# CPV in $b \to s\mu\mu$

Aleks Smolkovic

3. 11. 2022

N. Kosnik, A. S. - *Phys.Rev.D* 104 (2021) 11
D. Becirevic, S. Fajfer, N. Kosnik, A. S. - *Eur.Phys.J.C* 80 (2020) 10

UNIVERSITÄT BERN
AEC
ALBERT EINSTEIN CENTER
FOR FUNDAMENTAL PHYSICS

# SMEFT and flavour

single CPV phase

$$\mathscr{L} = \mathscr{L}_{\rm SM} + \frac{1}{\Lambda^2}\sum_i C_i Q_i$$

59 operators for a single generation

$$Q_{lq}^{(1)} = (\bar{L}_p \gamma^\mu L_r)(\bar{Q}_s \gamma_\mu Q_t),$$
$$Q_{lq}^{(3)} = (\bar{L}_p \gamma^\mu \tau^I L_r)(\bar{Q}_s \gamma_\mu \tau^I Q_t)$$
$$\dots$$

E.g. B. Grzadkowski et al. - *JHEP* 10 (2010) 085

Adding flavour to the SMEFT:

increasing symmetry ←

A. Greljo et al.- 2203.09561

increasing symmetry ↑

| SMEFT $\mathcal{O}(1)$ terms (dim-6, $\Delta B = 0$) | | Lepton sector | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | $\mathrm{MFV}_L$ | | $\mathrm{U}(3)_V$ | | $\mathrm{U}(2)^2 \times \mathrm{U}(1)^2$ | | $\mathrm{U}(2)^2$ | | $\mathrm{U}(2)_V$ | | $\mathrm{U}(1)^6$ | | $\mathrm{U}(1)^3$ | | No symm. | |
| Quark sector | $\mathrm{MFV}_Q$ | 41 | 6 | 45 | 9 | 59 | 6 | 62 | 9 | 67 | 13 | 81 | 6 | 93 | 18 | 207 | 132 |
| | $\mathrm{U}(2)^2 \times \mathrm{U}(3)_d$ | 72 | 10 | 78 | 15 | 95 | 10 | 100 | 15 | 107 | 21 | 122 | 10 | 140 | 28 | 281 | 169 |
| | $\mathrm{U}(2)^3 \times \mathrm{U}(1)_{d_3}$ | 86 | 10 | 92 | 15 | 111 | 10 | 116 | 12 | 123 | 21 | 140 | 10 | 158 | 28 | 305 | 175 |
| | $\mathrm{U}(2)^3$ | 93 | 17 | 100 | 23 | 118 | 17 | 124 | 23 | 132 | 30 | 147 | 17 | 168 | 38 | 321 | 191 |
| | No symmetry | 703 | 570 | 734 | 600 | 756 | 591 | 786 | 621 | 818 | 652 | 813 | 612 | 906 | 705 | 1350 | 1149 |

CP conserving

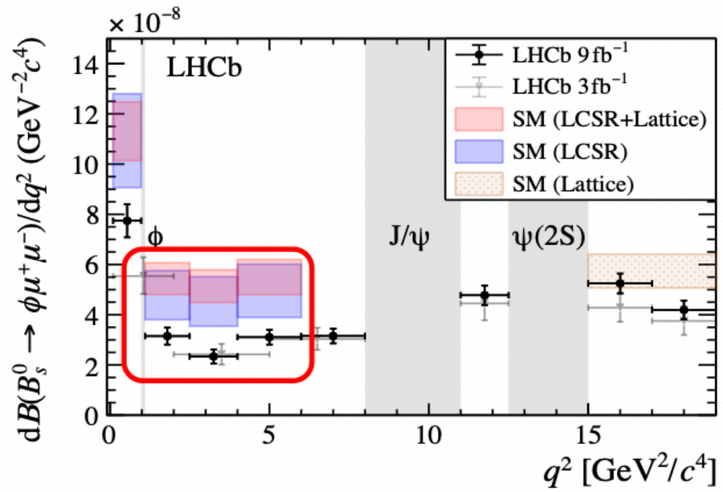
CP violating

Where is all the CPV?

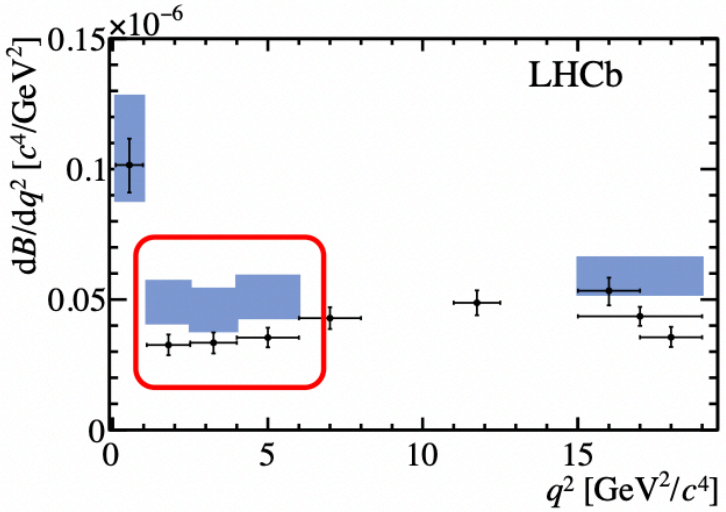
See also:
D. A. Faroughy et al. - *JHEP* 08 (2020) 166
Q. Bonnefoy et al. - 2112.03889

# Neutral current B anomalies

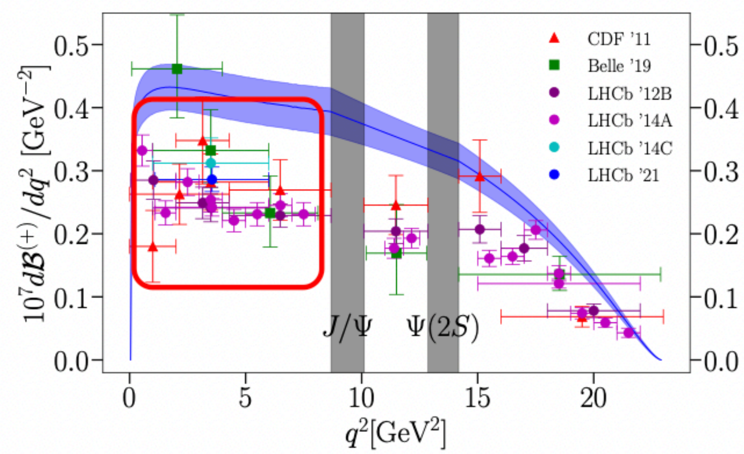
LHCb $B_s^0 \to \phi\mu^+\mu^-$ [PRL 127 (2021) 151801]



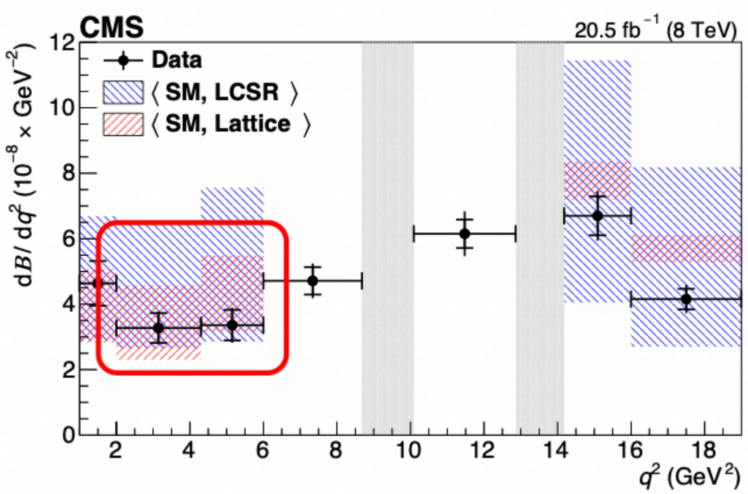

LHCb $B^0 \to K^{*0}\mu^+\mu^-$ [JHEP 11 (2016) 047]



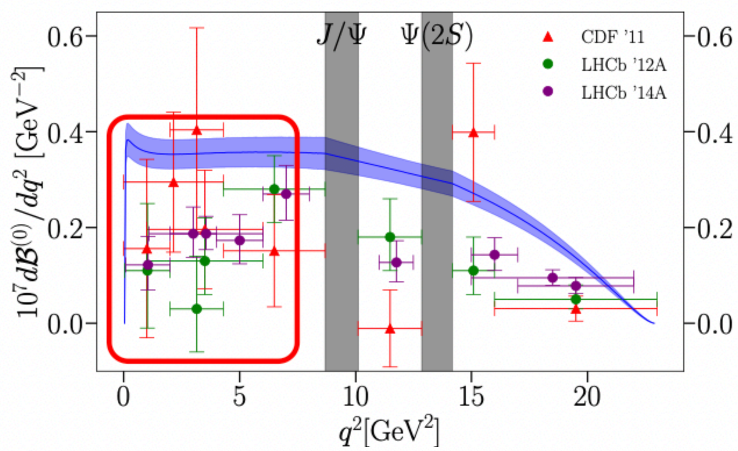

Lattice $B^+ \to K^+\mu^+\mu^-$ [arXiv:2207.13371]



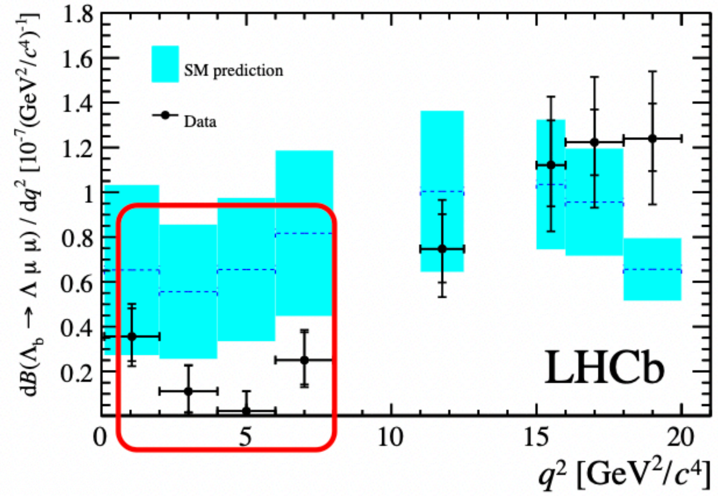

CMS $B^0 \to K^{*0}\mu^+\mu^-$ [PLB 753 (2016) 424]



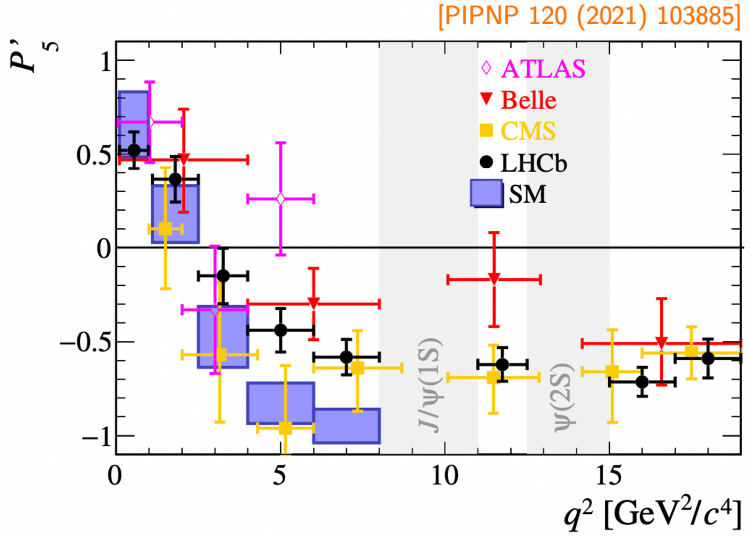

Lattice $B^0 \to K^0\mu^+\mu^-$ [arXiv:2207.13371]

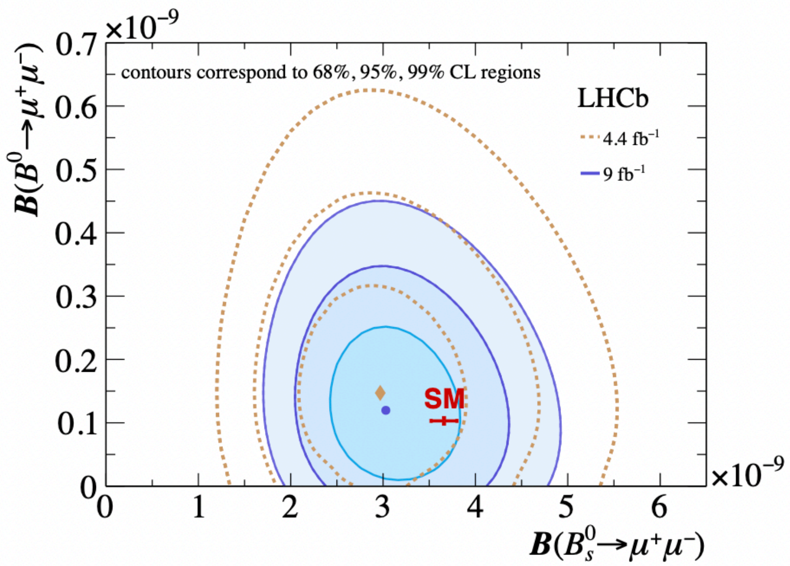



LHCb $\Lambda_b^0 \to \Lambda\mu^+\mu^-$ [JHEP 06 (2015) 115]



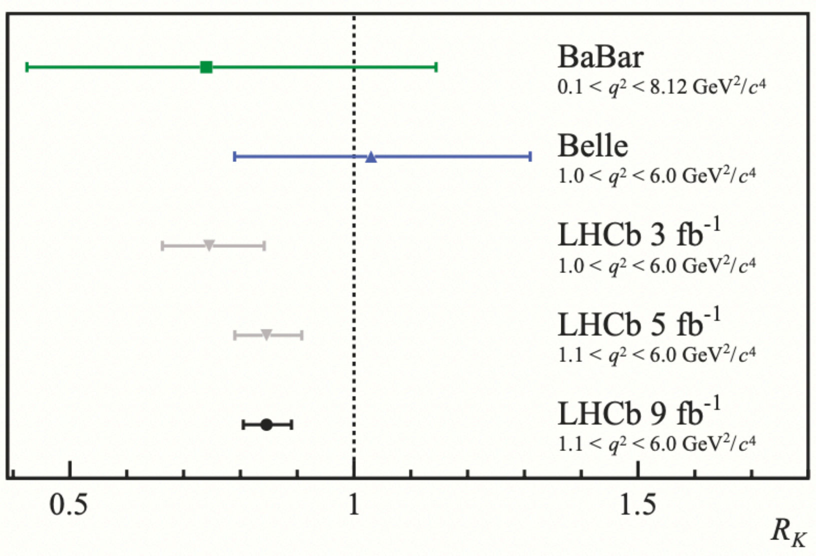

[PIPNP 120 (2021) 103885]

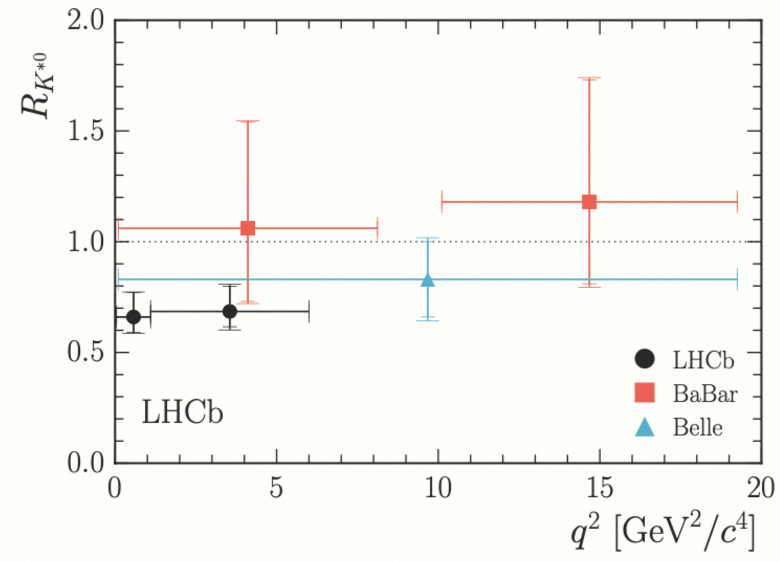



collection by C. M. Langenbruch at LHCb implications 2022

# LFUV and global fits



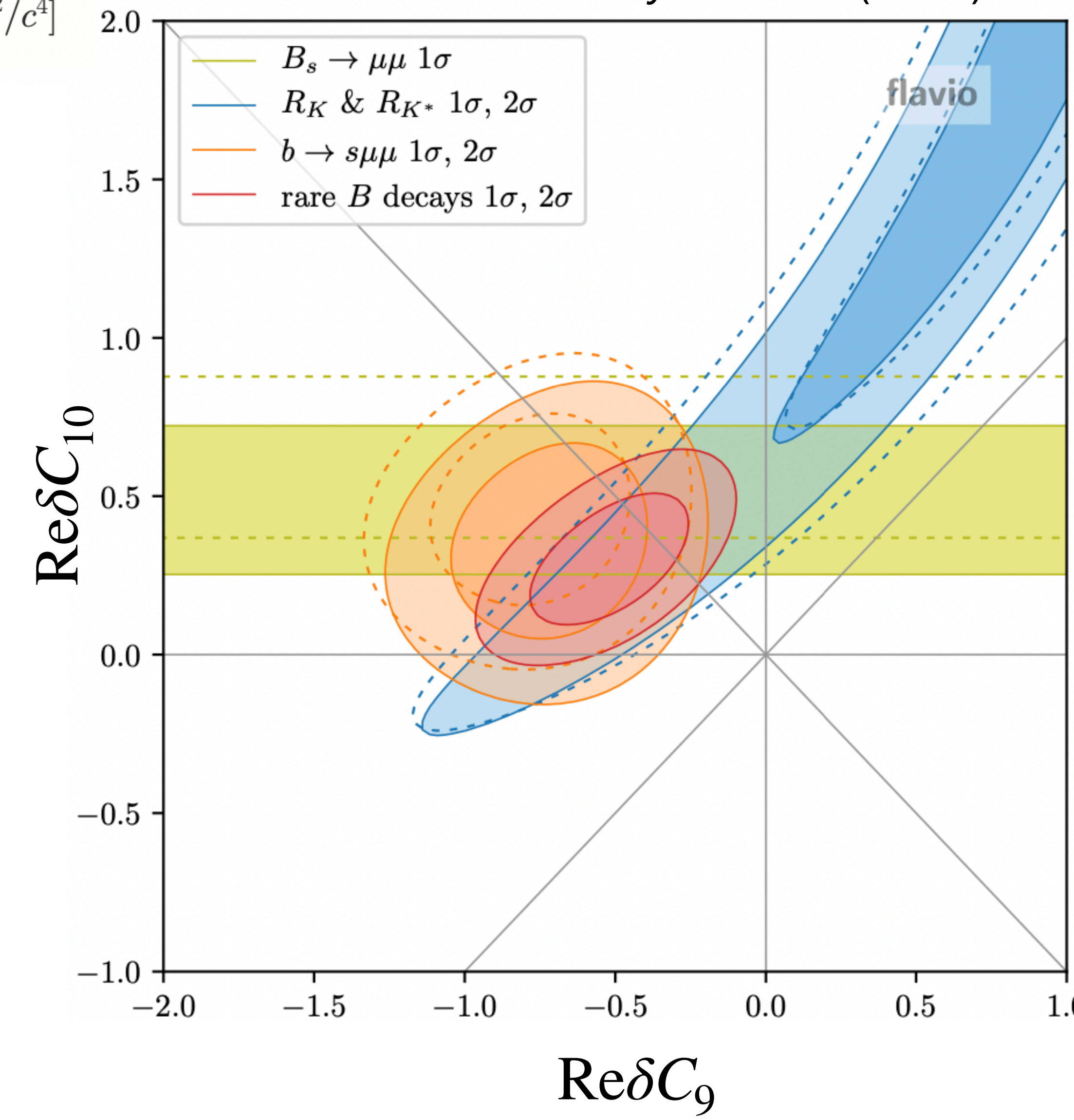

$$R_{K^{(*)}} = \frac{\Gamma(B \to K^{(*)}\mu\mu)}{\Gamma(B \to K^{(*)}ee)}$$

W. Altmannshofer, P. Stangl
*Eur.Phys.J.C* 81 (2021) 10

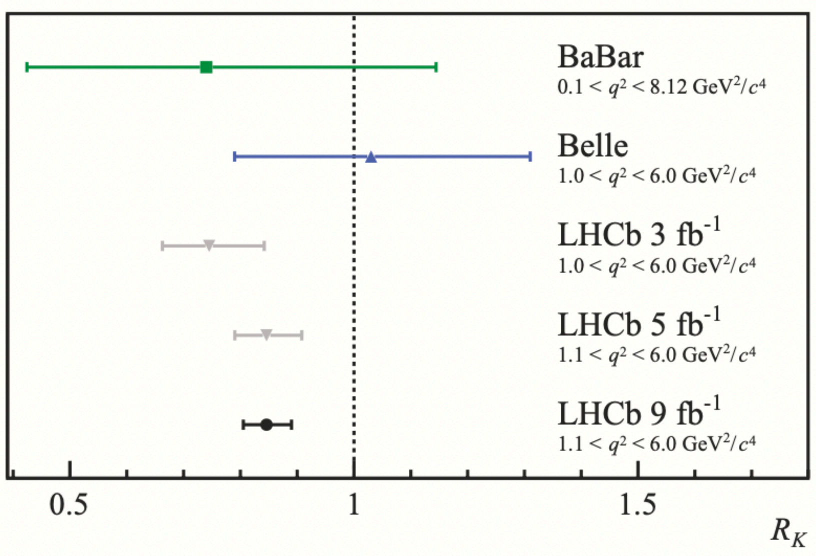
Weak effective Hamiltonian:

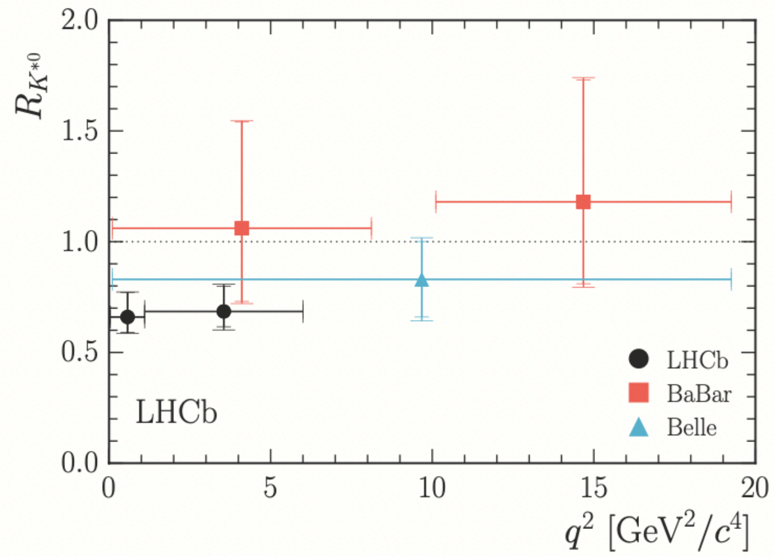
$$\mathcal{H}_{\text{eff}} = \mathcal{H}_{\text{eff}}^{\text{SM}} - \frac{4G_F}{\sqrt{2}} V_{tb}V_{ts}^* \frac{e^2}{16\pi^2} \sum_i \delta C_i O_i$$

$$O_9 = (\bar{s}\gamma_\mu P_L b)(\bar{\mu}\gamma^\mu \mu) \qquad O_{10} = (\bar{s}\gamma_\mu P_L b)(\bar{\mu}\gamma^\mu \gamma_5 \mu)$$



# LFUV and CPV

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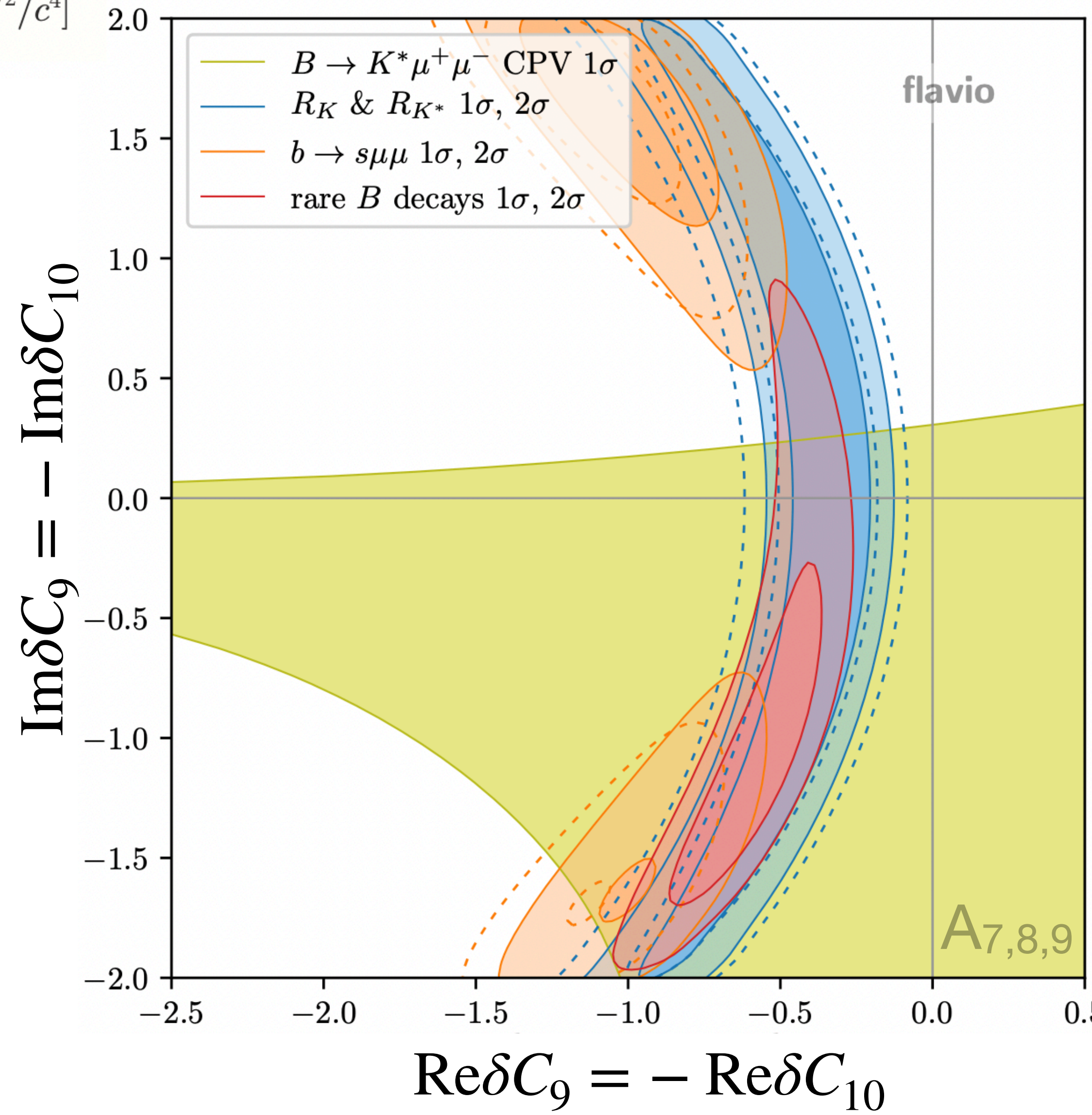


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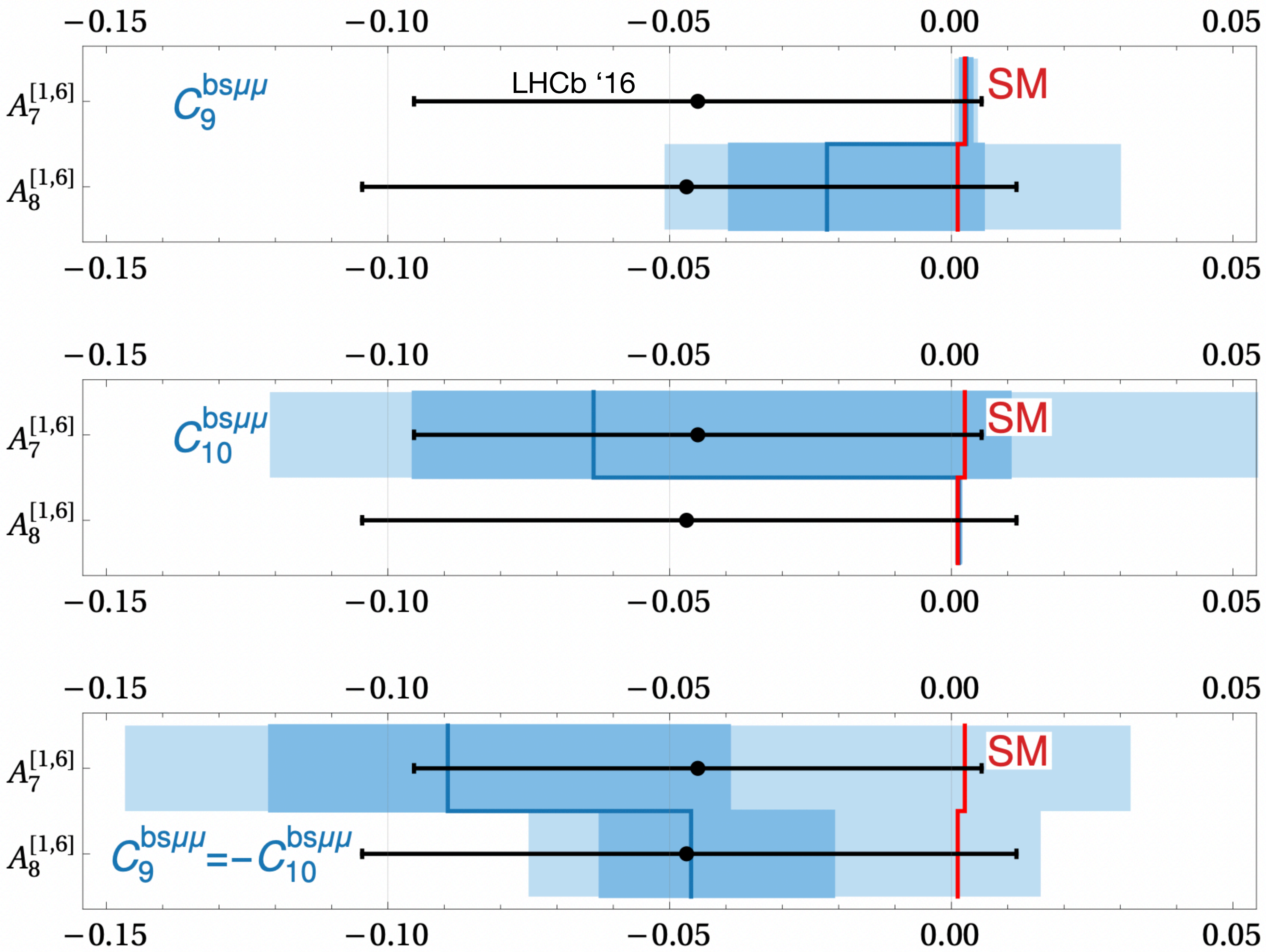
$$O_9 = (\bar{s}\gamma_\mu P_L b)(\bar{\mu}\gamma^\mu \mu) \qquad O_{10} = (\bar{s}\gamma_\mu P_L b)(\bar{\mu}\gamma^\mu \gamma_5 \mu)$$

- Allow for NP contributions $\delta C_i$ to be complex
- We focus on $\delta C_9 = -\delta C_{10}$ scenario
- Large CPV phase consistent with data

See also:
A. Carvunis et al *JHEP* 12 (2021) 078

# Discriminating power of CPV




See also:
A. Alok et al. - *Phys.Rev.D* 96 (2017) 1

W. Altmannshofer, P. Stangl
*Eur.Phys.J.C* 81 (2021) 10

# A $S_3$ LQ model

$S_3$ is the only scalar LQ that resolves the $R_K$ tension

| Model | | $R_{K^{(*)}}$ | $R_{D^{(*)}}$ | $R_{K^{(*)}}$ & $R_{D^{(*)}}$ |
|---|---|---|---|---|
| $S_3$ | $(\bar{\mathbf{3}}, \mathbf{3}, 1/3)$ | ✓ | ✗ | ✗ |
| $S_1$ | $(\bar{\mathbf{3}}, \mathbf{1}, 1/3)$ | ✗ | ✓ | ✗ |
| $R_2$ | $(\mathbf{3}, \mathbf{2}, 7/6)$ | ✗ | ✓ | ✗ |
| $U_1$ | $(\mathbf{3}, \mathbf{1}, 2/3)$ | ✓ | ✓ | ✓ |
| $U_3$ | $(\mathbf{3}, \mathbf{3}, 2/3)$ | ✓ | ✗ | ✗ |

A. Angelescu et al. *Phys.Rev.D* 104 (2021) 5, 055017

$$\mathscr{L} \supset y_{ij} \overline{Q_i^C} (i\tau^2 \tau^I) L_j S_3^I + h.c.$$

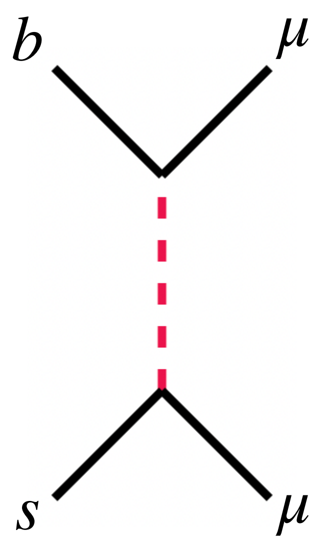
($y_{ij}$ → complex)

SMEFT:

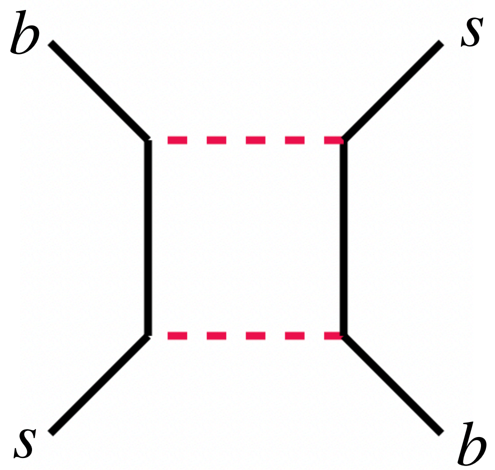
$$C_{lq}^{(1)} = \frac{3 y_{b\mu} y_{s\mu}^*}{4 m_{S_3}^2}, \qquad C_{lq}^{(3)} = \frac{y_{b\mu} y_{s\mu}^*}{4 m_{S_3}^2},$$

WET:

$$\delta C_9 = -\delta C_{10} = \frac{\pi y_{b\mu} y_{s\mu}^*}{\sqrt{2} G_F V_{tb} V_{ts}^* \alpha_{\rm em} m_{S_3}^2}$$




At 1-loop level we generate contributions to CP even/odd $B_s$ mixing observables




$$\mathscr{L}_{bs} = -\frac{4G_F}{\sqrt{2}} (V_{tb} V_{ts}^*)^2 C_{bs}^{LL}(\mu) \, (\bar{s}_L \gamma^\mu b_L)^2$$

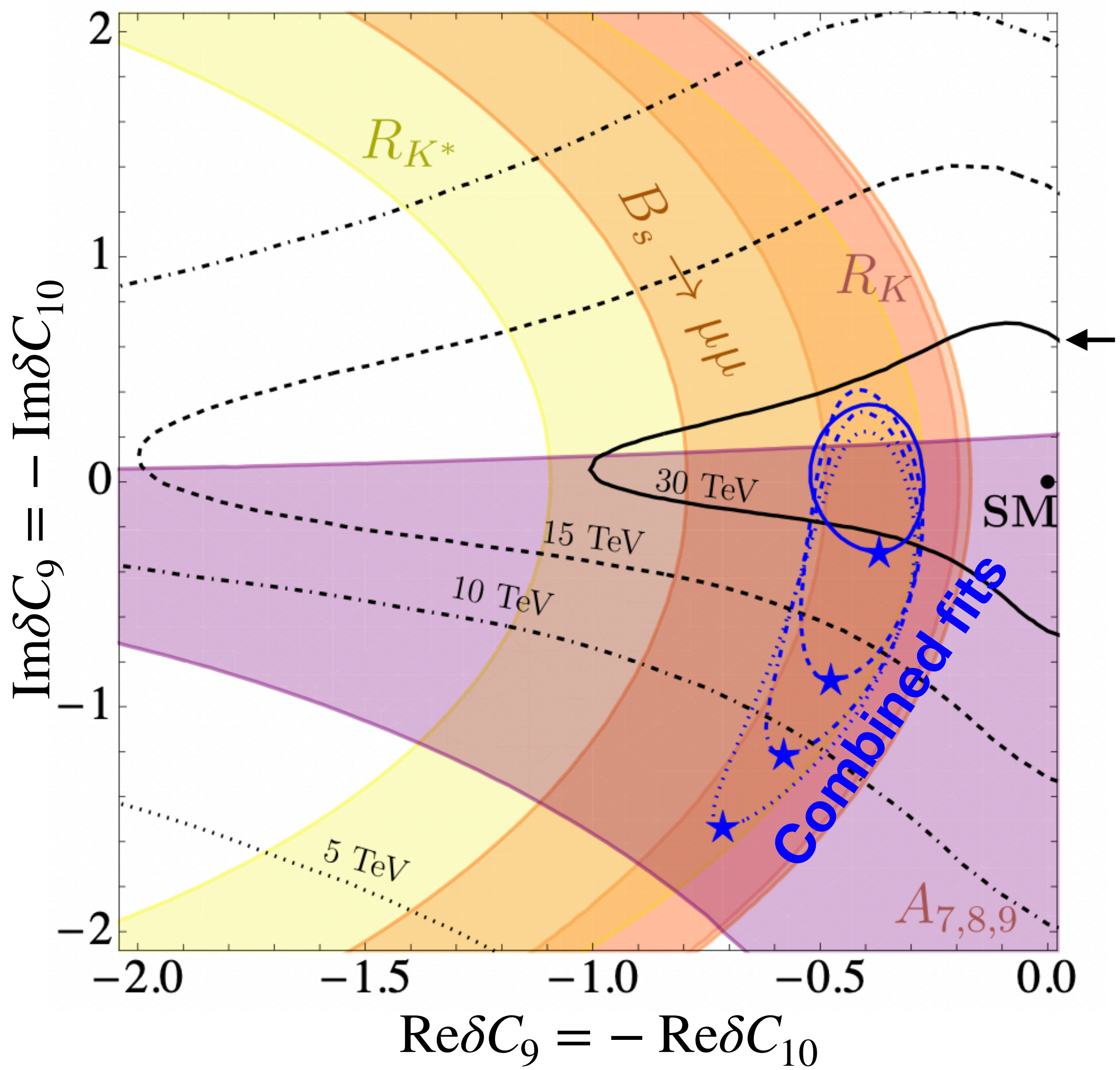
$$C_{bs}^{LL} = C_{bs}^{LL(\mathrm{SM})} + \delta C_{bs}^{LL} \qquad \delta C_{bs}^{LL} = \eta^{6/23} \frac{5 G_F \alpha_{\rm em}^2}{128\sqrt{2}\pi^4} (\delta C_9)^2 m_{S_3}^2$$

N. Kosnik, A. S. - *Phys.Rev.D* 104 (2021) 11

Bounds in the complex plane:

$$\delta C_{bs}^{LL} = \eta^{6/23} \frac{5 G_F \alpha_{\rm em}^2}{128\sqrt{2}\pi^4} (\delta C_9)^2 m_{S_3}^2$$

→ $B_s$ mixing more constraining for larger masses (black contours)




← $\Delta M_s = (17.74 \pm 0.02)\ \mathrm{ps}^{-1}$

$S_{\psi\phi} = -0.050 \pm 0.019$

[FLAG, HFLAV]

**O(1) Im$\delta C_9$ possible for LQ of few TeV**

D. Becirevic, S. Fajfer, N. Kosnik, A. S. - *Eur.Phys.J.C* 80 (2020) 10

# Resonantly enhanced $\mathscr{A}_{\rm CP}$

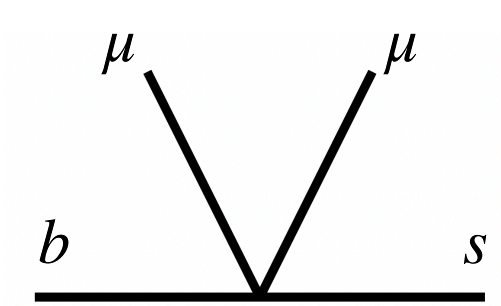
$$\mathscr{A}_{\rm CP} = \frac{\mathscr{B}(\overline{B} \to \overline{K}\mu\mu) - \mathscr{B}(B \to K\mu\mu)}{\mathscr{B}(\overline{B} \to \overline{K}\mu\mu) + \mathscr{B}(B \to K\mu\mu)}$$

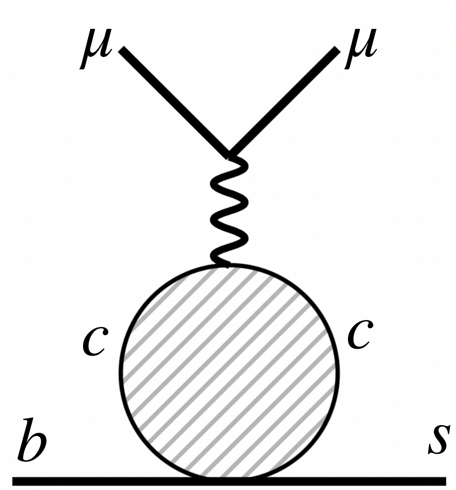
interference of two amplitudes with differing **weak** and **strong** phases needed

tiny in SM

Short-distance $C_9$:

Long-distance $C_9(q^2)$:

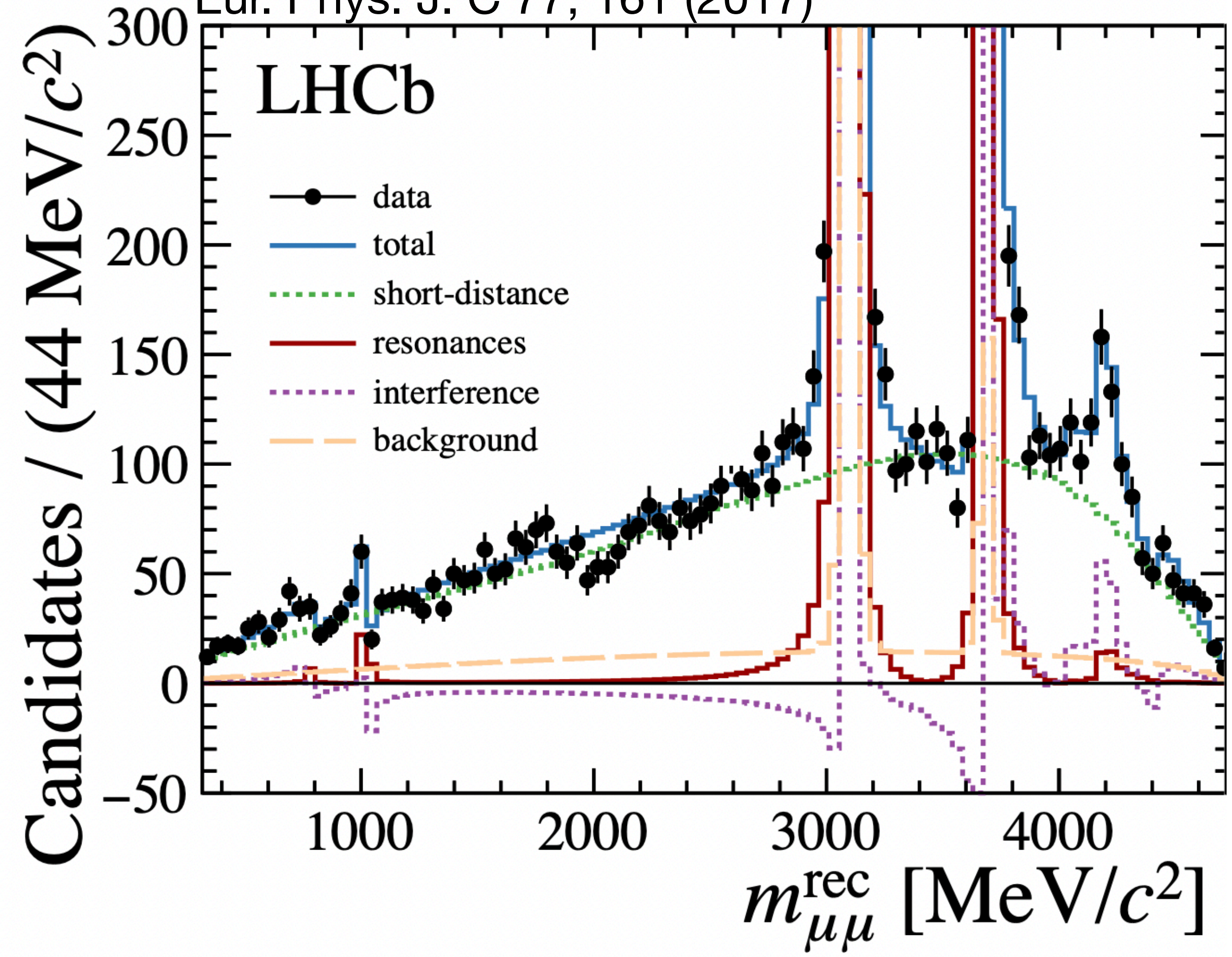



Effective model of charmonium contributions:

$$C_9^{\rm eff}(q^2) = C_9 + C_9^{\rm res}(q^2)$$
$$= C_9 + \sum_j \frac{m_j\,\Gamma_j\,\eta_j\,e^{i\delta_j}}{m_j^2 - q^2 - i\,m_j\Gamma_j(q^2)}$$

Eur. Phys. J. C 77, 161 (2017)



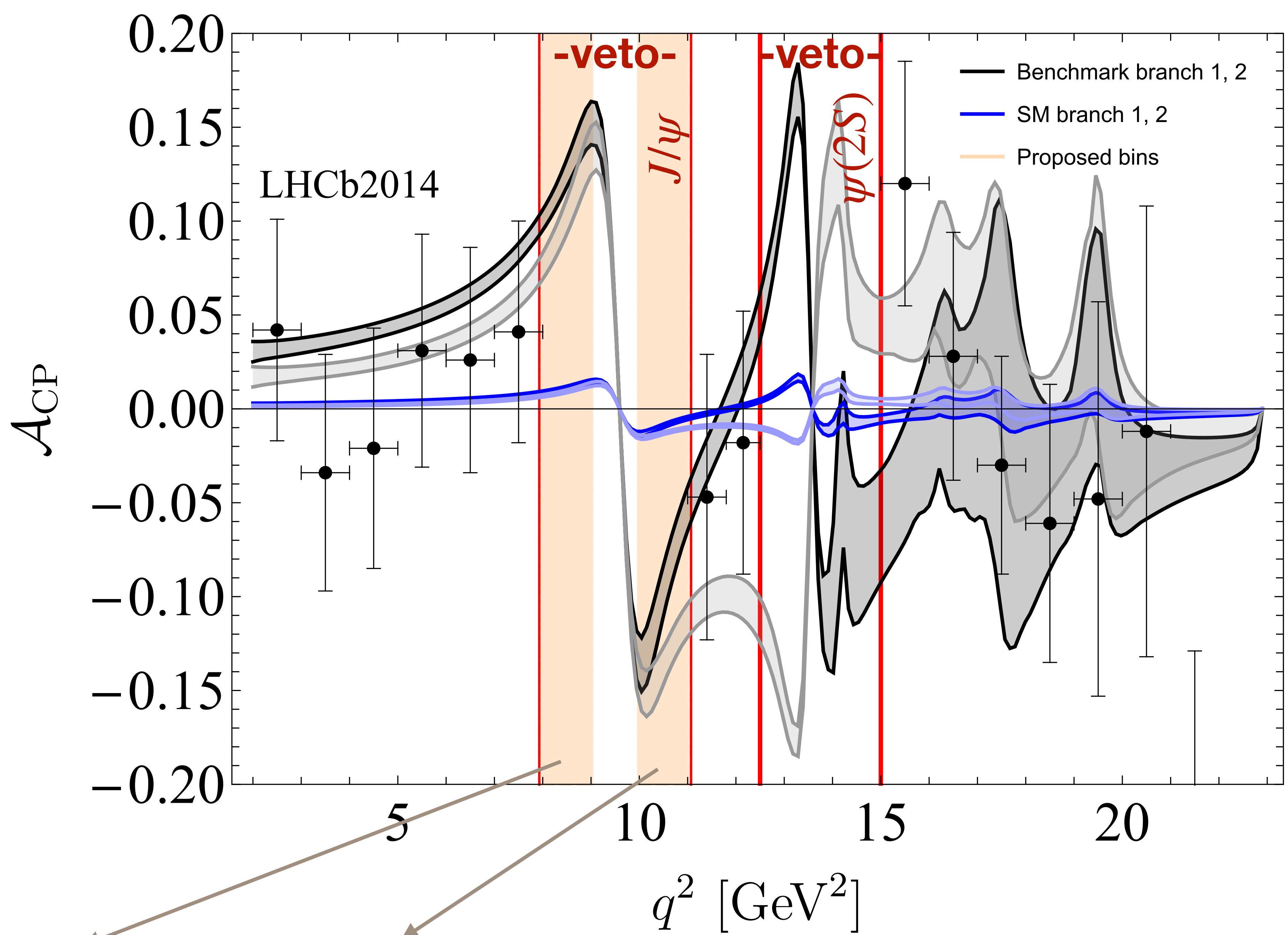

We use the extracted $\eta_j$ and $\delta_j$ to predict $\mathscr{A}_{\rm CP}$

See also:
T. Blake et al. - Eur.Phys.J.C 78 (2018) 6

D. Becirevic, S. Fajfer, N. Kosnik, A. S. - *Eur.Phys.J.C* 80 (2020) 10

Prediction for a benchmark scenario:

$$\delta C_9 = -\delta C_{10} = -0.46 - 0.71i$$




**Proposal:**

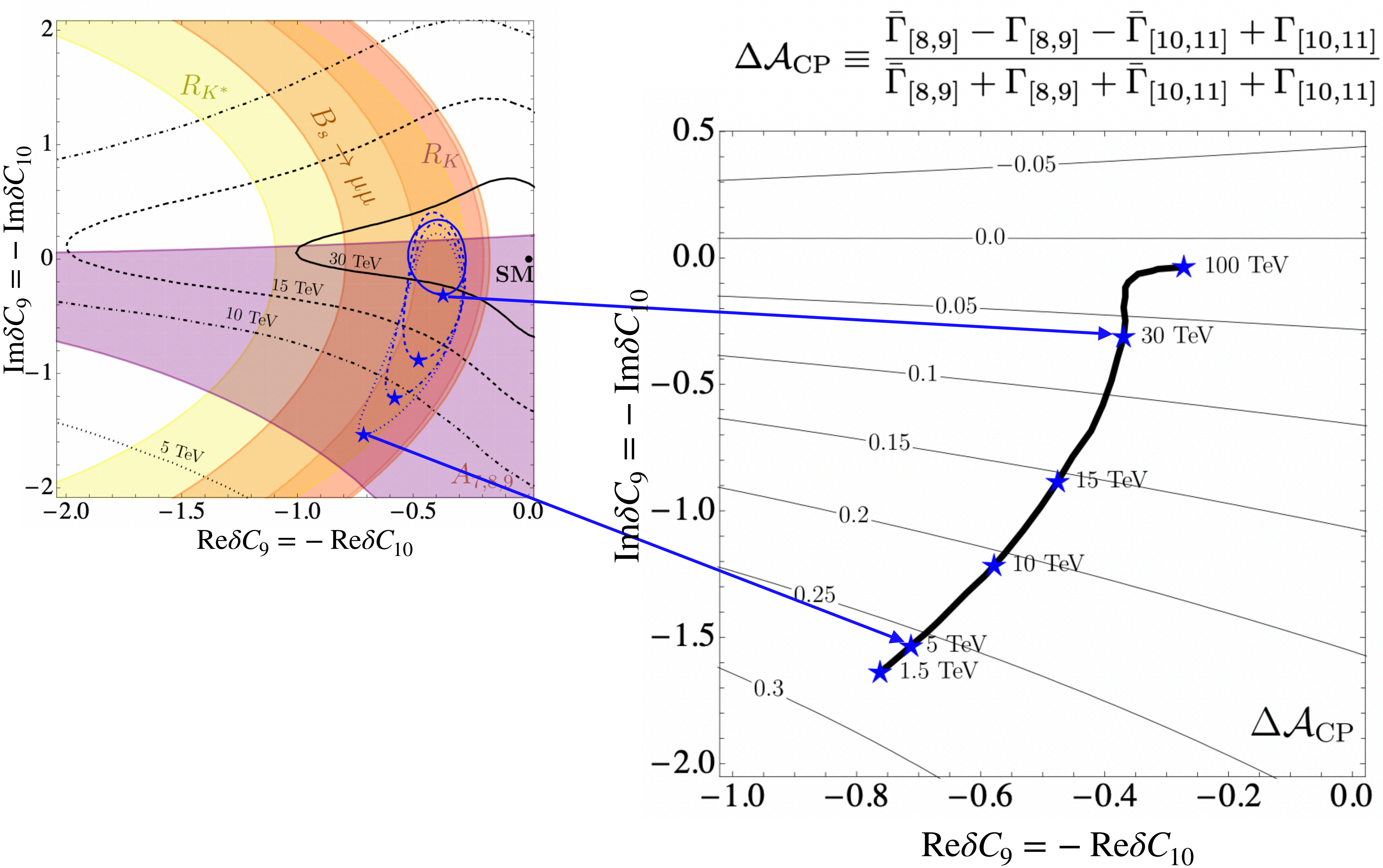
$$\Delta\mathcal{A}_{\rm CP} \equiv \frac{\bar\Gamma_{[8,9]} - \Gamma_{[8,9]} - \bar\Gamma_{[10,11]} + \Gamma_{[10,11]}}{\bar\Gamma_{[8,9]} + \Gamma_{[8,9]} + \bar\Gamma_{[10,11]} + \Gamma_{[10,11]}}$$

**Measurement of a nonzero value would be a clean sign of (CPV) NP**

N. Kosnik, A. S. - *Phys.Rev.D* 104 (2021) 11

## Back to $S_3$:

$$\Delta\mathcal{A}_{\rm CP} \equiv \frac{\bar\Gamma_{[8,9]} - \Gamma_{[8,9]} - \bar\Gamma_{[10,11]} + \Gamma_{[10,11]}}{\bar\Gamma_{[8,9]} + \Gamma_{[8,9]} + \bar\Gamma_{[10,11]} + \Gamma_{[10,11]}}$$




Other new proposals for CPV observables:
S. Descotes-Genon et al. *JHEP* 02 (2021) 129
A. Carvunis et al. *JHEP* 12 (2021) 078 [See talk by C. Normand]

**~25% effect for LQ of few TeV**

# Conclusions

- CP nature of potential NP in $b \to s\mu\mu$ should be scrutinised
- Discriminating power of CPV (NP scenarios, NP vs hadronic effects)
- Proposal: to measure enhanced CPA around J/$\psi$
  nonzero measurement: clean sign of CPV NP
- In $S_3$ model: Large CPV possible for O(TeV) mass with
  up to ~25% effect in proposed $\Delta\mathscr{A}_{\mathrm{CP}}$