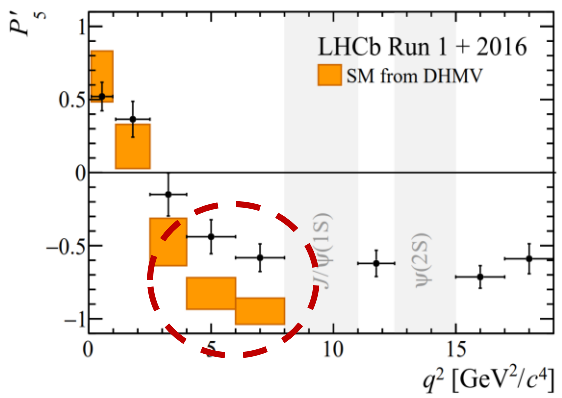
Sensitive to form factors; extensively studied!

- CP asymmetries

➡ Theoretically clean; much less explored!




**CP violation in FCNC decays is very interesting but much less explored!**

# CP-violating observables in FCNC decays

- **Time-Integrated CP violation in the decay $B \to f$**

$$A_{CP}^{TI} = \frac{\Gamma(\bar{B} \to \bar{f}) - \Gamma(B \to f)}{\Gamma(\bar{B} \to \bar{f}) + \Gamma(B \to f)}$$

- **Time-Dependent CP violation in neutral $B_q^0$ decays to a CP eigenstate**

$$A_{CP}(t) = \frac{-C\cos(\Delta m_d t) + S\sin(\Delta m_d t)}{\cosh\left(\frac{\Delta\Gamma_q t}{2}\right) + A_\Delta \sinh\left(\frac{\Delta\Gamma_q t}{2}\right)}$$

$C$: direct CP violation
$S$: mixing-induced CP violation
$A_\Delta$: CP-even, accessible only in $B_s^0$

- **This talk focuses on TD CPV observables**
  - SM predictions largely independent of form factors
  - Providing much more information than TI observables

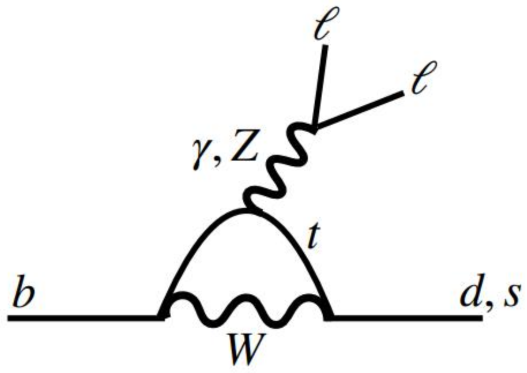
# CP violation in $b \to s\mu^+\mu^-$ decays

# FCNC $b \to s l^+ l^-$ decays

- Precision tests of the SM and NP

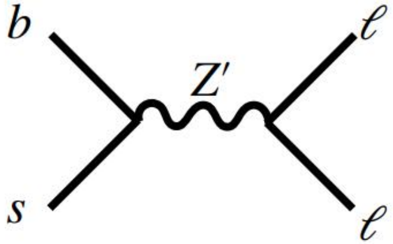
**SM:**

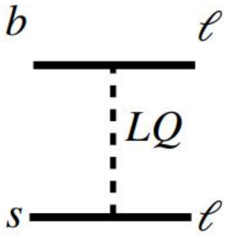
FCNCs: loop and CKM suppressed, breakdown of GIM due to $t$




**NP:**

Could enter already at tree-level, highly sensitive to short-distance NP



# FCNC $b \to s l^+ l^-$ decays

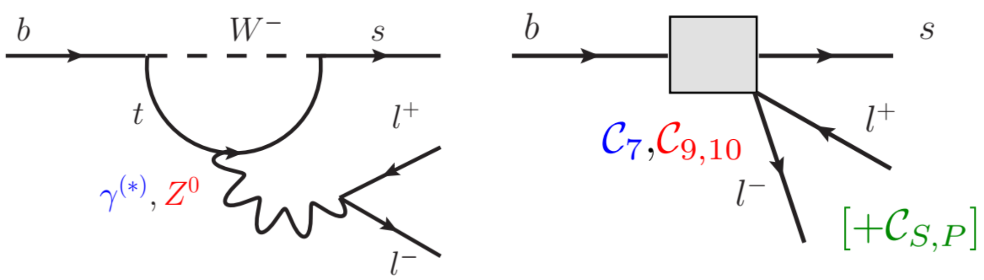
- **$b \to s l^+ l^-$ decays described by effective Hamiltonian**

$$H^{\mathrm{eff}} = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \sum_i (C_i \, O_i + C_i' O_i')$$

SM : $C_9 \approx -C_{10}$, $C'_{7,9,10} \approx 0$

New physics can alter Wilson coefficients $C_i$

- **Consider NP effects in $C^{(\prime)}_{7,9,10,S,P}$**

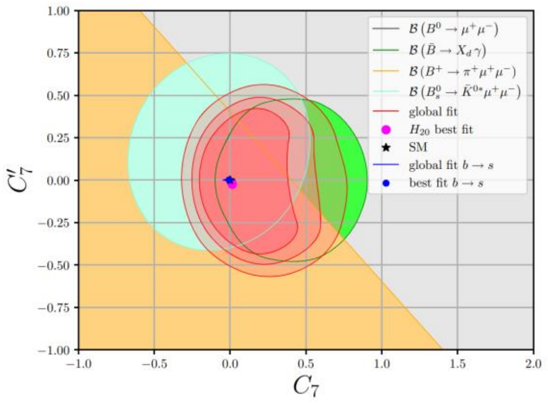


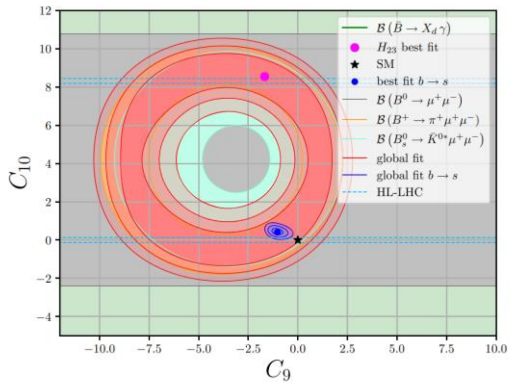

- $B^0_{(s)} \to l^+ l^-$
  $[C_{10}, C_S, C_P]$
- $b \to s l^+ l^-$
  $[C_7, C_9, C_{10}]$

7: photon penguin; 9,10: EW penguin; S,P: (pseudo-)scalar penguin

# FCNC $b \to sl^+l^-$ decays

- **Global $b \to sl^+l^-$ results for Wilson coefficients, using rate and angular observables and assuming real Wilson coefficient** [EPJC 83 (2023) 419]




- **CP asymmetries can be used to constrain phases of the relevant Wilson coefficients** [JHEP 03 (2023) 113]
  - Direct CP violation sensitive to $C_9$ or $C_T$
  - Mixing-induced CP violation sensitive to phases of any Wilson coefficients

# CP violation in $B^0 \to K_S^0 \mu^+ \mu^-$

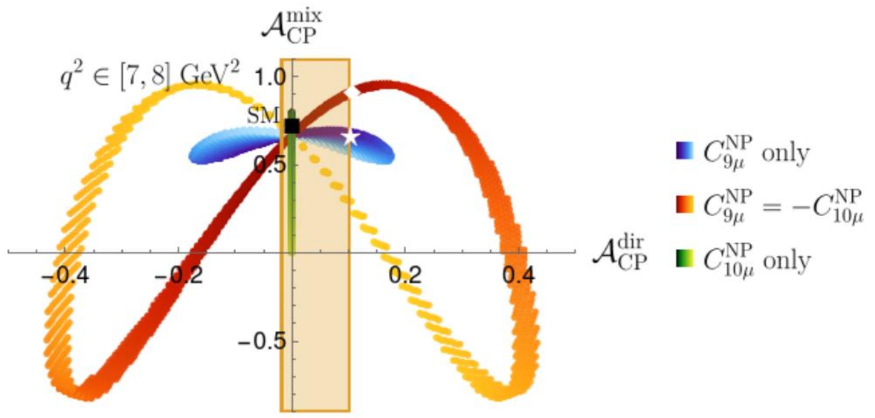
- **Tiny CP-violating phase in $b \to s\mu^+\mu^-$ decay in the SM** [PRD 104 (2021) 115004]

$$A_{CP}(t) = C\cos(\Delta m_d t) - S\sin(\Delta m_d t)$$

SM: $C \approx 0,\ S \approx \sin 2\beta^{c\bar{c}s}$ below $J/\psi$

- **Large CP-violating phase in $b \to s\mu^+\mu^-$ decay possible in NP models**

e.g. $S_3$ leptoquark model with $M_{LQ} \sim$ a few TeV [JHEP 03 (2023) 113]




**No experimental info on mixing-induced CP violation**

# CP violation in $B^0 \to K_S^0 \mu^+ \mu^-$

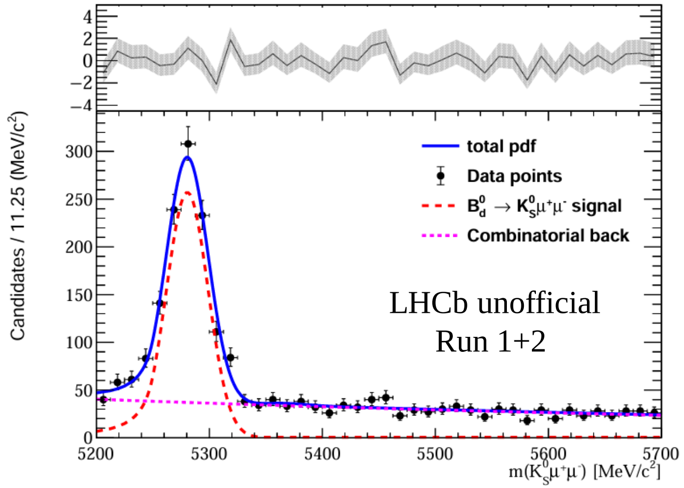
## Sensitivity study [Kechen Li, PhD Thesis]

- About 1k signals in Run 1+2 data
- Expected precision with with 9 /50 /300 fb$^{-1}$

$$\sigma_S \approx \sigma_C \approx 0.29/0.11/0.045$$

- Measure $S, C$ in three $q^2$ regions with 50 fb$^{-1}$ or more

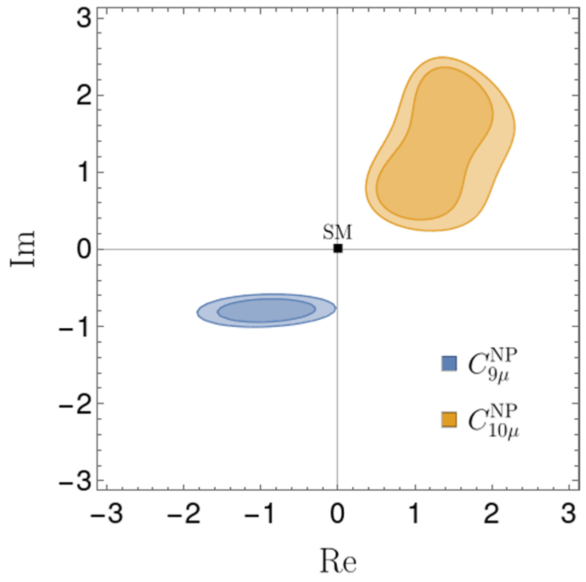
$q^2 \in [1.1, 6.0]\ \mathrm{GeV}^2$ $q^2 \in [8, 9]\ \mathrm{GeV}^2$ $q^2 \in [15, 22]\ \mathrm{GeV}^2$




## An Upgrade II example [JHEP 03 (2023) 113]

$$\mathcal{A}_{\mathrm{CP}}^{\mathrm{dir}}[8,9] = 0.16 \pm 0.02\,,$$
$$\mathcal{B}[1.1, 6.0] = (1.15 \pm 0.02) \times 10^{-7}\,,$$

$$\mathcal{A}_{\mathrm{CP}}^{\mathrm{mix}}[1.1, 6] = 0.94 \pm 0.04\,,$$
$$\mathcal{B}[15, 22] = (0.908 \pm 0.018) \times 10^{-7}$$



# CPV in $B_s^0 \to \phi\mu^+\mu^-$ and $B_s^0 \to \mu^+\mu^-$

## $B_s^0 \to \phi\mu^+\mu^-$

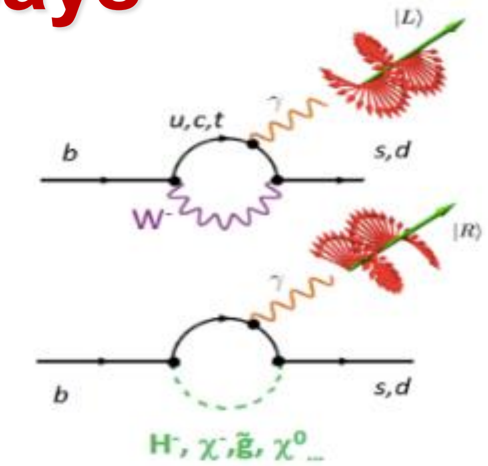
- **TD CP violation in $B_s^0 \to \phi\mu^+\mu^-$ as a probe of NP** [JHEP 04 (2015) 045]
- **Sensitivity study** [Yilong Wang, PhD Thesis]
  - ~2k signals found in Run 1+2 data
  - In analogy to $B_s^0 \to J/\psi\phi$, measure a phase $\phi_s^{s\mu\mu}$. In the SM, $\phi_s^{s\mu\mu} \approx 0$.
  - Expected precision with 9 /50 /300 $\mathrm{fb}^{-1}$: $\boldsymbol{\sigma(\phi_s^{s\mu\mu}) \approx 0.29/0.11/0.045}$ **rad**
  - Possible to investigate $q^2$ and polarization dependence with 300 $\mathrm{fb}^{-1}$

## $B_s^0 \to \mu^+\mu^-$

- **CP violation in $B_s^0 \to \mu^+\mu^-$ sensitive to (pseudo-) scalar interactions** [PRL 109 (2012) 041801]
- **LHCb precision with 300 $\mathrm{fb}^{-1}$: $\boldsymbol{\sigma_S = 0.2}$** [LHCb-pub-2018-009]
- **Interesting case for a combined analysis of LHCb, ATLAS, CMS**

# CP violation in radiative $B$ decays

# Photon polarization in $b \to s/d\gamma$ decays




- Photons in $b \to s/d\gamma$ are predominantly left-handed
- Right-handed contribution can be enhanced in BSM models

$$\mathcal{H}_{\text{eff}} = -\frac{4G_F}{\sqrt{2}} V_{\text{tb}} V_{\text{ts}}^* \sum_i \Big( \underbrace{C_i \mathcal{O}_i}_{\text{left-handed}} + \underbrace{C_i' \mathcal{O}_i'}_{\text{right-handed}} \Big) + h.c.$$

$$\mathcal{O}_7^{(\prime)} = \frac{e^2}{16\pi^2} m_b \left[\bar{s}\sigma_{\mu\nu} P_{R(L)} b\right] F^{\mu\nu}$$

$$r = \frac{C_7'}{C_7} = \frac{A(b \to s/d\gamma_R)}{A(b \to s/d\gamma_L)} = \mathcal{O}\left(\frac{m_{s/d}}{m_b}\right)$$

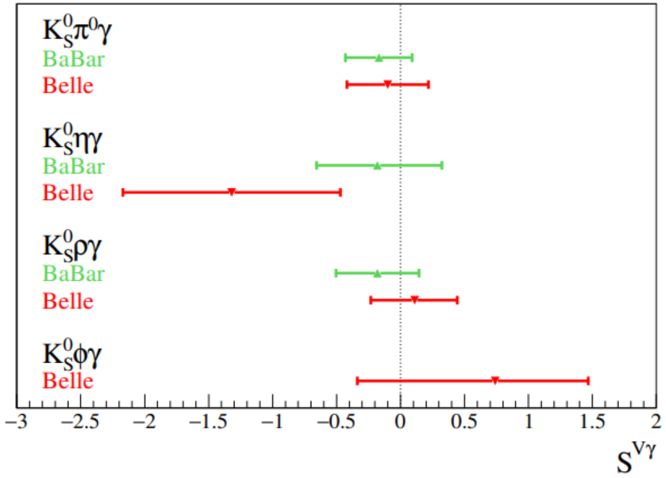
- TD CP violation in $B_q^0 \to M_{CP}\gamma$, with $\eta$ being the CP eigenvalue of $M_{CP}$

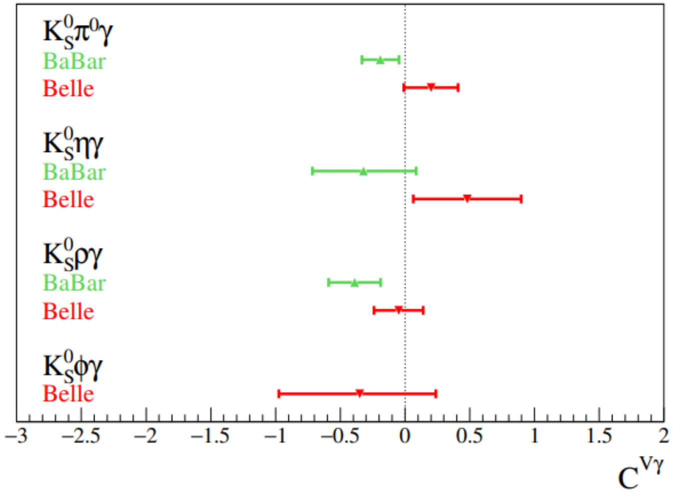
$$A_{CP}(t) = \frac{-C\cos(\Delta m_d t) + S\sin(\Delta m_d t)}{\cosh\left(\frac{\Delta\Gamma_q t}{2}\right) + A_\Delta \sinh\left(\frac{\Delta\Gamma_q t}{2}\right)}$$

SM: $S \approx 2\eta|r|\sin(\phi_M - \phi_L - \phi_R) \approx 0$
$A_\Delta \approx 2\eta|r|\cos(\phi_M - \phi_L - \phi_R) \approx 0$
$C \approx 0$

# Current status of CPV in $b \to s/d\gamma$

$b \to s\gamma$: $B^0$




$b \to s\gamma$: $B_s^0$

$B_s^0 \to \phi\gamma$

$S = 0.43 \pm 0.30 \pm 0.11$

$C = 0.11 \pm 0.29 \pm 0.11$

$A^{\Delta} = -0.67^{+0.37}_{-0.41} \pm 0.17$

[LHCb, PRL 123 (2019) 081802]

$b \to d\gamma$

$B^0 \to \rho^0\gamma$

$S = -0.83 \pm 0.65 \pm 0.18$

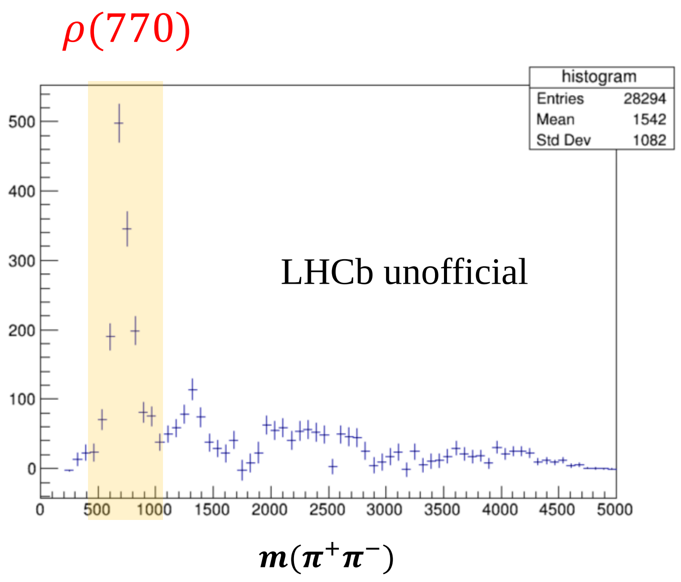
$C = +0.44 \pm 0.49 \pm 0.14$

[Belle, PRL 100 (2008) 021602]

# CP violation in $B^0 \to \pi^+\pi^-\gamma$

- $B^0 \to \pi^+\pi^-\gamma$ is dominated by a $b \to d\gamma$ transition: $S \approx 0$ and $C \approx 0$ in the SM
- $\pi^+\pi^-$ is always in a CP-even eigenstate

  $C(\pi^+\pi^-) = (-1)^{L+S} = (-1)^L$, $P(\pi^+\pi^-) = (-1)^L$, $CP(\pi^+\pi^-) = (-1)^{2L} = +1$
- Measure TD CP violation in $B^0 \to \pi^+\pi^-\gamma$ using the full $\pi^+\pi^-$ spectrum
  - No need for amplitude analysis to distinguish different resonances




- Gain 200% more signals than $B^0 \to \rho^0\gamma$
- Expect ~18k signals in Run 1+2 data
- Expected precision with 9/50/300 $\mathrm{fb}^{-1}$

  $\sigma_S \approx \sigma_c \approx 0.09/0.035/0.015$

c.f. Belle results on $B^0 \to \rho^0\gamma$

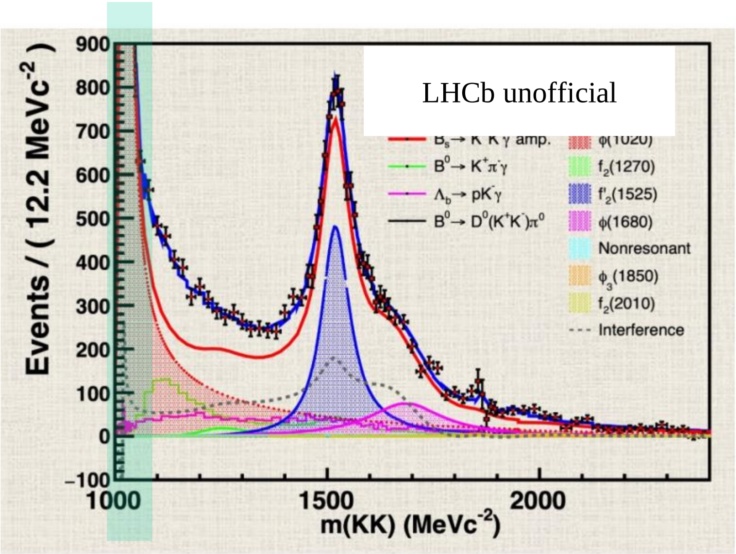
$S = -0.83 \pm 0.65 \pm 0.18$

$C = +0.44 \pm 0.49 \pm 0.14$

# CPV in $B_s^0 \to K^+K^-\gamma$ decays

- $B_s^0 \to K^+K^-\gamma$ is dominated by a $b \to s\gamma$ transition: $S \approx 0, A_\Delta = 0$ and $C \approx 0$ in the SM
- Measure TD CP violation in $B_s^0 \to K^+K^-\gamma$ using the full $K^+K^-$ spectrum

$\phi(1020)$




- Gain 100% more signals than $B_s^0 \to \phi\gamma$
- Expect ~10k signals in Run 1+2
- Expected precision with 9/50/300 $\mathrm{fb}^{-1}$

$$\sigma_S \approx \sigma_C \approx 0.20/0.08/0.03$$

$$\sigma_{A_\Delta} \approx 0.25/0.11/0.04$$

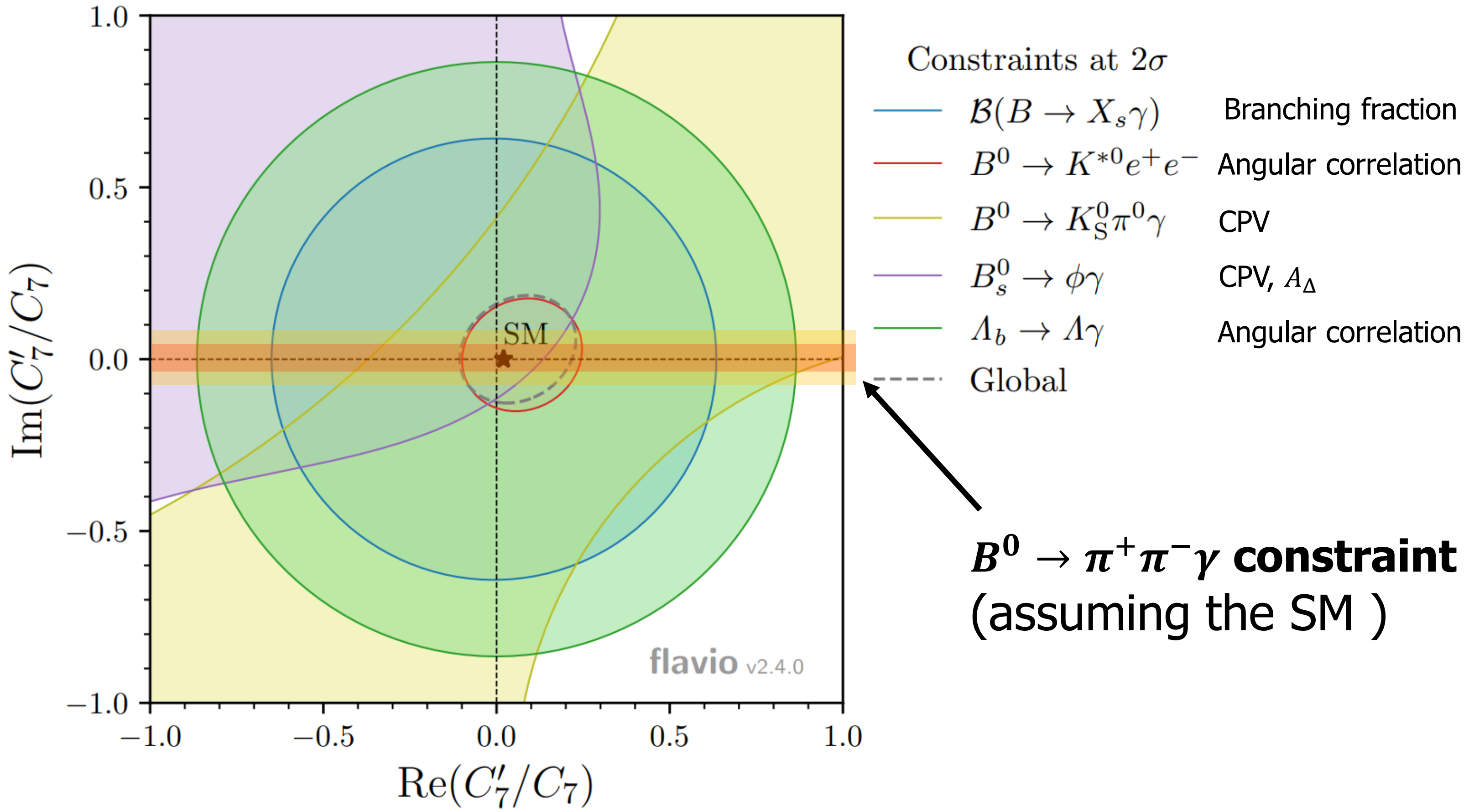
c.f. LHCb results on $B_s^0 \to \phi\gamma$ (9 $\mathrm{fb}^{-1}$)

$S = 0.43 \pm 0.30 \pm 0.11$

$C = 0.11 \pm 0.29 \pm 0.11$

$A^\Delta = -0.67^{+0.37}_{-0.41} \pm 0.17$

# Constraints on $C_7'/C_7$



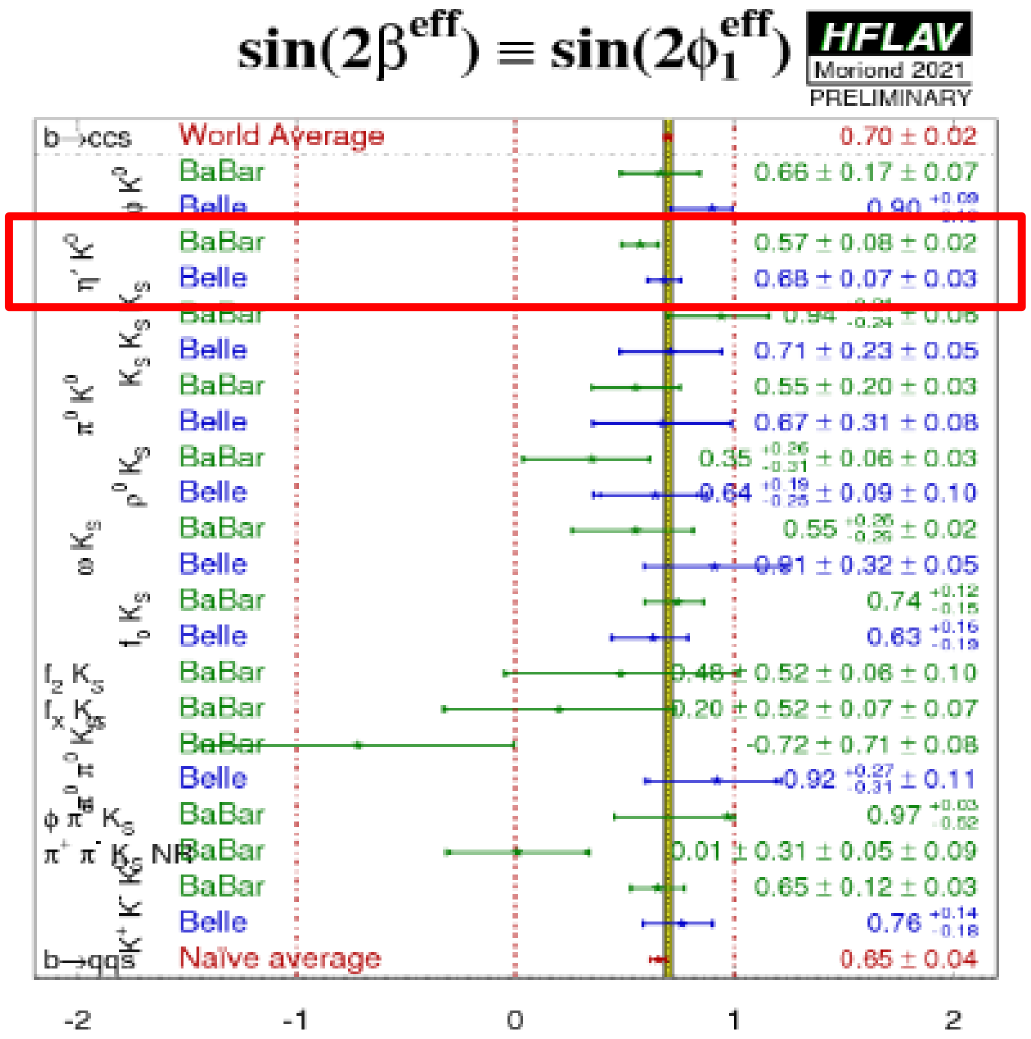

$B^0 \to \pi^+\pi^-\gamma$ **constraint with 50/300** $\mathbf{fb^{-1}}$
(assuming the SM )

**CPV in $B^0 \to \pi^+\pi^-\gamma$ is very powerful for constraining the complex phase of $C_7'/C_7$**

# CP violation in hadronic $b \to s$ decays

# CP violation in hadronic $b \to s$ decays

$b \to s\bar{q}q$: $B^0$




$b \to s\bar{q}q$: $B_s^0$

$B_s^0 \to \phi\phi$

$\phi_s^{s\bar{s}s} = -0.074 \pm 0.069$ rad

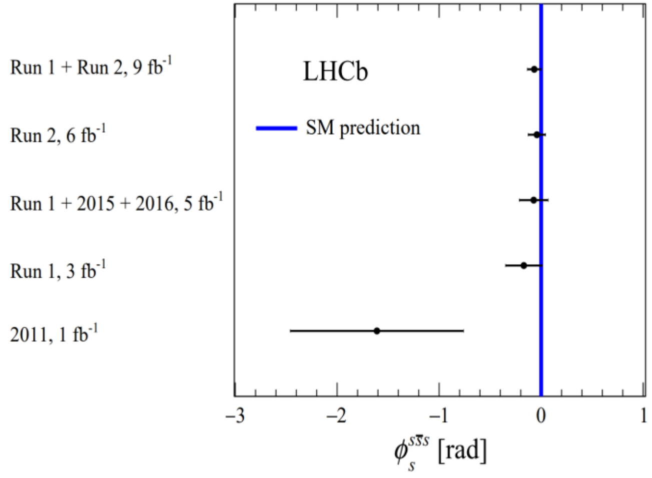
$B_s^0 \to K^{*0}\bar{K}^{*0}$

$\phi_s^{s\bar{d}d} = -0.10 \pm 0.13 \pm 0.14$ rad

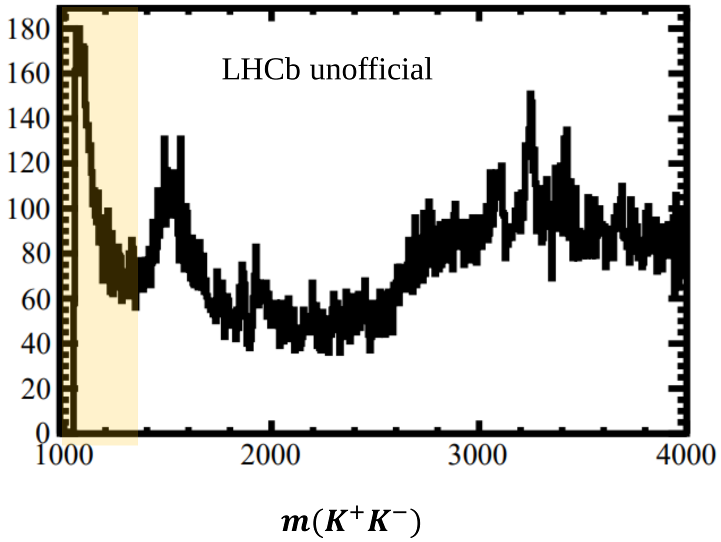
# From $B_s^0 \to \phi\phi$ to $B_s^0 \to \phi K^+ K^-$

- **LHCb has measured TD CP violation in $B_s^0 \to \phi\phi$ using Run 1+2 data, where $\phi \to K^+ K^-$**

$$\phi_s^{s\bar{s}s} = -0.074 \pm 0.069 \text{ rad}$$




$\phi(1020)$




- **Extend this study to $B_s^0 \to \phi K^+ K^-$**
  - Gain ~100% more signals than $B_s^0 \to \phi\phi$
  - Expected precision with 9/50/300 fb$^{-1}$

$$\boldsymbol{\sigma(\phi_s^{s\bar{s}s}) \approx 0.05/0.02/0.008 \text{ rad}}$$

  - A tagged time-dependent amplitude analysis is needed, similar to the analysis of $B_s^0 \to J/\psi K^+ K^-$ in the mass range above $\phi(1020)$ [JHEP 08 (2017) 037]

# Summary

- **LHCb has great potential to study CP violation in rare $B$ decays**
- **Some new ideas**
  - First measurements of CP violation in $b \to s\mu^+\mu^-$ decays
  - New decay modes to study CP violation in radiative $B$ decays
  - Extending the study of CP violation in hadronic $b \to s$ decays

| Modes | Key measure | Present data ($9\ \mathrm{fb}^{-1}$) | Upgrade I ($50\ \mathrm{fb}^{-1}$) | Upgrade II ($300\ \mathrm{fb}^{-1}$) |
|---|---|---|---|---|
| $B^0 \to K_S^0\mu^+\mu^-$ | $\sigma_S \approx \sigma_C$ | $0.29$ | $0.11$ | $0.045$ |
| $B_s^0 \to \phi\mu^+\mu^-$ | $\sigma(\phi_s^{s\mu\mu})$ | $0.29$ rad | $0.12$ rad | $0.045$ rad |
| $B^0 \to \pi^+\pi^-\gamma$ | $\sigma_S \approx \sigma_C$ | $0.09$ | $0.035$ | $0.015$ |
| $B_s^0 \to K^+K^-\gamma$ | $\sigma_S \approx \sigma_C$ | $0.20$ | $0.08$ | $0.03$ |
| $B_s^0 \to \phi K^+K^-$ | $\sigma(\phi_s^{s\bar{s}s})$ | $0.05$ rad | $0.02$ rad | $0.008$ rad |

# Backup slides

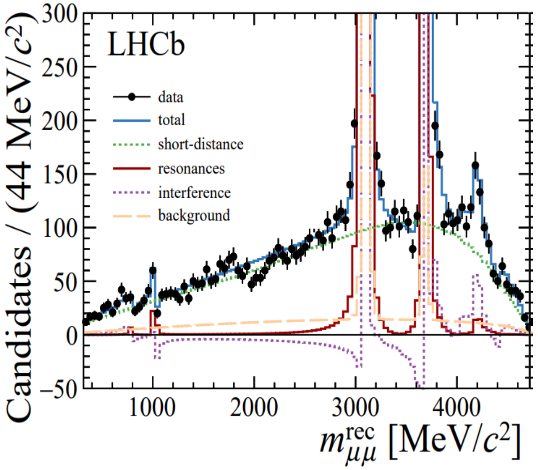
# CP violation in $B^+ \to K^+\mu^+\mu^-$

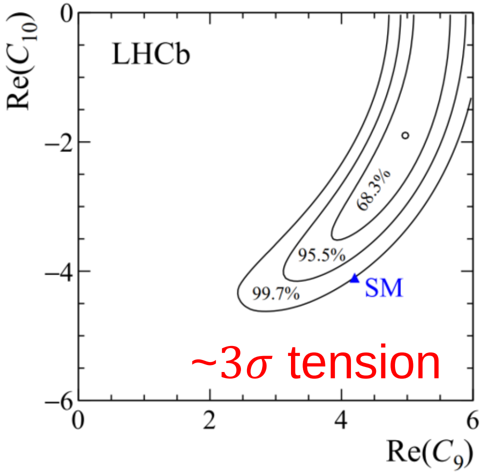
- Interference of short and long distance contributions

$$\frac{\mathrm{d}\Gamma}{\mathrm{d}q^2} = \frac{G_F^2\alpha^2|V_{tb}V_{ts}^*|^2}{128\pi^5}|\boldsymbol{k}|\beta\left\{\frac{2}{3}|\boldsymbol{k}|^2\beta^2\left|\mathcal{C}_{10}f_+(q^2)\right|^2 + \frac{4m_\mu^2(m_B^2-m_K^2)^2}{q^2m_B^2}\left|\mathcal{C}_{10}f_0(q^2)\right|^2 + |\boldsymbol{k}|^2\left[1-\frac{1}{3}\beta^2\right]\left|\mathcal{C}_9f_+(q^2)+2\mathcal{C}_7\frac{m_b+m_s}{m_B+m_K}f_T(q^2)\right|^2\right\},$$

$$\mathcal{C}_9^{\mathrm{eff}} = \mathcal{C}_9 + \boxed{\sum_j \eta_j e^{i\delta_j} A_j^{\mathrm{res}}(q^2),}$$

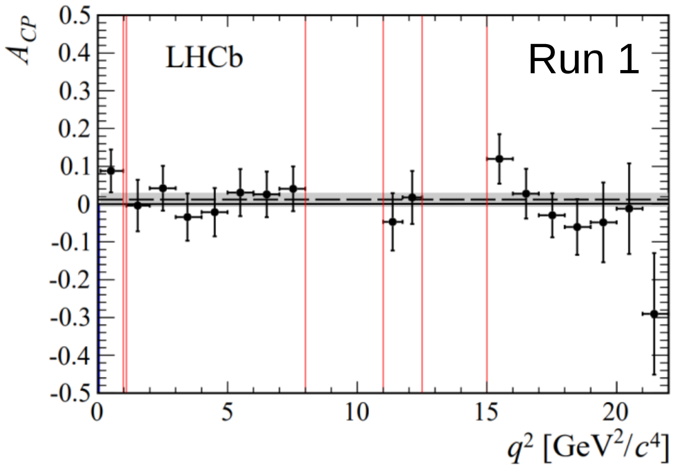
long distance



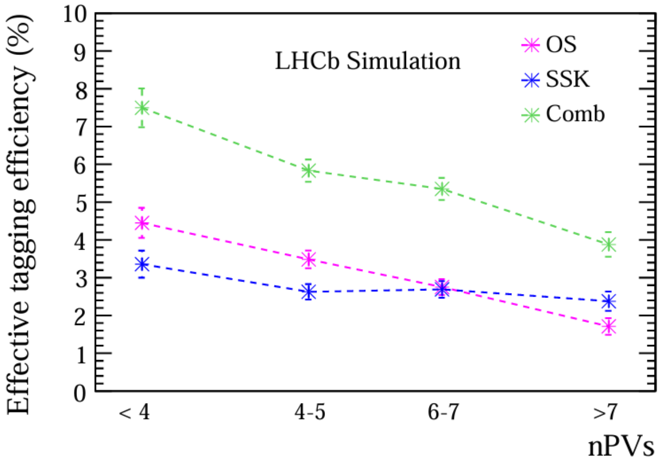



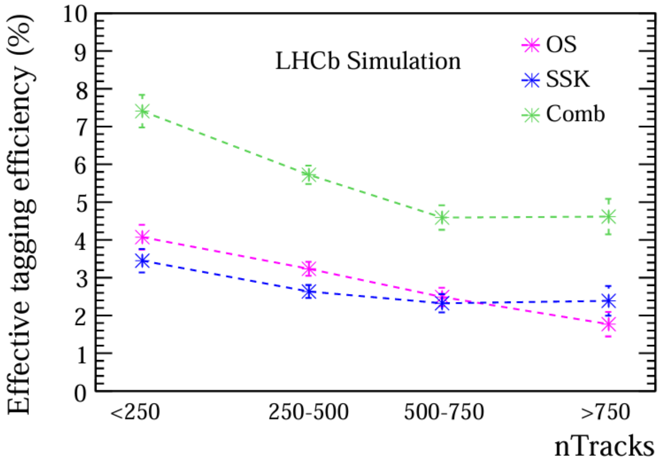

~3$\sigma$ tension

- New analysis can be performed with separate relative phases $\delta_j$ for $B^+$ and $B^-$ to account for CP violation
- Large improvement in direct CP violation $A_{CP}(q^2)$ also expected with LHCb Upgrades

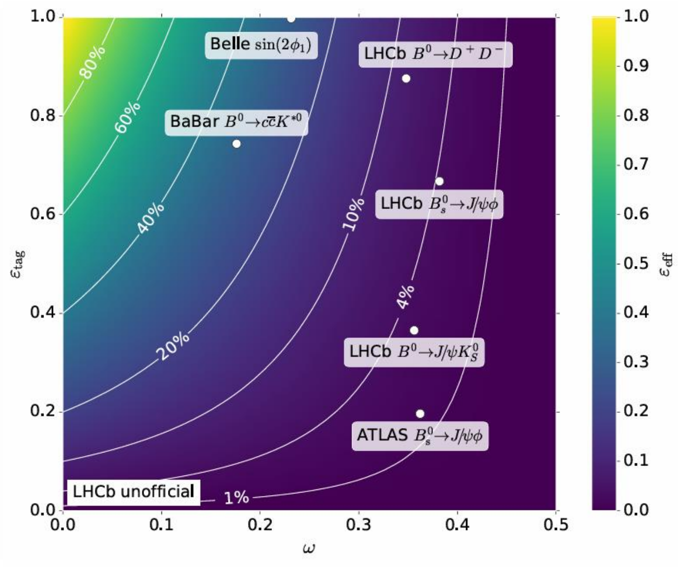


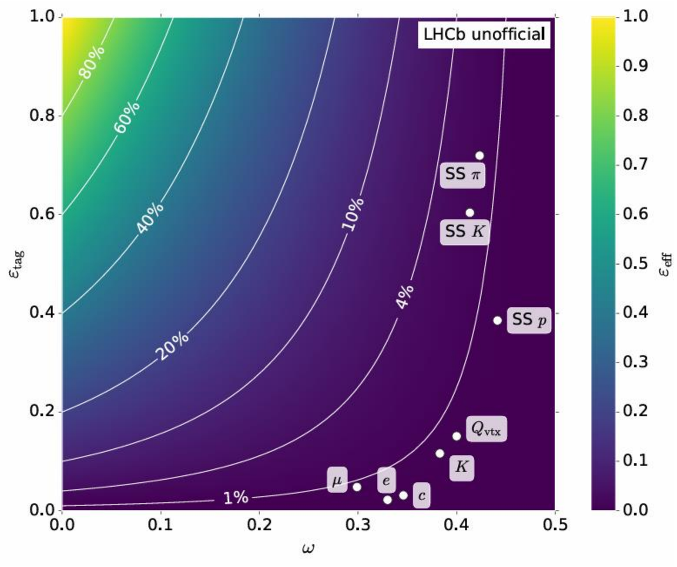
# Flavour tagging at high pile-up



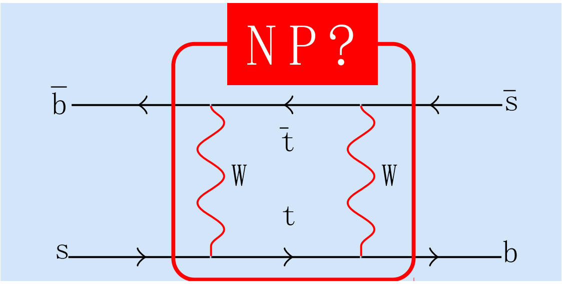

$$B_s^0 \to D_s^- \pi^+$$



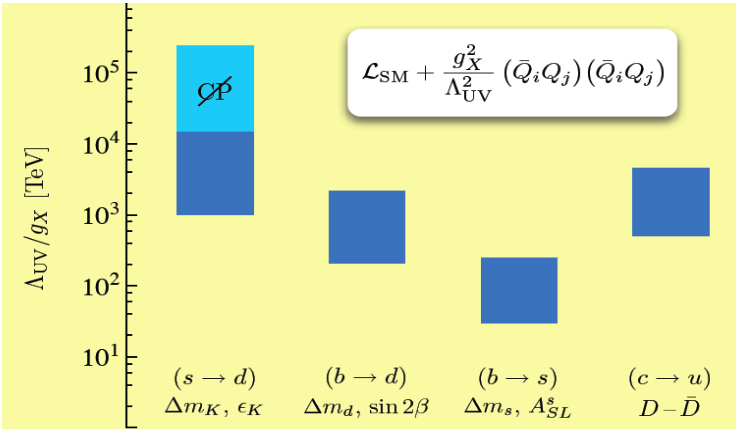



# New physics searches in flavour sector

- **Flavour physics can indirectly probe new physics, complementary to direct searches**
  - Exploring NP scale >> TeV
  - Distinguishing NP models








Generic bounds on New Physics scale (for $g_X$~1)

- **Major processes and observables for new physics searches**

  - Neutral meson mixing
  - FCNC decays
  - Forbidden decays

  - Decay rates
  - CP asymmetries
  - Angular correlations
  - Lepton universality ratios