# The prospects of the LHCb experiment

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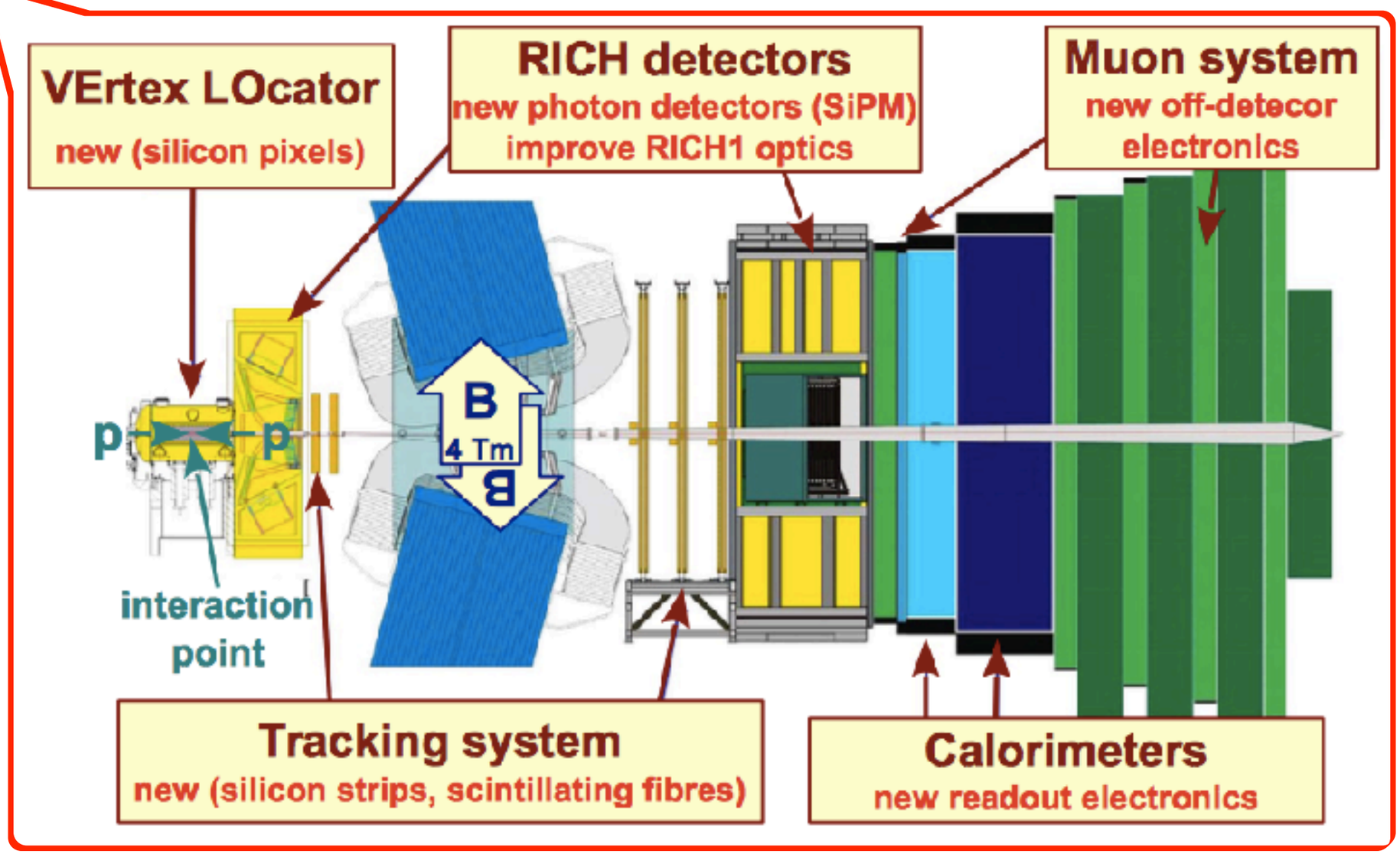
# Outline

- LHCb schedule and upgrades
- The prospects of selected LHCb physics
  - Rare decay: $B_{(s)}^0 \to \mu^+\mu^-$
  - $b \to sll$ transitions
  - Test for LU in $B \to D^*\tau\nu$
  - CKM angle $\gamma$
  - CPV in $B_s$ mixing
- Summary

# LHCb schedule

| 2019 | 2020 | 2021 | 2022 | 2023 | 2024 | 2025 | 2026 | 2027 | 2028 | 2029 | 2030 | 2031 | 2032 | 203+ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Run III | | | | | | Run IV | | | | | Run V | |
| LS2 | | | | | | LS3 | | | | | LS4 | | | |
| LHCb 40 MHz UPGRADE | | $L = 2 \times 10^{33}$ | | | LHCb Consolidation | | | $L = 2 \times 10^{33}$ $50\ fb^{-1}$ | | | LHCb Ph II UPGRADE * | | $L = 2 \times 10^{34}$ $300\ fb^{-1}$ | |



# LHCb schedule

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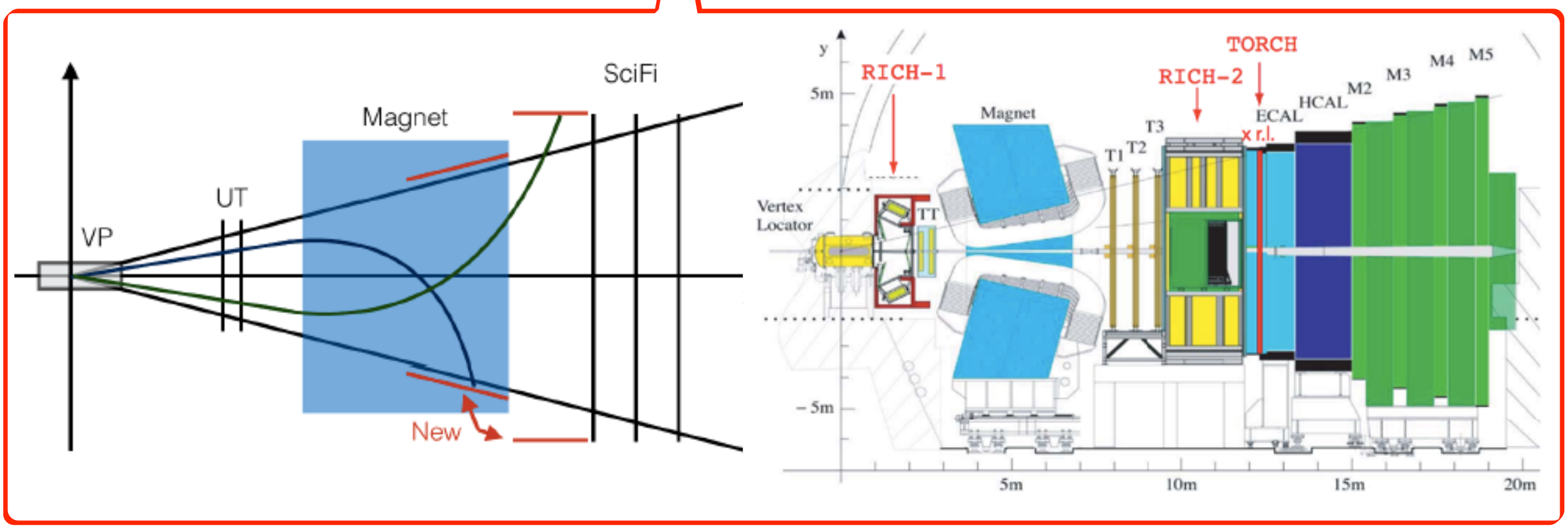


Prospects for

- Rare decay: $B_{(s)}^0 \to \mu^+\mu^-$
- $b \to sll$ transitions
- Test for LU in $B \to D^*\tau\nu$
- CKM angle $\gamma$
- CPV in $B_s$ mixing

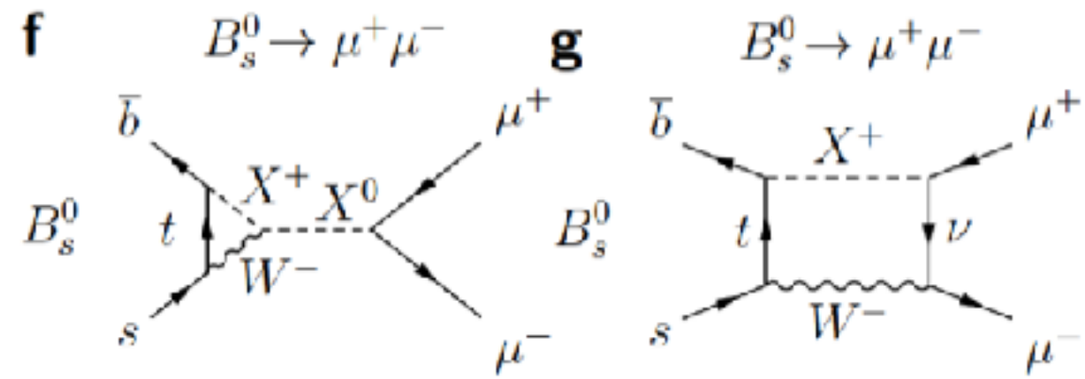
# $B_{(s)}^0 \to \mu^+\mu^-$

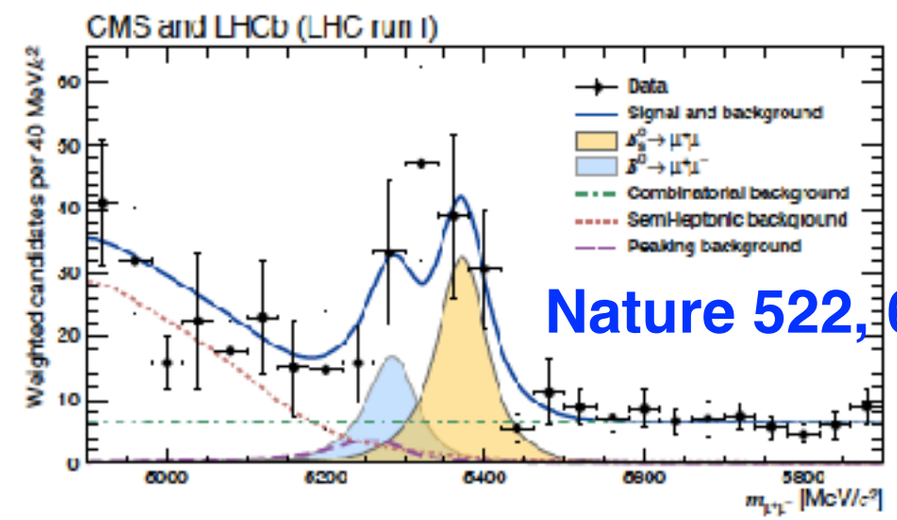
Powerful test for the SM and NP

- BF precisely predicted by SM
- Sensitive to BSM physics

CMS+LHCb Run 1

- 6.2σ (3.0σ) for $B_{(s)}^0 \to \mu^+\mu^-$
- $Br(B_s^0 \to \mu^+\mu^-)/Br(B^0 \to \mu^+\mu^-)$: consistent with SM within 2.3σ




**Nature 522, 68**

| | $\mathcal{B}(B_s^0 \to \mu^+\mu^-)$ | $\mathcal{B}(B^0 \to \mu^+\mu^-)$ | |
|---|---|---|---|
| CMS | $(3.0^{+1.0}_{-0.9}) \times 10^{-9}$ | $< 1.1 \times 10^{-9}$ (95% CL) | [PRL 111 101804 (2013)] |
| LHCb | $(2.9^{+1.1}_{-1.0}) \times 10^{-9}$ | $< 7.4 \times 10^{-10}$ (95% CL) | [PRL 111 101805 (2013)] |
| ATLAS | $(0.9^{+1.1}_{-0.8}) \times 10^{-9}$ | $< 4.2 \times 10^{-10}$ (95% CL) | [arXiv:1604.04263] |
| CMS+LHCb | $(2.8^{+0.7}_{-0.6}) \times 10^{-9}$ | $(3.9^{+1.6}_{-1.4}) \times 10^{-10}$ | [Nature 522 (2015) 68] |
| SM | $(3.66 \pm 0.23) \times 10^{-9}$ | $(1.06 \pm 0.09) \times 10^{-10}$ | [PRL 112, 101801 (2014)] |

# Prospects for $Br(B_{(s)}^0 \to \mu^+\mu^-)$

- LHCb will collect 50 $fb^{-1}$ and 300 $fb^{-1}$ at LHC-HL (3 $ab^{-1}$ for CMS)
- Systematics: 5% $f_s/f_d$, 3% $B^+ \to J/\psi K^+$ (normalisation channel)

| | $\sigma\left(\mathcal{B}(B_s^0 \to \mu^+\mu^-)\right)$ | $\sigma\left(\frac{\mathcal{B}(B_s^0 \to \mu^+\mu^-)}{\mathcal{B}(B^0 \to \mu^+\mu^-)}\right)$ | |
|---|---|---|---|
| LHCb Run I | $1 \times 10^{-9}$ | 80% | [Nature 522 (2015) 68] |
| LHCb 8 $fb^{-1}$ (Run 2) | $0.49 \times 10^{-9}$ | 39% | |
| LHCb 50 $fb^{-1}$ (Run 3&4) | $0.25 \times 10^{-9}$ | 16% | |
| LHCb 300 $fb^{-1}$ (Run 5) | $0.19 \times 10^{-9}$ | 8% | |
| CMS 3 $ab^{-1}$ (barrel) | [1]$0.3 \times 10^{-9}$ | 21% | [CMS-PAS-FTR-14-015] |
| Theory | $0.3 \times 10^{-9}$ | 5% | [PRL 112, 101801 (2014)] |

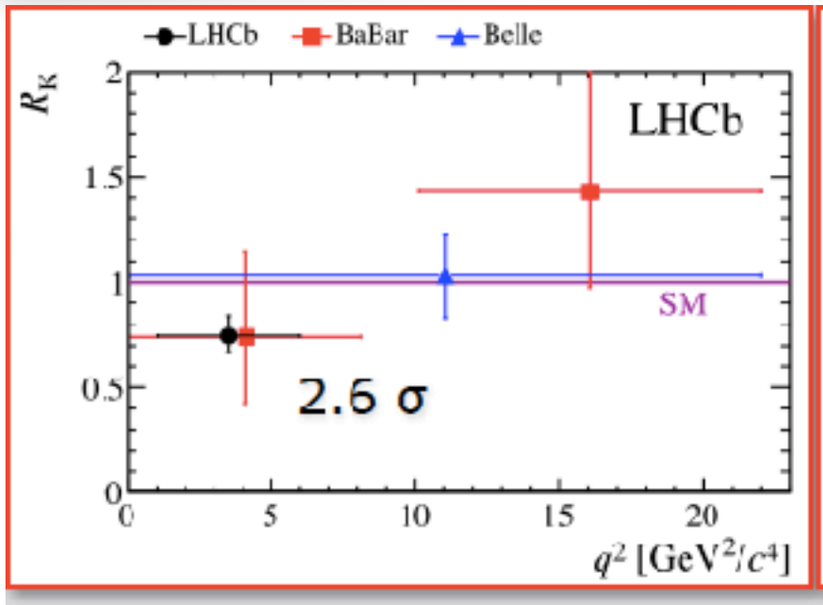
# Prospects for

- Rare decay: $B(s)0 \to \mu+\mu-$
- $b \to sll$ transitions
- Test for LU in $B \to D^*\tau\nu$
- CKM angle $\gamma$
- CPV in $B_s$ mixing

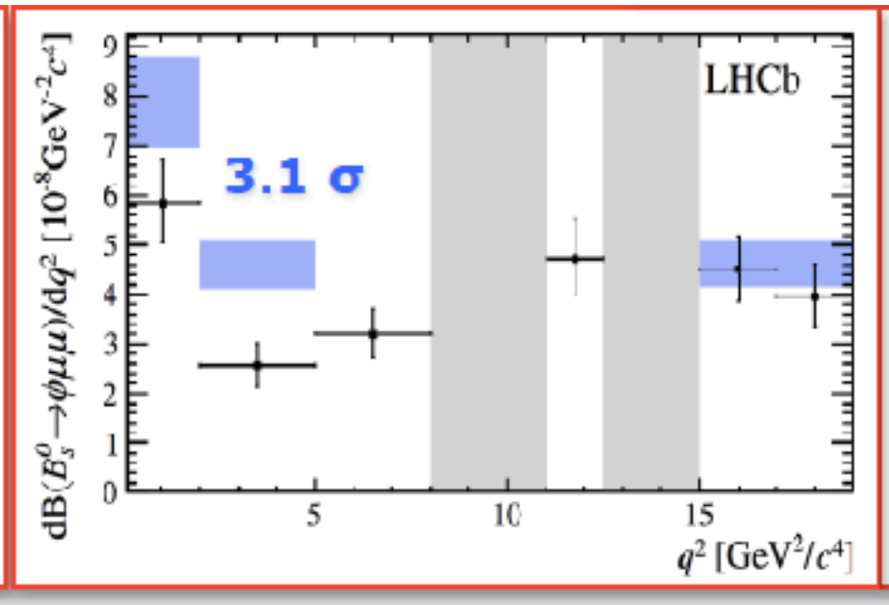
# b→sll transitions

Many observables in many decays ➡ a rich set of results

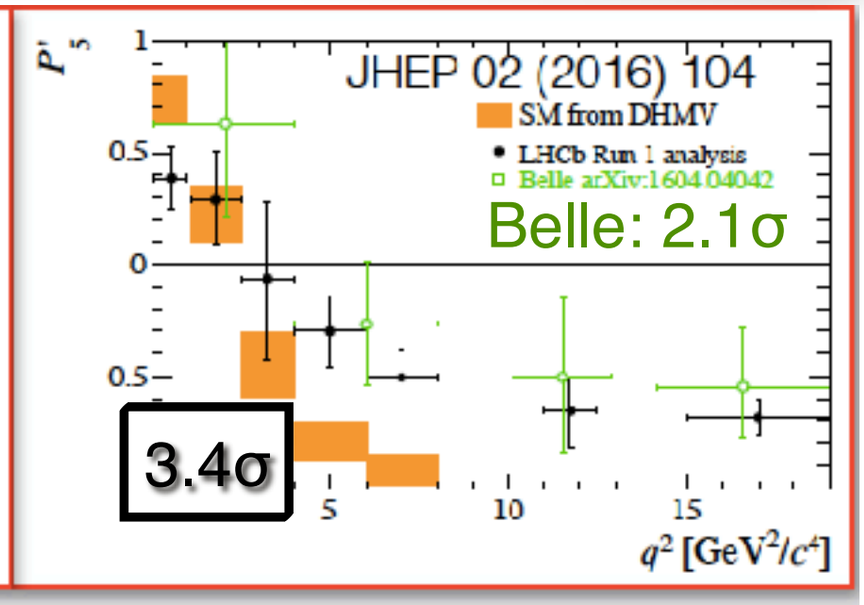
- $dBr/dq^2$; Br; $A_{cp}$; Angular …
- $B^+ \to K(\pi)^+\mu(e)^+\mu(e)^-$; $B^0 \to K^{(*)0}\mu(e)^+\mu(e)^-$; $B_s^0 \to \Phi\mu^+\mu^-$; $\Lambda_b^0 \to \Lambda\mu^+\mu^-$…




LHCb, PRL113 (2014) 151601




LHCb, JHEP 1509 (2015) 179




LHCb, JHEP 1602 (2016) 104

Intriguing results:

- Tests of lepton universality with $B^+ \to K^+\mu(e)^+\mu(e)^-$: 2.6σ
- Differential BF of $B^0 \to K^*\mu^+\mu^-$, $\Lambda_b^0 \to \Lambda\mu^+\mu^-$, $B_s^0 \to \Phi\mu^+\mu^-$: 1~3σ
- Angular analyses of $B^0 \to K^{(*)0}\mu(e)^+\mu(e)^-$, $B_s^0 \to \Phi\mu^+\mu^-$, $\Lambda_b^0 \to \Lambda\mu^+\mu^-$: ~3σ

# Prospects for $B^0 \to K^{*0}\mu^+\mu^-$

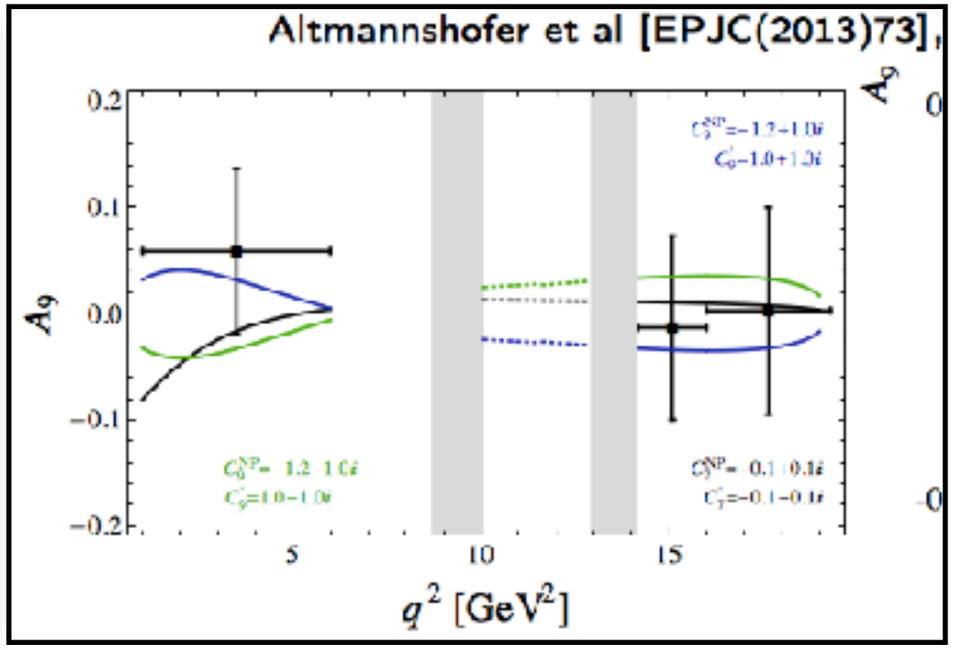
| channel | Run 1 | Run 2 | Run 3,4 ($50 fb^{-1}$) |
|---|---|---|---|
| $B^0 \to K^{*0}(K^+\pi^-)\mu^+\mu^-$ | 2,400 | 9,000 | 80,000 |
| $B^0 \to K^{*+}(K^0_S\pi^+)\mu^+\mu^-$ | 160 | 600 | 5,500 |
| $B^0 \to K^0_S\mu^+\mu^-$ | 180 | 650 | 5,500 |
| $B^+ \to K^+\mu^+\mu^-$ | 4,700 | 17,500 | 150,000 |
| $\Lambda_b \to \Lambda\mu^+\mu^-$ | 370 | 1500 | 10,000 |
| $B^+ \to \pi^+\mu^+\mu^-$ | 93 | 350 | 3,000 |
| $B^0_s \to \mu^+\mu^-$ | 15 | 60 | 500 |
| $B^0 \to K^{*0}e^+e^-$ (low $q^2$) | 150 | 550 | 5,000 |
| $B_s \to \phi\gamma$ | 4,000 | 15,000 | 150,000 |

Run 5 300 $fb^{-1}$

Signal yields ~ 0.5 M

Uncertainties suppressed

- Complete set of CP asymmetric observables
  ➡ have been measured
- Uncertainties in plots shrink by ~ ×10
- Sensitive to NP contributions



# Prospects for $\Lambda_b^0 \to \Lambda^* \mu^+ \mu^-$

| channel | Run 1 | Run 2 | Run 3,4 ($50 fb^{-1}$) |
|---|---|---|---|
| $B^0 \to K^{*0}(K^+\pi^-)\mu^+\mu^-$ | 2,400 | 9,000 | 80,000 |
| $B^0 \to K^{*+}(K_S^0\pi^+)\mu^+\mu^-$ | 160 | 600 | 5,500 |
| $B^0 \to K_S^0\mu^+\mu^-$ | 180 | 650 | 5,500 |
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| $B^0 \to K^{*0}e^+e^-$ (low $q^2$) | 150 | 550 | 5,000 |
| $B_s \to \phi\gamma$ | 4,000 | 15,000 | 150,000 |

Run 5 300 $fb^{-1}$

Signal yields ~ 60 K

More observables will be measured

- In Run 1: $dBr/dq^2$, $A^l_{FB}$ and $A^h_{FB}$ have been measured
- In future: BF, CPV, $A^p_{FB}$ ➡ more sensitive to NP
- LHCb will uniquely contribute these observables

# Prospect for

- Rare decay: $B(s)0 \rightarrow \mu+\mu-$
- $b \rightarrow sll$ transitions
- Test for LU in $B \rightarrow D^*\tau\nu$
- CKM angle $\gamma$
- CPV in $B_s$ mixing

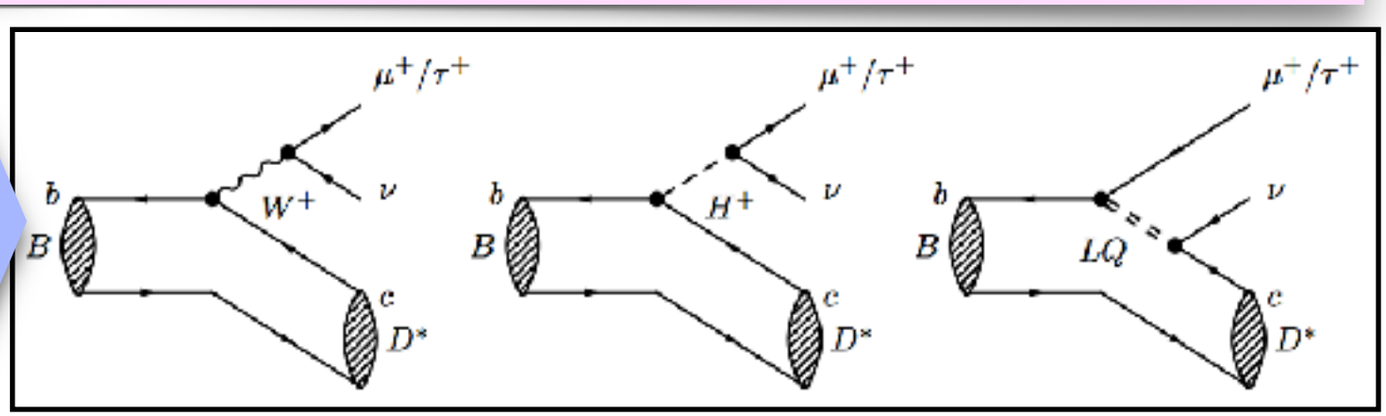
# Lepton universality (LU)

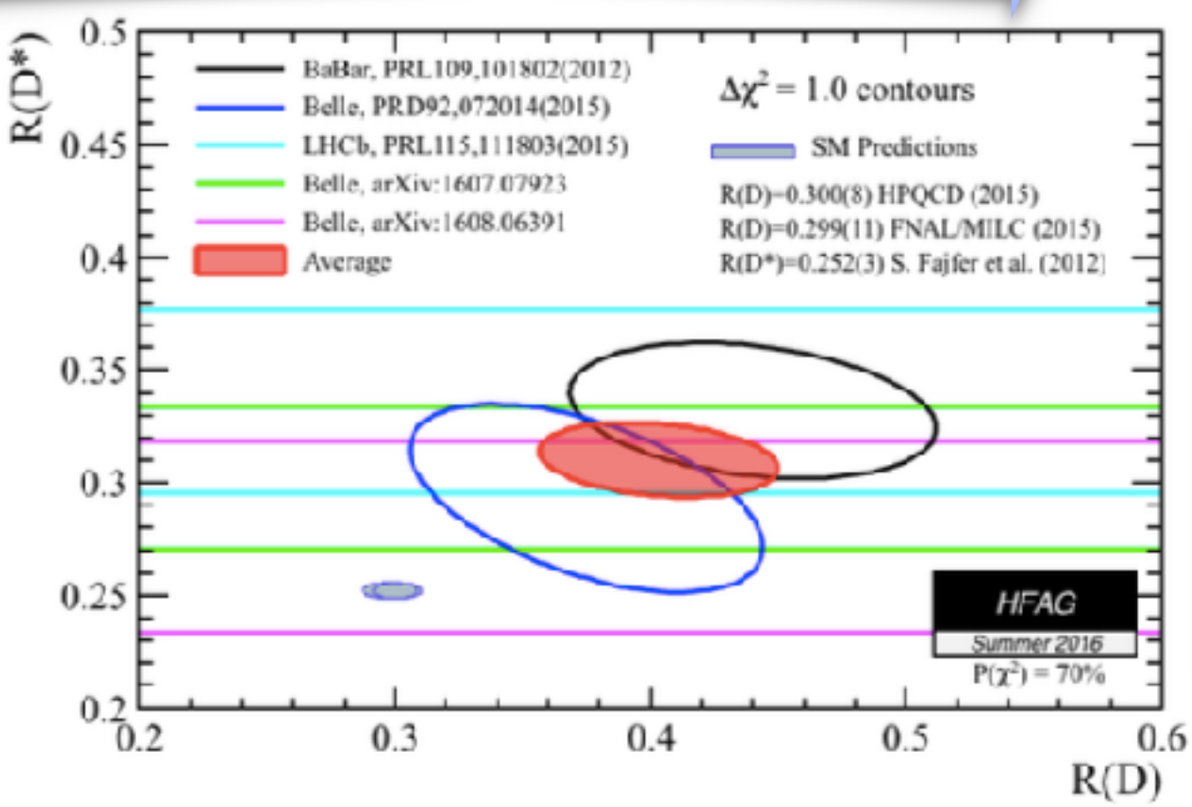
Popular NP test via: $$R(D) = \frac{\mathcal{B}(B \to D\tau\overline{\nu}_\tau)}{\mathcal{B}(B \to Dl\overline{\nu}_l)}, \quad R(D^*) = \frac{\mathcal{B}(B \to D^*\tau\overline{\nu}_\tau)}{\mathcal{B}(B \to D^*l\overline{\nu}_l)}$$

- In SM, only difference between B→D*τν and B→D*μν ➡ mass of lepton

Powerful test for the SM and NP

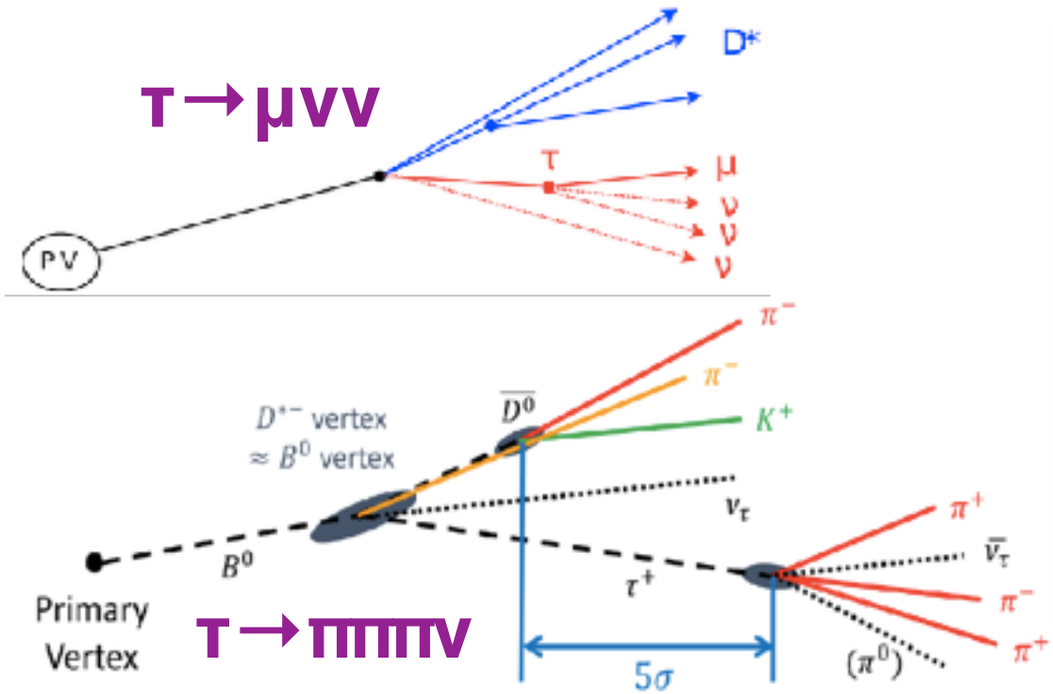
- BF precisely predicted by SM
- Sensitive to NP




- Latest HFAG average: 3.9σ
  - With Belle new R(D*)
- Strong motivation for improved measurements

# Prospects of B→D*τν




Analysis strategy improved

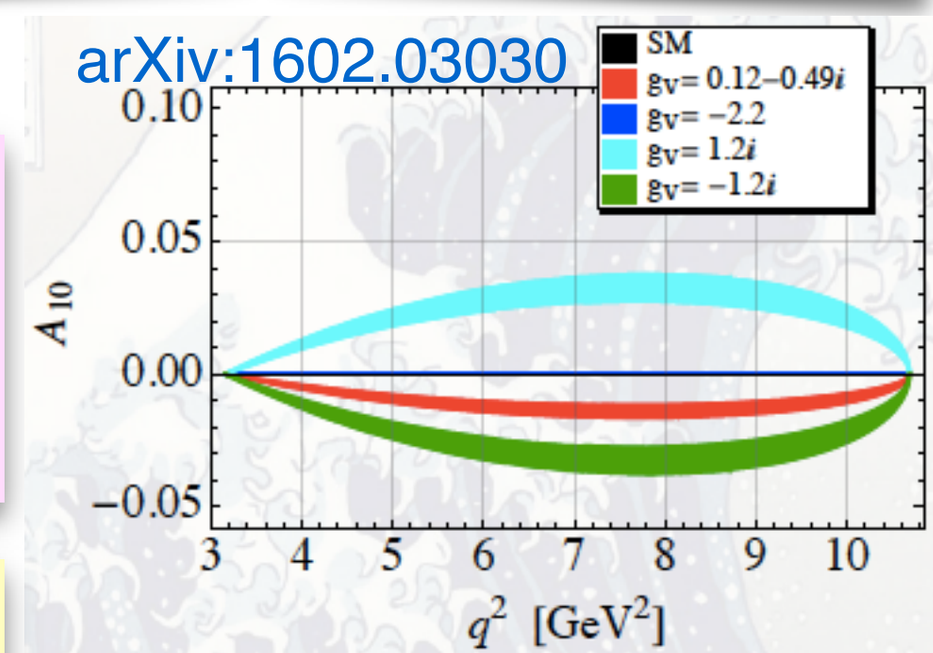
- Current LHCb result: leptonic decay
- 3-prong pion decay ➡ in the future
  - Good τ decay vertex but Br ↓

A tiny fraction of sample analysed

- With 300 fb$^{-1}$, τ→μνν samples will grow by a factor ~ ×200, τ→πππν samples by ~ ×400

More observables will be measured

- O(10$^7$) B→D*τν(τ→μνν) ➡ angular analysis
- O(10$^6$) $B_c$→J/ψμνX ➡ R(J/ψ) to be measured




$A_{10}$: Sensitive to Im[$g_{V,P,T}$]

$$g_{V,A} \sim \mathcal{O}(\frac{v^2}{\Lambda_{\rm NP}^2}), \quad g_T \sim \frac{1}{v}\mathcal{O}(\frac{v^2}{\Lambda_{\rm NP}^2})$$

# Prospect for

- Rare decay: $B(s)0 \rightarrow \mu+\mu-$
- $b \rightarrow sll$ transitions
- Test for LU in $B \rightarrow D^*\tau\nu$
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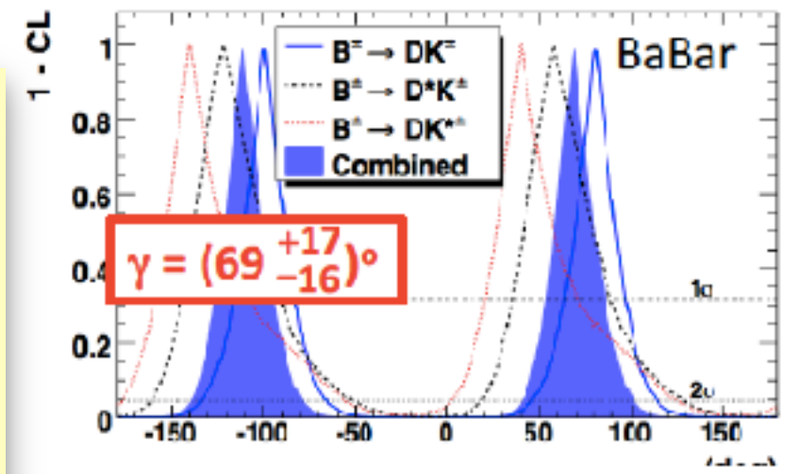
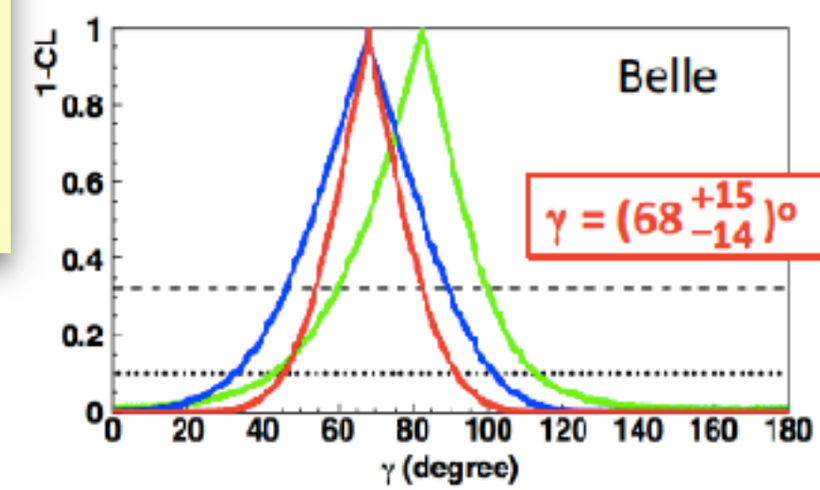
- CPV in $B_s$ mixing

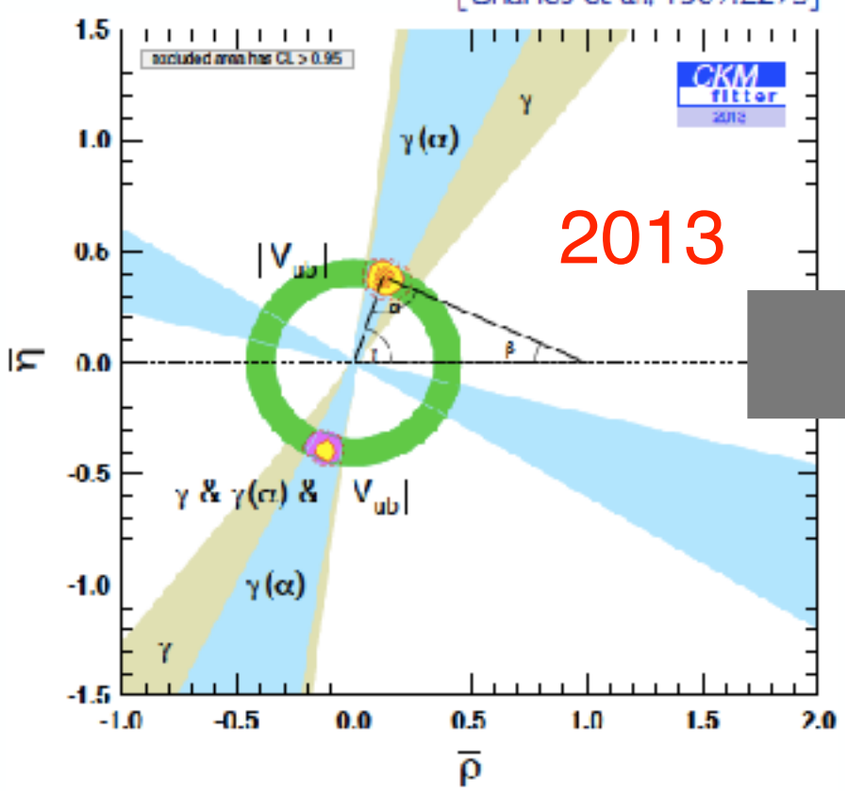
# CKM angle γ

- LHCb dominates now the world average
- No limits for systematic nor theoretical prediction
- σ(γ) ~ 0.1° in Run5, combining all modes:
  - New D modes: $D \to KK\pi\pi$, $D \to K_S^0\pi\pi\pi^0$
  - New B modes: $B \to D^*K$, $B \to DK^{*+}$, $B_s^0 \to D_s^{*+}K$




[Charles et al., 1309.2293]

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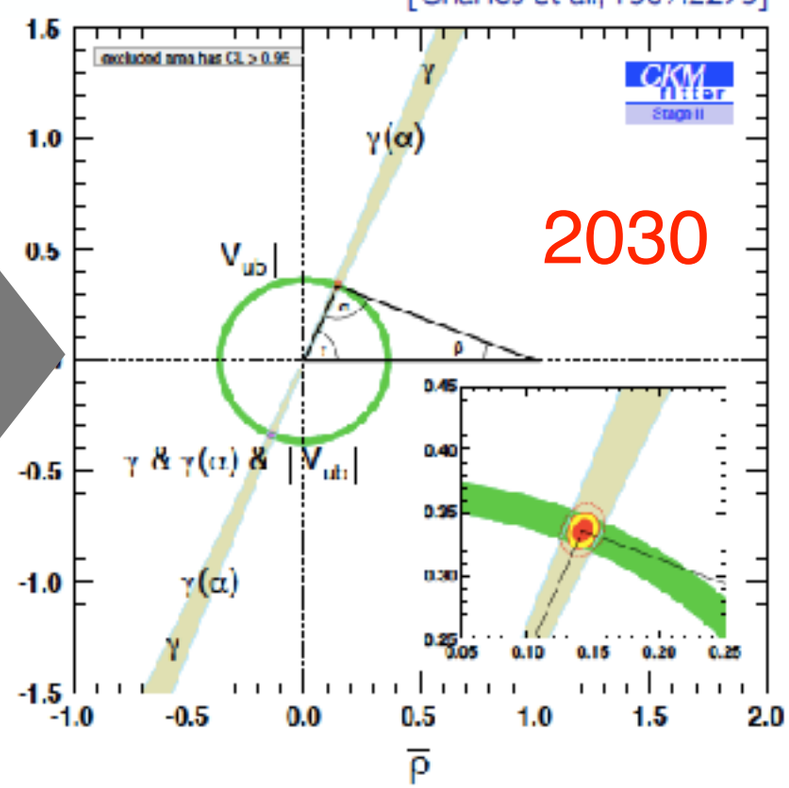
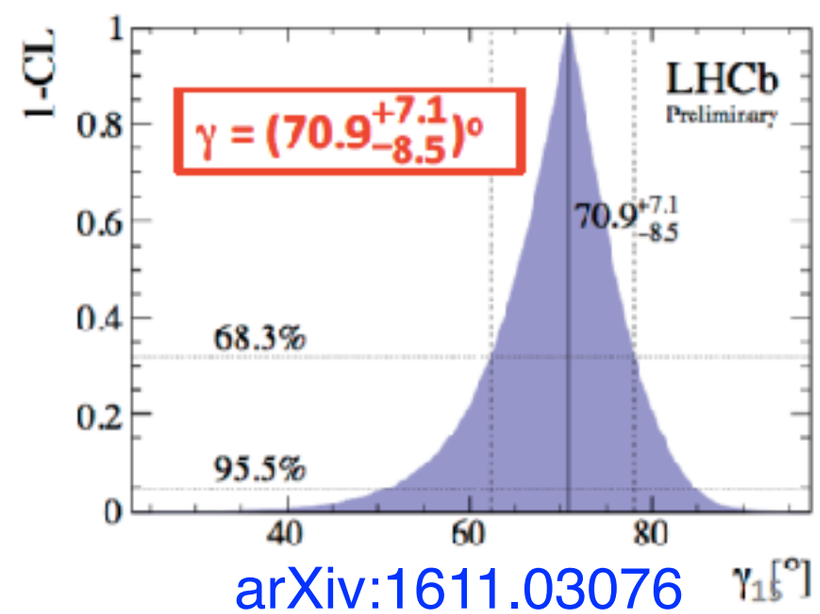


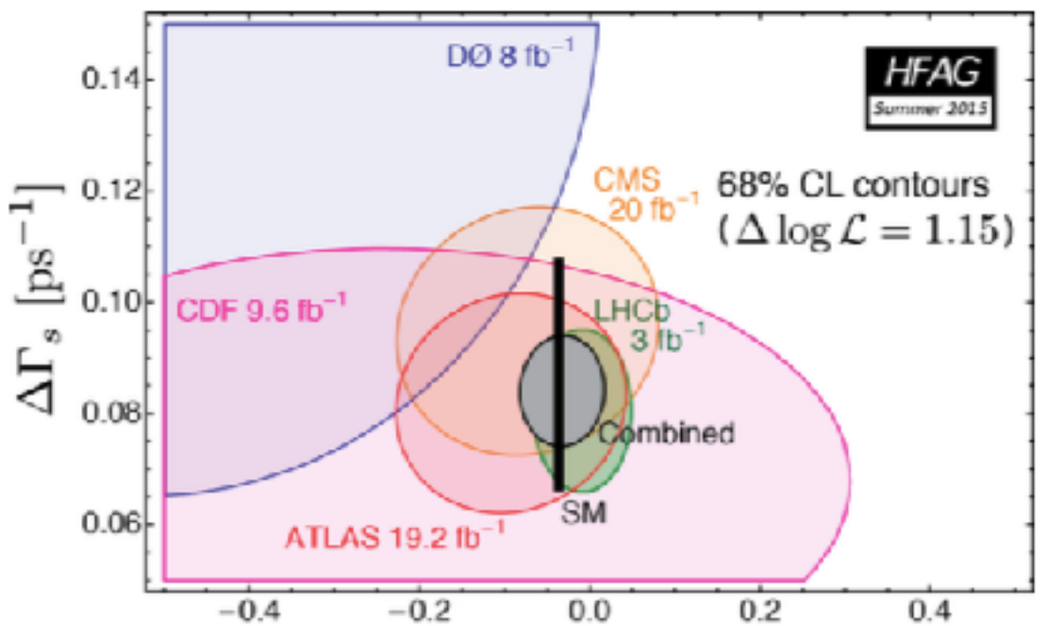

arXiv:1611.03076

# Prospect for

- Rare decay: $B(s)0 \to \mu+\mu-$
- $b \to sll$ transitions
- Test for LU in $B \to D^*\tau\nu$
- CKM angle $\gamma$
- CPV in Bs mixing

# CPV in $B_s$ mixing: $B_s \to J/\psi X$

$\phi_s$(SM) = -36.4 ± 1.6 mrad

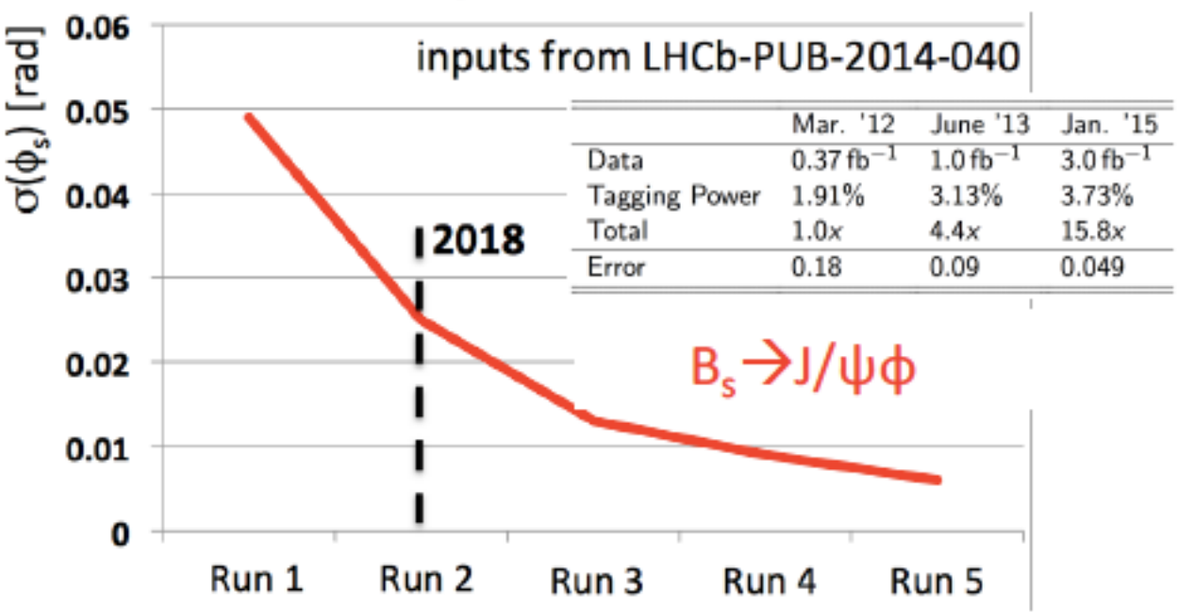



HFAG average: $\phi_s$ = -34 ± 33 mrad

LHCb results with 3 fb$^{-1}$

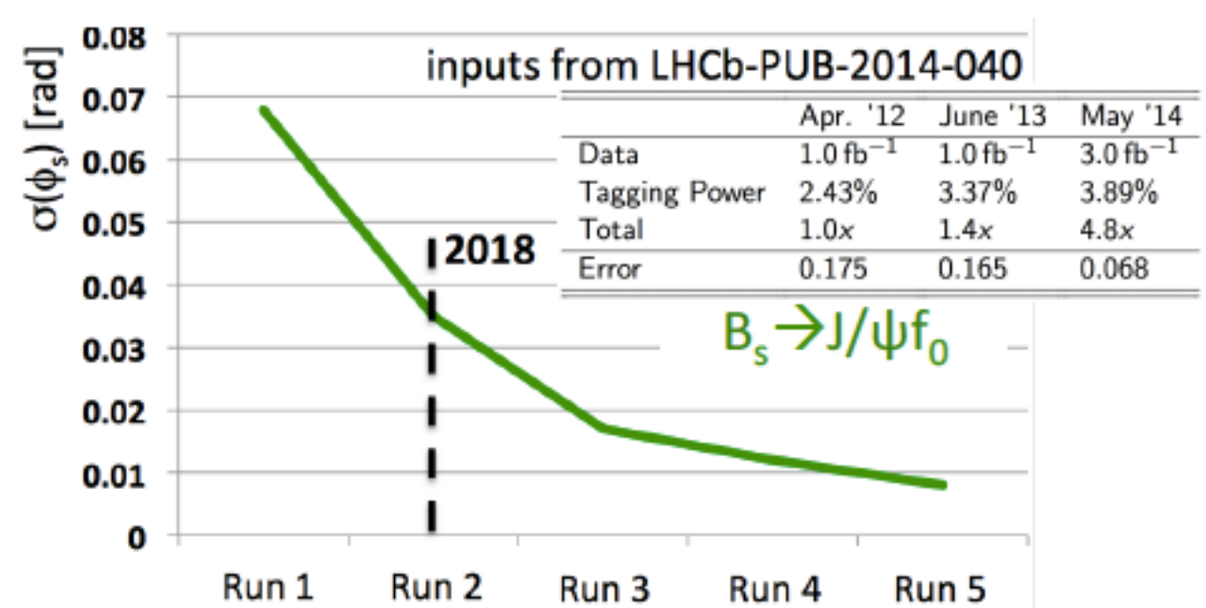
- $B_s^0 \to J/\psi K^+K^-$, $\Phi_s$=-58±49±6 mrad
- $B_s^0 \to J/\psi \pi^+\pi^-$, $\Phi_s$=70±68±8 mrad
- $B_s^0 \to D_s^+D_s^-$, $\Phi_s$=20±170±20 mrad

LHCb average: $\Phi_s$=10±40 mrad




| | Mar. '12 | June '13 | Jan. '15 |
|---|---|---|---|
| Data | 0.37 fb$^{-1}$ | 1.0 fb$^{-1}$ | 3.0 fb$^{-1}$ |
| Tagging Power | 1.91% | 3.13% | 3.73% |
| Total | 1.0$x$ | 4.4$x$ | 15.8$x$ |
| Error | 0.18 | 0.09 | 0.049 |

$\sigma(\phi_s)$ ~4 mrad with 300 fb$^{-1}$




| | Apr. '12 | June '13 | May '14 |
|---|---|---|---|
| Data | 1.0 fb$^{-1}$ | 1.0 fb$^{-1}$ | 3.0 fb$^{-1}$ |
| Tagging Power | 2.43% | 3.37% | 3.89% |
| Total | 1.0$x$ | 1.4$x$ | 4.8$x$ |
| Error | 0.175 | 0.165 | 0.068 |

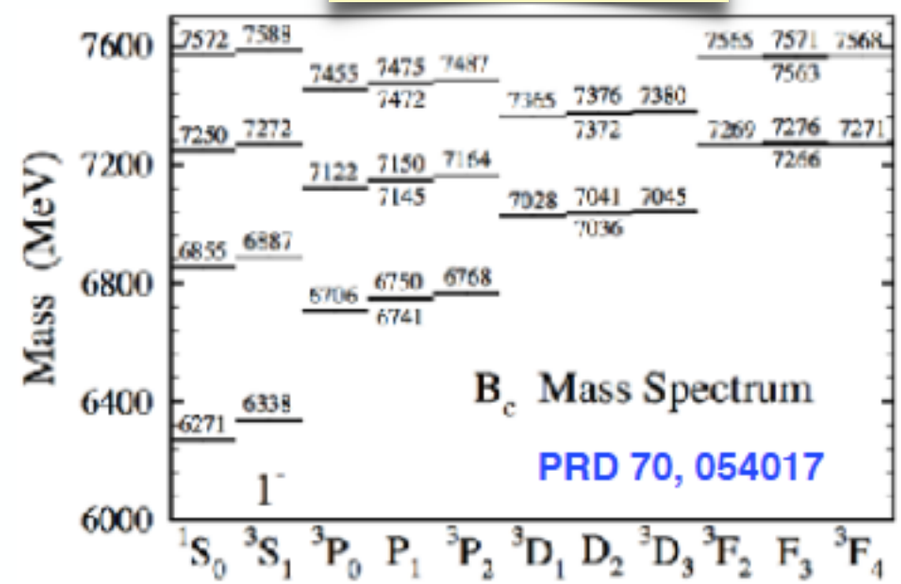
$\sigma(\phi_s)$ ~5 mrad with 300 fb$^{-1}$

# Other measurements

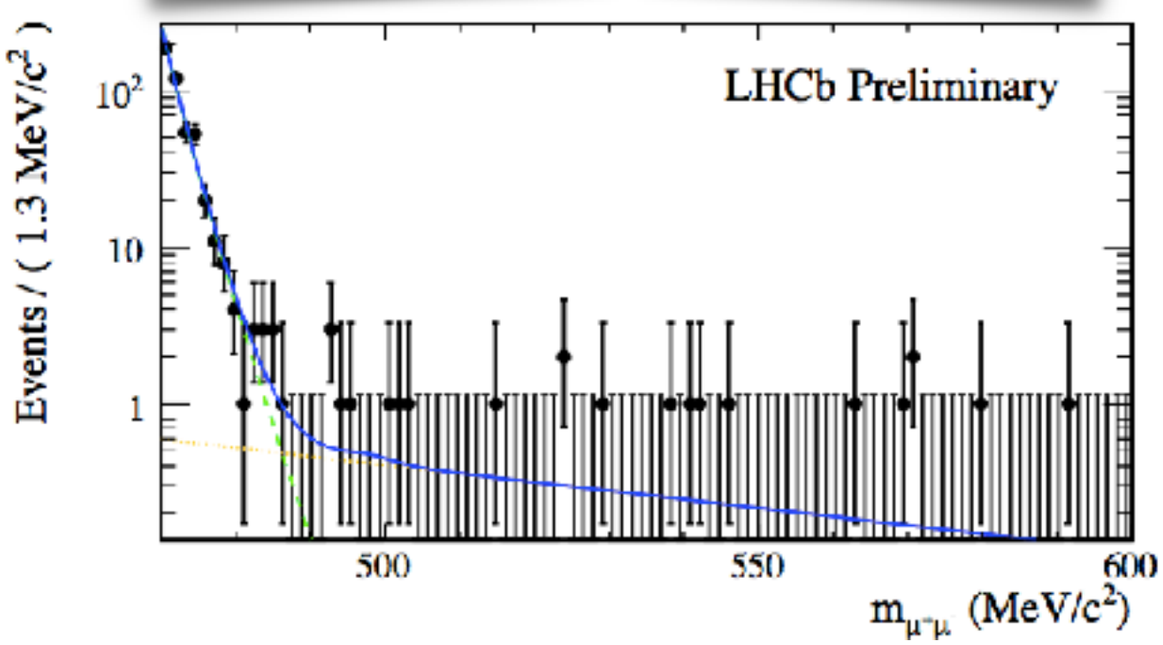
## CPV in Charm sector

| Run | σ(x) ($10^{-3}$) | σ(y) ($10^{-3}$) | σ(\|q/p\|) ($10^{-3}$) | σ(Φ) (mrad) |
|---|---|---|---|---|
| I | 1.22 | 0.53 | 59 | 89 |
| II | 0.92 | 0.37 | 44 | 70 |
| III | 0.42 | 0.15 | 20 | 33 |
| IV | 0.25 | 0.09 | 12 | 20 |

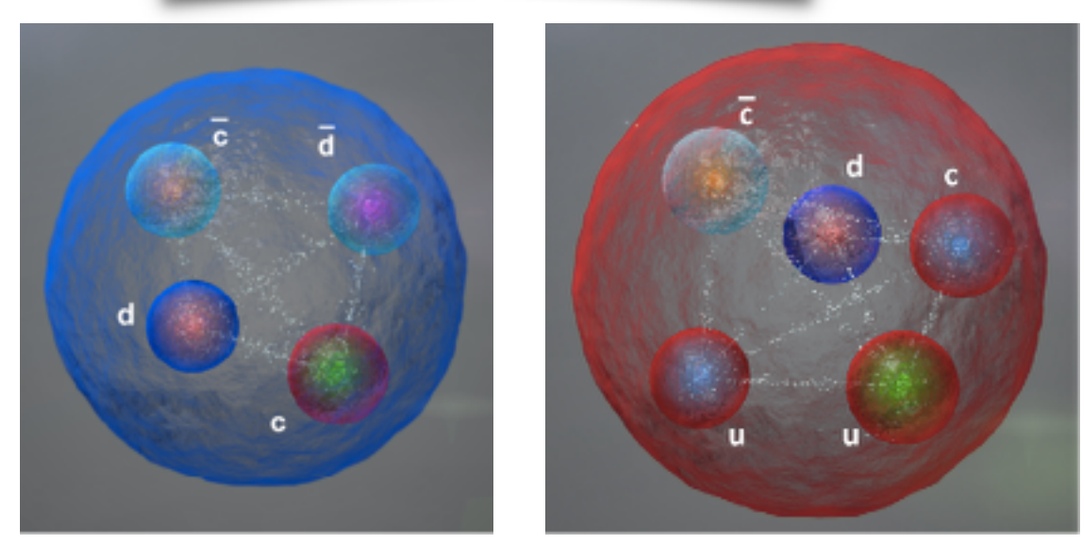
## Exited $B_c^+$




## Strangeness RD: $K_s^0 \to \mu^+\mu^-$




## Exotic states



# Conclusion

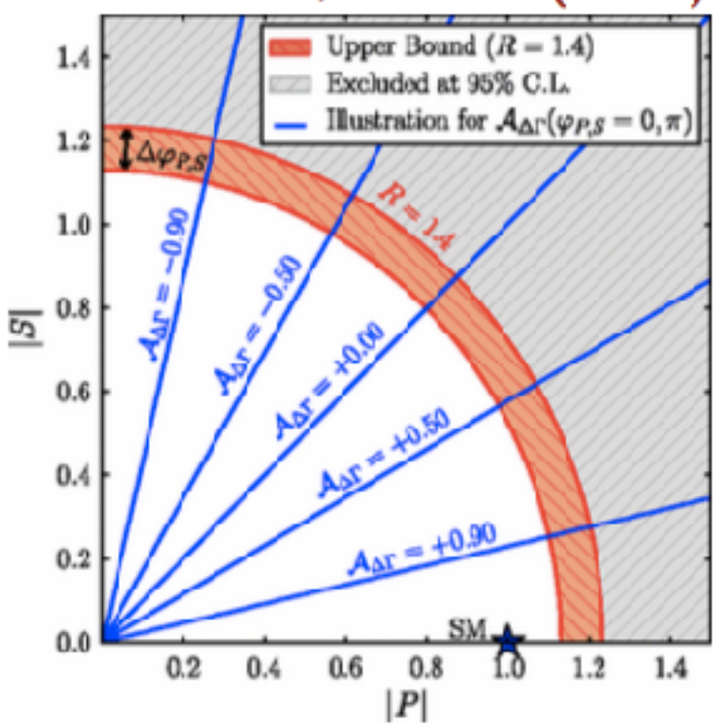
- LHCb: one of main players on flavor physics
- With the future upgrade
  - ⇨ Indirect search for NP: much improved precision
    - Rare decay: $B_{(s)}^0 \to \mu^+\mu^-$
    - $b \to sll$ transitions
    - Test for LU in $B \to D^*\tau\nu$
    - CKM angle $\gamma$
    - CPV in $B_s$ mixing
- Inputs from you are always welcome

*Thank you for your attentions*

# Backup

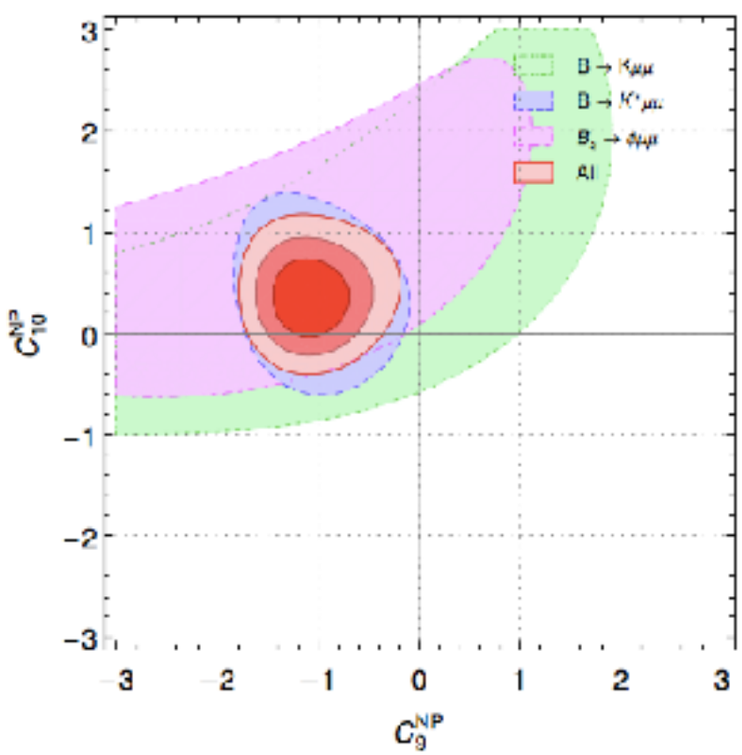
# Constraints to NP

PRL 109, 041801 (2012)




Future data gives access to further observables

- Effective lifetime $\tau_{\mu\mu}(\mathcal{A}_{\Delta\Gamma})$
  - Scalar and pseudo-scalar/-vector contribution differentiation




Electroweak penguin processes ($b \to s l^+ l^-$): FCNC transitions

- Suppressed in SM
- NP contributions at the same level as SM

# Constraints to NP

| Type | Observable | Current precision | LHCb 2018 | **Upgrade** ($50\ \mathrm{fb}^{-1}$) | Theory uncertainty |
|---|---|---|---|---|---|
| $B_s^0$ mixing | $2\beta_s(B_s^0 \to J/\psi\phi)$ | 0.10 [139] | 0.025 | 0.008 | ~0.003 |
| | $2\beta_s(B_s^0 \to J/\psi f_0(980))$ | 0.17 [219] | 0.045 | 0.014 | ~0.01 |
| | $a_{\mathrm{sl}}^s$ | $6.4 \times 10^{-3}$ [44] | $0.6 \times 10^{-3}$ | $0.2 \times 10^{-3}$ | $0.03 \times 10^{-3}$ |
| Gluonic penguins | $2\beta_s^{\mathrm{eff}}(B_s^0 \to \phi\phi)$ | – | 0.17 | 0.03 | 0.02 |
| | $2\beta_s^{\mathrm{eff}}(B_s^0 \to K^{*0}\overline{K}^{*0})$ | – | 0.13 | 0.02 | $< 0.02$ |
| | $2\beta^{\mathrm{eff}}(B^0 \to \phi K_S^0)$ | 0.17 [44] | 0.30 | 0.05 | 0.02 |
| Right-handed currents | $2\beta_s^{\mathrm{eff}}(B_s^0 \to \phi\gamma)$ | – | 0.09 | 0.02 | <0.01 |
| | $\tau^{\mathrm{eff}}(B_s^0 \to \phi\gamma)/\tau_{B_s^0}$ | – | 5 % | 1 % | 0.2 % |
| Electroweak penguins | $S_3(B^0 \to K^{*0}\mu^+\mu^-; 1 < q^2 < 6\ \mathrm{GeV}^2/c^4)$ | 0.08 [68] | 0.025 | 0.008 | 0.02 |
| | $s_0 A_{\mathrm{FB}}(B^0 \to K^{*0}\mu^+\mu^-)$ | 25 % [68] | 6 % | 2 % | 7 % |
| | $A_{\mathrm{I}}(K\mu^+\mu^-; 1 < q^2 < 6\ \mathrm{GeV}^2/c^4)$ | 0.25 [77] | 0.08 | 0.025 | ~0.02 |
| | $\mathcal{B}(B^+ \to \pi^+\mu^+\mu^-)/\mathcal{B}(B^+ \to K^+\mu^+\mu^-)$ | 25 % [86] | 8 % | 2.5 % | ~10 % |
| Higgs penguins | $\mathcal{B}(B_s^0 \to \mu^+\mu^-)$ | $1.5 \times 10^{-9}$ [13] | $0.5 \times 10^{-9}$ | $0.15 \times 10^{-9}$ | $0.3 \times 10^{-9}$ |
| | $\mathcal{B}(B^0 \to \mu^+\mu^-)/\mathcal{B}(B_s^0 \to \mu^+\mu^-)$ | – | ~100 % | ~35 % | ~5 % |
| Unitarity triangle angles | $\gamma(B \to D^{(*)}K^{(*)})$ | ~10–12° [252, 266] | 4° | 0.9° | negligible |
| | $\gamma(B_s^0 \to D_s K)$ | – | 11° | 2.0° | negligible |
| | $\beta(B^0 \to J/\psi K_S^0)$ | 0.8° [44] | 0.6° | 0.2° | negligible |
| Charm *CP* violation | $A_\Gamma$ | $2.3 \times 10^{-3}$ [44] | $0.40 \times 10^{-3}$ | $0.07 \times 10^{-3}$ | – |
| | $\Delta\mathcal{A}_{CP}$ | $2.1 \times 10^{-3}$ [18] | $0.65 \times 10^{-3}$ | $0.12 \times 10^{-3}$ | – |