B meson anomalies and large $B^+ \to K^+ \nu \bar{\nu}$ in nonuniversal U(1)′ models

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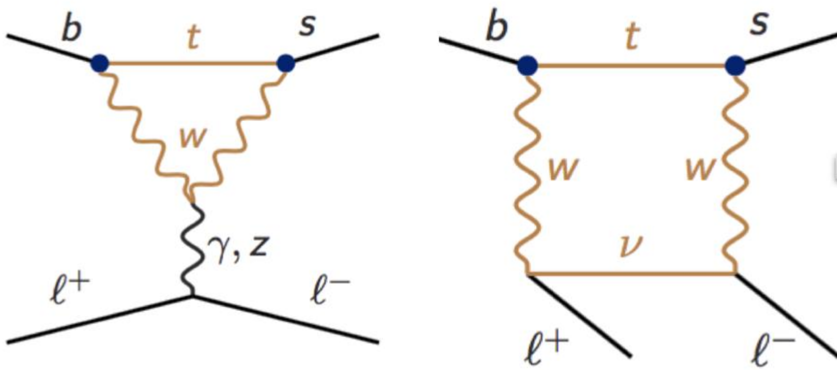
Based on Peter Athron, R. Martinez, **CS,** arXiv: 2308.13426 [hep-ph]

B meson semileptonic decays in the SM



e.g., $B \to K^{(*)}\mu^+\mu^-$

Top quark contribution dominates

Most general dim-6 effective Hamiltonian

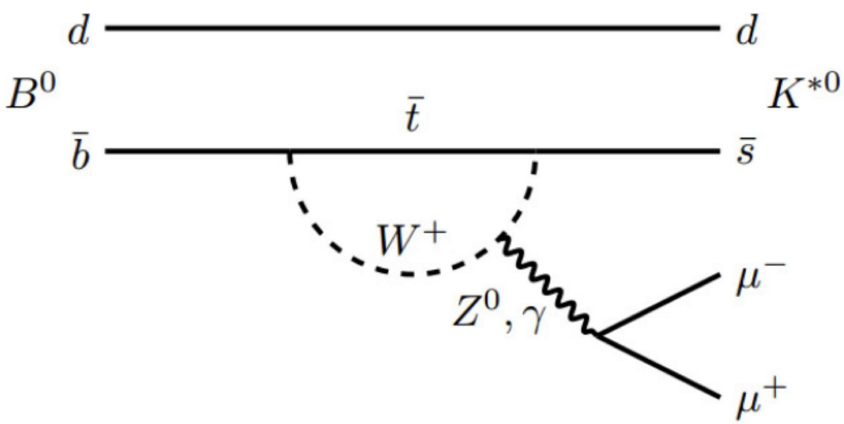
$$\mathcal{H}_{\rm eff} = -\frac{4\,G_F}{\sqrt{2}}\left(\lambda_t \mathcal{H}_{\rm eff}^{(t)} + \lambda_u \mathcal{H}_{\rm eff}^{(u)}\right) \qquad \lambda_i = V_{ib}V_{is}^*$$

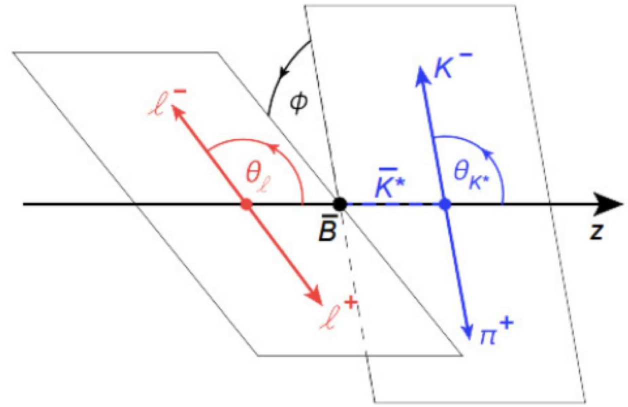
$$\mathcal{H}_{\rm eff}^{(t)} = C_1 Q_1^c + C_2 Q_2^c + \sum_{i=3}^{6} C_i Q_i + \sum_{i=7,8,9,10,P,S} (C_i Q_i + C_i' Q_i'),$$

$$\mathcal{H}_{\rm eff}^{(u)} = C_1 (Q_1^c - Q_1^u) + C_2 (Q_2^c - Q_2^u).$$

Credit: Rusa Mandal at
2023 Belle II Physics Week

Important observables: B meson semilep. decays





Decay fully described by three helicity angles $\vec{\Omega} = (\theta_\ell, \theta_K, \phi)$ and $q^2 = m^2_{\mu\mu}$

$$\frac{1}{\mathrm{d}(\Gamma+\bar{\Gamma})/\mathrm{d}q^2}\frac{\mathrm{d}^3(\Gamma+\bar{\Gamma})}{\mathrm{d}\vec{\Omega}} = \frac{9}{32\pi}\Big[\tfrac{3}{4}(1-F_{\mathrm{L}})\sin^2\theta_K + F_{\mathrm{L}}\cos^2\theta_K + \tfrac{1}{4}(1-F_{\mathrm{L}})\sin^2\theta_K\cos 2\theta_\ell$$
$$- F_{\mathrm{L}}\cos^2\theta_K\cos 2\theta_\ell + S_3\sin^2\theta_K\sin^2\theta_\ell\cos 2\phi$$
$$+ S_4\sin 2\theta_K\sin 2\theta_\ell\cos\phi + S_5\sin 2\theta_K\sin\theta_\ell\cos\phi$$
$$+ \tfrac{4}{3}A_{\mathrm{FB}}\sin^2\theta_K\cos\theta_\ell + S_7\sin 2\theta_K\sin\theta_\ell\sin\phi$$
$$+ S_8\sin 2\theta_K\sin 2\theta_\ell\sin\phi + S_9\sin^2\theta_K\sin^2\theta_\ell\sin 2\phi\Big]$$

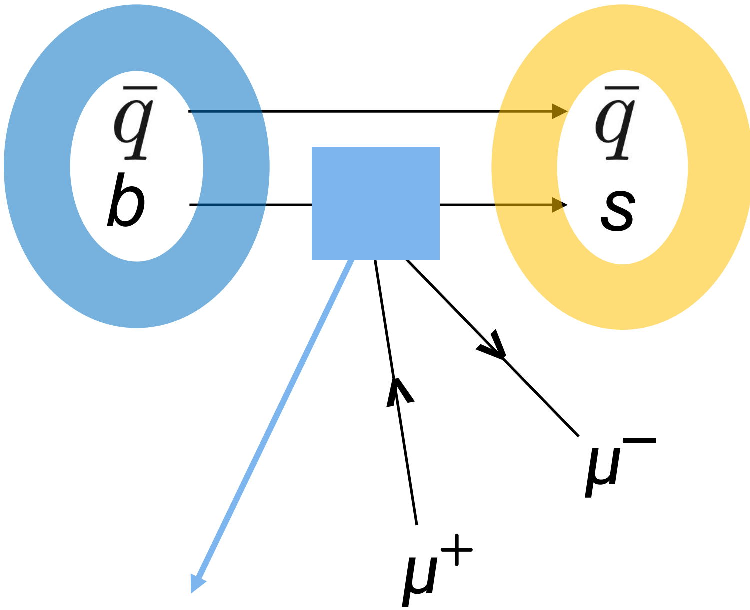
$$\boxed{P_5' = \frac{S_5}{\sqrt{F_{\mathrm{L}}(1-F_{\mathrm{L}})}}}$$

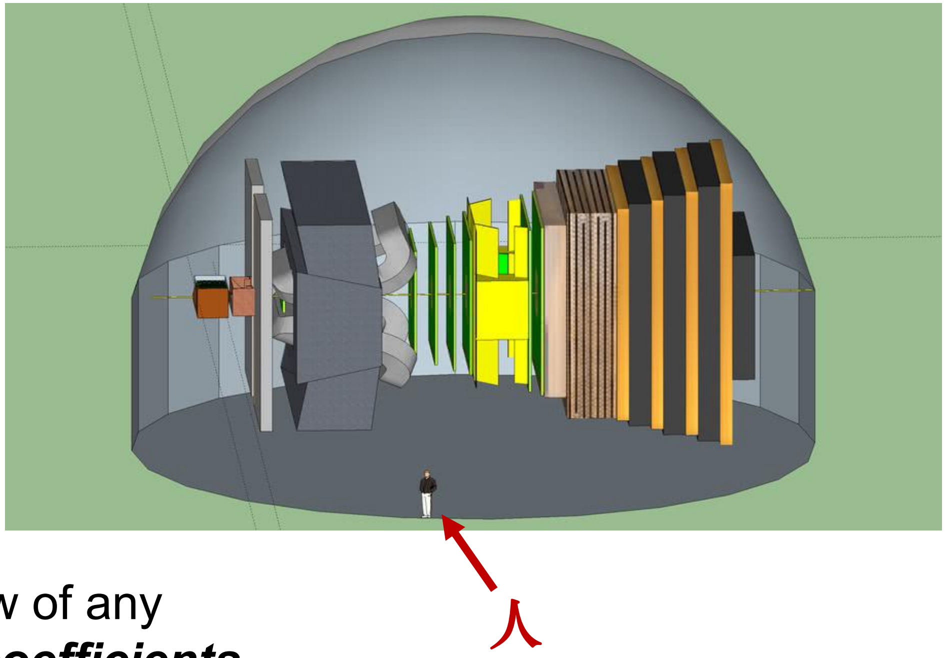
Credit: C. Langenbruch
at Moriond EW 2023

B meson semileptonic decays at the LHC

Most precise measurements related to b->smumu decays come from the LHCb detector

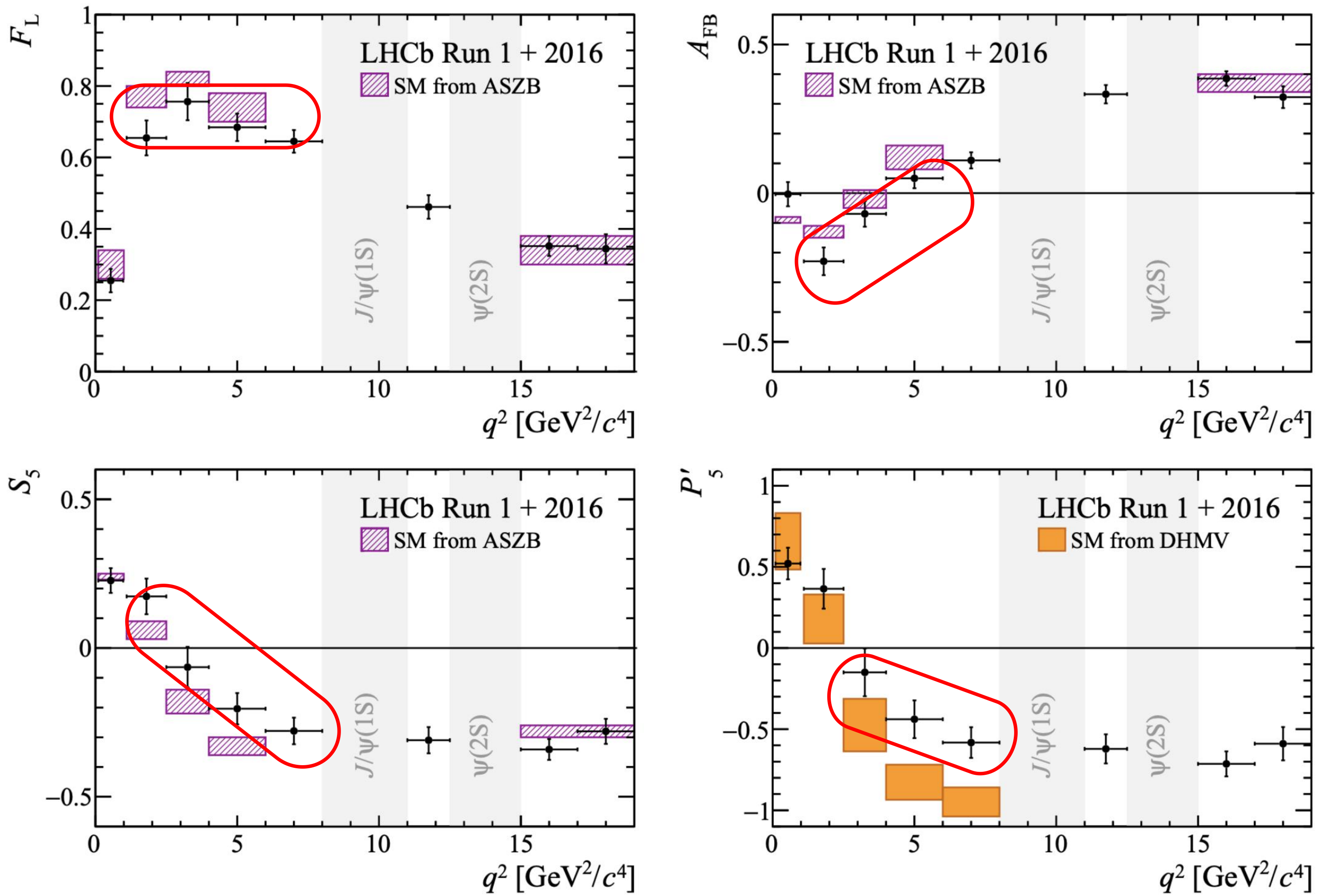
$$B \to K^{(*)}\mu^+\mu^-$$





Explanations from the NP point of view of any anomaly will be via effective ***Wilson coefficients***

Anomalies in B meson semileptonic decays

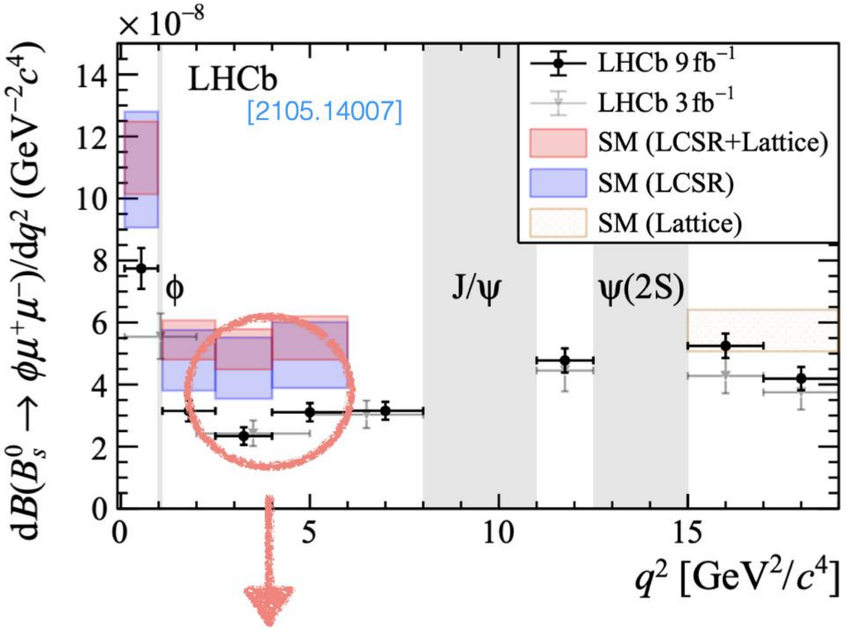


~3σ deviation

Anomalies in B meson semileptonic decays

Same WCs appear in other channels with same partonic level transition

$$B_s \to \phi\mu^+\mu^- : \; C_{7,9,10}$$



Tension in differential distribution $\sim 2\sigma$

$$B_s \to \mu^+\mu^- : C_{10}$$

$$\mathcal{B}^{\mathrm{Av.}}_{B_s\to\mu^+\mu^-} = (3.52^{+0.32}_{-0.30}) \times 10^{-9}$$

$$\mathcal{B}(\mathrm{B}^0_\mathrm{s} \to \mu^+\mu^-) = (3.66 \pm 0.14) \times 10^{-9}$$

Tension in BR $\sim 2\sigma$

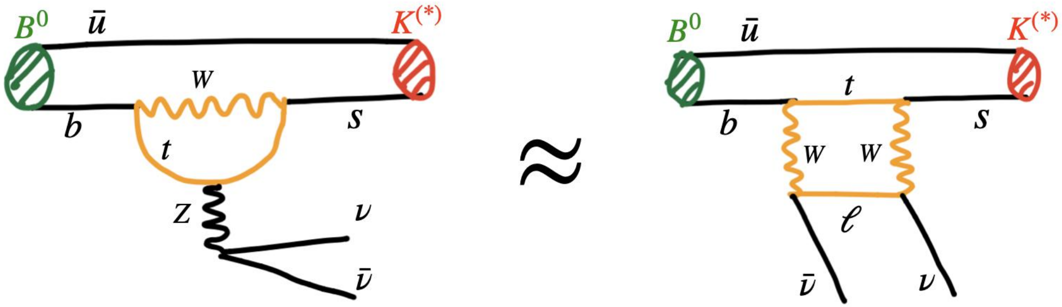
Also measured by CMS and ATLAS.

Any modification to WCs has to be consistent with other channels

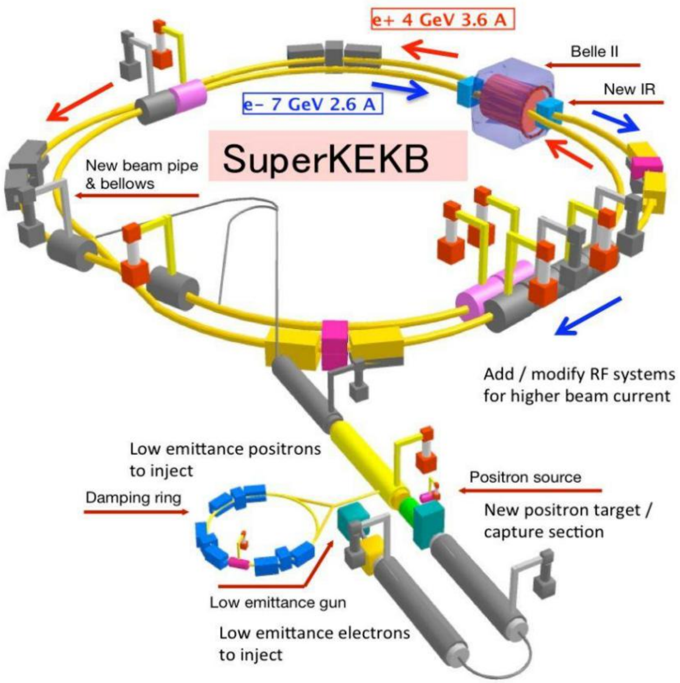
Credit: Rusa Mandal at 2023 Belle II Physics Week

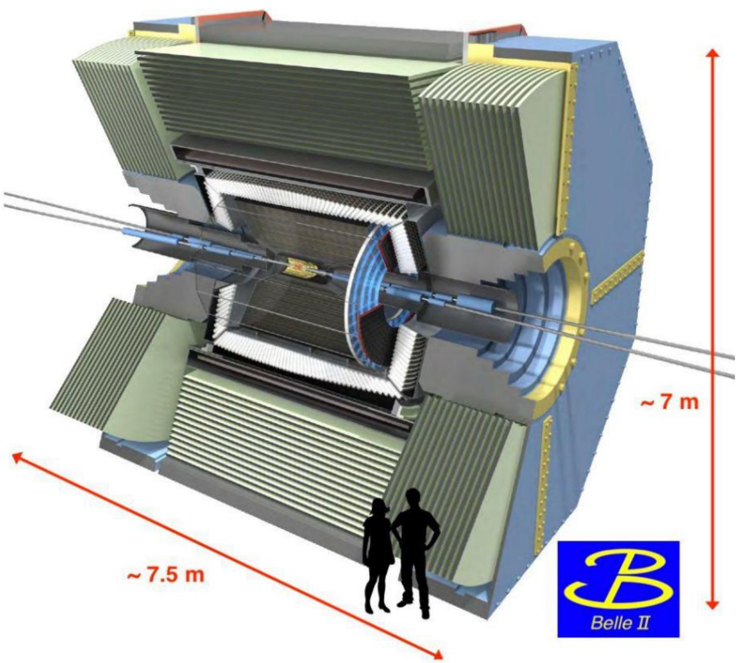
New data: Belle II measurement

Mode with same quarks but charged leptons → Neutrinos



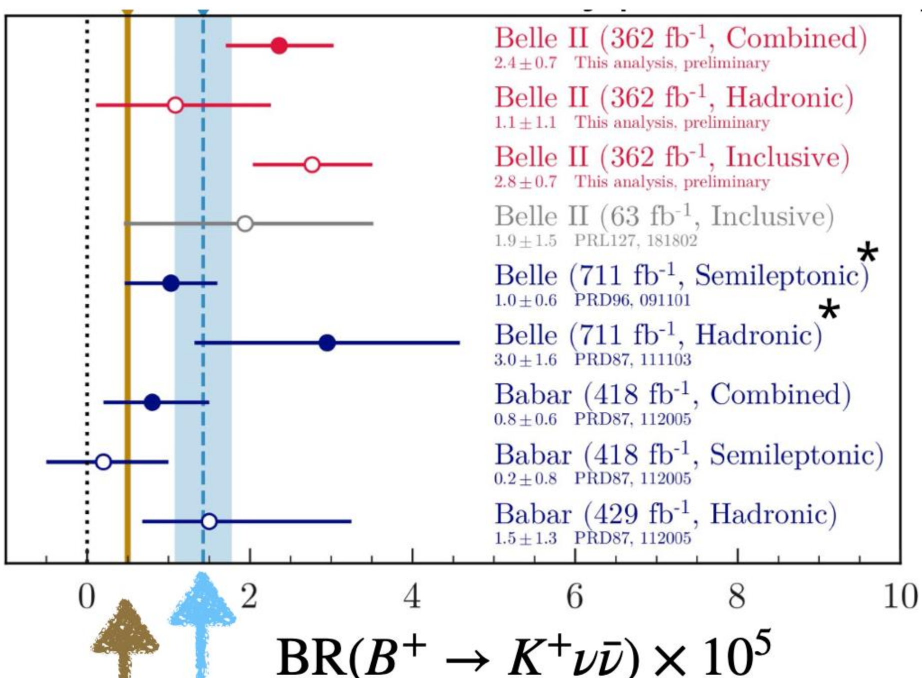
This is me!

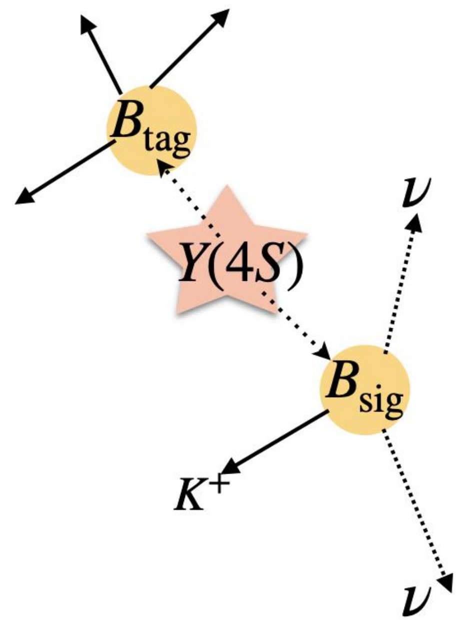




New data: Belle II measurement

- Inclusive tagging technique from Belle II has higher efficiency~4%



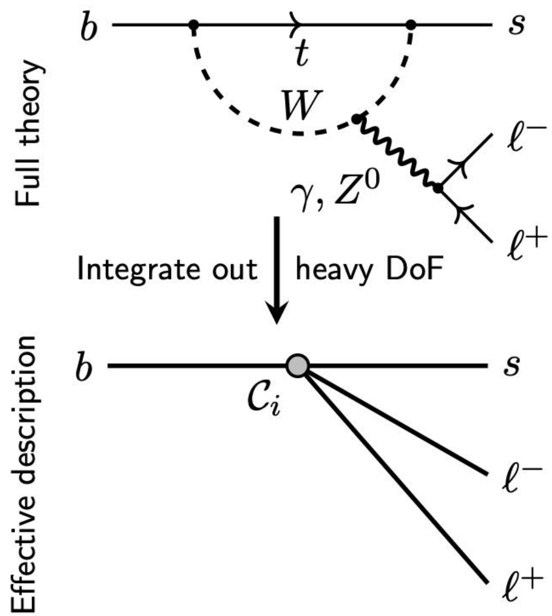


$$\left.\begin{array}{l}\mathrm{Exp}_{\mathrm{avg}} = (2.4 \pm 0.7) \times 10^{-5} \\ \mathrm{SM} = (4.6 \pm 0.5) \times 10^{-6}\end{array}\right\}$$

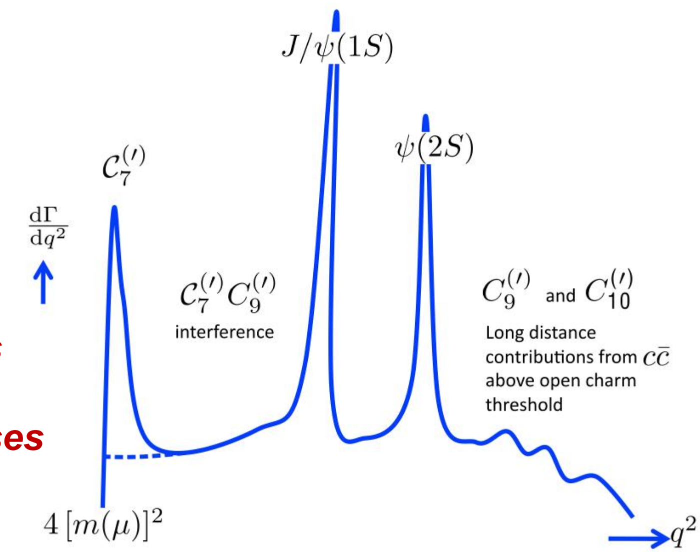
2.8σ deviation from SM

Credit: Rusa Mandal at
2023 Belle II Physics Week

How to explain them?: New Physics Story



-Leptoquarks
-Z' bosons
-Heavy Higgses
-?



- $b \to s\ell\ell$ transitions described model-independently in effective theory

Local operator

$$\mathcal{H}_{\text{eff}} = -\frac{4G_F}{\sqrt{2}} V_{\text{tb}} V_{\text{ts}}^* \frac{e^2}{16\pi^2} \sum_i \boxed{\mathcal{C}_i} \boxed{\mathcal{O}_i}$$

Wilson coefficient (“effective coupling”)

Effective couplings in $b \to s\ell\ell$ transitions

	Wilson coefficient	Operator
γ-penguin	$\mathcal{C}_7^{(\prime)}$	$\frac{e}{g^2} m_b (\bar{s}\sigma_{\mu\nu} P_{R(L)} b) F^{\mu\nu}$
ew. penguin	$\mathcal{C}_9^{(\prime)}$	$\frac{e^2}{g^2} (\bar{s}\gamma_\mu P_{L(R)} b)(\bar{\mu}\gamma^\mu \mu)$
	$\mathcal{C}_{10}^{(\prime)}$	$\frac{e^2}{g^2} (\bar{s}\gamma_\mu P_{L(R)} b)(\bar{\mu}\gamma^\mu \gamma_5 \mu)$
scalar	$\mathcal{C}_S^{(\prime)}$	$\frac{e^2}{16\pi^2} m_b (\bar{s} P_{R(L)} b)(\bar{\mu}\mu)$
pseudoscalar	$\mathcal{C}_P^{(\prime)}$	$\frac{e^2}{16\pi^2} m_b (\bar{s} P_{R(L)} b)(\bar{\mu}\gamma_5\mu)$

For completeness

- Different $q^2 = m^2(\ell^+\ell^-)$ regions probe different operator combinations

Credit: C. Langenbruch at Moriond EW 2023

How to explain them? Model independent

dim-6 basis including new physics operators

$$Q_7 = \frac{e}{g_s^2} m_b(\mu)(\bar{s}\sigma_{\mu\nu}P_R b)F^{\mu\nu}, \qquad Q_7' = \frac{e}{g_s^2} m_b(\mu)(\bar{s}\sigma_{\mu\nu}P_L b)F^{\mu\nu},$$

$$Q_8 = \frac{1}{g_s} m_b(\mu)(\bar{s}\sigma_{\mu\nu}T^a P_R b)G^{\mu\nu\,a}, \qquad Q_8' = \frac{1}{g_s} m_b(\mu)(\bar{s}\sigma_{\mu\nu}T^a P_L b)G^{\mu\nu\,a},$$

$$Q_9 = \frac{e^2}{g_s^2}(\bar{s}\gamma_\mu P_L b)(\bar{\mu}\gamma^\mu \mu), \qquad Q_9' = \frac{e^2}{g_s^2}(\bar{s}\gamma_\mu P_R b)(\bar{\mu}\gamma^\mu \mu),$$

$$Q_{10} = \frac{e^2}{g_s^2}(\bar{s}\gamma_\mu P_L b)(\bar{\mu}\gamma^\mu \gamma_5 \mu), \qquad Q_{10}' = \frac{e^2}{g_s^2}(\bar{s}\gamma_\mu P_R b)(\bar{\mu}\gamma^\mu \gamma_5 \mu),$$

$$Q_S = \frac{e^2}{16\pi^2} m_b(\mu)(\bar{s}P_R b)(\bar{\mu}\mu), \qquad Q_S' = \frac{e^2}{16\pi^2} m_b(\mu)(\bar{s}P_L b)(\bar{\mu}\mu),$$

$$Q_P = \frac{e^2}{16\pi^2} m_b(\mu)(\bar{s}P_R b)(\bar{\mu}\gamma_5\mu), \qquad Q_P' = \frac{e^2}{16\pi^2} m_b(\mu)(\bar{s}P_L b)(\bar{\mu}\gamma_5\mu).$$

In SM (neglecting small q^2 dependence)

$$C_7^{\rm eff} = -0.2957, \quad C_8^{\rm eff} = -0.1630, \quad C_9 = 4.114, \quad C_{10} = -4.193.$$

$$C_{7-10}', C_S^{(\prime)}, C_P^{(\prime)} = 0$$

Credit: Rusa Mandal at
2023 Belle II Physics Week

Which Wilson Coefficients?

dim-6 basis including new physics operators

$$\cancel{Q_7 = \frac{e}{g_s^2} m_b(\mu)(\bar{s}\sigma_{\mu\nu}P_R b)F^{\mu\nu}}, \qquad \cancel{Q_7' = \frac{e}{g_s^2} m_b(\mu)(\bar{s}\sigma_{\mu\nu}P_L b)F^{\mu\nu}},$$

$$\cancel{Q_8 = \frac{1}{g_s} m_b(\mu)(\bar{s}\sigma_{\mu\nu}T^a P_R b)G^{\mu\nu\,a}}, \qquad \cancel{Q_8' = \frac{1}{g_s} m_b(\mu)(\bar{s}\sigma_{\mu\nu}T^a P_L b)G^{\mu\nu\,a}},$$

$$Q_9 = \frac{e^2}{g_s^2}(\bar{s}\gamma_\mu P_L b)(\bar{\mu}\gamma^\mu \mu), \qquad Q_9' = \frac{e^2}{g_s^2}(\bar{s}\gamma_\mu P_R b)(\bar{\mu}\gamma^\mu \mu),$$

$$Q_{10} = \frac{e^2}{g_s^2}(\bar{s}\gamma_\mu P_L b)(\bar{\mu}\gamma^\mu \gamma_5 \mu), \qquad Q_{10}' = \frac{e^2}{g_s^2}(\bar{s}\gamma_\mu P_R b)(\bar{\mu}\gamma^\mu \gamma_5 \mu),$$

$$\cancel{Q_S = \frac{e^2}{16\pi^2} m_b(\mu)(\bar{s}P_R b)(\bar{\mu}\mu)}, \qquad \cancel{Q_S' = \frac{e^2}{16\pi^2} m_b(\mu)(\bar{s}P_L b)(\bar{\mu}\mu)},$$

$$\cancel{Q_P = \frac{e^2}{16\pi^2} m_b(\mu)(\bar{s}P_R b)(\bar{\mu}\gamma_5\mu)}, \qquad \cancel{Q_P' = \frac{e^2}{16\pi^2} m_b(\mu)(\bar{s}P_L b)(\bar{\mu}\gamma_5\mu)}.$$

No $q^2 < 1\,\mathrm{GeV}^2$ bins in the fit

Strongly constrained by $B_s \to \mu^+\mu^-$

In SM (neglecting small q^2 dependence)

$$C_7^{\text{eff}} = -0.2957, \quad C_8^{\text{eff}} = -0.1630, \quad C_9 = 4.114, \quad C_{10} = -4.193.$$

$$C_{7-10}', C_S^{(\prime)}, C_P^{(\prime)} = 0$$

Credit: Rusa Mandal at 2023 Belle II Physics Week

Fit to some simplified 2D scenarios

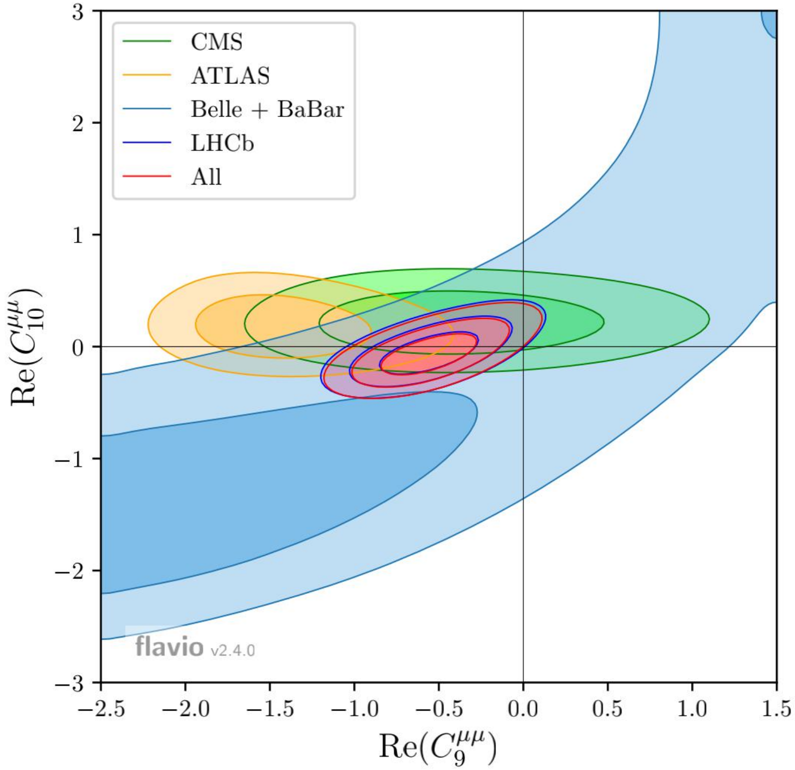
We use more than 200 observables on $b \to s$ transitions using the *flavio* package (most of them are the angular observables)

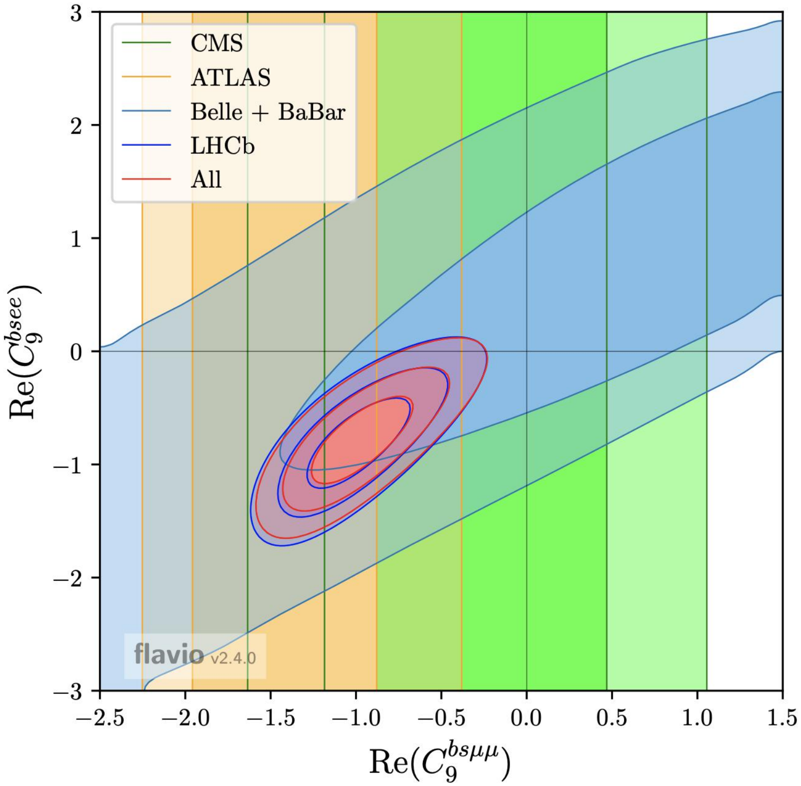
$$\mathrm{Pull_{SM}} = \sqrt{2}\,\mathrm{Erf}^{-1}\left[F(\Delta\chi^2; n_{\mathrm{dof}})\right]$$

where F is the χ^2 cumulative distribution function

2D Hyp	Best-fit point	ρ	$\Delta\chi^2$	$\mathrm{Pull_{SM}}$
$C_9^{\mu\mu}$	-0.97 ± 0.14	0.72	20.7	$6.1\,\sigma$
C_9^{ee}	-0.77 ± 0.18			
$C_9^{\mu\mu}$	-0.58 ± 0.13	-0.61	12.0	$4.5\,\sigma$
$C_{10}^{\mu\mu}$	-0.08 ± 0.09			

Fit to 2D scenarios





Lepton flavour universality is preferred

How to explain them? U(1)' model proposal

Gauge structure of the SM of Particle Physics

$$SU(3)_c \times SU(2)_L \times U(1)_Y \times U(1)_X$$

strong: color

weak: isospin

hypercharge

NP quantum numbers

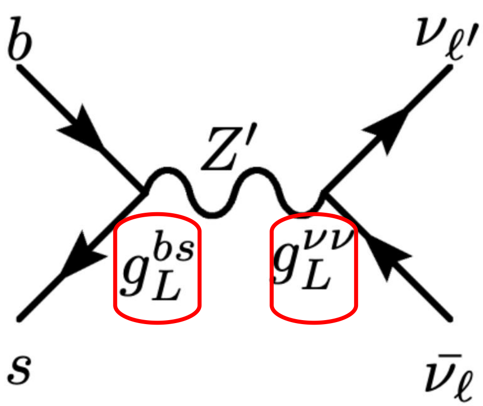
Fermions: three generations			$SU(3)_C$	$SU(2)_L$	$U(1)_Y$	$U(1)_X$
e_R	μ_R	τ_R	**1**	**1**	-1	X^l_R
$L_1 = (\nu_e, e_L)^\top$	$L_2 = \left(\nu_\mu, \mu_L\right)^\top$	$L_3 = (\nu_\tau, \tau_L)^\top$	**1**	**2**	$-\frac{1}{2}$	X^l_L
u_R	c_R	t_R	**3**	**1**	$\frac{2}{3}$	X^u_R
d_R	s_R	b_R	**3**	**1**	$-\frac{1}{3}$	X^d_R
$Q_1 = (u_L, d_L)^\top$	$Q_2 = (c_L, s_L)^\top$	$Q_3 = (t_L, b_L)^\top$	**3**	**2**	$\frac{1}{6}$	X^f_L

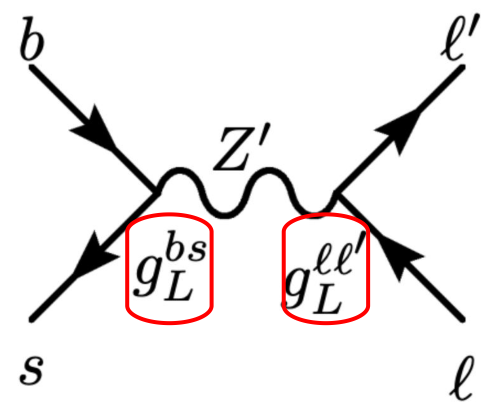
Free Parameters for the fit

Credit: Rusa Mandal at 2023 Belle II Physics Week

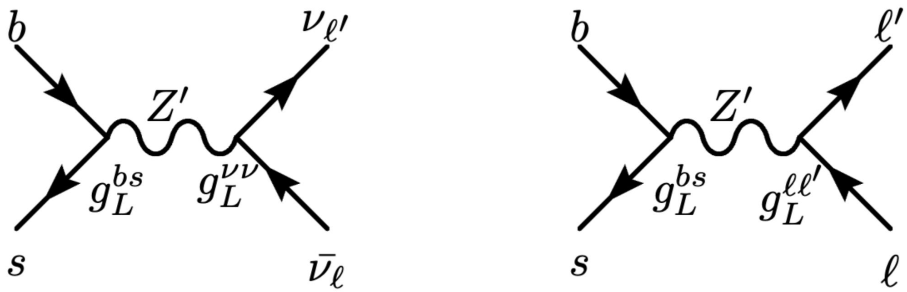
How to explain them? U(1)' model

$$\mathcal{L}_{Z'f\bar{f}} = \sum_{i,j,f_L} g_L^{ij} \overline{f}^i_L \gamma^\mu P_L f^j_L Z'_\mu + \sum_{i,j,f_R} g_R^{ij} \overline{f}^i_R \gamma^\mu P_R f^j_R Z'_\mu,$$





How to explain them? U(1)' model



Simplified analysis assuming: ***NON-UNIVERSAL INTERACTIONS***

$$X_R = X_R^e = X_R^\mu = X_R^\tau. \qquad g_R^{bs} = 0$$

New Physics WCs:

$$C_9^{\ell\ell} = -\frac{\pi}{\sqrt{2}G_F\alpha V_{tb}V_{ts}^*}\frac{g_L^{bs}(g_L^{\ell\ell}+g_R^{\ell\ell})}{M_{Z'}^2},$$

$$C_{10}^{\ell\ell} = \frac{\pi}{\sqrt{2}G_F\alpha V_{tb}V_{ts}^*}\frac{g_L^{bs}(g_L^{\ell\ell}-g_R^{\ell\ell})}{M_{Z'}^2},$$

$$C_{LL}^{\nu_e\nu_e} = -\frac{\pi}{\sqrt{2}G_F\alpha V_{tb}V_{ts}^*}\frac{g_L^{bs}g_L^{\nu_e\nu_e}}{M_{Z'}^2},$$

Correlation betweeen operators:

$$[O^V]_{LL}^{\nu_\ell\nu_{\ell'}} = \mathcal{O}_9^{\ell\ell'} - \mathcal{O}_{10}^{\ell\ell'}$$

SM value:

$$C_{LL}^{\rm SM} = -6.38 \pm 0.06$$

How to explain them? U(1)' model

WC	Best-fit point	ρ				
$C_9^{\mu\mu}$	-0.97 ± 0.14	1.00	-0.06	0.29	-0.02	-0.05
$C_{10}^{\mu\mu}$	0.20 ± 0.11		1.00	-0.08	0.27	0.07
C_9^{ee}	-0.5 ± 0.5			1.00	0.89	-0.01
C_{10}^{ee}	0.5 ± 0.4				1.00	0.02
$C_{LL}^{\nu_e\nu_e}$	-6.8 ± 1.7					1.00

$$\Delta\chi^2 = 22.9 \text{ and } \mathrm{Pull}_{\mathrm{SM}} = 5.9\,\sigma.$$

Likelihood and projection onto parameter space

The likelihood function from flavio is approximated as

$$\boxed{\log \mathcal{L} = -\frac{\chi^2}{2}, \quad \chi^2(\mathbf{C}) \approx \chi^2_{min} + \frac{1}{2}\left(\mathbf{C} - \mathbf{C}_{\mathrm{bf}}\right)^T \mathrm{Cov}^{-1}\left(\mathbf{C} - \mathbf{C}_{\mathrm{bf}}\right)}$$

where $\mathbf{C} = \{C_9^{\mu\mu}, C_{10}^{\mu\mu}, C_9^{ee}, C_{10}^{ee}, C_{LL}^{\nu_e\nu_e}\}$

A random generator is requested to find points inside the ellipsoid:

$$\boxed{\Delta\chi^2 \leq \sigma,}$$

And the parameter space of the model is scanned in the following ranges:

$$X_L^i, X_R \in [-\sqrt{4\pi}, \sqrt{4\pi}], \qquad \alpha_L \in [0, 2\pi], \qquad \delta, \epsilon \in [0, 0.5],$$

$$M_{Z'} \in [1, 10]\,\mathrm{TeV},$$

Constraints to the parameter space

$B_s - \overline{B}_s$ mixing

$$\left(\frac{g_L^{bs}}{0.52}\right)^2 \left(\frac{10\text{TeV}}{M_{Z'}}\right)^2 = 0.110 \pm 0.090.$$

$\mu \to e\gamma$

$$\text{BR}(\mu \to e\gamma)_{\text{exp}} = 4.2 \times 10^{-13}\,, \quad 90\%\,\text{C.L.},$$

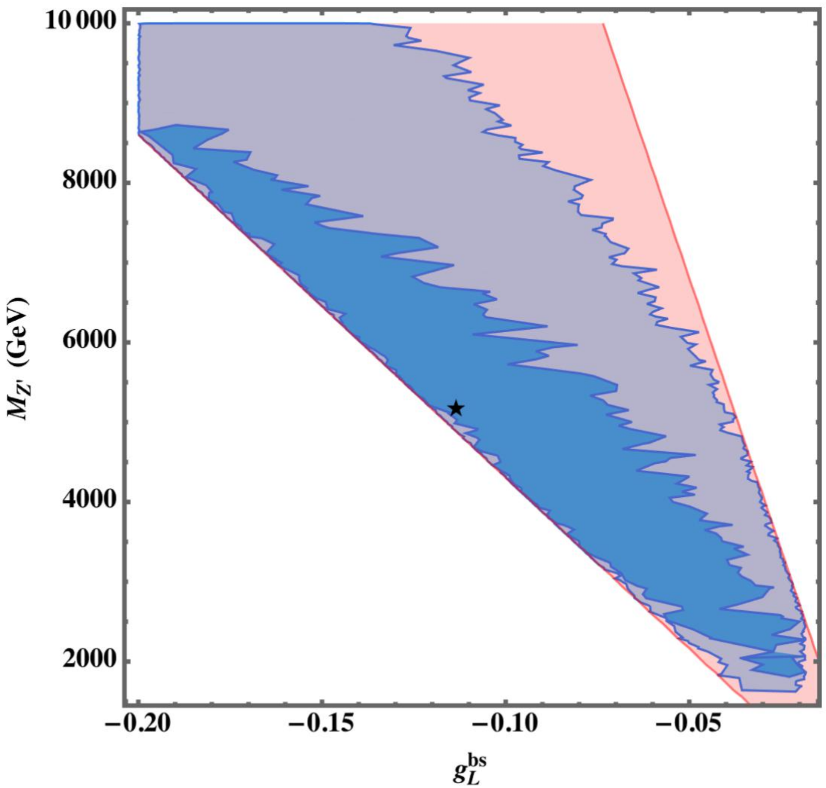
$$\text{BR}(\mu \to e\gamma)_{\text{th}} = \frac{m_\mu^3}{4\pi\Gamma_\mu}\left(|c_L^{12}|^2 + |c_R^{12}|^2\right),$$

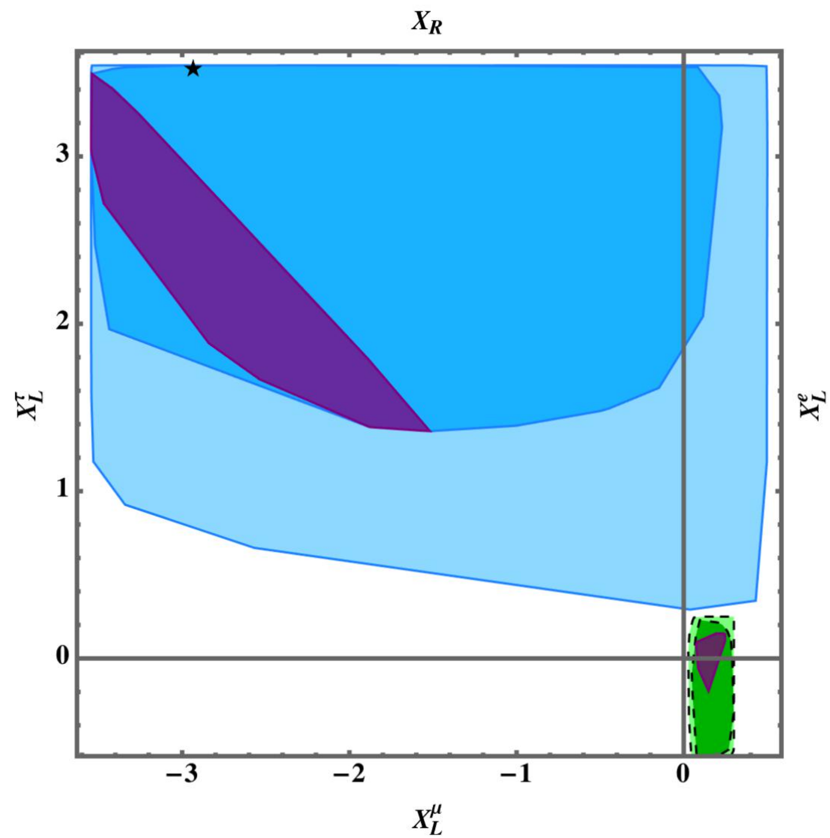
$$c_L^{12} = \frac{e}{48\pi^2 M_{Z'}^2}\sum_k \left(m_\mu\, g_{1k}^R\, g_{k2}^R - 3\, m_k\, g_{1k}^R\, g_{k2}^L + m_e\, g_{1k}^L\, g_{k2}^L\right),$$

Constraints to the parameter space

$B_s - \overline{B}_s$ mixing

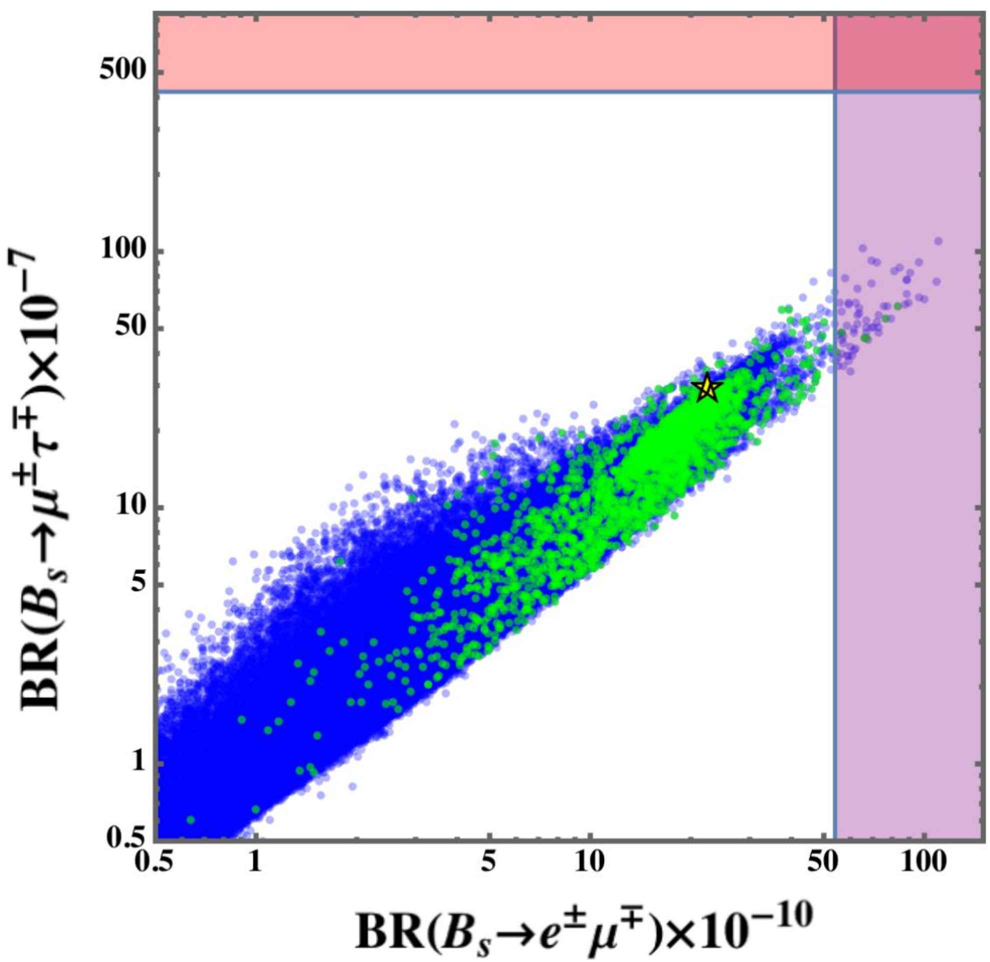
$\mu \to e\gamma$





$b \to s\ell\ell$ and $b \to s\nu\bar{\nu}$

CLFV predictions



Summary

- We presented a model independent fit to the B meson anomalies finding a preference for lepton universality given the latest LHCb data on RK&RK*.
- The fit was obtained using the flavio package and the resultant WCs were projected onto the parameter space of an nonuniversal $U(1)_X$ model.
- The parameter space is able to accomodate both the LHCb data and the recente Belle II measurment for B+->K+nunu while simultaneously respecting Bs-Bs mixing and mu->e gamma decays constraints.
- Predictions for CLFV were obtained for future measurements at both Belle II and the LHCb Upgrade II.

谢谢您的关注!

Backup slides

Fit to all Wilson Coefficients (WCs)

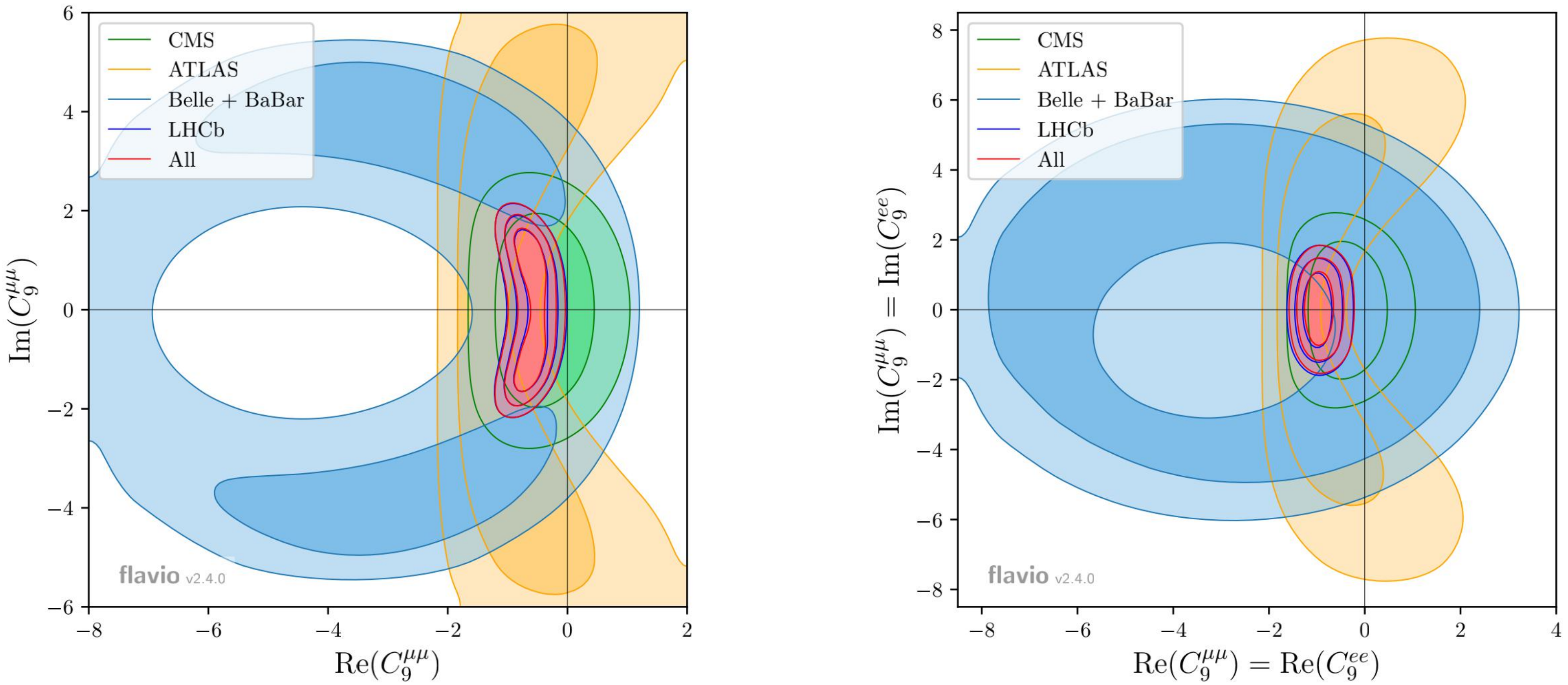


Figure 2: Fits to the B meson anomalies with complex Wilson coefficients. Left: $\{\mathrm{Re}(C_9^{\mu\mu}),\ \mathrm{Im}(C_9^{\mu\mu})\}$ scenario with $\Delta\chi^2 = 13.5$ and $\mathrm{Pull}_{\mathrm{SM}} = 4.8\sigma$. Right: $\{\mathrm{Re}(C_9^{\mu\mu}) = \mathrm{Re}(C_9^{ee}),\ \mathrm{Im}(C_9^{\mu\mu}) = \mathrm{Im}(C_9^{ee})\}$ new case with $\Delta\chi^2 = 18.7$ and $\mathrm{Pull}_{\mathrm{SM}} = 5.8\sigma$. Colours meaning are the same as in Fig.1.

How to explain them? U(1)' model

$$g^{\ell\ell}_{L,R} = V^{l\dagger}_{L,R} X_{L,R} V^{l}_{L,R},$$

$$V^{l\,\mathrm{SM}}_{L} = \begin{pmatrix} 1 & \sin\delta & \sin\epsilon \\ -\sin\delta & \cos\alpha_L & \sin\alpha_L \\ -\sin\epsilon & -\sin\alpha_L & \cos\alpha_L \end{pmatrix},$$

$$g^{\nu_e\nu_e}_{L} = (V^{\nu_l\dagger}_{L})_{1k} X_L (V^{\nu_l}_{L})_{k1} \qquad V^{\nu_l}_{L} = V^{l\,\mathrm{SM}}_{L} V_{\mathrm{PMNS}}$$

$$X_{L,R} = \mathrm{diag}\{X^{e}_{L,R},\, X^{\mu}_{L,R},\, X^{\tau}_{L,R}\},$$

Effective Hamiltonian for b->snunu decays

$$\mathcal{H}_{\text{eff}}^{bs\nu_i\nu_j} = -\frac{4\,G_F}{\sqrt{2}} V_{tb}V_{ts}^{*}(C_{LL}^{\text{SM}}\delta_{ij} + C_{LL}^{\nu_i\nu_j})[O^V]_{LL}^{\nu_i\nu_j} + \text{h.c.},$$

$$C_{LL}^{\text{SM}} = -X(x_t)/\sin^2\theta_w, \quad \text{and} \quad [O^V]_{LL}^{\nu_i\nu_j} = \frac{e^2}{16\pi^2}(\bar{s}\gamma_\mu P_L b)(\bar{\nu}_i\gamma^\mu(1-\gamma_5)\nu_j),$$

$$\text{BR}(B^+ \to K^+\nu\bar{\nu}) = \text{BR}(B^+ \to K^+\nu\bar{\nu})_{\text{SM}} \times \left[\frac{1}{3}\sum_{i=1}^{3}\left|1 + \frac{C_{LL}^{\nu_i\nu_i}}{C_{LL}^{\text{SM}}}\right|^2 + \sum_{i\neq j}\left|\frac{C_{LL}^{\nu_i\nu_j}}{C_{LL}^{\text{SM}}}\right|^2\right],$$