NOVEL CPV PHASES IN B-PHYSICS ANOMALIES

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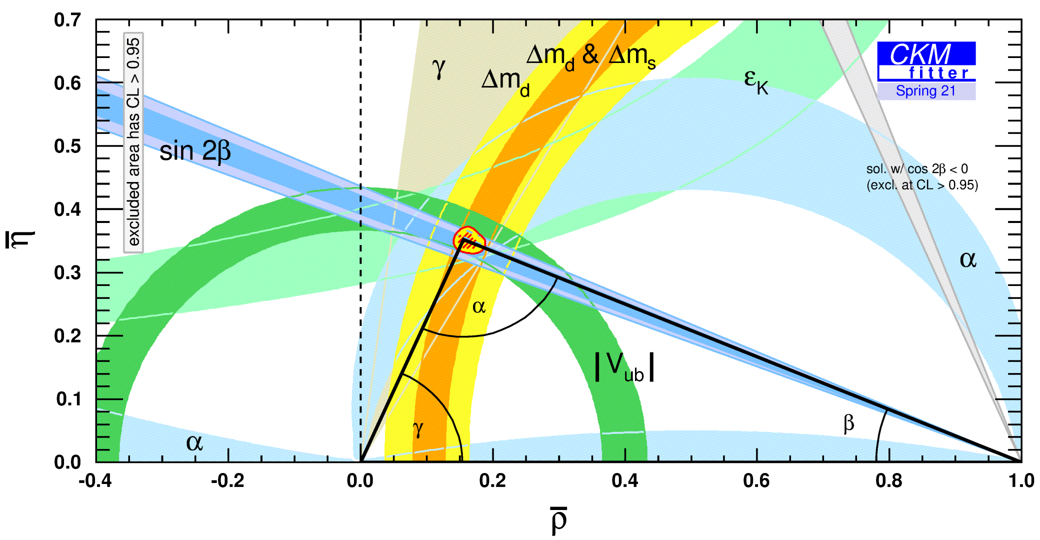
OUTLINE

- Flavour and CP violation in the SM(EFT)
- Lepton flavour universality and CPV
- Model dependent CP-sensitive observables

FLAVOUR AND CP VIOLATION IN THE SM(EFT)

SM(EFT)

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



1 CPV + 18 CP even parameters

$$\det(i[M_d, M_u]) = J(m_t - m_c)(m_t - m_u)\ldots$$

$J \approx 3 \times 10^{-5}$ *Jarlskog '85*

flavour (universality) violation from Yukawas

	$(\bar{L}L)(\bar{L}L)$
Q_{ll}	$(\bar{l}_p \gamma_\mu l_r)(\bar{l}_s \gamma^\mu l_t)$
$Q_{qq}^{(1)}$	$(\bar{q}_p \gamma_\mu q_r)(\bar{q}_s \gamma^\mu q_t)$
$Q_{qq}^{(3)}$	$(\bar{q}_p \gamma_\mu \tau^I q_r)(\bar{q}_s \gamma^\mu \tau^I q_t)$
$Q_{lq}^{(1)}$	$(\bar{l}_p \gamma_\mu l_r)(\bar{q}_s \gamma^\mu q_t)$
$Q_{lq}^{(3)}$	$(\bar{l}_p \gamma_\mu \tau^I l_r)(\bar{q}_s \gamma^\mu \tau^I q_t)$

$\ldots$

59 operators (not counting flavor)

1149 CPV + 1350 CP even flavor couplings

Grzadkowski et al '10
Alonso et al '13

699 Jarlskog-like invariants

Bonnefoy et al. '21

FLAVOR PUZZLE

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

	$(\bar{L}L)(\bar{L}L)$
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$\ldots$

If scale Λ is low, why do we only see CPV effect of a single Jarlskog invariant?

Do the SM flavour patterns encode more fundamental dynamics?

59 operators (not counting flavor)

with flavour:
1149 CPV + 1350 CP

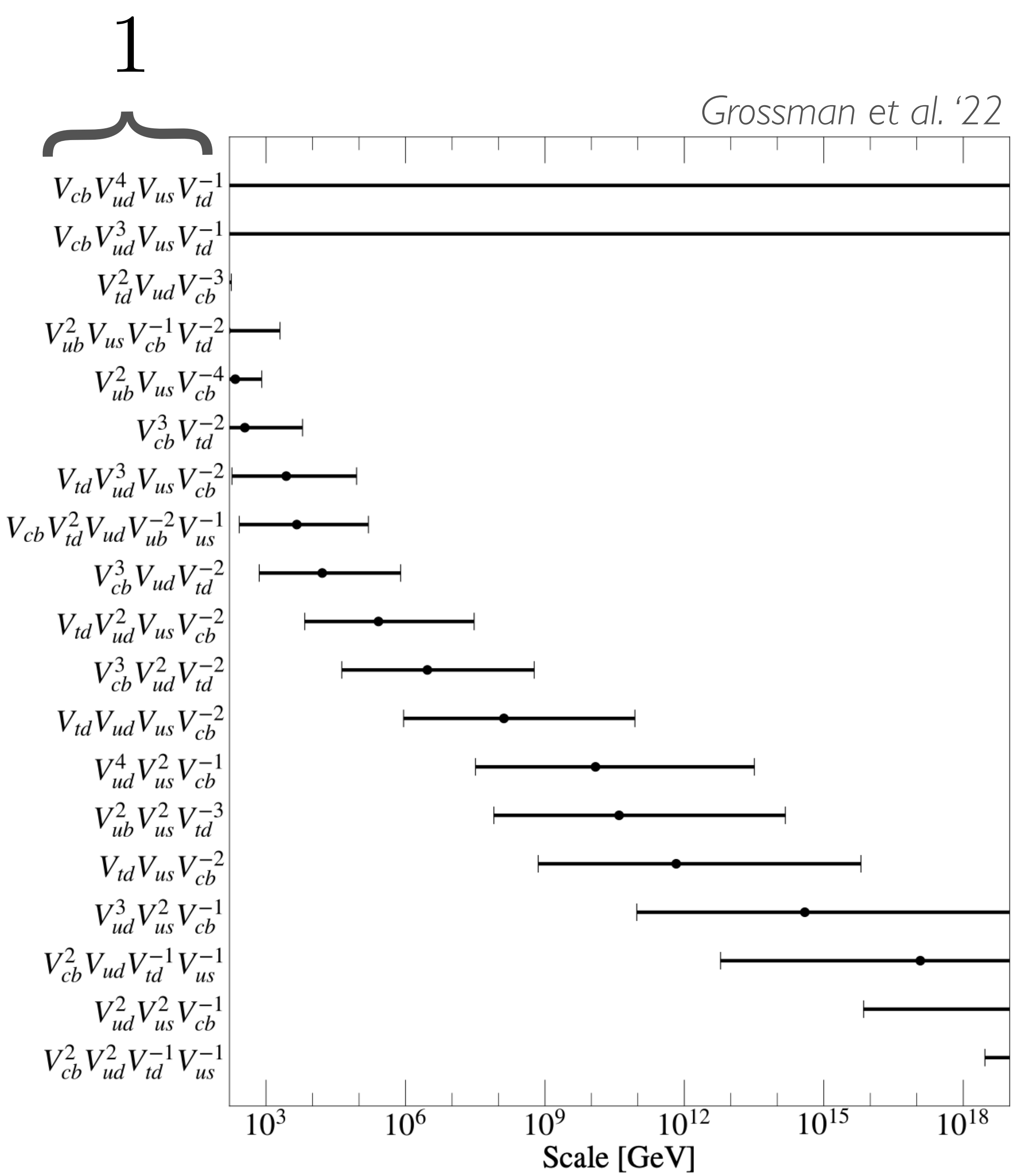
Grzadkowski et al '10
Alonso et al '13

699 Jarlskog-like invariants

Bonnefoy et al. '21

FLAVOR PUZZLE

Pattern in the CKM (besides Cabibbo hierarchy)?



Yukawa and CKM elements run

$|V_{td}V_{us}| = |V_{cb}^2|$ at scale $10^9 - 10^{15}\,\mathrm{GeV}$

Relation reproduced by

$$M_u = m_t \begin{pmatrix} 0 & x\lambda_u^3 & 0 \\ x\lambda_u^3 & x\lambda_u^2 & x\lambda_u \\ 0 & x\lambda_u & 1 \end{pmatrix}, \qquad M_d = m_b \begin{pmatrix} 0 & w\lambda_d^3 & 0 \\ w\lambda_d^3 & w\lambda_d^2 & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

What can we learn from this? Difficult to go beyond this texture.

FLAVOR PUZZLE

Minimal flavour violation (and variations) ~ embrace the fact that BSM flavour is aligned with the SM

Flavour violation is broken only by (higher powers of) Yukawa couplings

$$G_{\text{flavour}} = \begin{cases} SU(3)^5 \\ U(1)^5 \end{cases} \xrightarrow{Y_{e,u,d}\neq 0} \begin{matrix} U(1)_{e-\mu} \otimes U(1)_{\tau-\mu} \\ U(1)_B \otimes U(1)_L \otimes U(1)_Y \end{matrix}$$

$$Y_u \to U_q Y_u U_u^\dagger\,, \qquad Y_d \to U_q Y_d U_d^\dagger$$

reddit

"as flavour symmetric as the SM"

Chirality flipping SMEFT operators: Yukawa, dim-6 Yukawa, dipole operators

$$\frac{C^{rs}}{\Lambda^2}\,\bar{q}_r u_s \qquad \Rightarrow \qquad C^{rs} \sim Y_u^{rs} + \#(Y_u Y_u^\dagger Y_u)^{rs} + \cdots$$
$$+ \#(Y_d Y_d^\dagger Y_u)^{rs} + \cdots$$

D'Ambrosio et al '02

FLAVOR PUZZLE

Minimal flavour violation (and variations) ~ embrace the fact that BSM flavour is aligned with the SM

Reduced number of parameters.

SMEFT $\mathcal{O}(1)$ terms		Lepton sector															
(dim-6, $\Delta B = 0$)		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	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 even/odd

Greljo, Palavrić, Thomsen '22

see also Faroughy, Isidori, Wilsch, Yamamoto '21

Even in the full MFV case there are many new flavor and CPV effects waiting to be discovered.

Why not present already in hints of LFUV?

LEPTON FLAVOUR UNIVERSALITY AND CPV

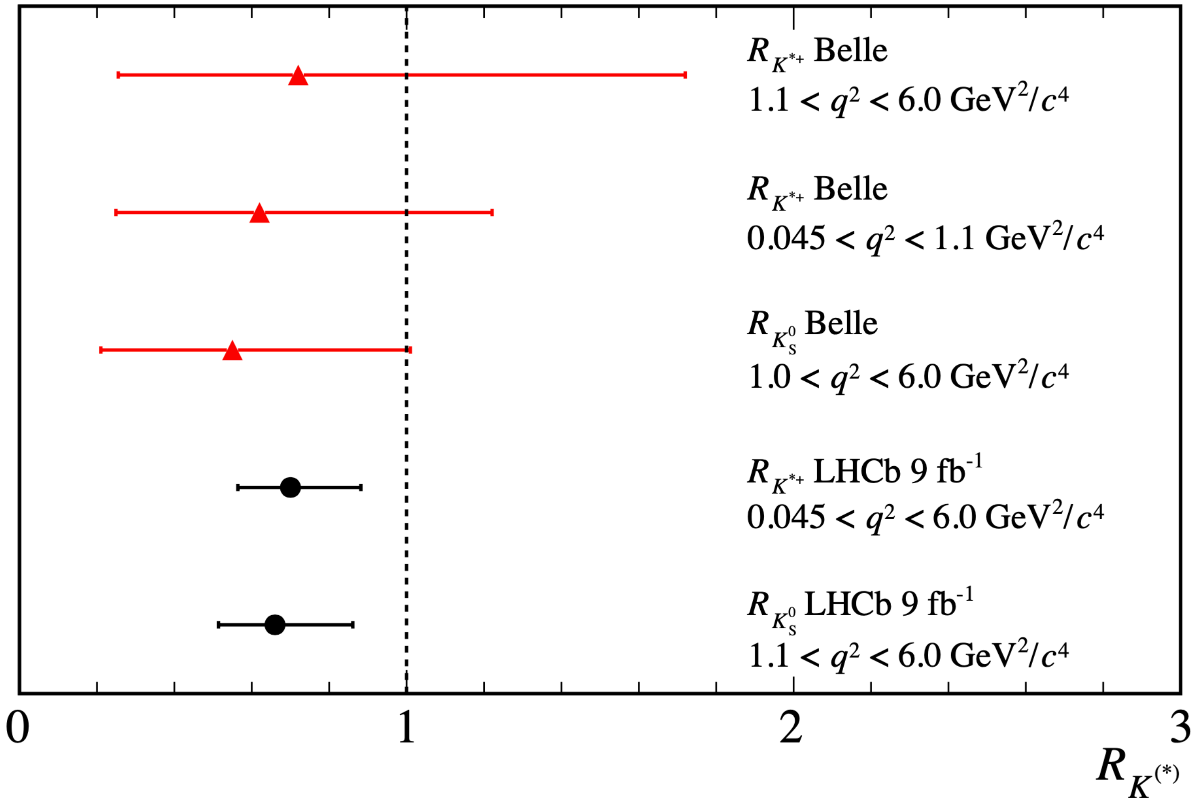
R_K

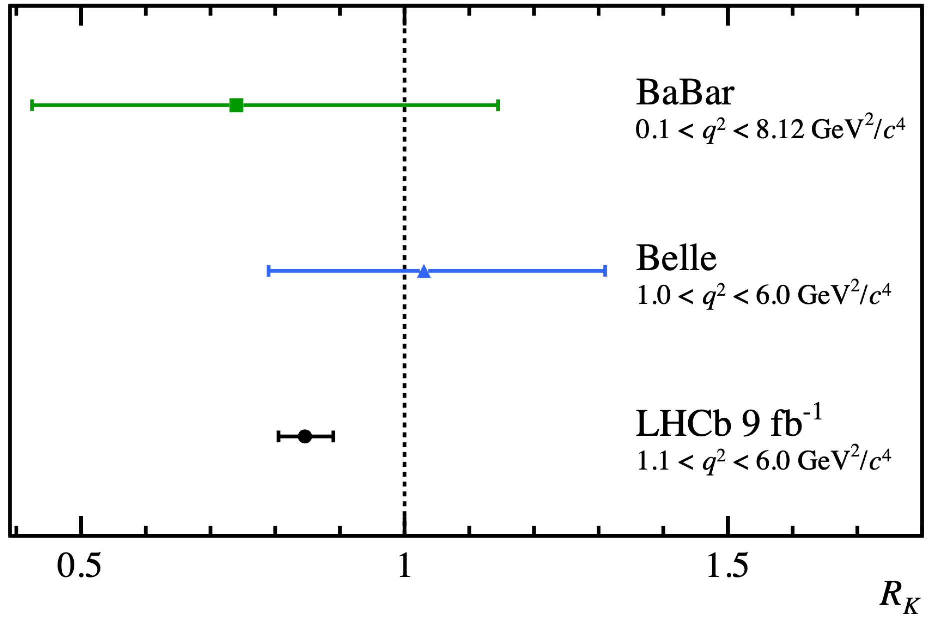
- Lepton flavour universality ratios (LFU) of b → sll

$$R_K = \left.\frac{\Gamma(B \to K\mu^+\mu^-)}{\Gamma(B \to K e^+ e^-)}\right|_{[q^2_{\rm min}, q^2_{\rm max}]}$$

$$R_K = 0.846^{+0.042}_{-0.039}\ (\text{stat.})\ {}^{+0.013}_{-0.012}\ (\text{syst.})$$

$$R_K^{\rm SM} = 1.00 \pm 0.01$$





D. Lancierini@Moriond '22

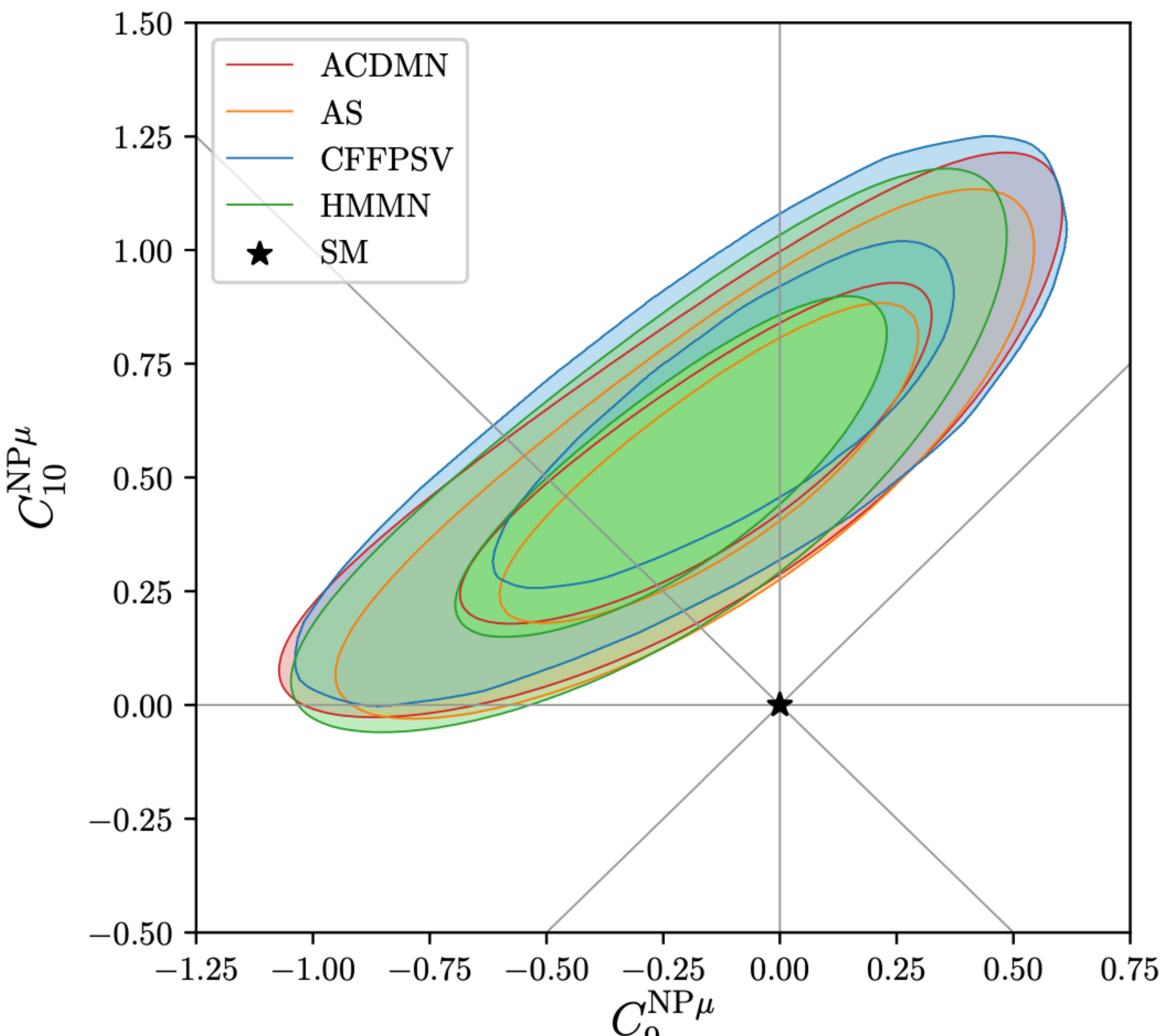
R_K

R_K is a ratio of CP-averaged rates

$$\mathcal{O}_{9(10)} = \frac{e^2}{(4\pi)^2}(\bar{s}_L\gamma_\nu b_L)(\bar{\mu}\gamma^\nu(\gamma^5)\mu)$$

SM amplitude is ~ CP even ($V_{tb} V_{ts}^*$)

$$|\mathcal{A}_{\rm SM}+\mathcal{A}_{\rm NP}|^2 + |\mathcal{A}_{\rm SM}+\mathcal{A}^*_{\rm NP}|^2 \quad \propto \quad |\mathcal{A}_{\rm SM}|^2 + |\mathcal{A}_{\rm NP}|^2 + 2\Re(\mathcal{A}_{\rm SM}(\mathcal{A}^*_{\rm NP}+\mathcal{A}_{\rm NP}))$$



LFUV fit

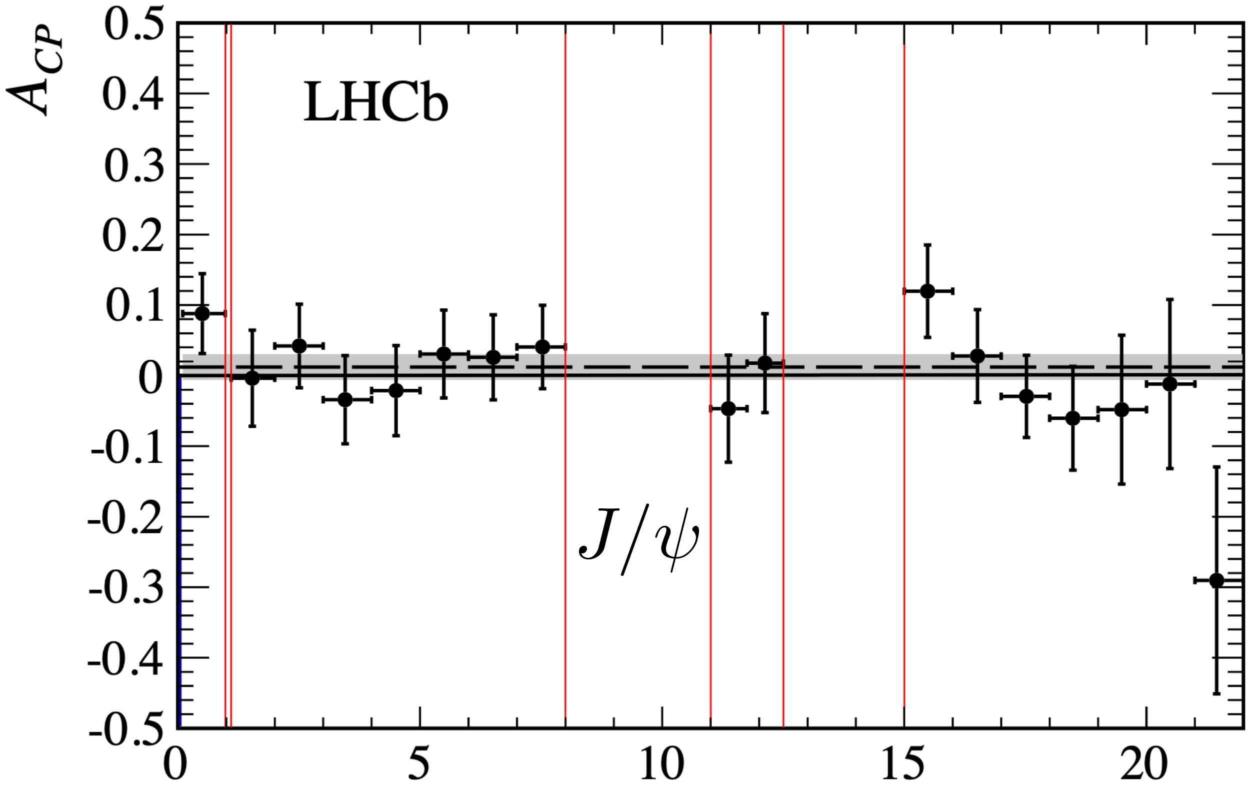
Consider $\delta C_9 = -\delta C_{10}$:

$$R_K = 1.00 + 0.48\,\mathrm{Re}(\delta C_9) - 8.3\times 10^{-3}\,\mathrm{Im}(\delta C_9) + 0.057\,|\delta C_9|^2$$

Insensitive to New Physics CPV phases

Marco Fedele, Tuesday

R_K: DIRECT ASYMMETRIES

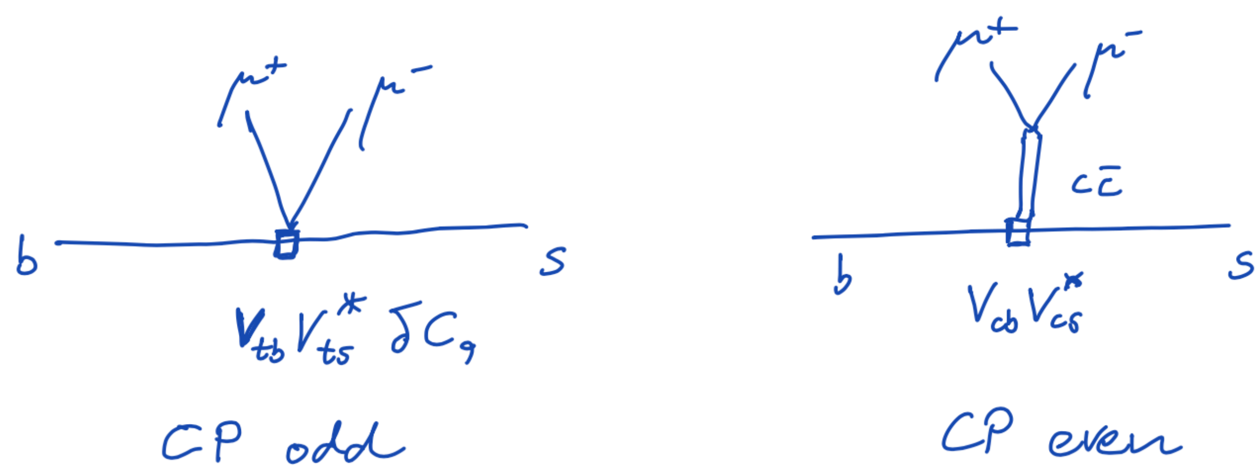


LHCb '14

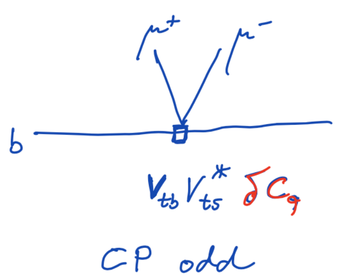
$$\mathcal{A}_{\rm CP}^{K^{(*)}} = \frac{\mathcal{B}(\overline{B} \to \overline{K}^{(*)}\mu\mu) - \mathcal{B}(B \to K^{(*)}\mu\mu)}{\mathcal{B}(\overline{B} \to \overline{K}^{(*)}\mu\mu) + \mathcal{B}(B \to K^{(*)}\mu\mu)}$$

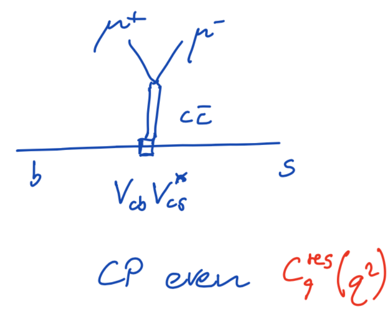
$$\mathcal{A}_{\rm CP}^{K^+} = 0.012(17)(1)$$

Interfering amplitudes with strong and weak phases difference?



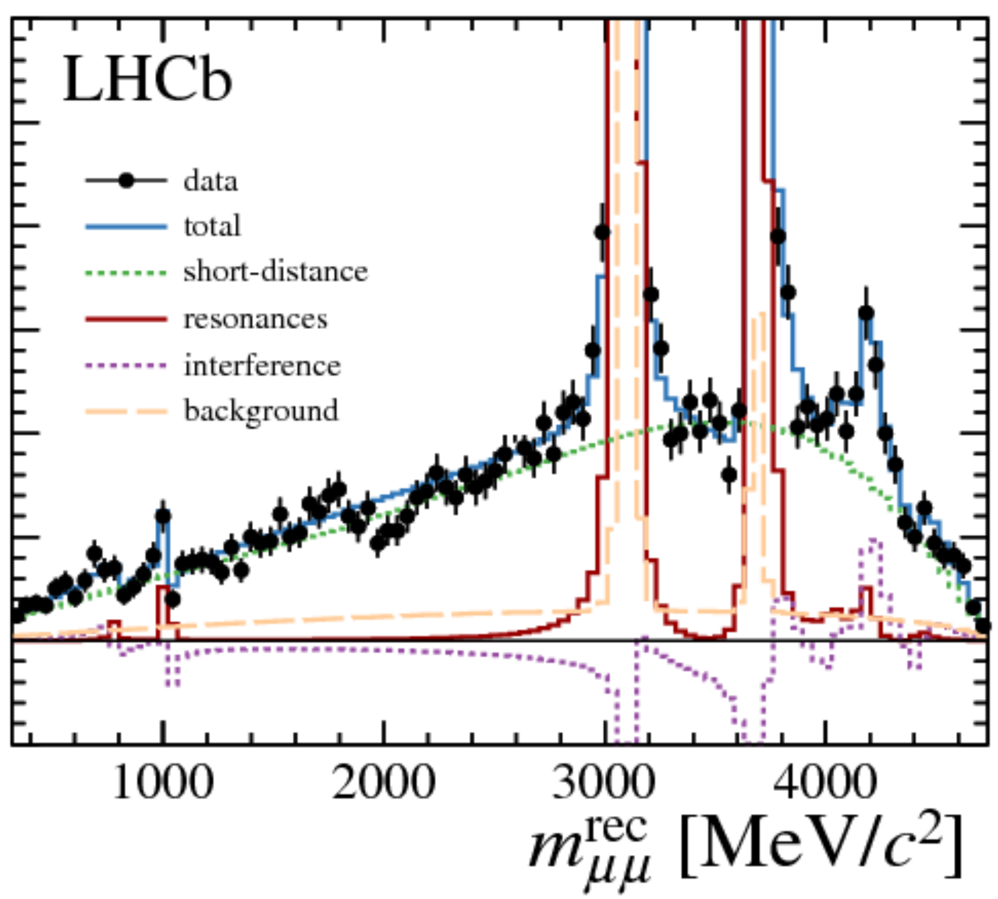
R_K: STRONG PHASE





$$C_9^{\rm res}(q^2) \approx \frac{m_j \Gamma_j \eta_j e^{i\delta_j}}{m_j^2 - q^2 - i m_j \Gamma_j}$$

δ_j : extract from CP-averaged non-blinded spectrum



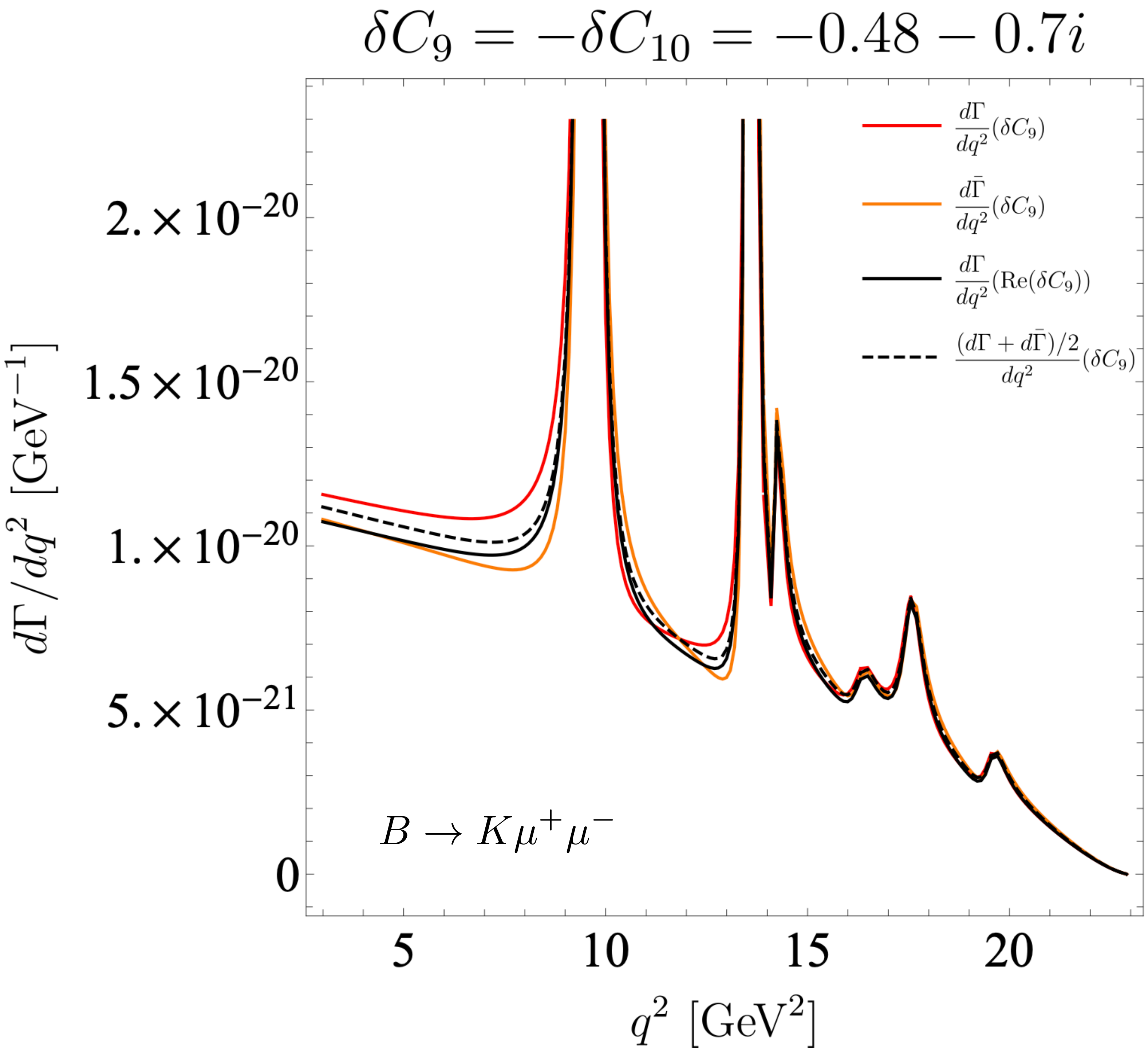
4-fold degeneracy of fit to the spectrum:

$$\text{Branch 1:} \quad \delta_{J/\psi} = -1.66\,, \quad \delta_{\psi(2S)} = -1.93\,,$$
$$\text{Branch 2:} \quad \delta_{J/\psi} = -1.50\,, \quad \delta_{\psi(2S)} = 2.08\,.$$

Branch 3,4 ~ Branch 1,2

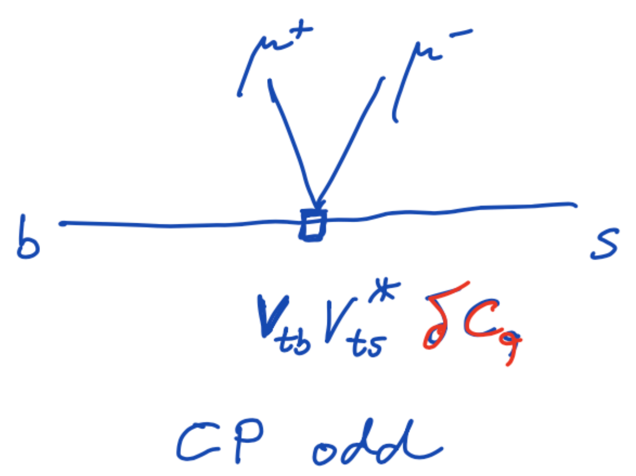
LHCb '16
see also Blake, Egede, Owen, Petridis, Pomery '17

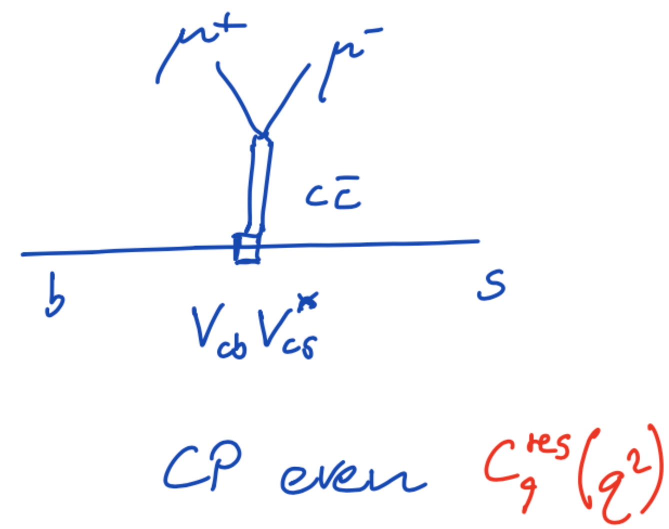
NO CP VS. CP-AVERAGE



Resonant parameters taken from the LHCb fit to CP averaged rates.

R_K: DIRECT ASYMMETRIES



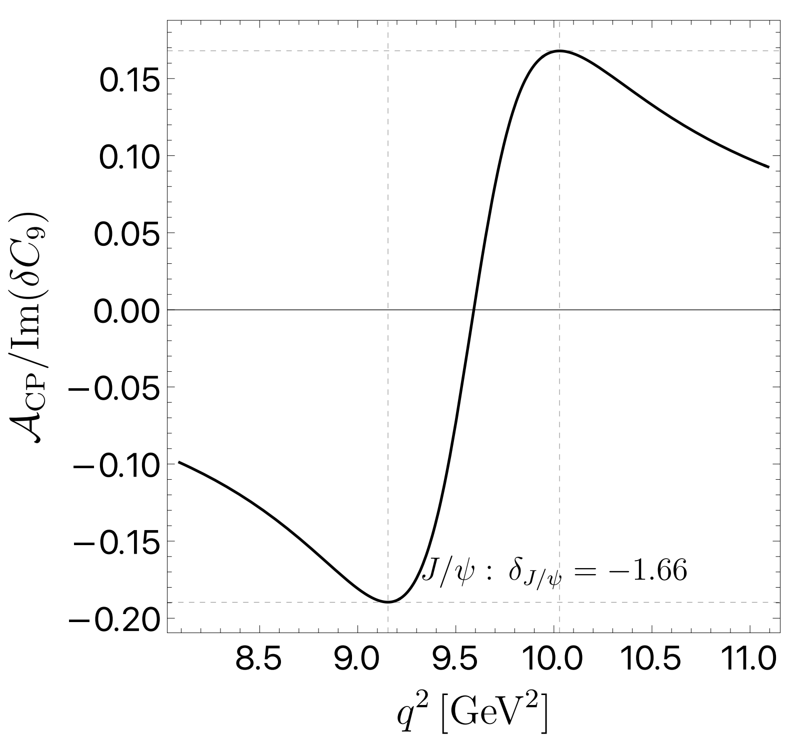


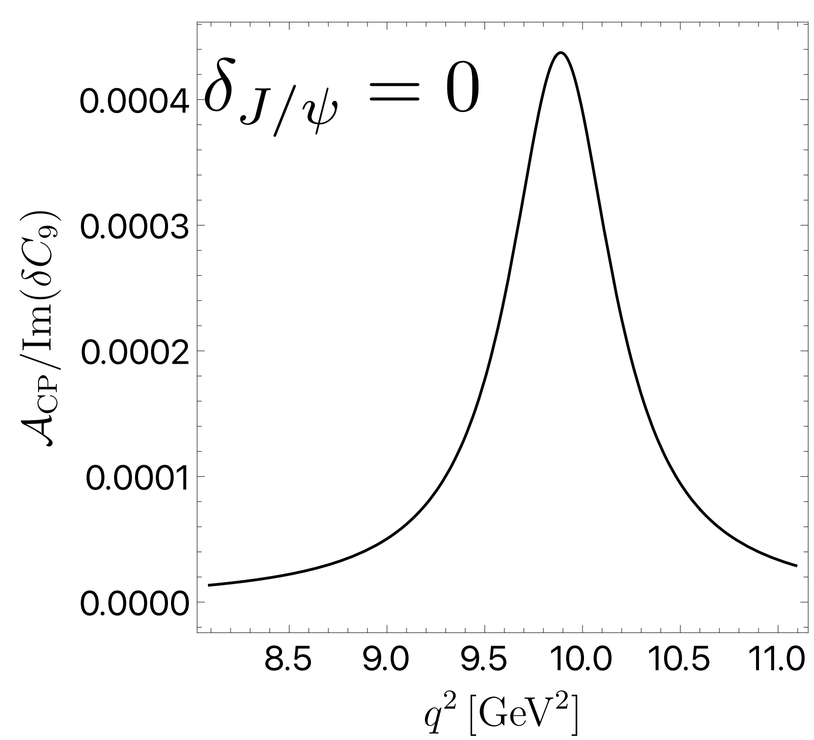
$$C_9^{\mathrm{res}}(q^2) \approx \frac{m_j \Gamma_j \eta_j e^{i\delta_j}}{m_j^2 - q^2 - i m_j \Gamma_j}$$

$$\mathcal{A}_{\mathrm{CP}} = \mathrm{Im}(\delta C_9) \frac{2\eta_j \left(\cos\delta_j - x \sin\delta_j\right)}{\eta_j^2 - 2\eta_j B \left[\sin\delta_j + x\cos\delta_j\right] + A\left[1 + x^2\right]}$$

$$x \equiv (q^2 - m_j^2)/(m_j \Gamma_j)$$

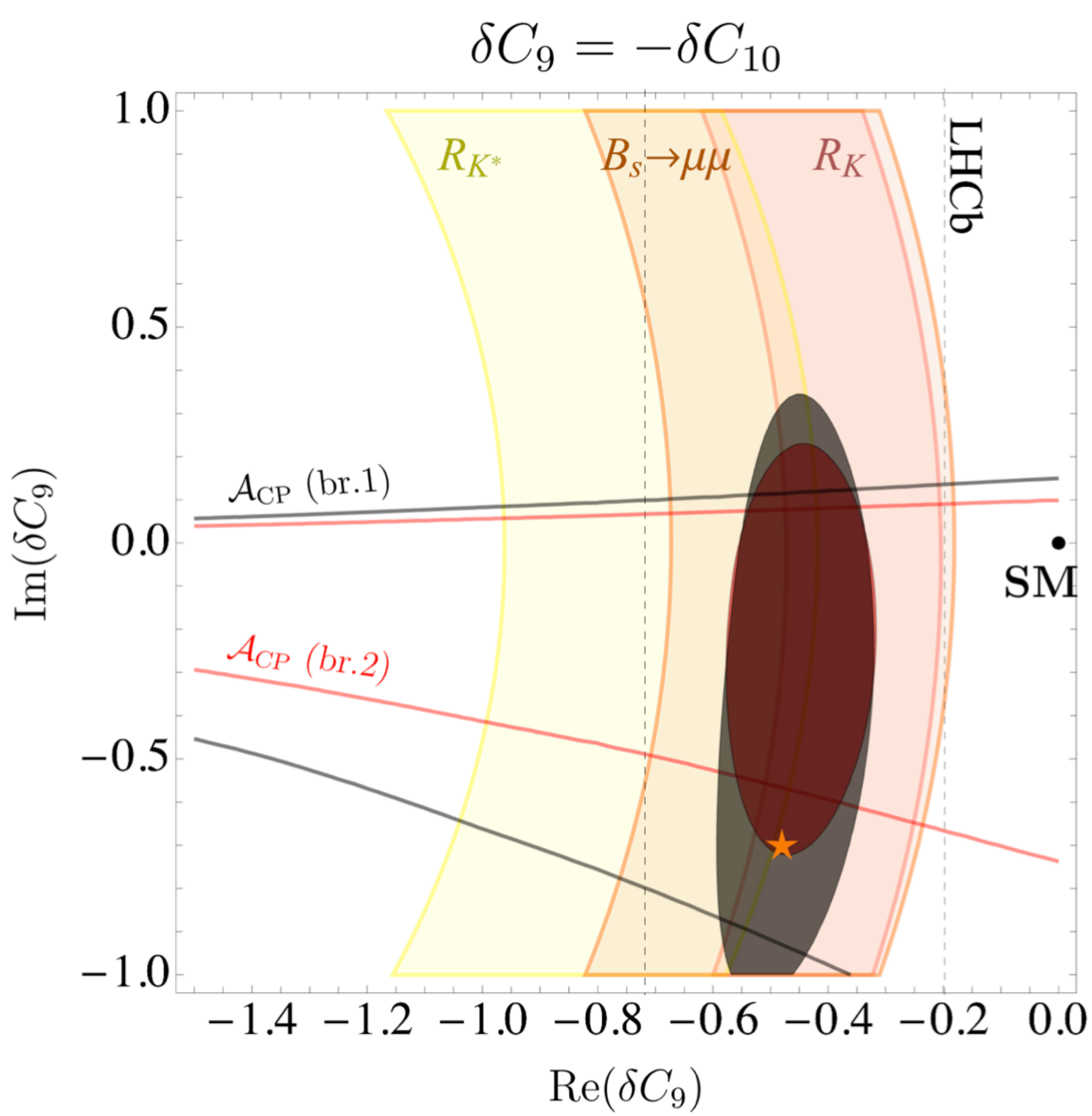
Input: off-peak strong phase δ_j





Sensitive to CPV in δC_9

R_K AND DIRECT CPV

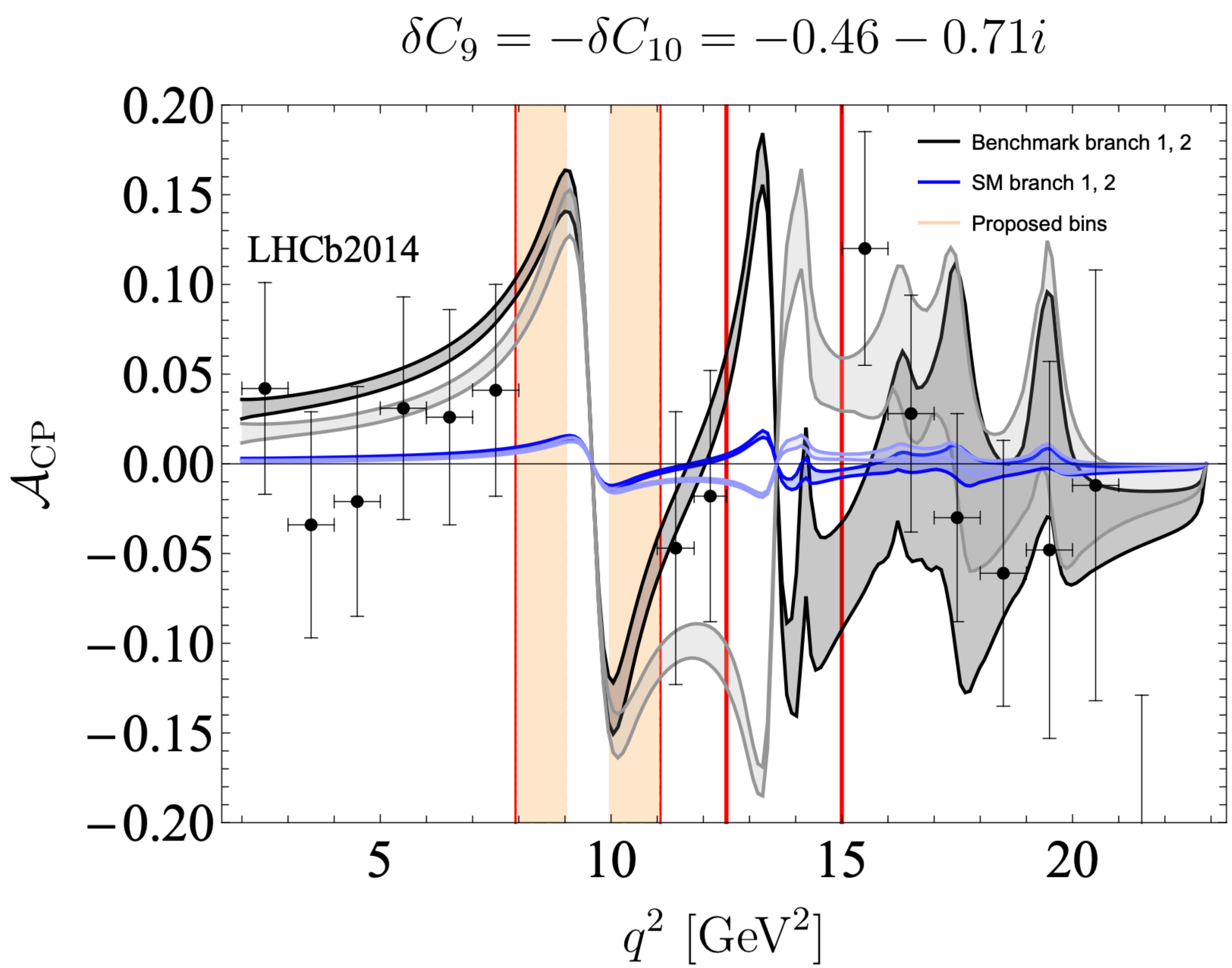


Orthogonality of constraints

- R_K and Br(Bs → $\mu\mu$)
- A_{CP} (2-8 GeV^2)

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

R_K AND DIRECT CPV



A. Smolkovic thesis'21
Becirevic et al, '20

Interesting region to look for direct CPV

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

$$\Delta\mathcal{A}_{\rm CP} = \frac{0.0108(2) - 0.139(3)\,{\rm Im}(\delta C_9)}{1 + 0.414(5)\,{\rm Re}(\delta C_9) - 0.0082(1)\,{\rm Im}(\delta C_9) + 0.054(1)\,|\delta C_9|^2}$$

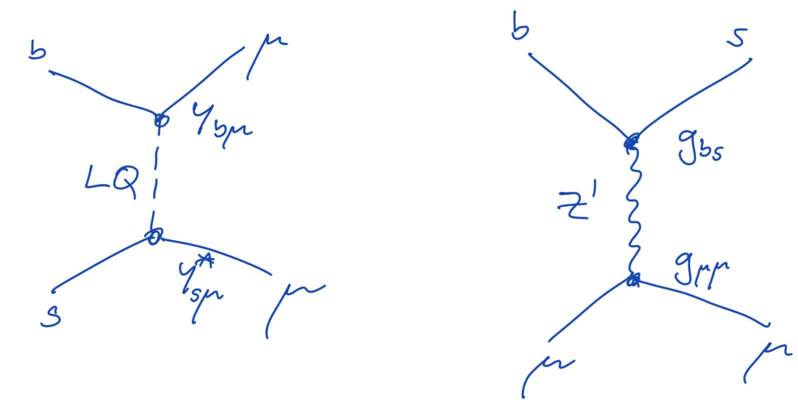
NK, A.Smolkovic, '21
for other CPV constraints see also
Descotes-Genon, Novoa-Brunet, Vos '20
Carvunis, Dettori, Gangal, Guadagnoli, Normand '21

MODEL DEPENDENT CP-SENSITIVE OBSERVABLES

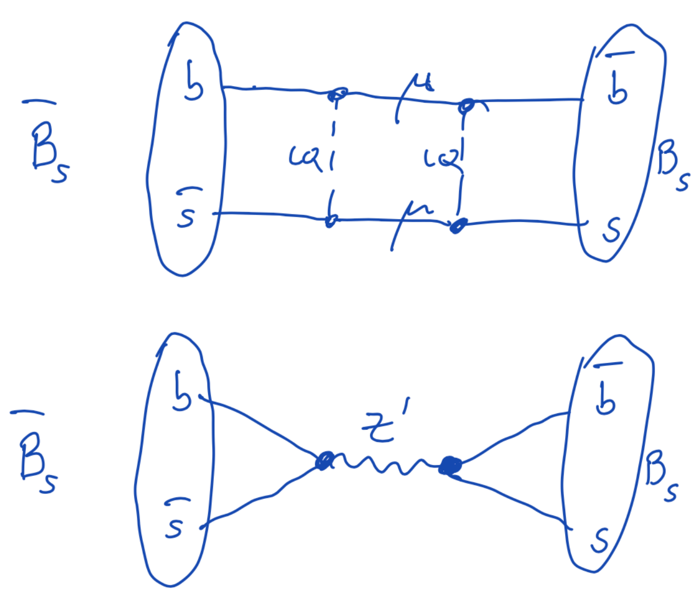
MODELS AND PREDICTIVITY

- Tree-level leptoquark or Z' models can explain $R_K^{(*)}$
- SMEFT operators

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



- LQ contrib. is correlated to small effect in ΔB=2
- Z' models allow for more tuning



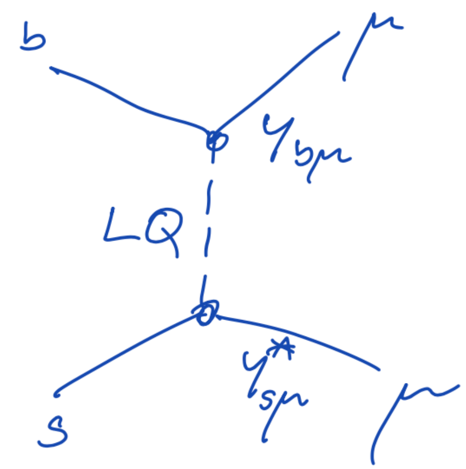
$$\sim (\delta C_9)^2 \frac{m_{LQ}^2}{(4\pi)^2}$$

$$\sim |g_{bs}|^2 / m_{Z'}^2$$

S_3 LEPTOQUARK

- SMEFT semileptonic operators leading to $\delta C_9 = -\delta C_{10}$

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



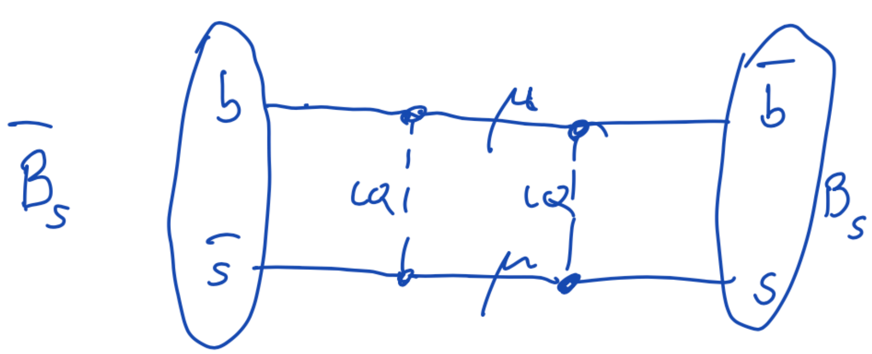
$$S_3 = (\bar{3}, 3)_{1/3}$$

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

- ΔB=2

$$Q_{qq}^{(1)} = (\bar{Q}_p \gamma^\mu Q_r)(\bar{Q}_s \gamma_\mu Q_t),$$
$$Q_{qq}^{(3)} = (\bar{Q}_p \gamma^\mu \tau^I Q_r)(\bar{Q}_s \gamma_\mu \tau^I Q_t)$$

$$C_{qq}^{(1)} = -\frac{9 (y_{b\mu} y_{s\mu}^*)^2}{256 \pi^2 m_{S_3}^2}, \qquad C_{qq}^{(3)} = -\frac{(y_{b\mu} y_{s\mu}^*)^2}{256 \pi^2 m_{S_3}^2}$$



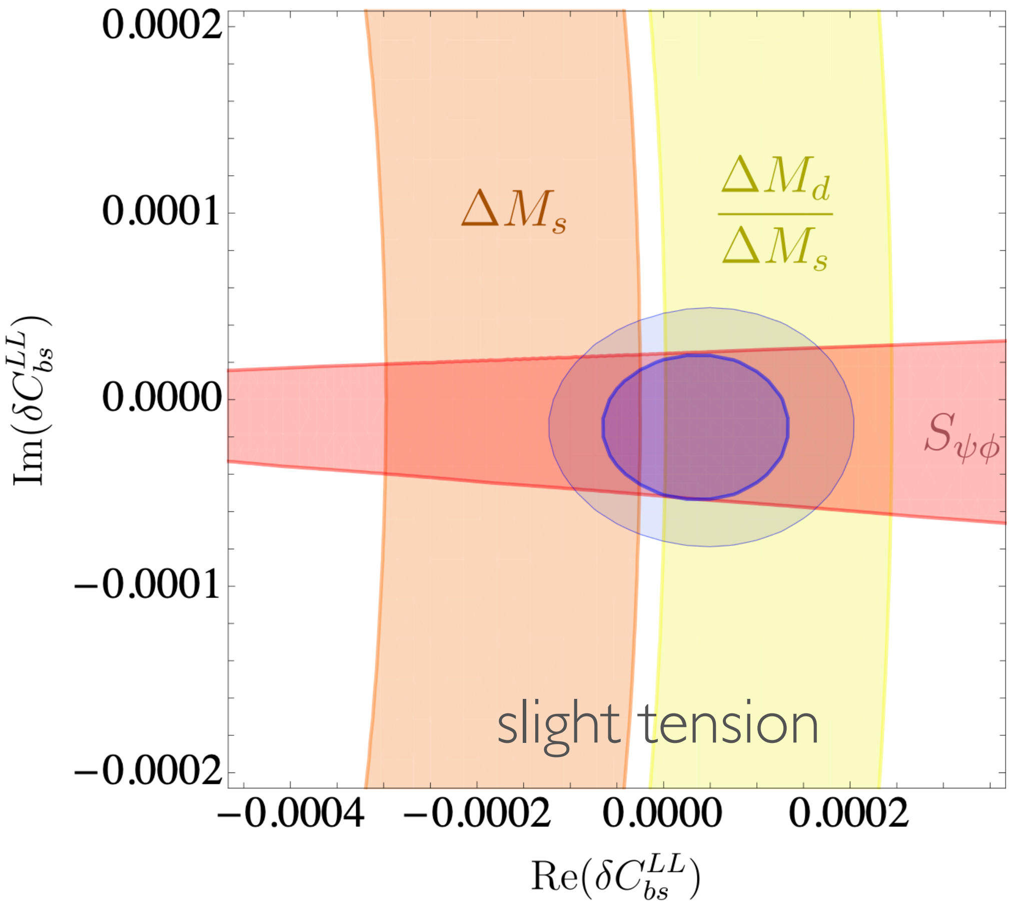
CP(V) effect in Δm_s and $S_{\psi\varphi}$?

S_3 LEPTOQUARK AND ΔB=2

- left-left currents

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

- $$\delta C_{bs}^{LL}(\mu = m_b) = \eta^{6/23}\frac{5(y_{b\mu}y_{s\mu}^*)^2}{256\sqrt{2}\pi^2 m_{S_3}^2 G_F (V_{tb}V_{ts}^*)^2} \qquad \sim (\delta C_9)^2 m_{S_3}^2$$



$$\Delta M_s^{\mathrm{SM}} = \frac{4\sqrt{2}}{3} G_F m_{B_s} C_{bs}^{LL(\mathrm{SM})} |V_{tb}V_{ts}^*|^2 \,(f_{B_s}\sqrt{B_{B_s}})^2$$

$$\left(\frac{\Delta M_d}{\Delta M_s}\right)^{\mathrm{SM}} = \frac{1}{\xi^2}\left|\frac{V_{td}}{V_{ts}}\right|^2 \frac{M_{B_d}}{M_{B_s}} = 0.0311^{+0.0018}_{-0.0017}$$

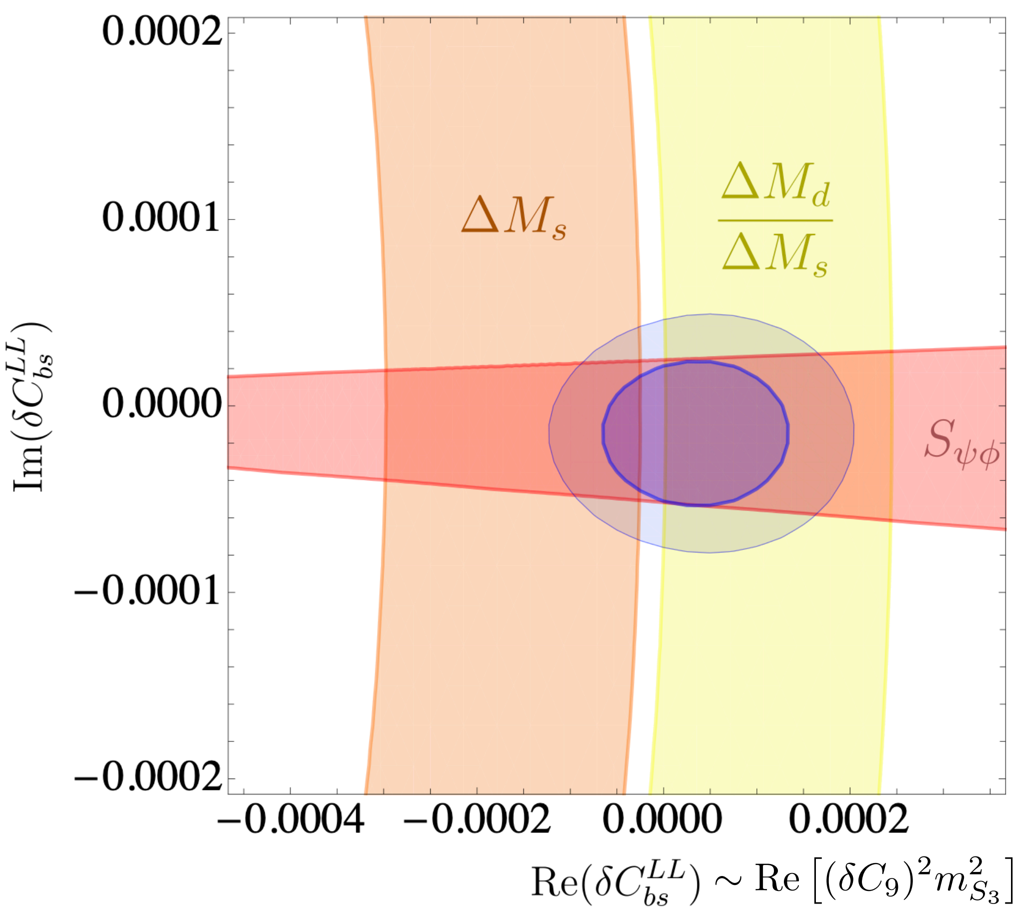
$$S_{\psi\phi} \equiv \sin(-2\beta_s + \delta\phi),$$

$$\delta\phi = \mathrm{Arg}\left(1 + \frac{\delta C_{bs}^{LL}(m_b)}{C_{bs}^{LL(\mathrm{SM})}(m_b)}\right)$$

Huge thanks to
FLAG lattice averaging group
HFLAV
and those contributing

S_3 LEPTOQUARK AND ΔB=2

$$\delta C_{bs}^{LL}(\mu = m_b) = \eta^{6/23} \frac{5(y_{b\mu} y_{s\mu}^*)^2}{256\sqrt{2}\pi^2 m_{S_3}^2 G_F (V_{tb} V_{ts}^*)^2} \sim (\delta C_9)^2 m_{S_3}^2$$



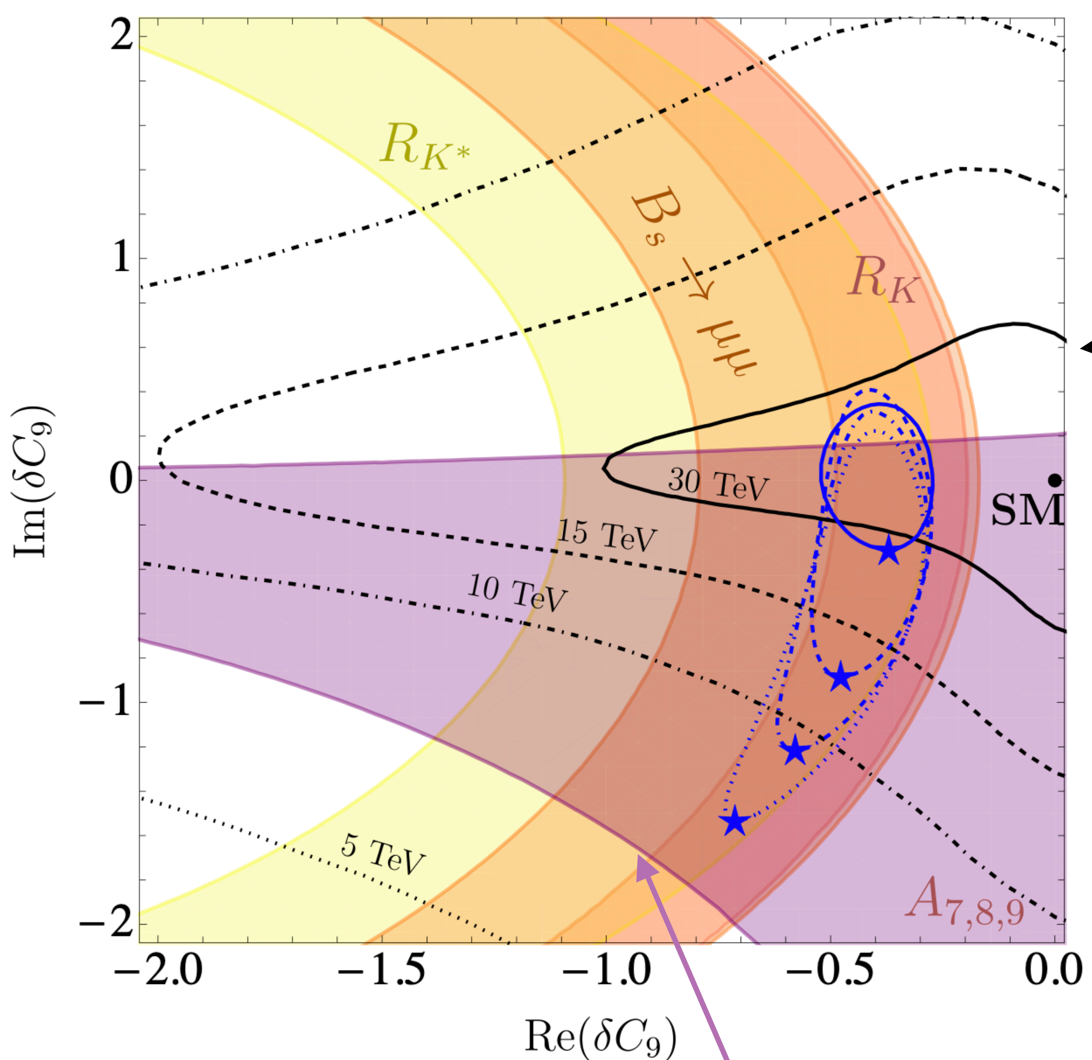
$\Delta M_s < \Delta M_s^{\mathrm{SM}}$ requires Im(δC9) !

$S_{\psi\varphi}$ is sensitive to Re(δC9) Im(δC9)

NK, A. Smolkovic '21
see also Di Luzio, Kirk, Lenz, Rauh '19

S_3 : PUTTING IT TOGETHER

Black contours from $\Delta B=2$

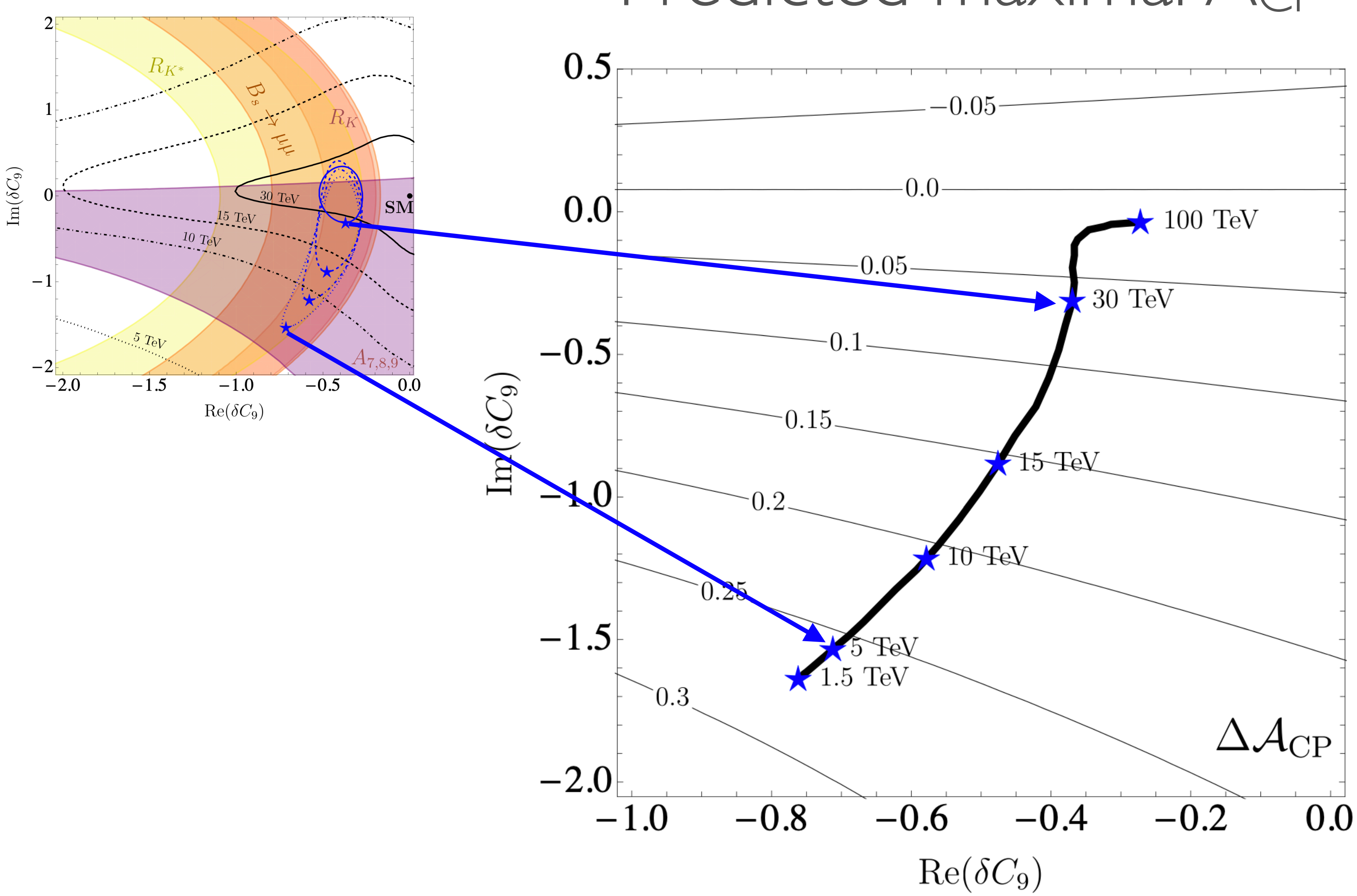


Δm_s and $S_{\psi\varphi}$

Angular CP asymmetries in B → K*μμ *(provided by* flavio *)*

S_3 : PUTTING IT TOGETHER

Predicted maximal A_{CP}



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

SUMMARY AND CONCLUSIONS

- There are strong hints of NP in lepton flavour universality ratios.
- These observables are insensitive to CP.
- If this is indeed a NP effect CPV should be probed.
- The proposal is to measure potentially large CPV around J/ψ.
- LQ model: large effects possible with small LQ mass.
- CPV effects also possible for $R_{D^{(*)}}$, R_2 leptoquark solution entails CPV.
- Testable in high-pT angular correlations/asymmetries.

Thanks!