New Perspectives for Testing Electron-Muon Universality

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New perspectives for testing electron-muon universality

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Abstract: Intriguing results for tests of the universality of electrons and muons through measurements of rates of $B \to K\ell^+\ell^-$ and similar decays have been in the spotlight for years. The LHCb collaboration has recently reported new results which are in agreement with Lepton Flavour Universality, while the individual decay rates are found below their Standard Model predictions. In view of this new situation, we explore how much space is left for a violation of electron-muon universality. Considering new sources of CP violation and taking the new LHCb measurements into account, we show that significant differences between the short-distance coefficients for electronic and muonic final states are actually allowed by the current data. These patterns can be revealed through CP asymmetries in neutral and charged $B \to K\ell^+\ell^-$ decays. We obtain correlations between these observables and map them to the short-distance coefficients. This results in regions in New Physics parameter space with large differences between CP asymmetries of the decays with final-state electrons and muons, thereby leaving a lot of room for possible surprises in the future high-precision era.

Keywords: Bottom Quarks, CP Violation, Rare Decays

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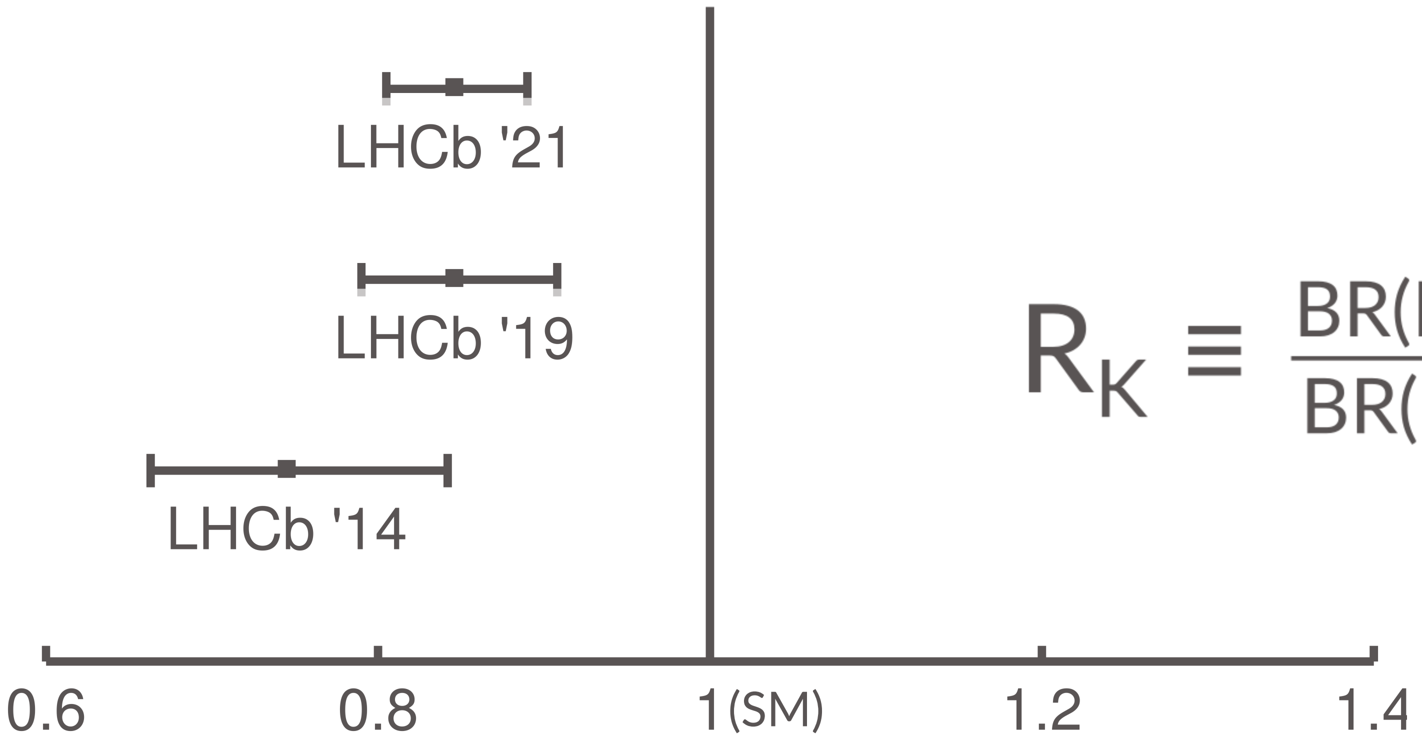
R_K anomaly gone...

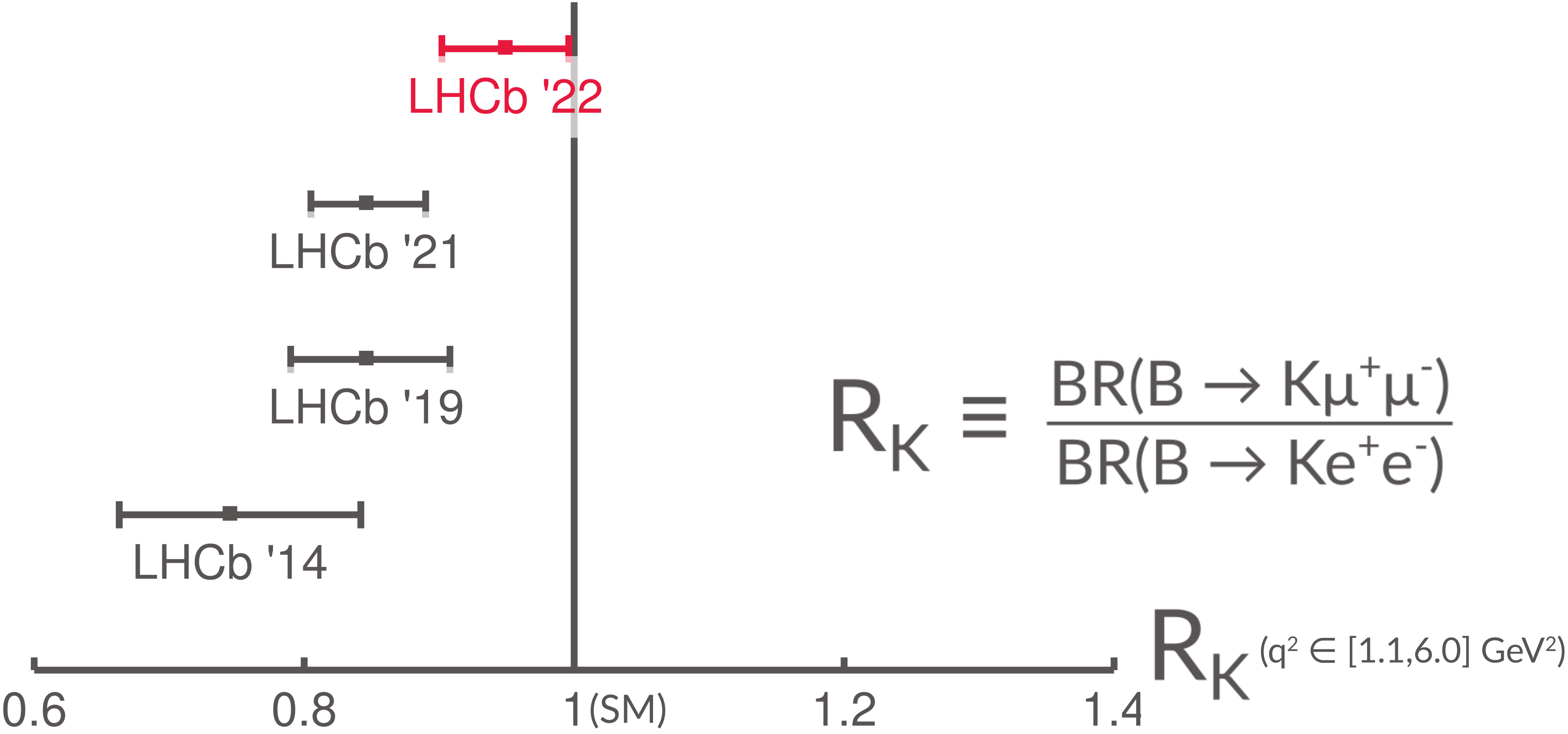
R_K anomaly gone... Exciting new prospects!

?

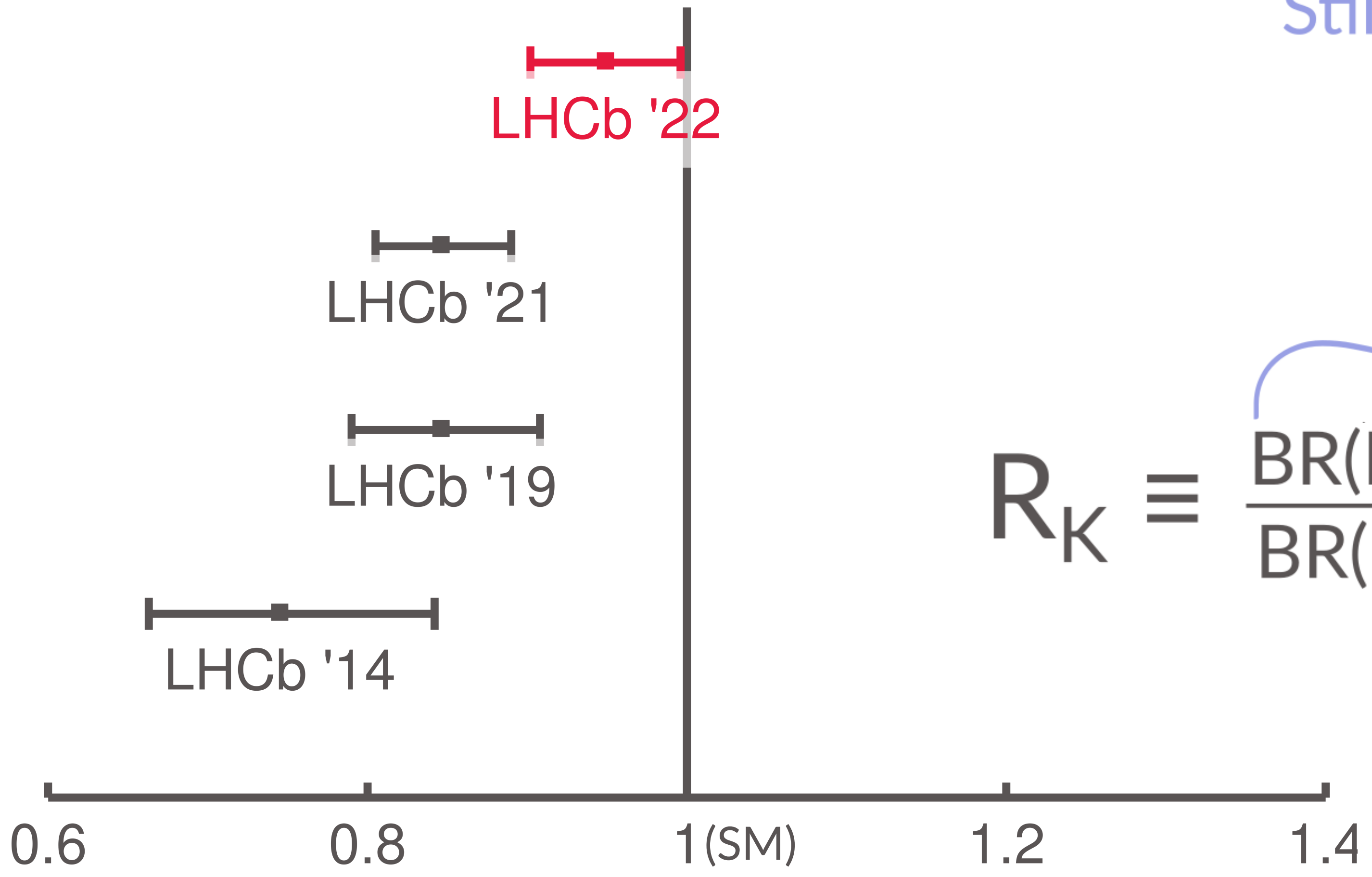


$R_K \; (q^2 \in [1.1, 6.0] \text{ GeV}^2)$

$$R_K \equiv \frac{BR(B \to K\mu^+\mu^-)}{BR(B \to Ke^+e^-)}$$



$$R_K \equiv \frac{BR(B \to K\mu^+\mu^-)}{BR(B \to Ke^+e^-)}$$

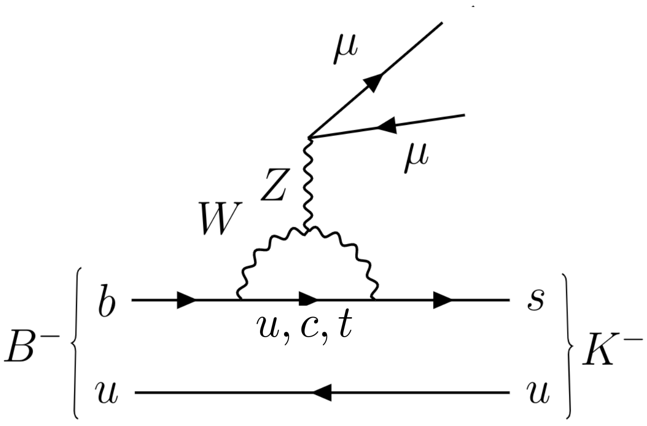


$R_K^{(q^2 \in [1.1, 6.0]\ \mathrm{GeV}^2)}$

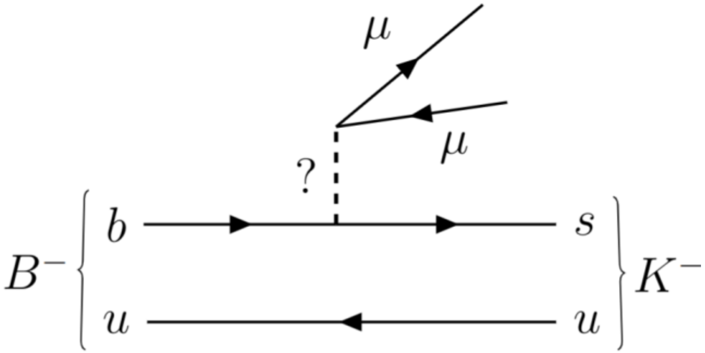
Still off by ~4σ!

$$R_K \equiv \frac{BR(B \to K\mu^+\mu^-)}{BR(B \to K e^+ e^-)}$$

Standard Model



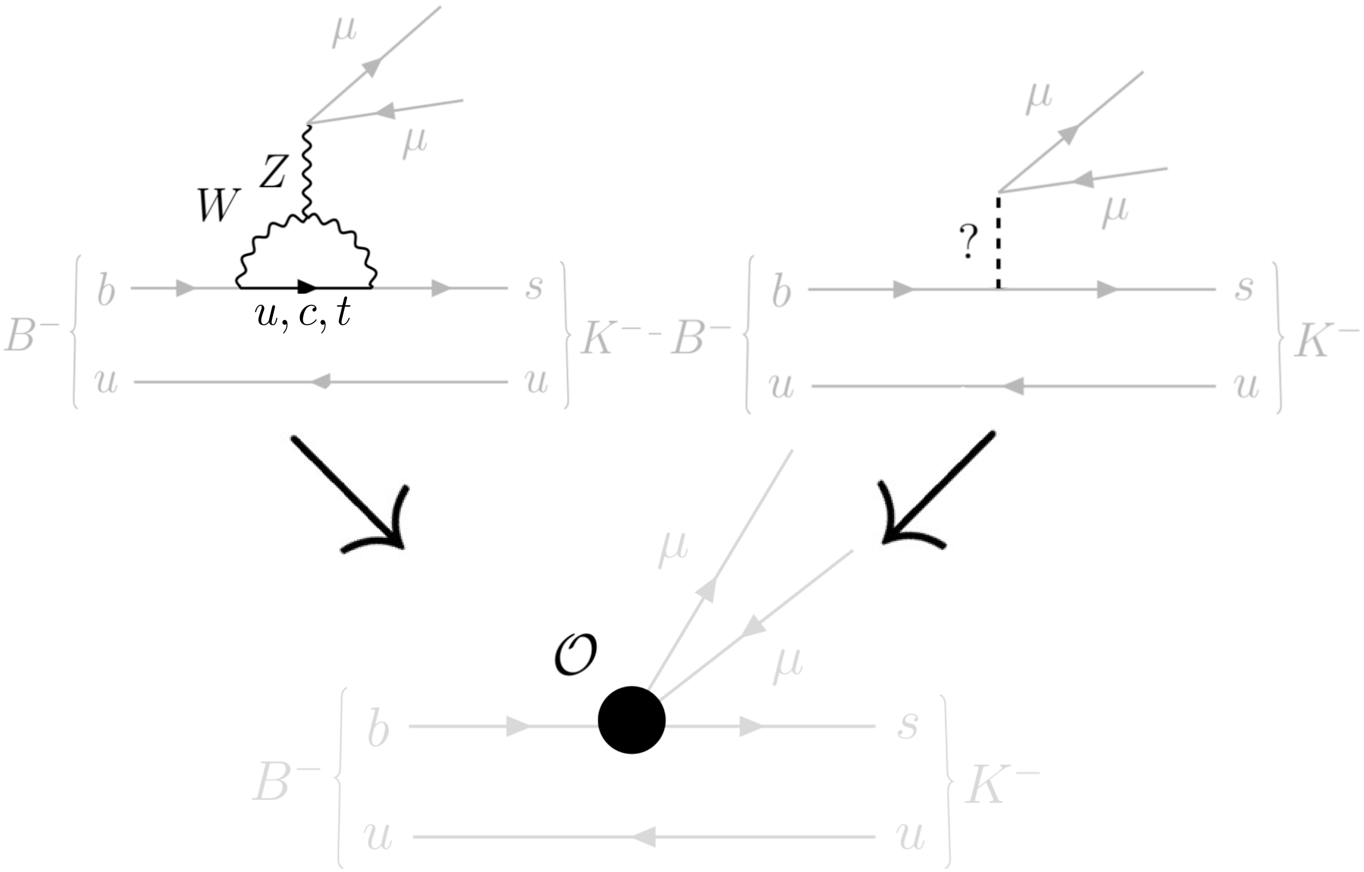
New physics?



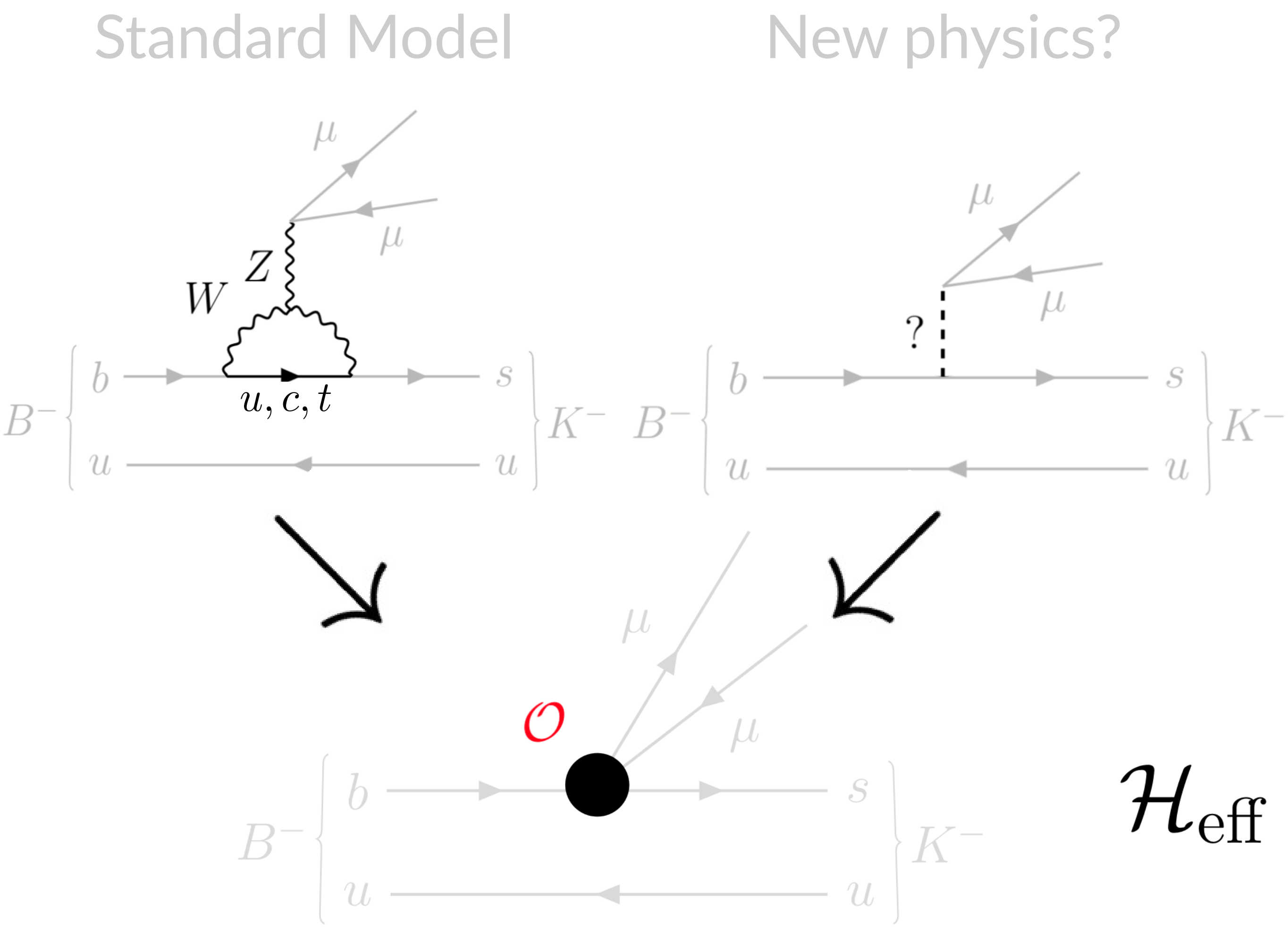
Effective Field Theory

Standard Model

New physics?

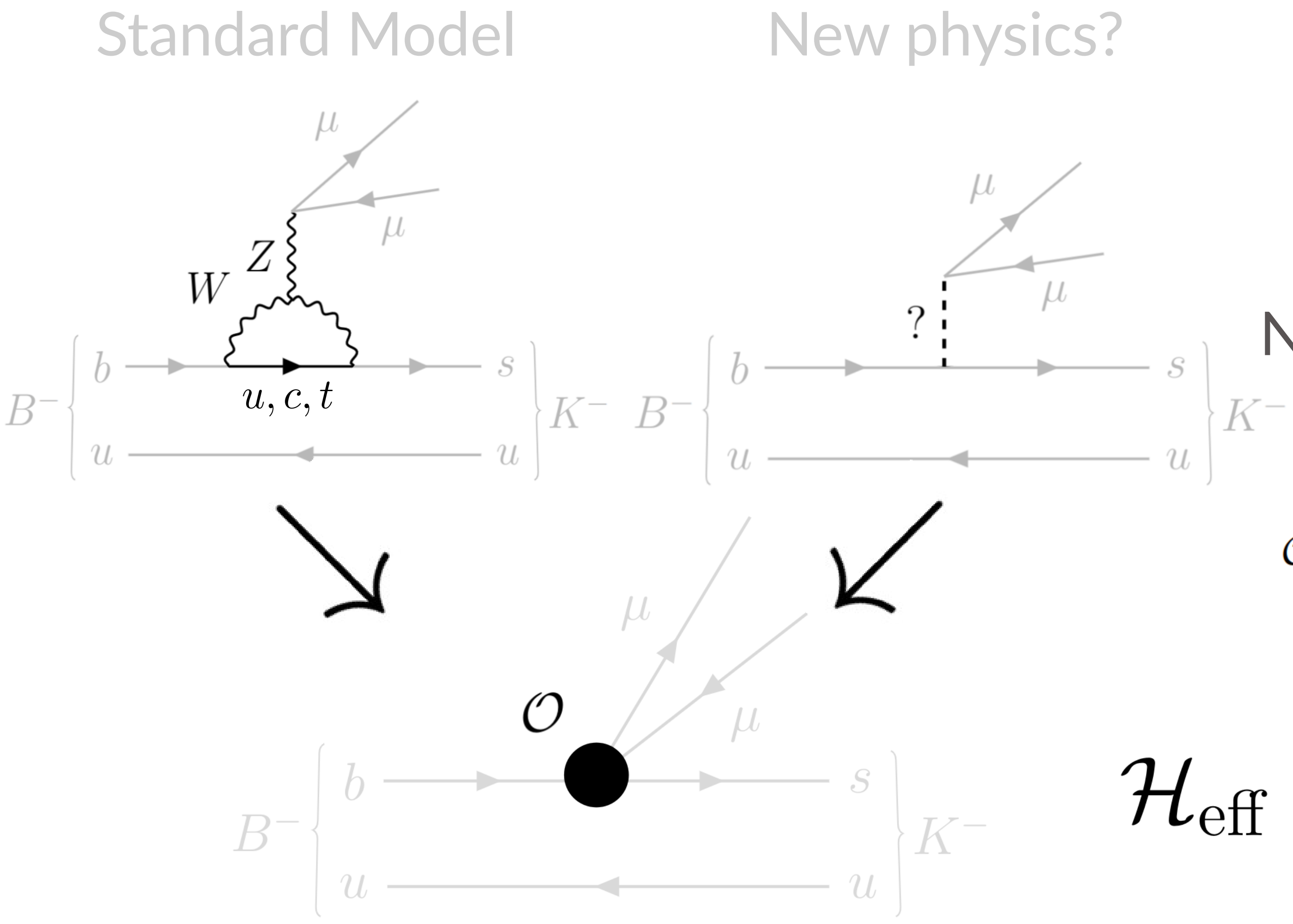


Effective Field Theory



$$\mathcal{H}_{\text{eff}} = \sum_i C_i \mathcal{O}_i$$

Effective Field Theory



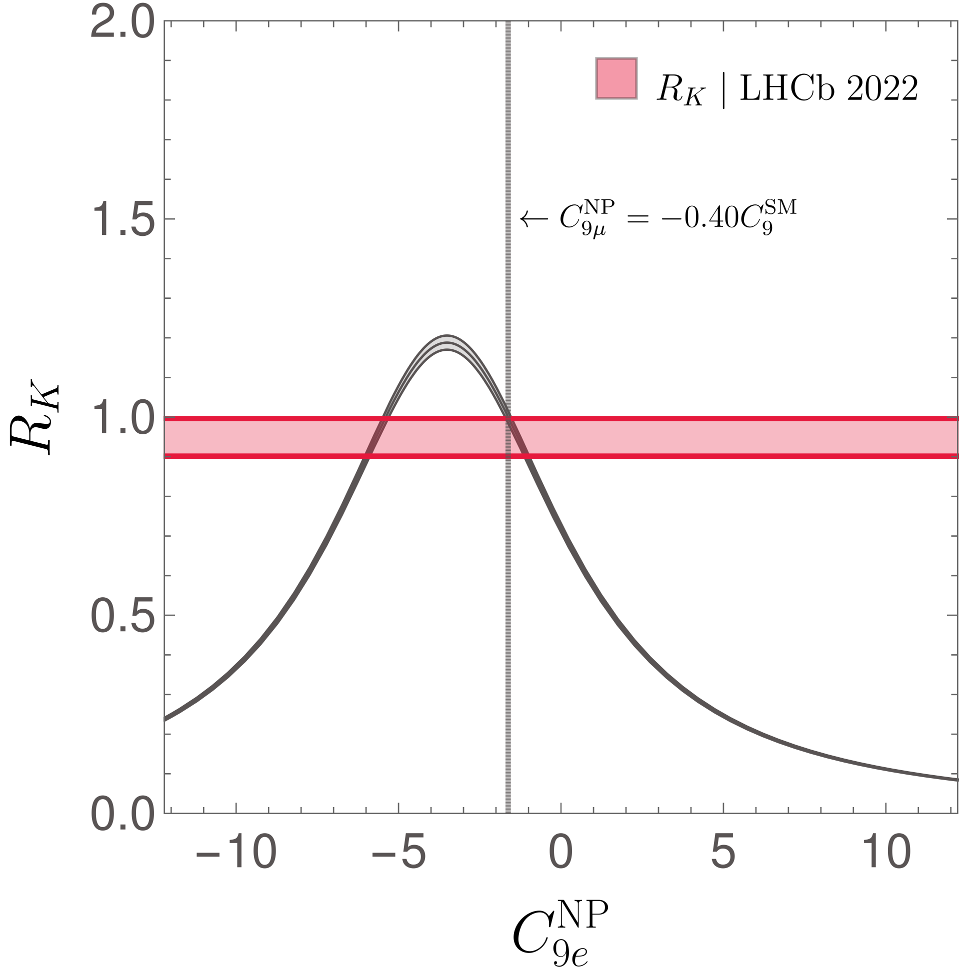
NP in μ AND e sectors:

$C_{9\mu}$, C_{9e}

$$\mathcal{O}_{9(\prime)\ell} = \frac{e^2}{(4\pi)^2}[\bar{s}\gamma^\mu P_{L(R)} b](\bar{\ell}\gamma_\mu \ell)$$

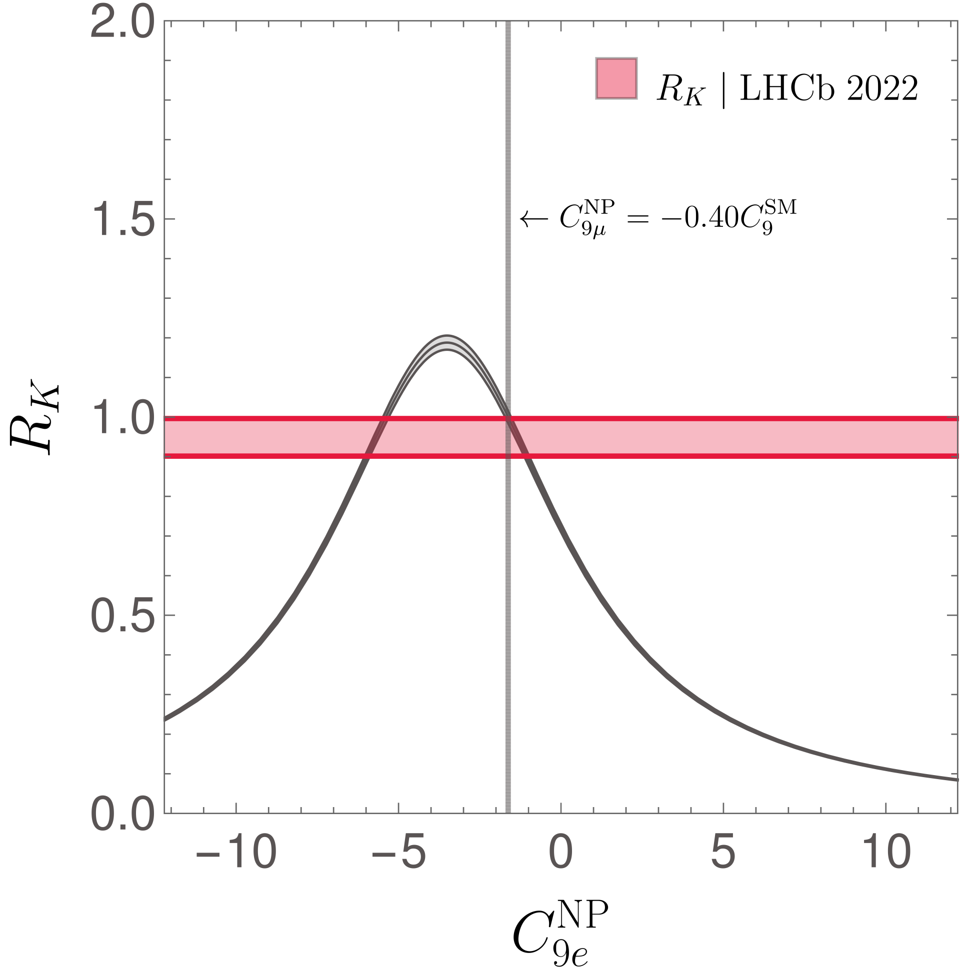
Wilson coefficient

$$\mathcal{H}_{\text{eff}} = \sum_i C_i \mathcal{O}_i$$



BR($B \to K\mu^+\mu^-$):

$$C_{9\mu}^{\rm NP} \in [-1.32, -0.40] C_9^{\rm SM}$$

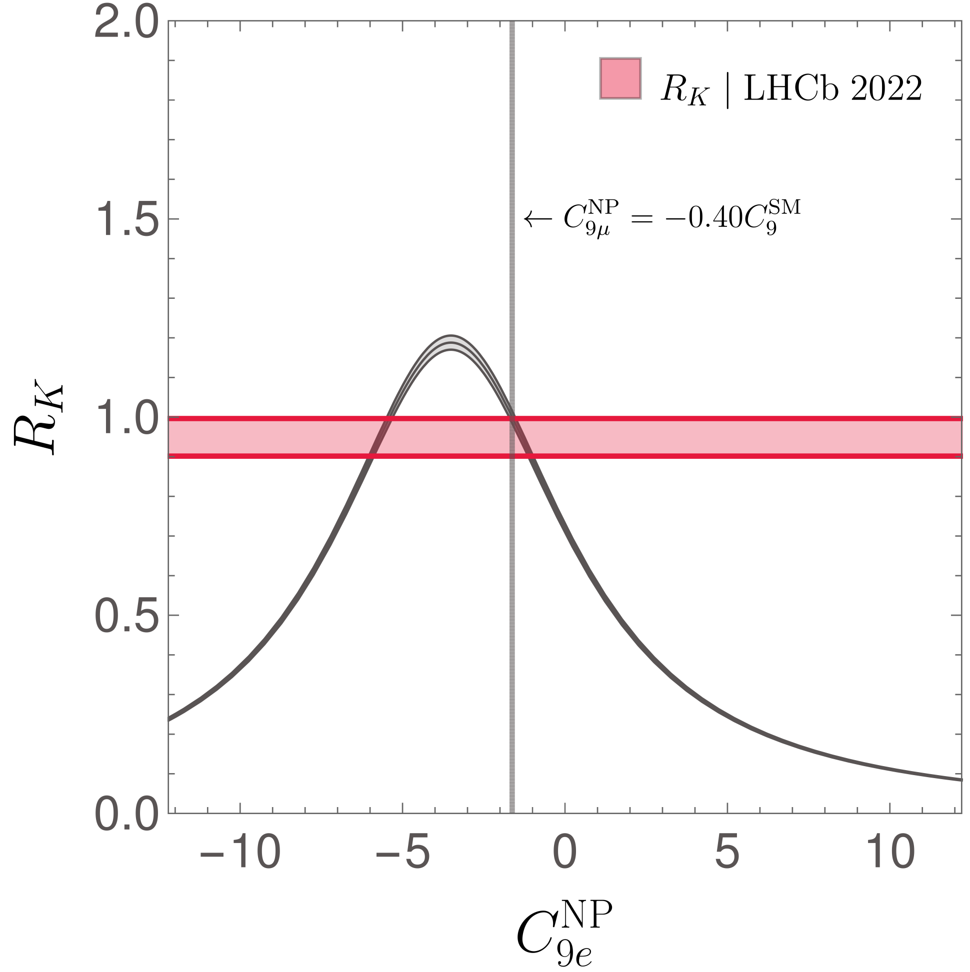


BR(B → Kμ⁺μ⁻):

$$C_{9\mu}^{\rm NP} \in [-1.32, -0.40] C_9^{\rm SM}$$

$$C_{9\mu} \overset{R_K}{\approx} C_{9e}$$

very limited room for nonuniversality...



BR(B → Kμ⁺μ⁻):

$C_{9\mu}^{NP} \in [-1.32, -0.40] C_9^{SM}$

R_K

$C_{9\mu} \approx C_{9e}$

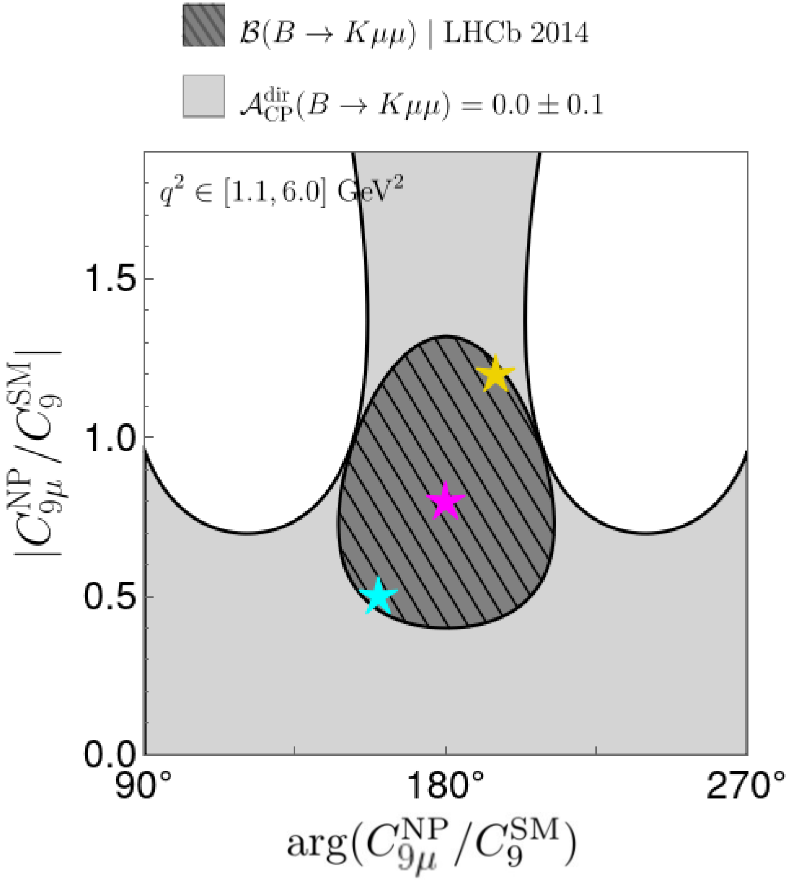
very limited room for nonuniversality...

$C_9 \in \mathbb{R}$

$C_9 \in \mathbb{C}$?

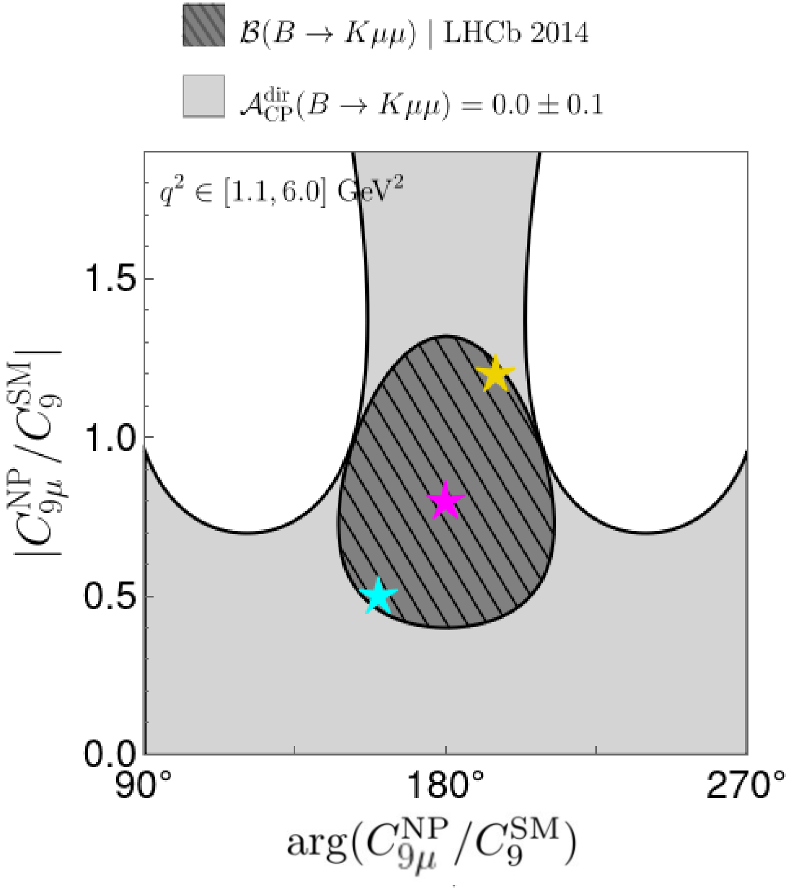
$C_9 \in \mathbb{C} \to$ CP violation

$C_9 \in \mathbb{C} \rightarrow$ CP violation

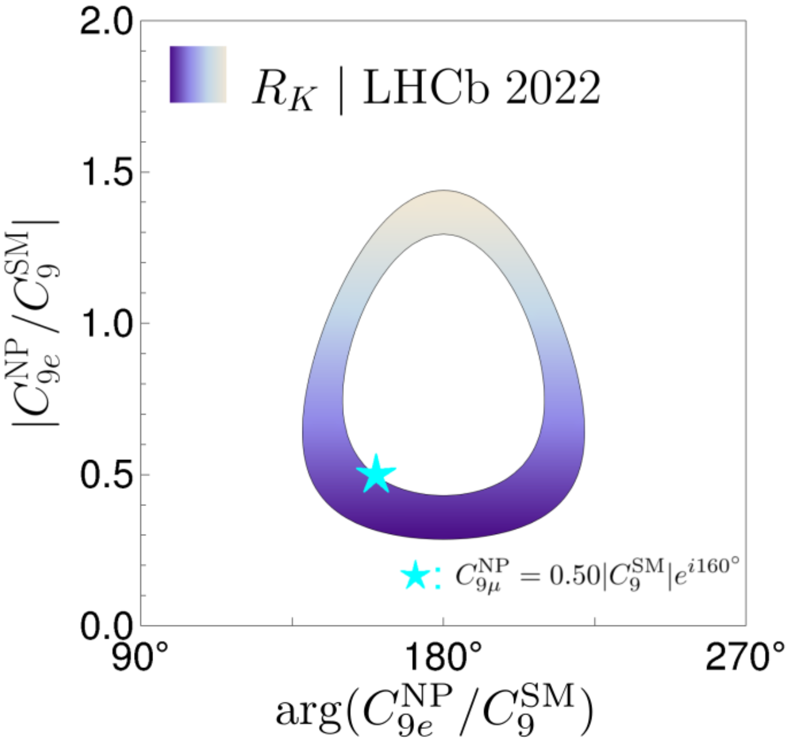


$$A_{CP}^{dir} = \frac{BR(B^+ \to K^+\mu^+\mu^-) - BR(B^- \to K^-\mu^+\mu^-)}{BR(B^+ \to K^+\mu^+\mu^-) + BR(B^- \to K^-\mu^+\mu^-)}$$

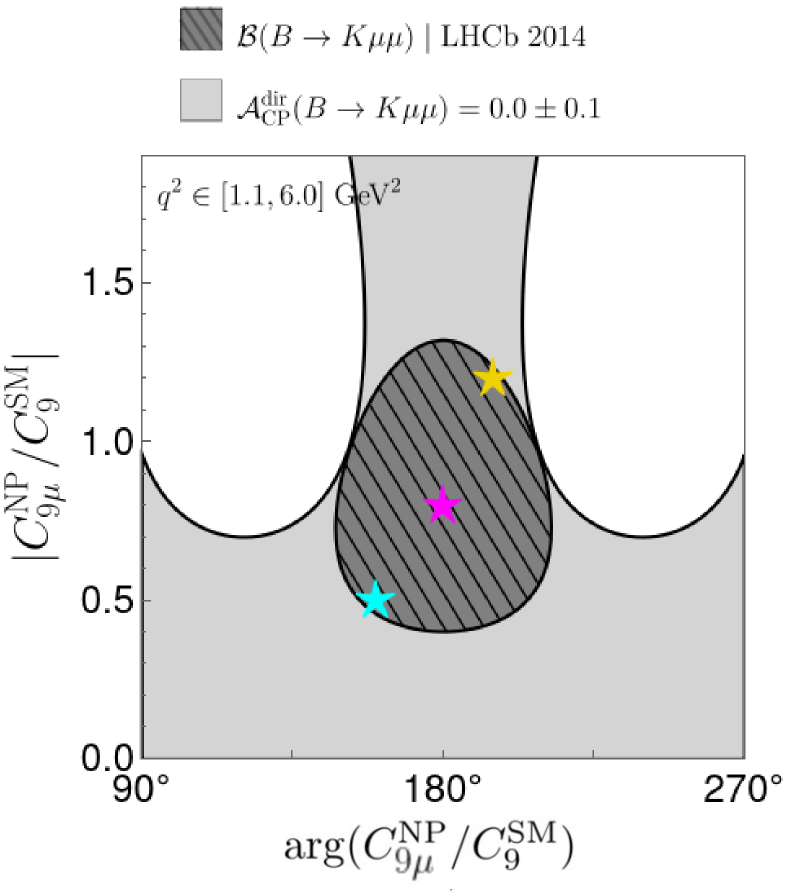
$C_9 \in \mathbb{C} \to$ CP violation



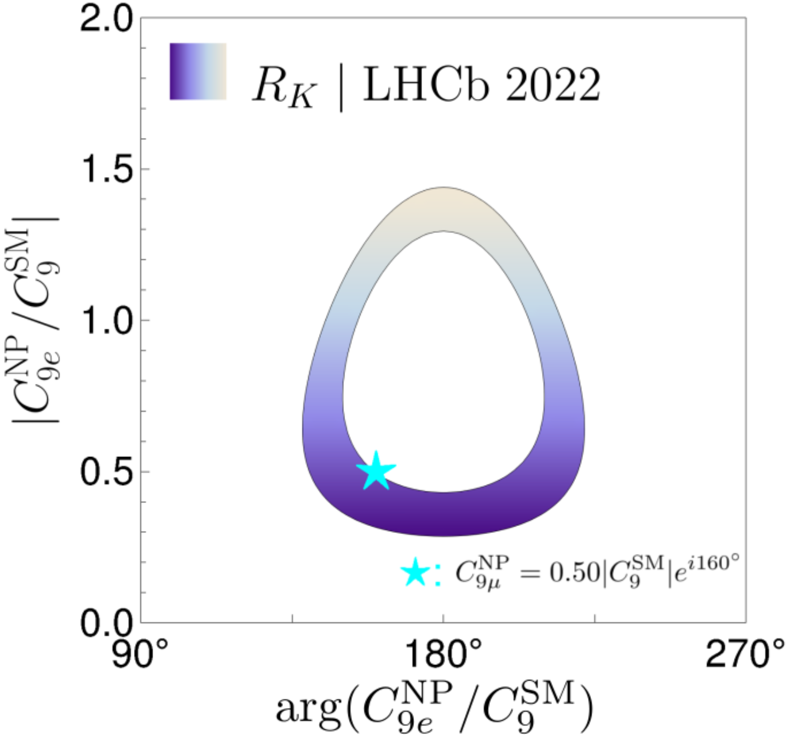
What does this imply for NP in the electron sector?



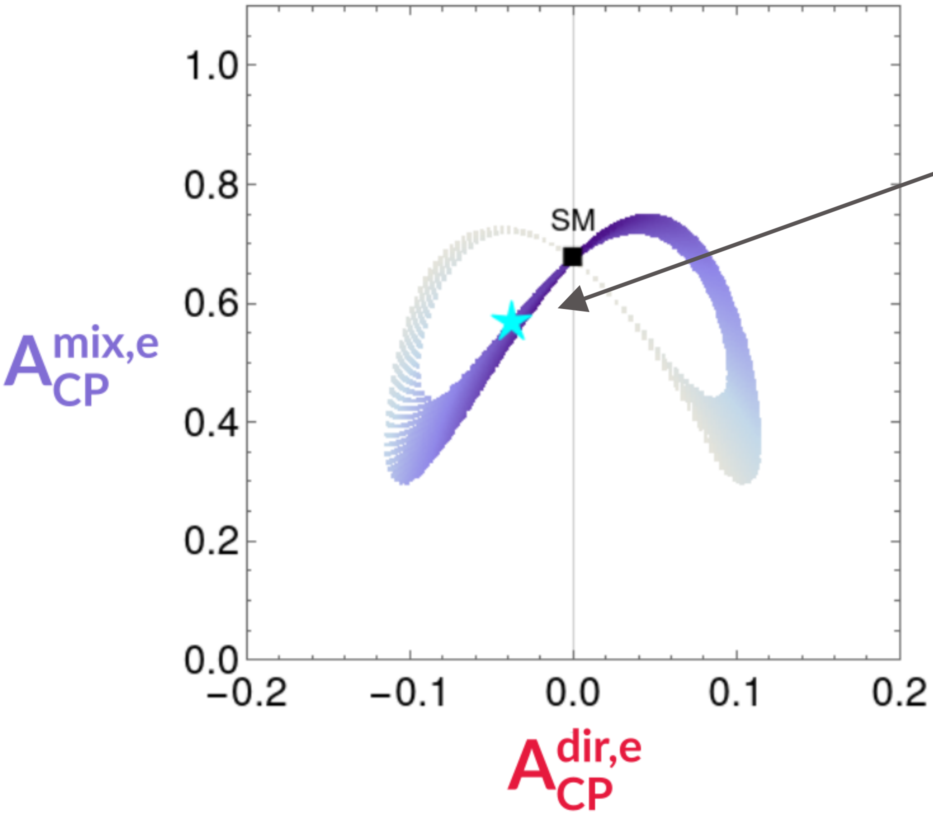
$C_9 \in \mathbb{C} \rightarrow$ CP violation

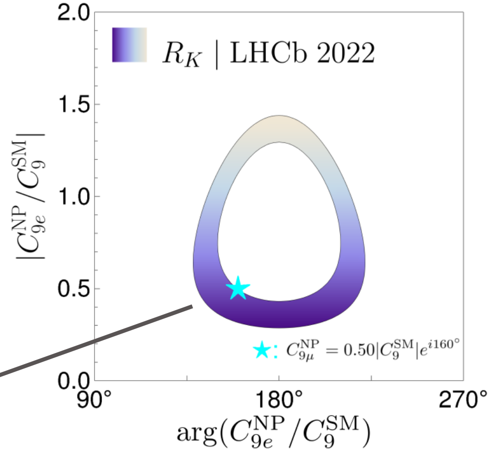


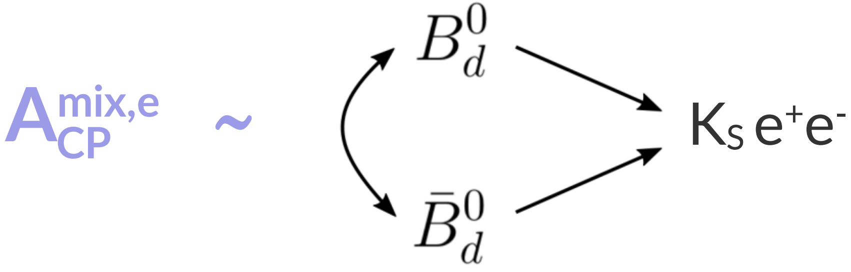
A surprising amount of space for μ/e nonuniversality!



To explore this space, we need to measure CP asymmetries:



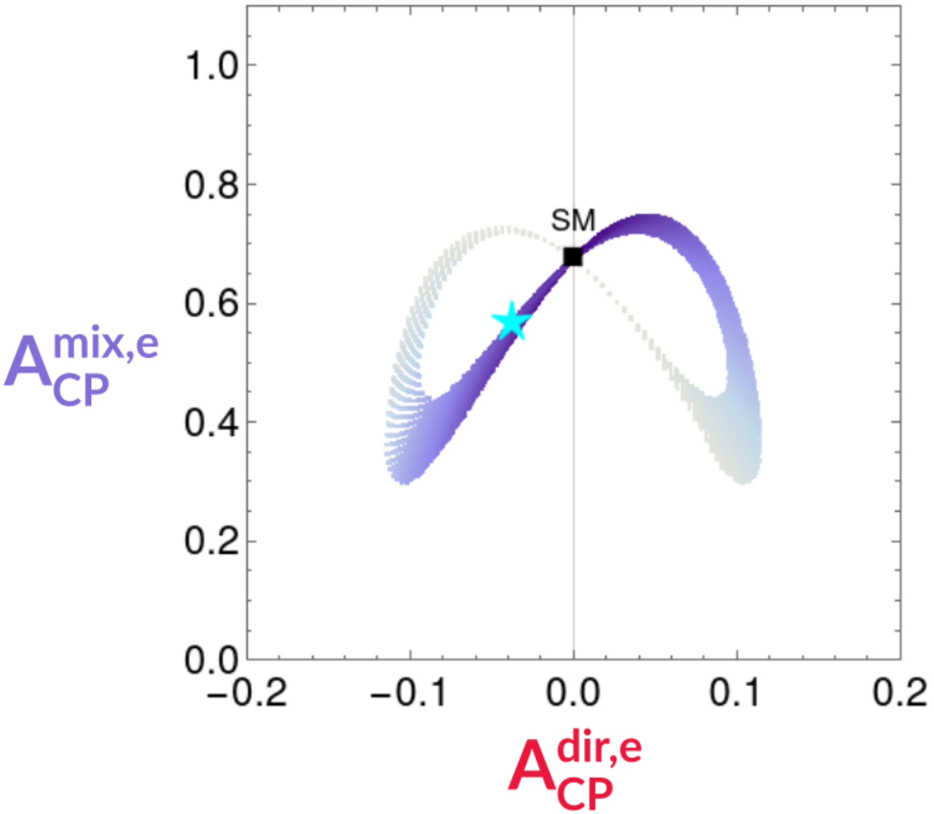




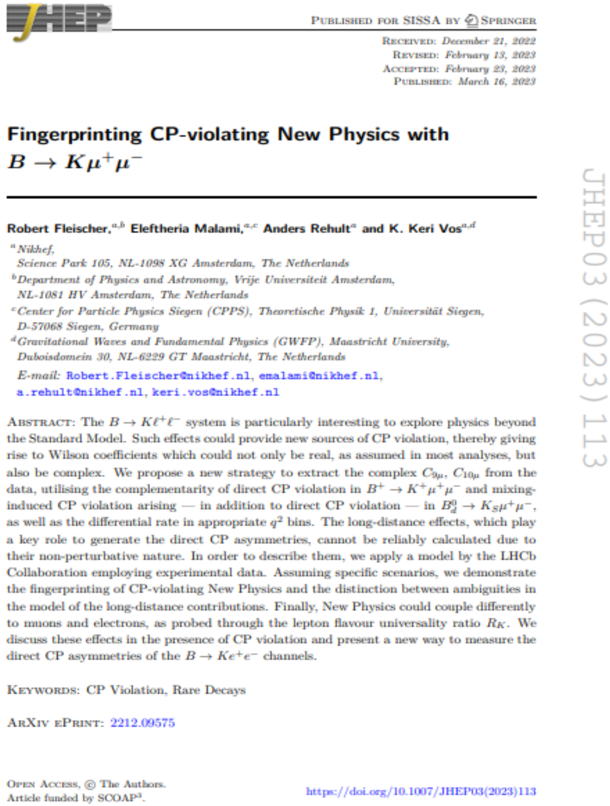
Measured?

	A_{CP}^{dir}	A_{CP}^{mix}
μ	✓	✗
e	✗	✗

To explore this space, we need to measure CP asymmetries:



Bonus! Measuring A_{CP}^{dir}, A_{CP}^{mix} lets us determine complex C_9 and C_{10}



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Fingerprinting CP-violating New Physics with $B \to K\mu^+\mu^-$

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ABSTRACT: The $B \to K\ell^+\ell^-$ system is particularly interesting to explore physics beyond the Standard Model. Such effects could provide new sources of CP violation, thereby giving rise to Wilson coefficients which could not only be real, as assumed in most analyses, but also be complex. We propose a new strategy to extract the complex $C_{9\mu}$, $C_{10\mu}$ from the data, utilising the complementarity of direct CP violation in $B^+ \to K^+\mu^+\mu^-$ and mixing-induced CP violation arising — in addition to direct CP violation — in $B_d^0 \to K_S\mu^+\mu^-$, as well as the differential rate in appropriate q^2 bins. The long-distance effects, which play a key role to generate the direct CP asymmetries, cannot be reliably calculated due to their non-perturbative nature. In order to describe them, we apply a model by the LHCb Collaboration employing experimental data. Assuming specific scenarios, we demonstrate the fingerprinting of CP-violating New Physics and the distinction between ambiguities in the model of the long-distance contributions. Finally, New Physics could couple differently to muons and electrons, as probed through the lepton flavour universality ratio R_K. We discuss these effects in the presence of CP violation and present a new way to measure the direct CP asymmetries of the $B \to Ke^+e^-$ channels.

KEYWORDS: CP Violation, Rare Decays

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Conclusions

- $R_K|_{LHCb'22} \approx R_K|_{SM}$
- $C_i \in \mathbb{R}$ → **very limited room** for μ/e nonuniversality in $B \to K l^+ l^-$
- However, $C_i \in \mathbb{C}$ → **lots of space** for nonuniversality!
- To probe this space, we need to measure **CP asymmetries** in $B \to K\mu^+\mu^-$ and $B \to K e^+ e^-$

Thank you!

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Backup slides

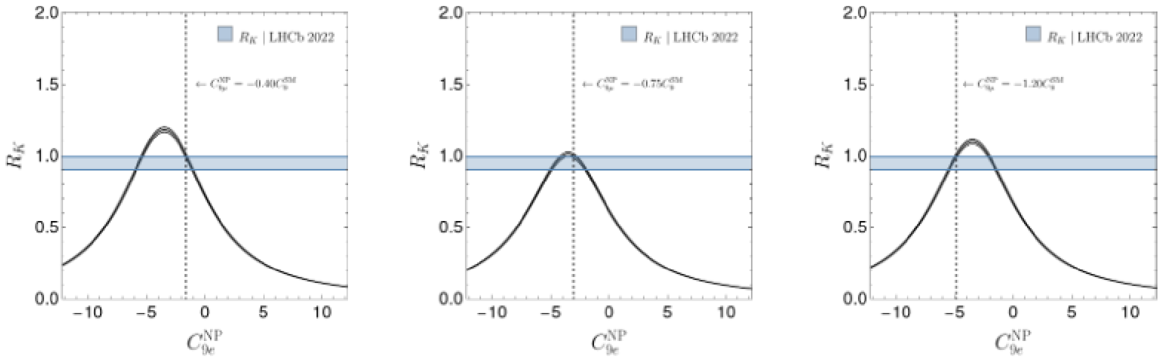


Figure 1: The $\langle R_K \rangle$ ratio as a function of $C_{9e}^{\rm NP}$ for Scenario 1. Each of the plots corresponds to a different benchmark point for $C_{9\mu}^{\rm NP}$.

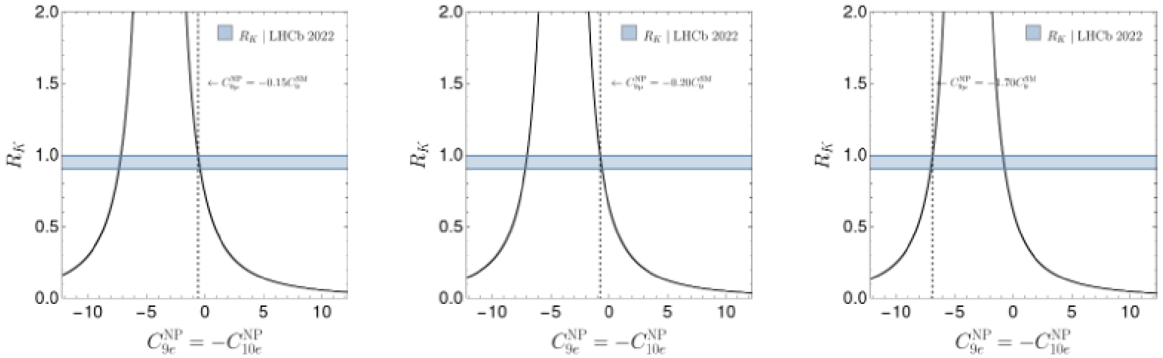


Figure 2: The $\langle R_K \rangle$ ratio as a function of $C_{9e}^{\rm NP} = -C_{10e}^{\rm NP}$ for Scenario 2. Each of the plots corresponds to a different benchmark point for the muon channel with $C_{9\mu}^{\rm NP} = -C_{10\mu}^{\rm NP}$.

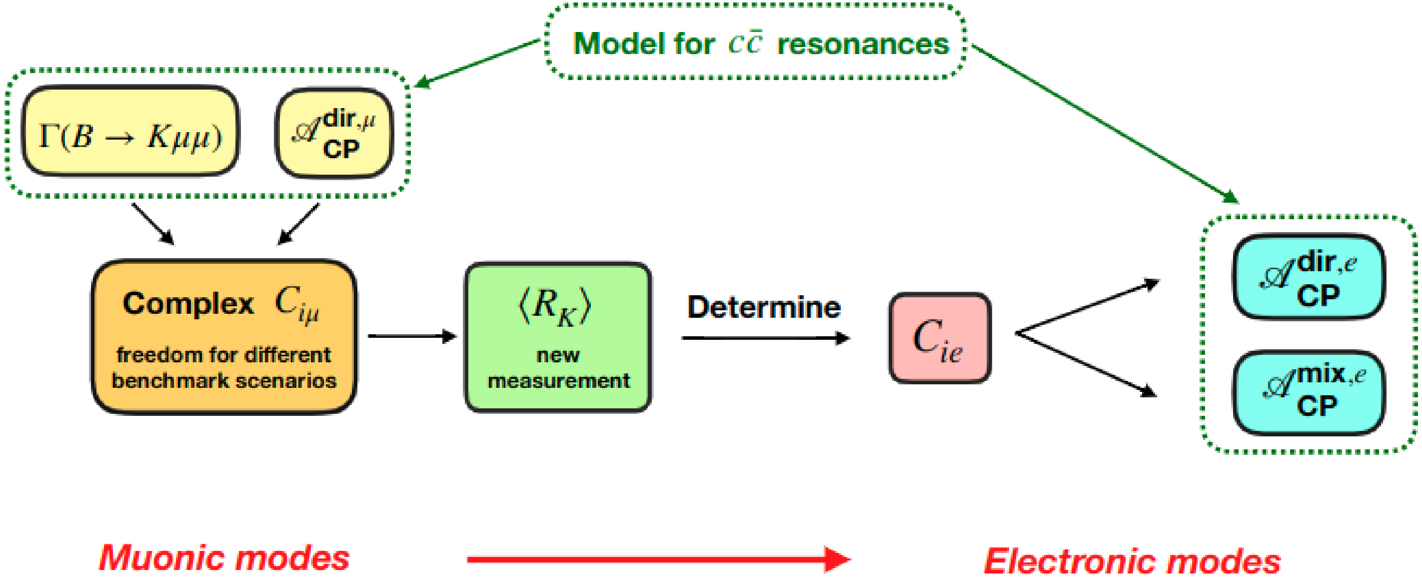


Figure 3: Illustration of our procedure to determine the NP signals in the electronic CP asymmetries.

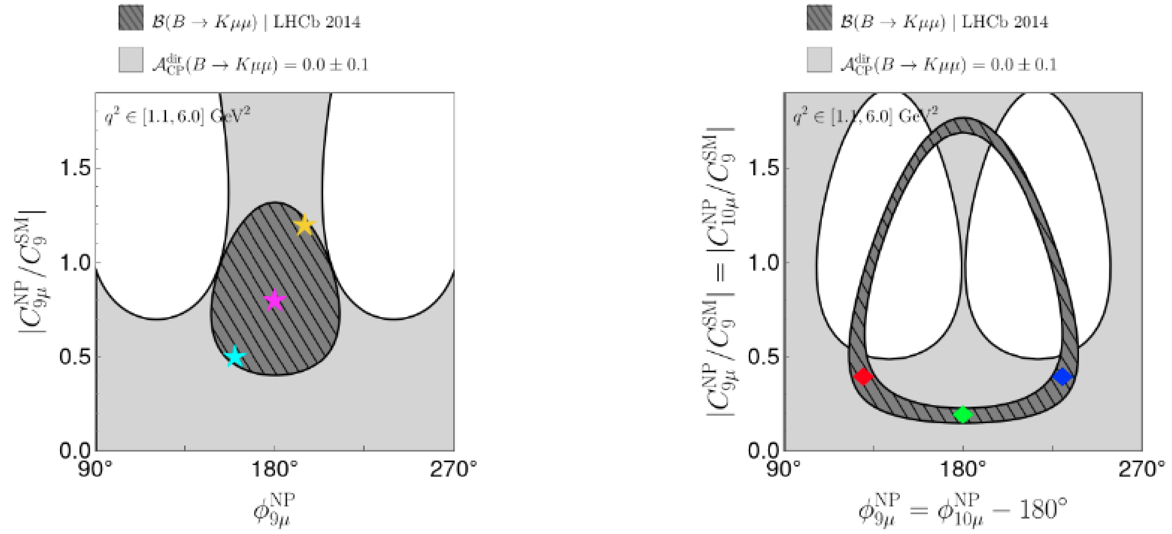


Figure 4: Current bounds on $C_{9\mu}^{\rm NP}$ for NP Scenario 1 (left) and Scenario 2 (right) from the experimental measurements of the $B \to K\mu^+\mu^-$ branching ratio (gray) and the direct CP asymmetry (striped). The stars and diamonds indicate benchmark points as discussed in the text.

$C_9^{\rm only}$ (Stars)		$C_9^{\rm NP} = -C_{10}^{\rm NP}$ (Diamonds)	
Cyan	$0.50\|C_9^{\rm SM}\|e^{i160°}$	Red	$0.40\|C_9^{\rm SM}\|e^{i130°}$
Magenta	$0.80\|C_9^{\rm SM}\|e^{i180°}$	Green	$0.20\|C_9^{\rm SM}\|e^{i180°}$
Yellow	$1.20\|C_9^{\rm SM}\|e^{i195°}$	Blue	$0.40\|C_9^{\rm SM}\|e^{i230°}$

Table 1: Six different benchmark points that cover the allowed regions for $C_{9\mu}$.

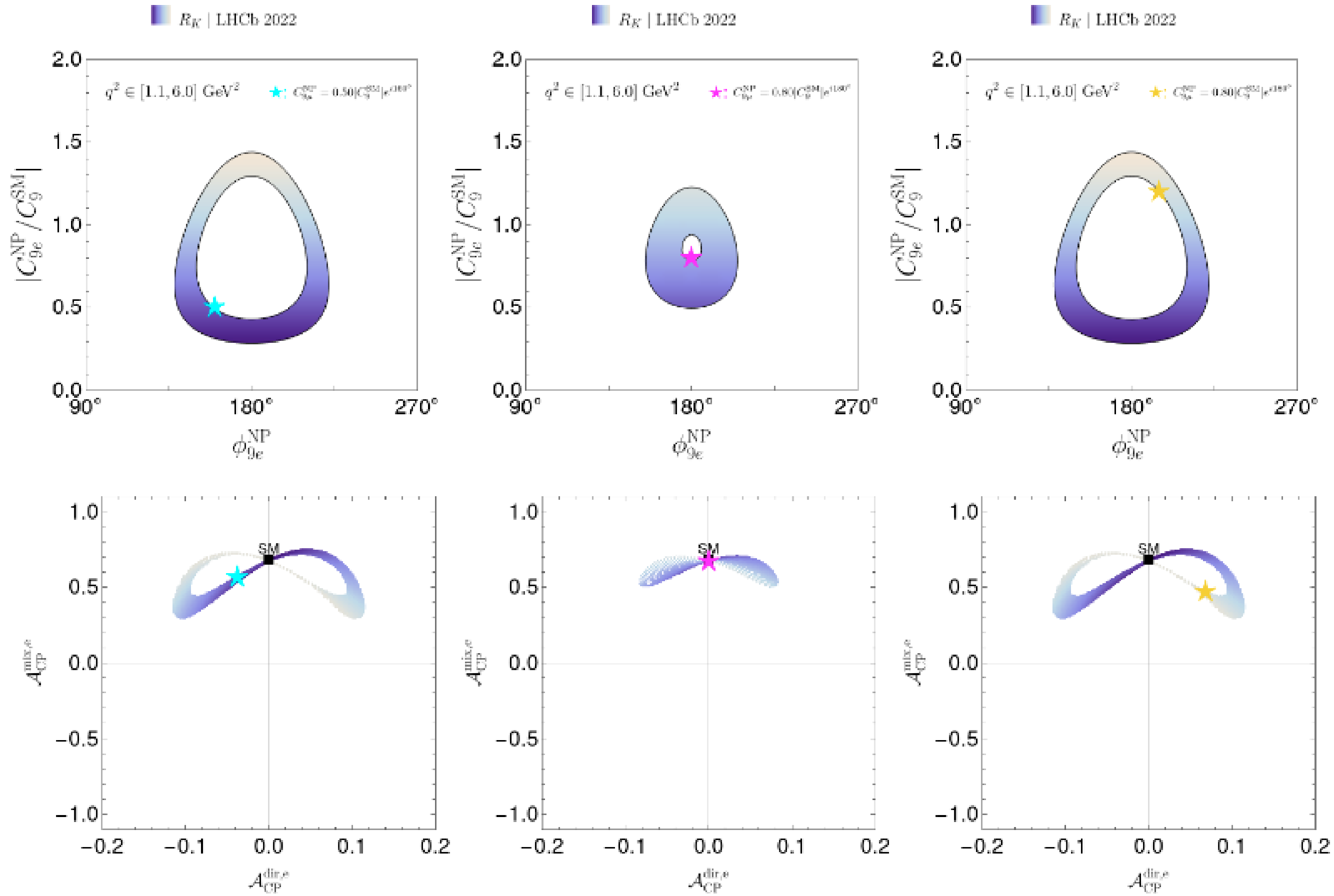


Figure 5: Constraints on $C_{9e}^{\rm NP}$ (upper) for the different benchmark points of Scenario 1 and the corresponding constraints on the CP asymmetries (lower).

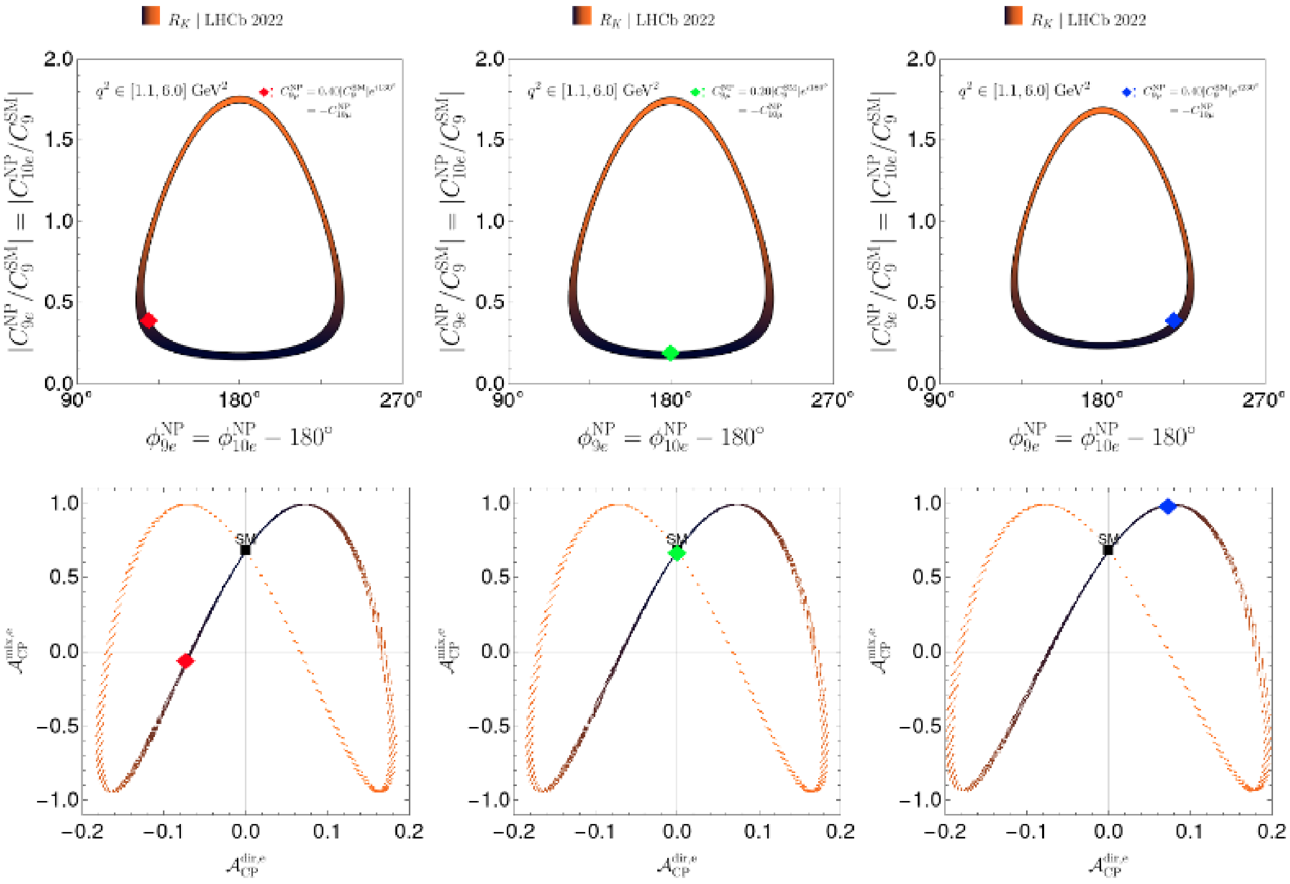
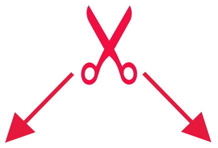


Figure 6: Constraints on $C_{9e}^{\rm NP}$ (upper) for the different benchmark points of Scenario 2 and the corresponding constraints on the CP asymmetries (lower).

$$\langle R_K \rangle$$



$$R_K \equiv \frac{\Gamma_\mu}{\Gamma_e} , \qquad \bar{R}_K \equiv \frac{\bar{\Gamma}_\mu}{\bar{\Gamma}_e} ,$$

$$\mathcal{A}_{\rm CP}^{\rm dir,e} = \frac{2\langle R_K \rangle - R_K - \bar{R}_K}{\bar{R}_K - R_K}$$

$$= \frac{2\langle R_K \rangle}{\bar{R}_K - R_K} - \frac{1}{\mathcal{A}_{\rm CP}^{R_K}} .$$

$$\mathcal{A}_{\rm CP}^{\rm dir,e} = \frac{\mathcal{A}_{\rm CP}^{R_K}}{\mathcal{A}_{\rm CP}^{\rm dir,\mu}\left(1 + \mathcal{A}_{\rm CP}^{R_K}\right)}$$

$$\mathcal{A}_{\rm CP}^{R_K} \equiv \frac{\bar{R}_K - R_K}{\bar{R}_K + R_K} ,$$

$$\mathcal{A}_{\rm CP}^{R_K} = \left[\frac{\mathcal{A}_{\rm CP}^{\rm dir,\mu} - \mathcal{A}_{\rm CP}^{\rm dir,e}}{1 - \mathcal{A}_{\rm CP}^{\rm dir,\mu}\ \mathcal{A}_{\rm CP}^{\rm dir,e}} \right]$$

$$\text{Scenario 1}: \quad C_{9\mu}^{\rm NP} = [-1.32, -0.40] C_9^{\rm SM},$$

$$\text{Scenario 2}: \quad C_{9\mu}^{\rm NP} = -C_{10\mu}^{\rm NP} = [-0.23, -0.15] C_9^{\rm SM} \cup [-1.76, -1.69] C_9^{\rm SM}$$

$$C_{9e}^{\rm NP} = (C_{9\mu}^{\rm NP})^* = 0.50 |C_9^{\rm SM}| e^{-i160^\circ}$$

$$\langle R_K \rangle = 1.001$$

$$R_K = 1.079, \qquad \bar{R}_K = 0.928, \qquad \mathcal{A}_{\rm CP}^{R_K} = -0.075 ,$$