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Quark-lepton correlations in a gauge anomaly free abelian extension of the Standard Model

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Overview:

- Standard Model (SM) & beyond
- Abelian extension of SM: ABCD model
- Analysis & Results
- Conclusions

SM & beyond: open problems & tensions

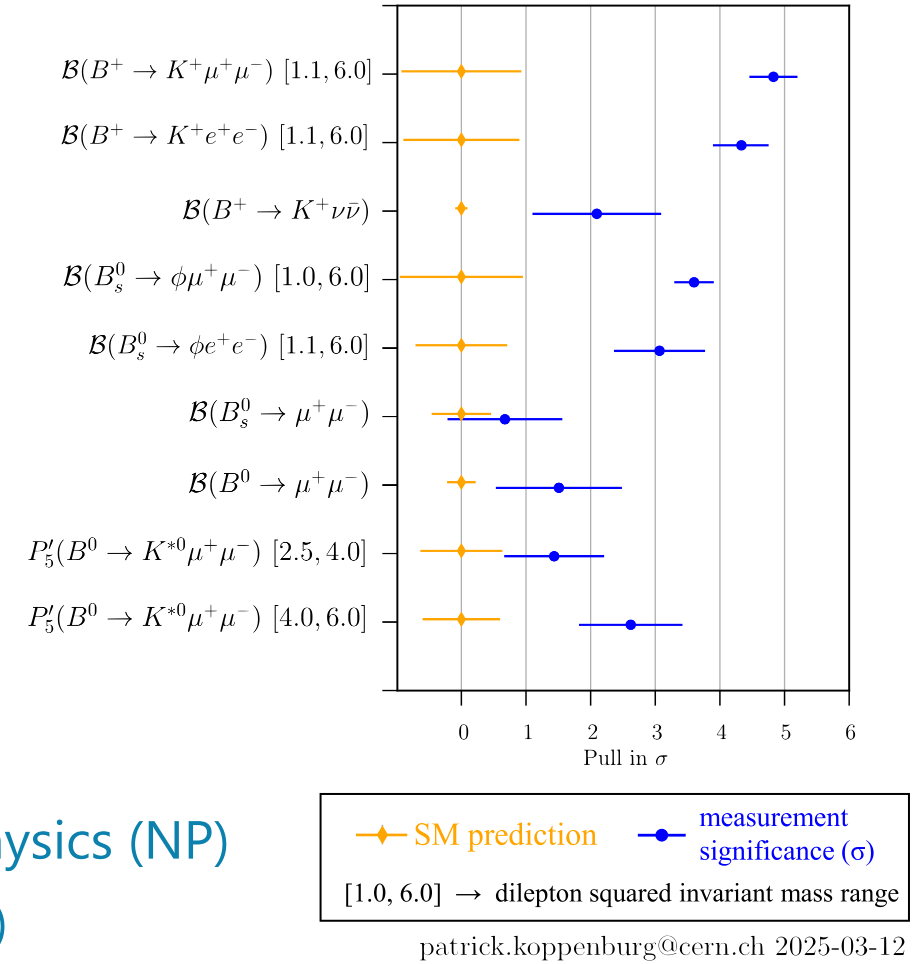
The SM is currently the best experimentally tested theory of fundamental particles & their interactions

However, it leaves many questions unanswered:

- Existing hierarchy among fermion masses
- Predicted CP-violation too small to explain baryogenesis

Moreover, several tensions are observed, regarding:

- Elements of CKM quark mixing matrix & its unitarity
  (e.g. exclusive/inclusive determinations of $|V_{ub}|$ and $|V_{cb}|$)
- Observables related to $b \to d, s$ transitions
  (B decays branching ratios, angular observables, etc.)



Deviations not large enough to be definitive evidence of new physics (NP)

However they are many and all hint at physics beyond SM (BSM)

ABCD model [1]

Abelian extension of the SM gauge group:

$$\underbrace{\mathrm{SU}(3)_C \times \mathrm{SU}(2)_L \times \mathrm{U}(1)_Y}_{\text{SM}} \times \underbrace{\mathrm{U}(1)'}_{\text{neutral } Z' \text{ boson}}$$

Interaction with SM fermions $\psi_{L/R}$ (flavor basis):

$$\mathcal{L}'_{\mathrm{int}} = -g_z \sum_{\psi} \sum_{i,j} \left[Z^{ij}_{\psi_L} \, \overline{\psi}_{iL} \gamma^\mu \psi_{jL} + Z^{ij}_{\psi_R} \, \overline{\psi}_{iR} \gamma^\mu \psi_{jR} \right] \mathbf{Z}'_\mu$$

coupling constant

Z' gauge field

$$Z^{ij}_{\psi} = \underbrace{z_{\psi_i}}_{\substack{z\text{-charges} \\ \text{(quantum numbers under U(1)}')}} \delta^{ij}$$

[1] Aebischer, Buras, Cerdà-Sevilla, De Fazio [JHEP 02(2020)183]

Gauge anomalies

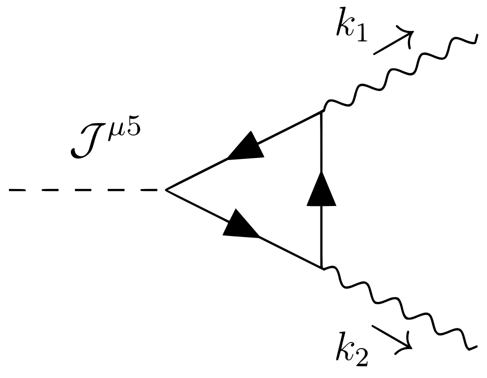
Noether's theorem: continuous global symmetry of action S → conserved current: $\partial_\mu \mathcal{J}^\mu = 0$

Symmetries of classical theory can be destroyed by quantum corrections

Anomalous non-conservation of axial current:

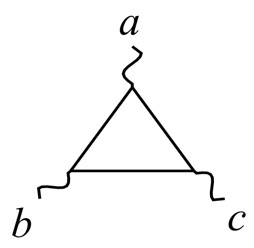
$$\boxed{\partial_\mu \mathcal{J}^{\mu 5} = -\frac{e^2}{16\pi^2}\epsilon^{\mu\nu\alpha\beta}\mathbf{F}_{\mu\nu}\mathbf{F}_{\alpha\beta}} \quad \rightarrow \quad \langle k_1, k_2|\partial_\mu \mathcal{J}^{\mu 5}|0\rangle \neq 0$$

Adler-Bell-Jackiw anomaly



Gauge anomalies lead to profound inconsistencies (e.g. electric charge not conserved)

Anomalous contribution comes from 1-loop correction to 3-gauge bosons vertex function (triangle diagrams)



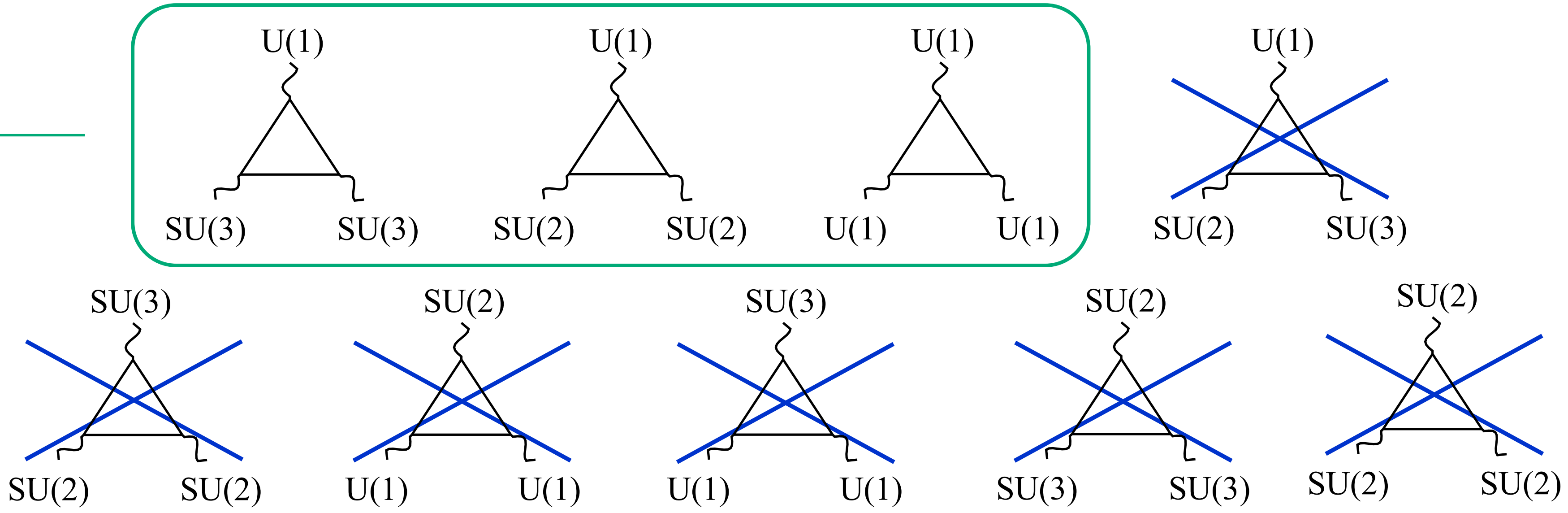
$$\propto \quad \mathrm{Tr}\left[\mathbf{T}_a\{\mathbf{T}_b, \mathbf{T}_c\}\right]$$

generators

Gauge theories (e.g. the SM) must be anomaly free → triangle diagrams must cancel

Anomalies cancellation – SM

In the SM, all permutations of $SU(3)_C \times SU(2)_L \times U(1)_Y$ generators must be considered



SU(N) generators are traceless:

$$\mathrm{Tr}[\mathbf{T}_a] = 0$$

3 anomaly cancellation equations (ACEs) left:

$$\begin{cases} A_{331} = 2y_q - y_u - y_d = 0 \\ A_{221} = 3y_q + y_\ell = 0 \\ A_{111} = 3(2y_q^3 - y_u^3 - y_d^3) + 2y_\ell^3 - y_e^3 = 0 \end{cases}$$

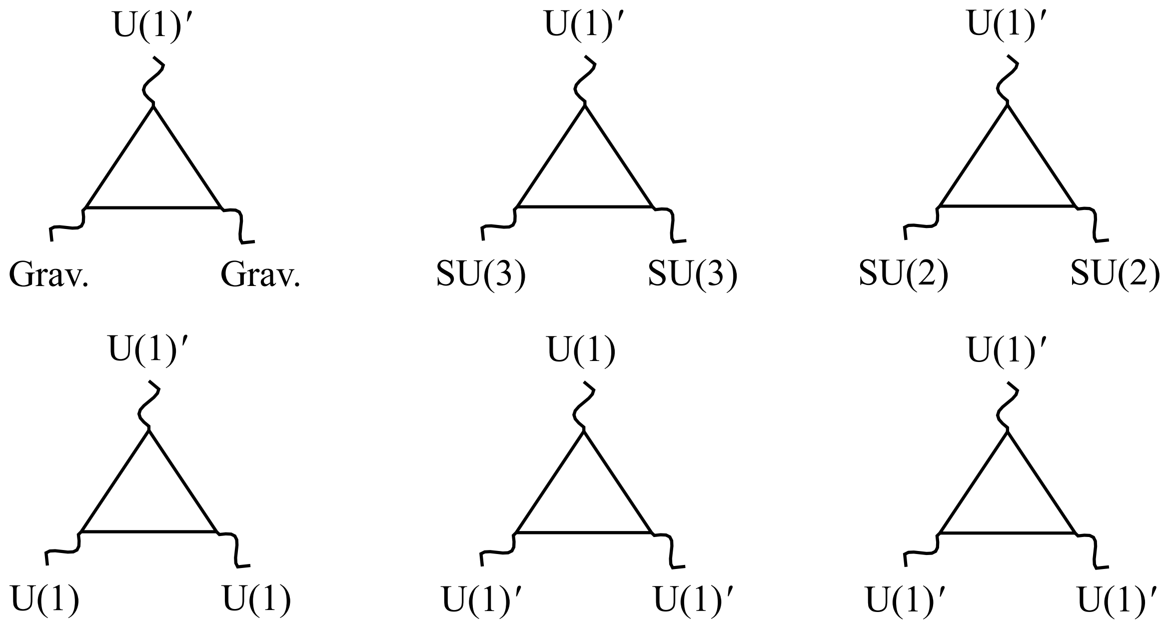
→ verified independently by each fermion generation

		Y
LH doublets	ℓ	$-1/2$
	q	$+1/6$
RH singlets	e	-1
	u	$+2/3$
	d	$-1/3$

(same for all 3 generations)

Anomalies cancellation – ABCD model

Abelian extension of the SM:



6 additional ACEs:

$$\begin{cases} A_{GG1'} = 2z_\ell - z_\nu - z_e = 0 \\ A_{331'} = 2z_q - z_u - z_d = 0 \\ A_{221'} = 3z_q + z_\ell = 0 \\ A_{111'} = \frac{1}{6}z_q - \frac{4}{3}z_u - \frac{1}{3}z_d + \frac{1}{2}z_\ell - z_e = 0 \\ A_{1'1'1} = z_q^2 - 2z_u^2 + z_d^2 - z_\ell^2 + z_e^2 = 0 \\ A_{1'1'1'} = 3(2z_q^3 - z_u^3 - z_d^3) + 2z_\ell^3 - z_\nu^3 - z_e^3 = 0 \end{cases}$$

ABCD assumption: generation-dependent z-charges

$$z_{\psi_i} = y_\psi + \epsilon_i$$

(i=1,2,3 generation index)

(SM weak hypercharges) (rational numbers)

i.e. ϵ_i is the same for all fermions (quarks & leptons) of a given generation

→

ACEs satisfied if:

$$\epsilon_1 + \epsilon_2 + \epsilon_3 = 0$$

#free parameters reduced:

$$\epsilon_3 = -(\epsilon_1 + \epsilon_2)$$

ABCD model – couplings

Rotation of fermion fields from flavor basis to mass basis by unitary matrices:

$$\mathscr{L}'_{\text{int}} = -\sum_{\psi}\sum_{i,j}\left[\overline{\psi}_{iL}\gamma^{\mu}\Delta^{ij}_{\psi_L}\psi_{jL} + \overline{\psi}_{iR}\gamma^{\mu}\Delta^{ij}_{\psi_R}\psi_{jR}\right]\mathbf{Z}'_{\mu}$$

flavor non-universal couplings

flavor changing neutral current (FCNC) transitions possible at tree-level, for example:

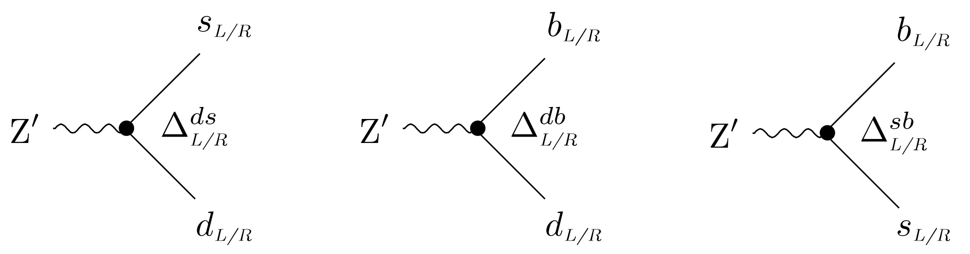
down quarks:

$$\Delta^{ij}_{d_L} = g_z \sum_k \epsilon_k V^*_{ki} V_{kj}$$

(CKM)

$$\Delta^{ij}_{d_R} = g_z \sum_k \epsilon_k (V^d_R)^*_{ki} (V^d_R)_{kj}$$

(CKM-like)



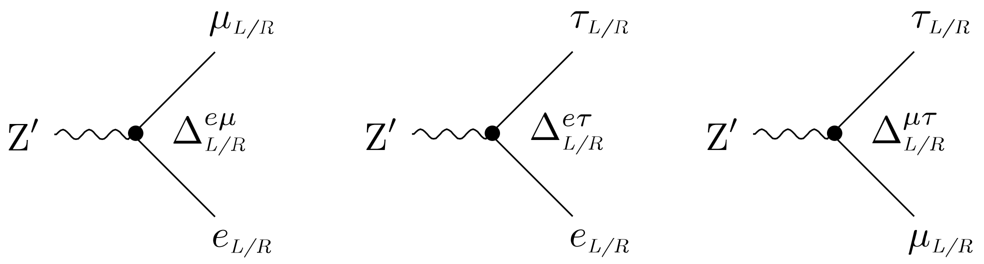
charged leptons:

$$\Delta^{ij}_{e_L} = g_z \sum_k \epsilon_k U_{ik} U^*_{jk}$$

(PMNS)

$$\Delta^{ij}_{e_R} = g_z \sum_k \epsilon_k (U^e_R)^*_{ki} (U^e_R)_{kj}$$

(CKM-like)



ABCD model – implications

- $\{\epsilon_1, \epsilon_2, \epsilon_3\}$ assumed to be the same for both quark & lepton sectors
  - ABCD model predicts correlations between hadron & lepton decays !
- For increasing $M_{Z'}$ ABCD model approaches SM
  - deviations from SM are possible, but small

Promising processes to be investigated:

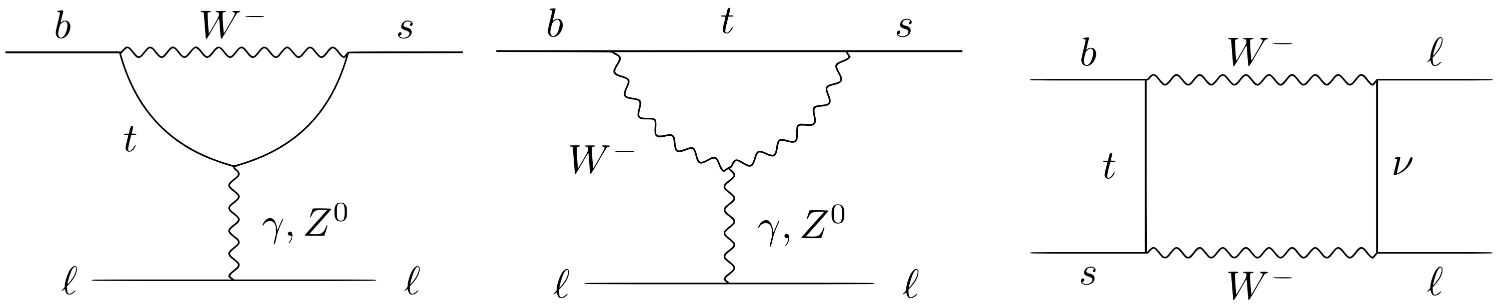
- SM-suppressed: rare B decays induced by FCNC transition $b \to s$
- SM-forbidden: lepton flavor violating (LFV) hadron & lepton decays

Many experiments currently involved !

Effective Hamiltonian for $b \to s\, \ell_i^- \ell_j^+$ – SM

FCNCs (e.g. $b \to s\ell^-\ell^+$) forbidden at tree-level due to unitarity of CKM matrix & universality of weak interactions

However, they can occur at 1-loop level through penguin & box diagrams



At typical hadron energies (m_b ~ 4.2 GeV) heavy fields can be *integrated out* ➜ effective point-like interaction

CKM factor

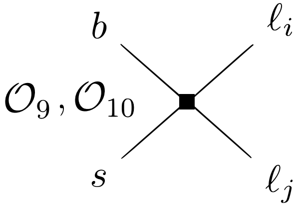
local 4-fermion operators

$$\mathcal{H}_{\text{eff}} = -4\frac{G_F}{\sqrt{2}} V_{tb}V_{ts}^* \sum_k C_k \mathcal{O}_k$$

Wilson coefficients: short-distance effects at scales $\mu > m_b$ (*effective coupling constants*)

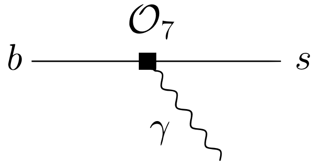
relevant operators for $b \to s\ell_i^-\ell_j^+$:

$$\mathcal{O}_9 = \frac{e^2}{16\pi^2}(\bar{\mathbf{s}}\gamma^\mu P_L \mathbf{b})(\bar{\boldsymbol{\ell}}_i \gamma_\mu \boldsymbol{\ell}_j)$$



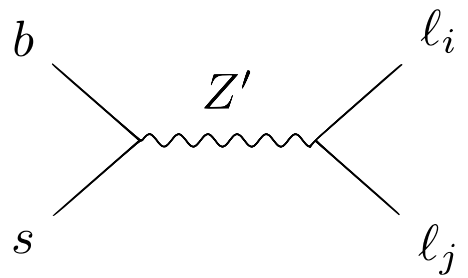
$$\mathcal{O}_{10} = \frac{e^2}{16\pi^2}(\bar{\mathbf{s}}\gamma^\mu P_L \mathbf{b})(\bar{\boldsymbol{\ell}}_i \gamma_\mu \gamma_5 \boldsymbol{\ell}_j)$$

$$\mathcal{O}_7 = \frac{e}{16\pi^2}\left[\bar{\mathbf{s}}\sigma^{\mu\nu}(m_s P_L + m_b P_R)\mathbf{b}\right]\mathbf{F}_{\mu\nu}\delta_{ij}$$



Effective Hamiltonian for $b \to s\, \ell_i^- \ell_j^+$ – ABCD model

In ABCD model, FCNC transition $b \to s\ell_i^- \ell_j^+$ can occur at tree-level mediated by a virtual Z' boson



quark & lepton flavor non-universal couplings

- lepton flavor conserving (LFC) FCNC transitions (ℓ_i=ℓ_j) at tree level **!**
- lepton flavor violating (LFV) FCNC transitions (ℓ_i≠ℓ_j) allowed **!**

Integrating out heavy Z' field, construct a low-energy effective Hamiltonian:

$$\mathcal{H}_{\rm eff} = -4\frac{G_F}{\sqrt{2}} V_{tb}V_{ts}^* \sum_k C_k \mathcal{O}_k$$

NP effects ➜ modification of Wilson coefficients: $(C_{9,10})_{ij} = C_{9,10}^{\rm SM}\delta_{ij} + (C_{9,10}^{\rm NP})_{ij}$, where:

$C_7^{\rm SM}$	$C_9^{\rm SM}$	$C_{10}^{\rm SM}$
-0.450	4.273	-4.166

Bordone, Cornella, Davighi [arXiv:2503.22635]

and

$$(C_{9,10}^{\rm NP})_{ij} = \mp \frac{g_t^2}{M_{Z'}^2} \Delta_{d_L}^{bs} \Delta_{e_L}^{ij}$$

with: $g_t^2 = \dfrac{4\pi^2}{8G_F^2 M_W^2 \sin^2\theta_W\, V_{tb}^* V_{ts}}$

(scenario A: LH couplings only)

Parameter space

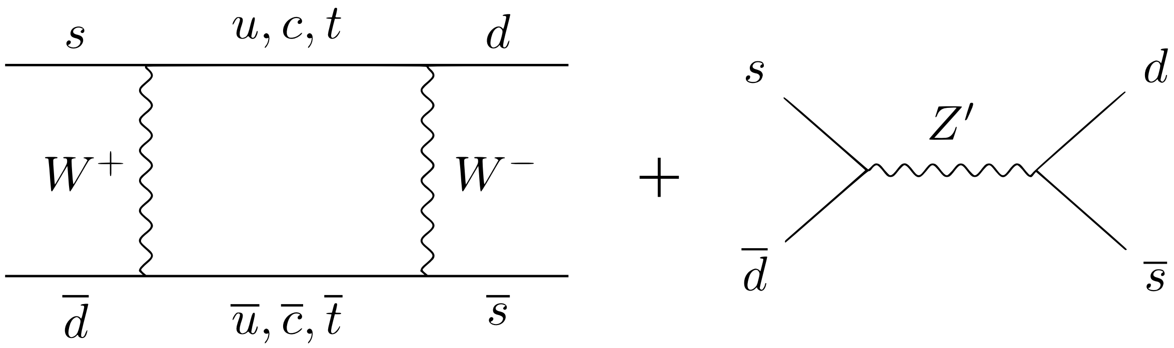
Free-parameters of the model:

$$\{g_z,\ M_{Z'},\ \epsilon_1,\ \epsilon_2,\ |V_{ub}|,\ |V_{cb}|\}$$

$$\begin{cases} 0.01 \leq g_z \leq 1 \\ M_{Z'} = 1\,\text{TeV and } 3\,\text{TeV} \end{cases} \qquad \begin{array}{l} |V_{ub}|_{\text{exc}} \leq |V_{ub}| \leq |V_{ub}|_{\text{inc}} \\ |V_{cb}|_{\text{exc}} \leq |V_{cb}| \leq |V_{cb}|_{\text{inc}} \end{array}$$

Constrain $\epsilon_1,\ \epsilon_2$ by requiring $\Delta F = 2$ observables ($\mathcal{F}$) to lie within experimental range:

$$\mathcal{F} = \mathcal{F}_{\text{SM}} + \mathcal{F}_{\text{NP}} \in \left[\mathcal{F}_{\text{exp}} - \delta\mathcal{F}_{\text{exp}},\ \mathcal{F}_{\text{exp}} + \delta\mathcal{F}_{\text{exp}}\right]$$



Example: $K^0 - \bar{K}^0$ mixing (SM+NP)

	$\mathcal{F}$	$\mathcal{F}_{\text{exp}} \pm \delta\mathcal{F}_{\text{exp}}$
$B_d - \bar{B}_d$ mixing	ΔM_d	$(0.5069 \pm 0.0019)\ \text{ps}^{-1}$
	$S_{\psi K_S}$	0.709 ± 0.011
$B_s - \bar{B}_s$ mixing	ΔM_s	$(17.765 \pm 0.004)\ \text{ps}^{-1}$
	$S_{\psi\phi}$	0.051 ± 0.046
$K^0 - \bar{K}^0$ mixing	ΔM_K	$(0.0059 \pm 0.0015)\ \text{ps}^{-1}$
	ε_K	$(2.25 \pm 0.25) \times 10^{-3}$

Parameter space

Free-parameters of the model:

$$\{g_z,\ M_{Z'},\ \epsilon_1,\ \epsilon_2,\ |V_{ub}|,\ |V_{cb}|\}$$

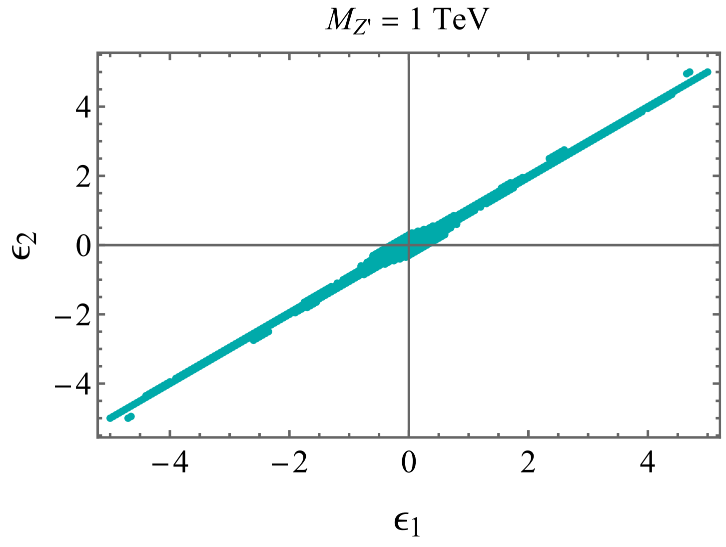
$$\begin{cases} 0.01 \le g_z \le 1 \\ M_{Z'} = 1\,\text{TeV and } 3\,\text{TeV} \end{cases}$$

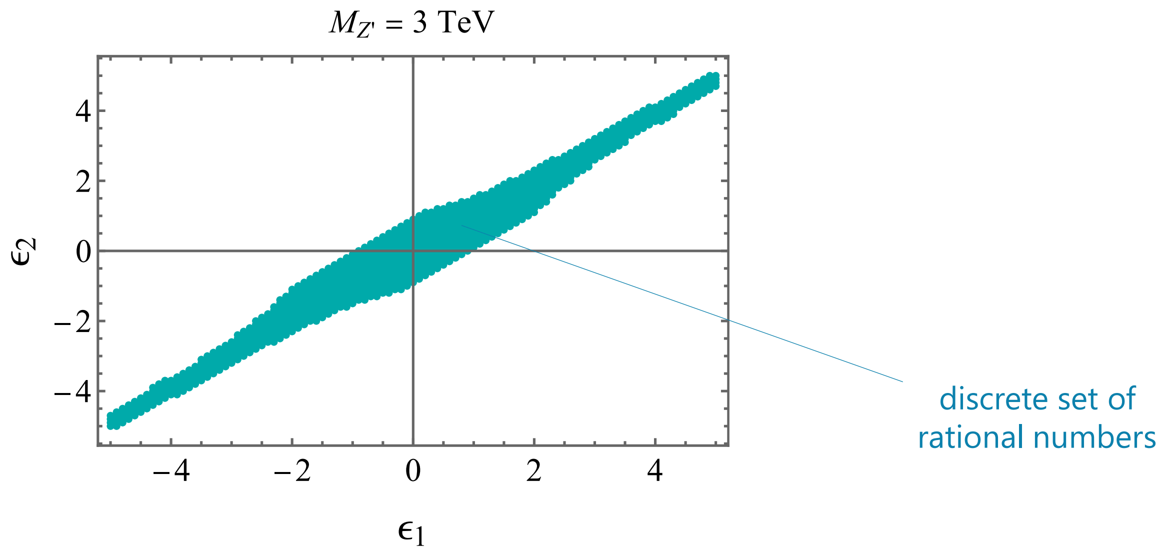
$$|V_{ub}|_{\text{exc}} \le |V_{ub}| \le |V_{ub}|_{\text{inc}}$$

$$|V_{cb}|_{\text{exc}} \le |V_{cb}| \le |V_{cb}|_{\text{inc}}$$

Constrain $\epsilon_1,\ \epsilon_2$ by requiring ΔF = 2 observables ($\mathcal{F}$) to lie within experimental range:

$$\mathcal{F} = \mathcal{F}_{\text{SM}} + \mathcal{F}_{\text{NP}} \in \left[\mathcal{F}_{\text{exp}} - \delta\mathcal{F}_{\text{exp}},\ \mathcal{F}_{\text{exp}} + \delta\mathcal{F}_{\text{exp}}\right]$$





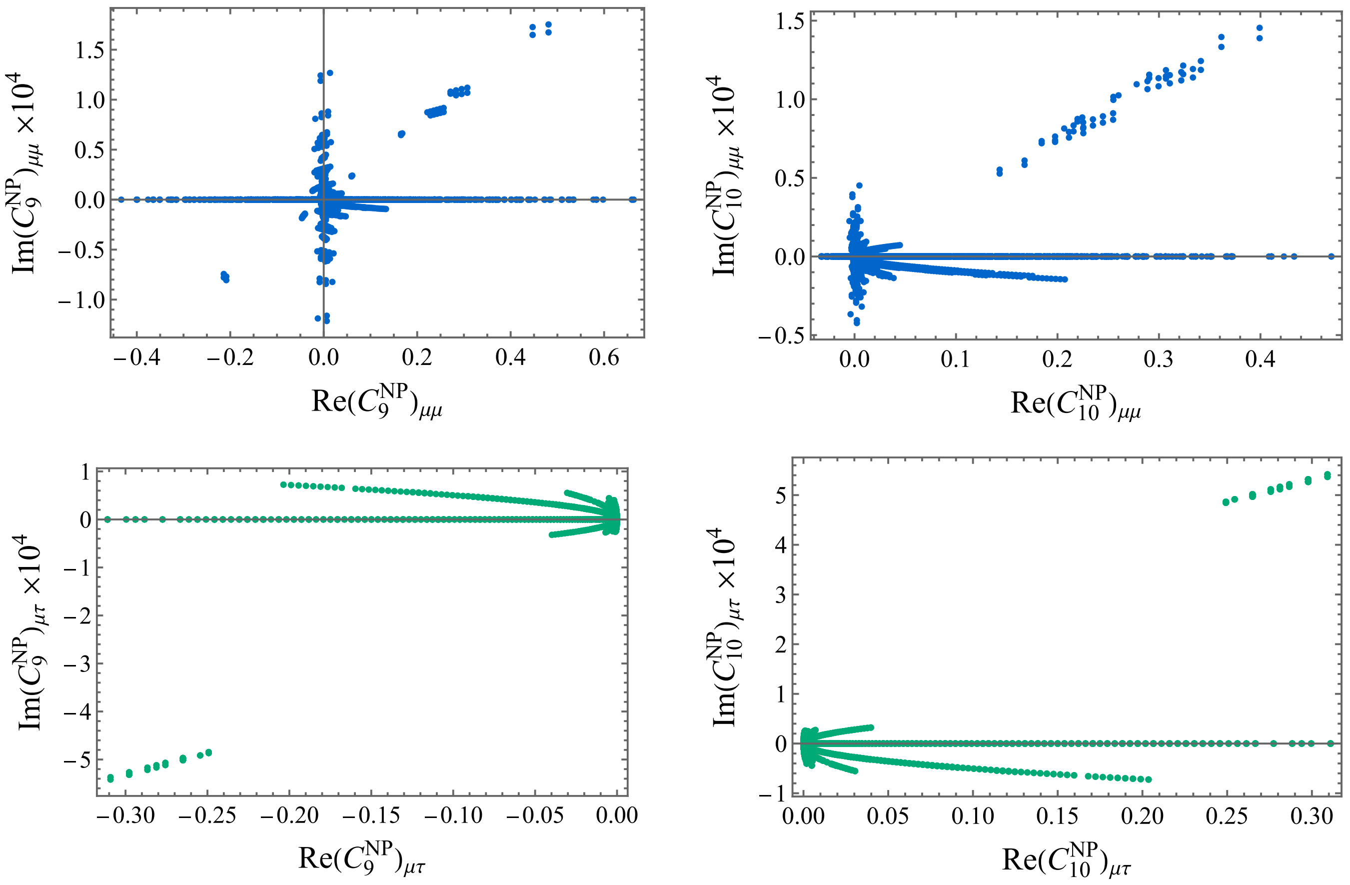
Hereafter only the case $M_{Z'}$ = 1 TeV is shown, but similar results hold for $M_{Z'}$ = 3 TeV

Wilson coefficients – $\mathrm{Re}(C_{9,10}^{\mathrm{NP}})$ vs $\mathrm{Im}(C_{9,10}^{\mathrm{NP}})$

NP contribution to relevant Wilson coefficients:

LFC ($b \to s\,\mu\mu$)

LFV ($b \to s\,\mu\tau$)



$\mathrm{Re}(C_k^{\mathrm{NP}})$ can be comparable with C_k^{SM} ➜ possible deviations from SM predictions

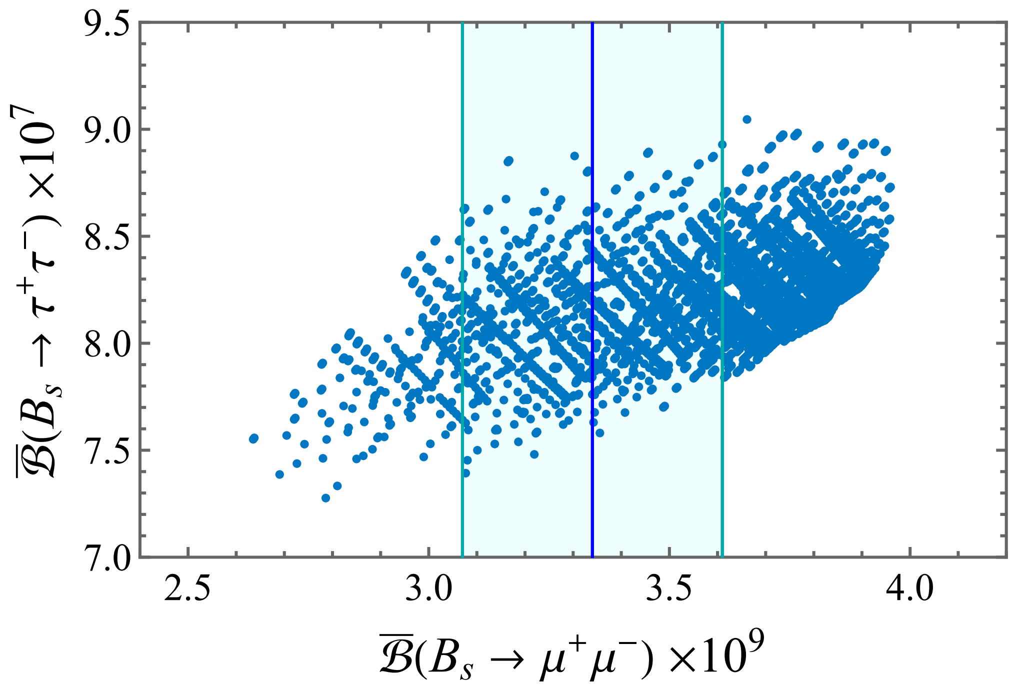
$B_s \to \ell_i^- \ell_j^+$

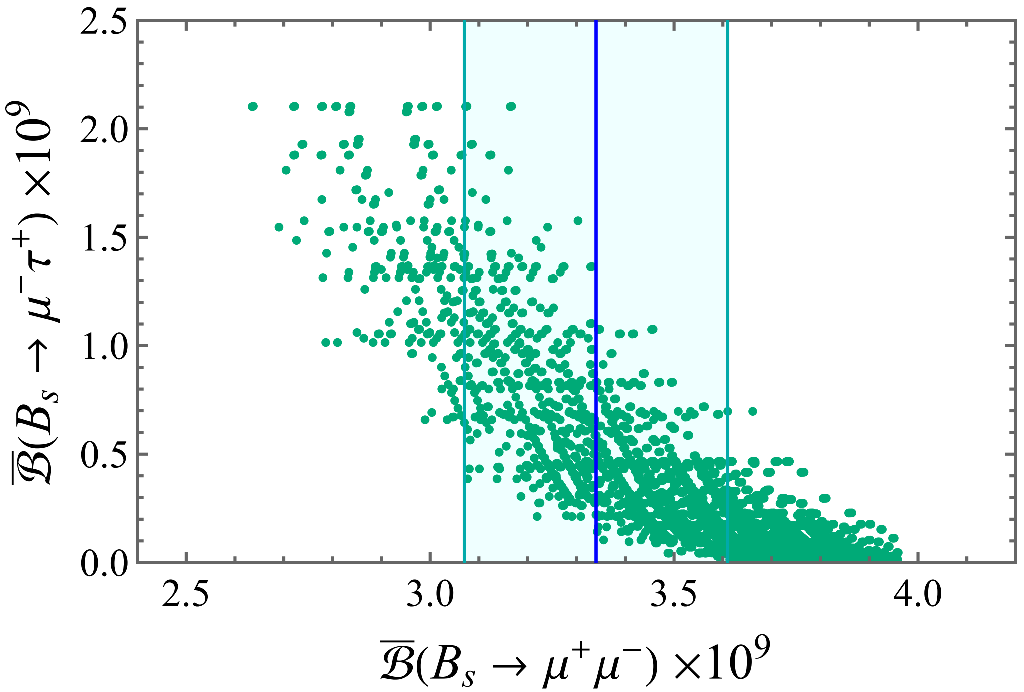
- What is the impact of NP on B meson decays?
- Simplest, theoretically-cleanest B decay mode induced by $b \to s$

$$\bar{\mathcal{B}}(B_s \to \ell_i^- \ell_j^+) = \frac{1}{(1-y_s)} \frac{\alpha^2 G_F^2 \tau_{B_s}}{64\pi^3 M_{B_s}^3} F_{B_s}^2 |V_{tb} V_{ts}^*|^2 \, \lambda^{1/2}(M_{B_s}^2, m_{\ell_i}^2, m_{\ell_j}^2)$$
$$\times \Big\{ [M_{B_s}^2 - (m_{\ell_i} + m_{\ell_j})^2] \, \big|(m_{\ell_i} - m_{\ell_j}) C_9\big|^2$$
$$+ [M_{B_s}^2 - (m_{\ell_i} - m_{\ell_j})^2] \, \big|(m_{\ell_i} + m_{\ell_j}) C_{10}\big|^2 \Big\}$$

- Hadronic uncertainties are only due to F_{B_s}
- In LFC case ($\ell_i = \ell_j$) only C_{10} contributes

$B_s \to \ell_i^- \ell_j^+$ – correlations





- LFC vs LFC: the requirement of experimental data (central value $\pm 1\sigma$) to be reproduced gives:

$$\bar{\mathcal{B}}(B_s \to \tau^+\tau^-) = (8.2 \pm 0.5) \times 10^{-7}$$

- LFC vs LFV: $\bar{\mathcal{B}}(B_s \to \mu^-\tau^+) \sim \mathcal{O}(10^{-9})$ ($\neq 0$ vs forbidden by SM), in the reach of future experiments
  Predicted value lowered by the requirement of experimental data (central value $\pm 1\sigma$) to be reproduced

$\bar{B}^0 \to \bar{K}^{*0} \ell_i^- \ell_j^+$

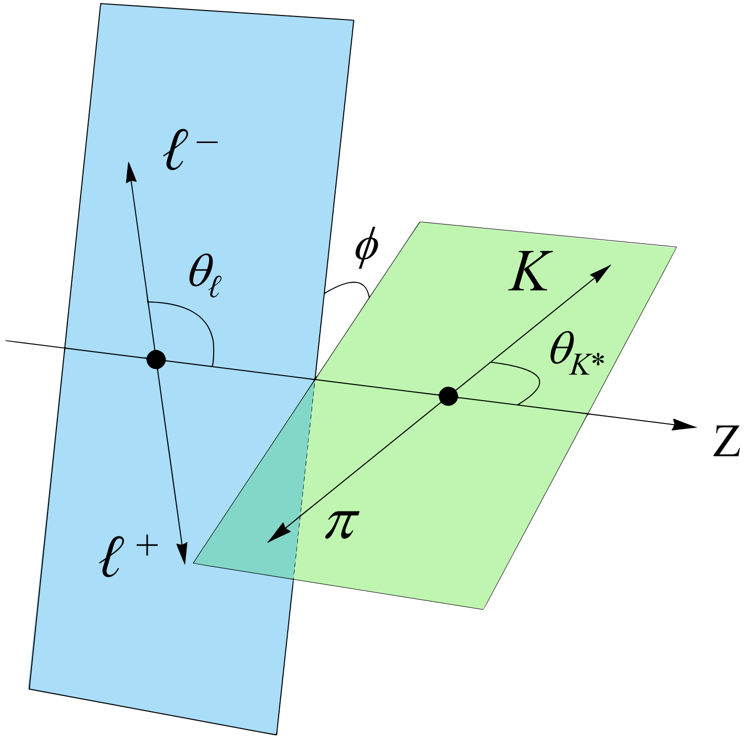
The actual decay observed experimentally is $\bar{B} \to \bar{K}^*(\to K\pi)\ell^-\ell^+$

Fully differential decay distribution:

$$\frac{d^4\Gamma}{dq^2\, d\cos\theta_\ell\, d\cos\theta_{K^*}\, d\phi} = \frac{9}{32\pi} I(q^2, \theta_\ell, \theta_{K^*}, \phi)$$

with:

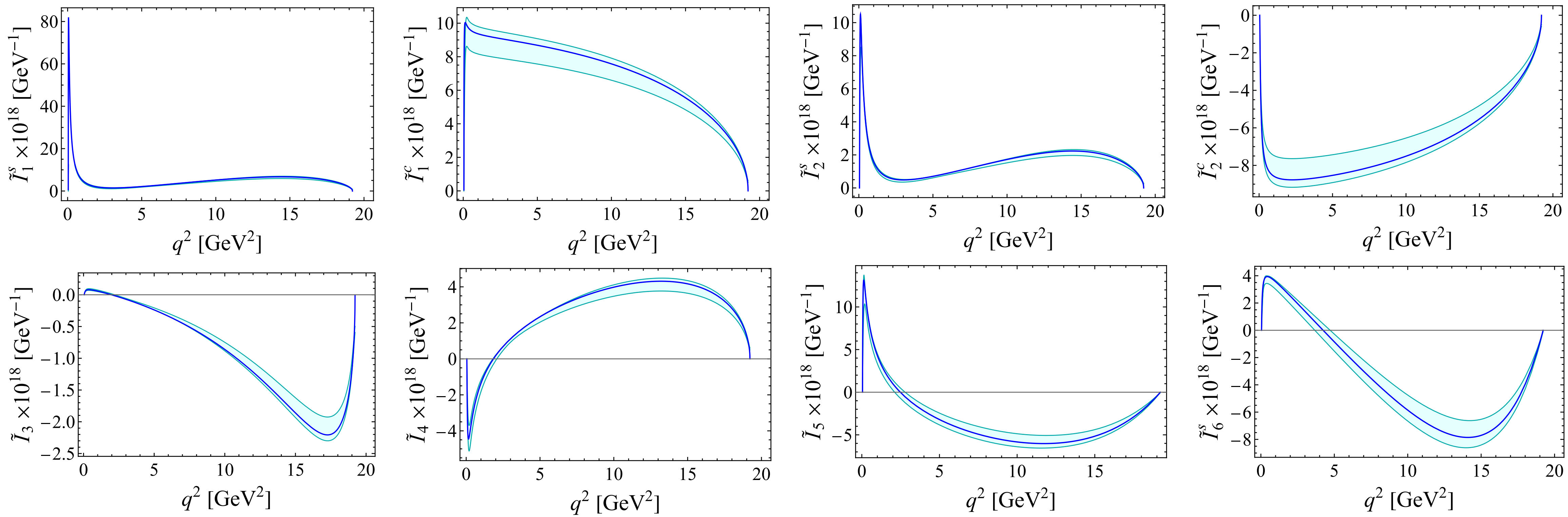
$$\begin{aligned}
I(q^2, \theta_\ell, \theta_{K^*}, \phi) = {} & I_1^s \sin^2\theta_{K^*} + I_1^c \cos^2\theta_{K^*} \\
& + \left[I_2^s \sin^2\theta_{K^*} + I_2^c \cos^2\theta_{K^*}\right] \cos 2\theta_\ell \\
& + I_3 \sin^2\theta_{K^*} \sin^2\theta_\ell \cos 2\phi + I_4 \sin 2\theta_{K^*} \sin 2\theta_\ell \cos\phi \\
& + I_5 \sin 2\theta_{K^*} \sin\theta_\ell \cos\phi + \left[I_6^s \sin^2\theta_{K^*} + I_6^c \cos^2\theta_{K^*}\right] \cos\theta_\ell \\
& + I_7 \sin 2\theta_{K^*} \sin\theta_\ell \sin\phi + I_8 \sin 2\theta_{K^*} \sin 2\theta_\ell \sin\phi + I_9 \sin^2\theta_{K^*} \sin^2\theta_\ell \sin 2\phi
\end{aligned}$$



The functions $I_i^{(a)}(q^2)$ are called angular coefficients and depend on *B→K* form factors*

$\bar{B}^0 \to \bar{K}^{*0}\,\mu^-\mu^+$ angular analysis – angular coefficients

- Eliminate dependence on CKM by defining: $\widetilde{I}_i^{(a)}(q^2) = I_i^{(a)}(q^2)/|V_{tb}^* V_{ts}|^2$



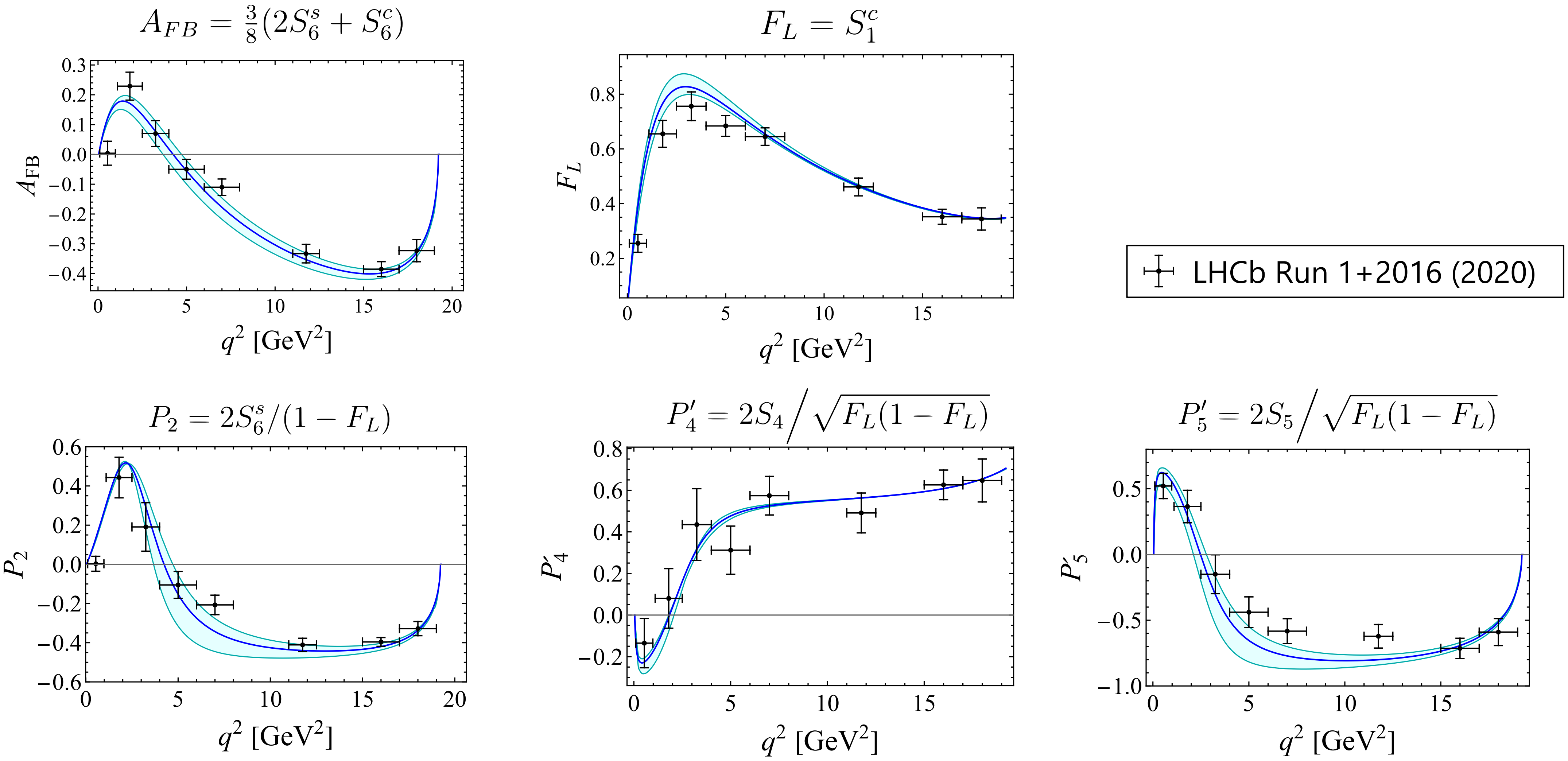
NP deviations (cyan band) from SM central value (blue line)

- Starting from angular coefficients, several observables can be constructed. Define:

$$S_i^{(a)}(q^2) = \left(I_i^{(a)}(q^2) + \bar{I}_i^{(a)}(q^2)\right) \Big/ \left(d\Gamma/dq^2 + d\bar{\Gamma}/dq^2\right)$$

(bar = CP-conjugated)

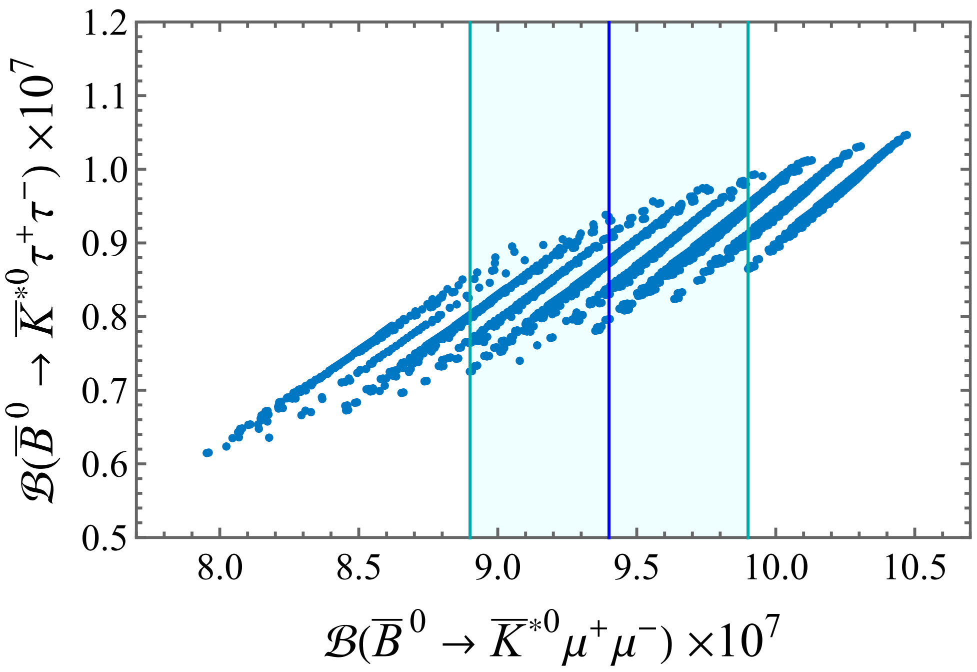
$\bar{B}^0 \to \bar{K}^{*0}\,\mu^-\mu^+$ angular analysis – observables

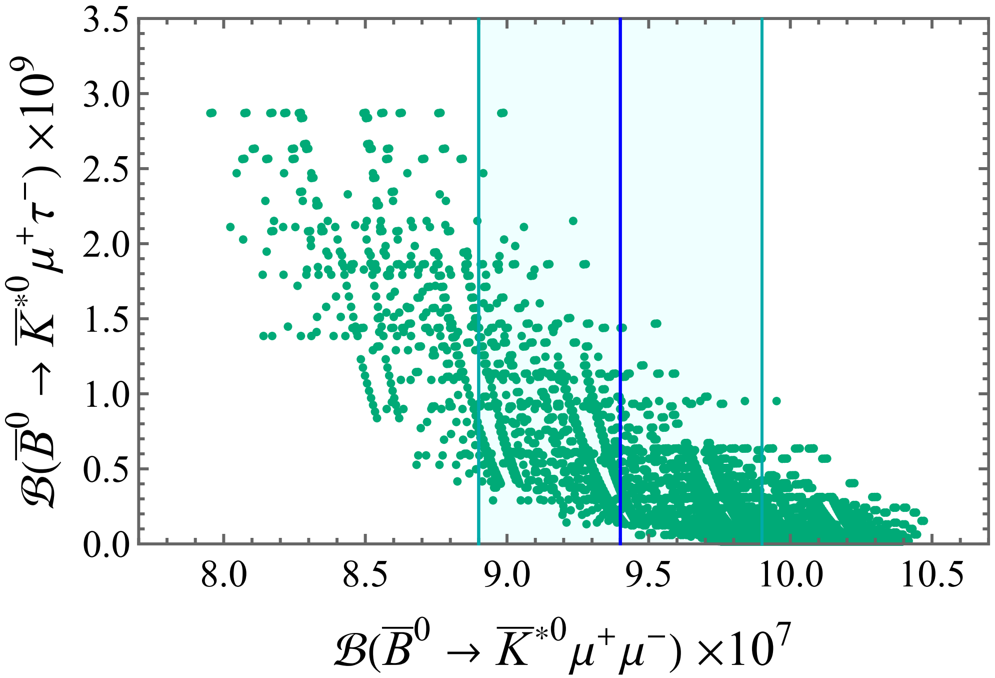


NP deviations (cyan band) from SM central value (blue line)

Angular analysis has been conducted also for $B \to K^* \tau^+\tau^-$ with similar results

$\bar{B}^0 \to \bar{K}^{*0}\ell_i^-\ell_j^+$ – correlations



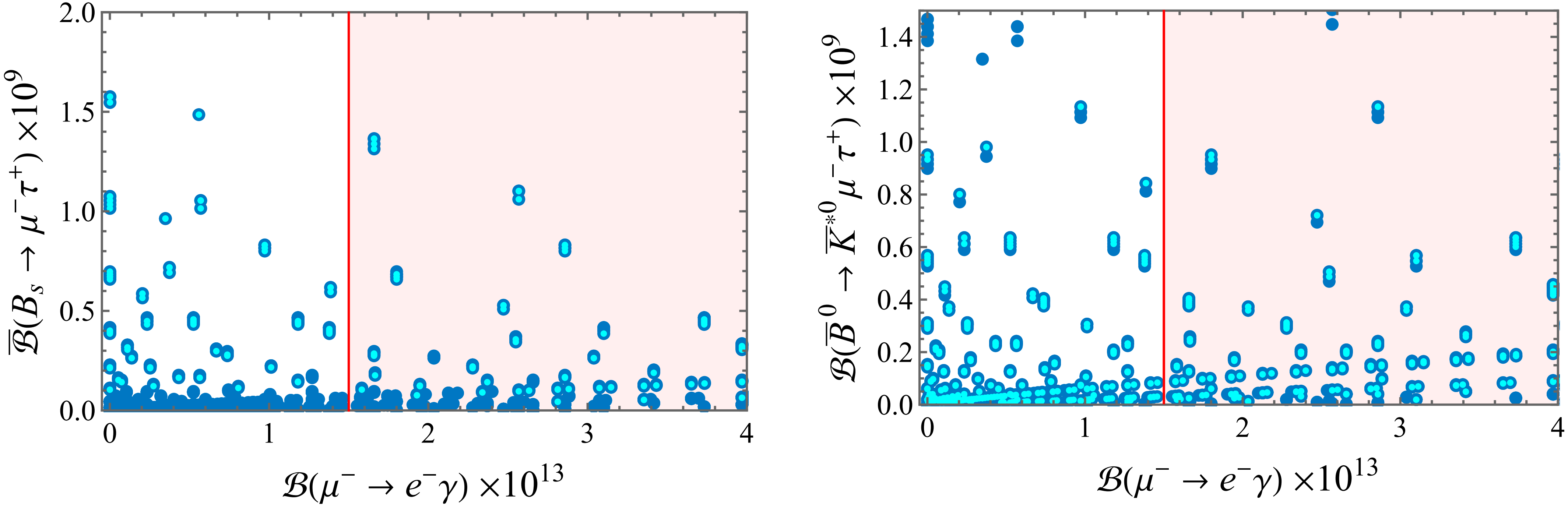


- LFC vs LFC: the requirement of experimental data (central value $\pm 1\sigma$) to be reproduced gives:

$$\mathcal{B}(\bar{B}^0 \to \bar{K}^{*0}\tau^+\tau^-) = (8.6 \pm 1.3) \times 10^{-8}$$

- LFC vs LFV: $\mathcal{B}(\bar{B}^0 \to \bar{K}^{*0}\mu^+\tau^-) \sim \mathcal{O}(10^{-9})$ ($\neq 0$ vs forbidden by SM), in the reach of future experiments
  Predicted value lowered by the requirement of experimental data (central value $\pm 1\sigma$) to be reproduced

LFV B decays vs $\mu \to e\gamma$



- **Cyan points:** extracted by constraining with corresponding LFC branching ratios
- **Red band:** excluded region by experimental upper bound (recently updated by MEG II [arXiv:2504.15711])

Correlations between lepton & hadron decays exist and can be used to constrain branching ratios !

Conclusions & perspectives

Summary of results:

Colangelo, De Fazio, Milillo [arXiv:2506.02552]

Observation of LFV decays to charged leptons: smoking gun for NP

	LFV mode	$\mathcal{B} \times 10^9$	Constrained by LFC mode $\mathcal{B}^{(1)} \times 10^9$	Constrained by $\mu \to e\gamma$ $\mathcal{B}^{(2)} \times 10^9$	Experiment
$M_{Z'}$ = 1 TeV	$B_s \to \tau^+\mu^-$	$0.00 \div 2.10$	$0.00 \div 2.10$	$0.00 \div 1.60$	$< 4.2 \times 10^{-5}$
	$\bar{B}^0 \to \bar{K}^{*0}\tau^+\mu^-$	$0.00 \div 2.90$	$0.00 \div 2.90$	$0.00 \div 1.15$	$< 1.0 \times 10^{-5}$
$M_{Z'}$ = 3 TeV	$B_s \to \tau^+\mu^-$	$0.00 \div 2.30$	$0.00 \div 1.50$	$0.00 \div 0.14$	$< 4.2 \times 10^{-5}$
	$\bar{B}^0 \to \bar{K}^{*0}\tau^+\mu^-$	$0.00 \div 3.10$	$0.00 \div 2.00$	$0.00 \div 0.20$	$< 1.0 \times 10^{-5}$

Future perspectives:

- Exploring other scenarios for the couplings
- Studying other decay modes
- Understanding Z' mass generation mechanism (Higgs-like?)

Thank you

Backup

Angular coefficients

Angular coefficients are expressed in terms of transversity amplitudes[2] $(A_{\perp,\parallel,0,t})_{L/R}$:

- $I_1^s = \frac{\lambda_\ell + 2[q^4 - (m_i^2 - m_j^2)^2]}{4q^2}\Big[|A_{\perp L}|^2 + |A_{\parallel L}|^2 + (L \to R)\Big] + \frac{4m_i m_j}{q^2}\,\mathrm{Re}\{A_{\perp L}A_{\perp R}^* + A_{\parallel L}A_{\parallel R}^*\}$
- $I_1^c = \frac{q^4 - (m_i^2 - m_j^2)^2}{q^4}\Big[|A_{0L}|^2 + |A_{0R}|^2\Big] + \frac{8m_i m_j}{q^2}\,\mathrm{Re}\{A_{0L}A_{0R}^* - A_{tL}A_{tR}^*\} - 2\,\frac{(m_i^2 - m_j^2)^2 - q^2(m_i^2 + m_j^2)}{q^4}\Big[|A_{tL}|^2 + |A_{tR}|^2\Big]$
- $I_2^s = \frac{\lambda_\ell}{4q^4}\Big[|A_{\perp L}|^2 + |A_{\parallel L}|^2 + (L \to R)\Big]$
- $I_2^c = -\frac{\lambda_\ell}{q^4}\Big[|A_{0L}|^2 + (L \to R)\Big]$
- $I_3 = \frac{\lambda_\ell}{2q^4}\Big[|A_{\perp L}|^2 - |A_{\parallel L}|^2 + (L \to R)\Big]$
- $I_4 = \frac{\lambda_\ell}{\sqrt{2}q^4}\Big[\mathrm{Re}\{A_{0L}A_{\parallel L}^*\} + (L \to R)\Big]$
- $I_5 = \frac{\sqrt{2}\lambda_\ell^{1/2}}{q^2}\Big[\mathrm{Re}\{A_{0L}A_{\parallel L}^* - (L \to R)\} - \frac{m_i^2 - m_j^2}{q^2}\mathrm{Re}\{A_{tL}A_{\parallel L}^* + (L \to R)\}\Big]$
- $I_6^s = \frac{2\lambda_\ell^{1/2}}{q^2}\Big[\mathrm{Re}\{A_{\parallel L}A_{\perp L}^*\} - (L \to R)\}\Big]$

[2] Altmannshofer, Ball, Bharucha, Buras, Straub, Wick [JHEP 01(2009)019]

Transversity amplitudes

- $$A_{\perp L,R} = \mathcal{N}\sqrt{2}\lambda_H^{1/2}\left[2(m_b+m_s)C_7\frac{T_1(q^2)}{q^2} + (C_9^+ \mp C_{10}^+)\frac{V(q^2)}{M_B+M_{K^*}}\right]$$
- $$A_{\parallel L,R} = -\mathcal{N}\sqrt{2}(M_B^2 - M_{K^*}^2)\left[2(m_b-m_s)C_7\frac{T_2(q^2)}{q^2} + (C_9^- \mp C_{10}^-)\frac{A_1(q^2)}{M_B-M_{K^*}}\right]$$
- $$A_{0L,R} = \frac{-\mathcal{N}}{2M_{K^*}\sqrt{q^2}}\left\{2(m_b-m_s)C_7\left[(M_B^2+3M_{K^*}^2-q^2)T_2(q^2) - \frac{\lambda_H T_3(q^2)}{M_B^2-M_{K^*}^2}\right]\right.$$
$$\left. + (C_9^- \mp C_{10}^-)\left[(M_B^2-M_{K^*}^2-q^2)(M_B+M_{K^*})A_1(q^2) - \frac{\lambda_H A_2(q^2)}{M_B+M_{K^*}}\right]\right\}$$
- $$A_{tL,R} = \frac{-\mathcal{N}}{\sqrt{q^2}}\lambda_H^{1/2}(C_9^- \mp C_{10}^-)A_0(q^2)$$

where: $\mathcal{N} = V_{tb}^* V_{ts}\left[\frac{G_F^2\alpha^2}{3\times 2^{10}\pi^5 M_B^3}\lambda_H^{1/2}\lambda_\ell^{1/2}\right]^{1/2}$

and: $C_k^\pm = C_k \pm C_k'$

with: $\lambda_H = \lambda(q^2, M_B^2, M_{K^*}^2)$

$\lambda_\ell = \lambda(q^2, m_i^2, m_j^2)$

(Källén function)

$A_{0,1,2}(q^2)$, $V(q^2)$, $T_{1,2,3}(q^2)$ are *$B \to K^*$ form factors*

$B \to K^*$ hadronic matrix elements

$B \to K^*$ hadronic matrix elements (standard parametrization):

- $\langle K^*(p',\epsilon)|\bar{\mathbf{s}}\gamma_\mu(1-\gamma_5)\mathbf{b}|B(p)\rangle = \epsilon_{\mu\nu\alpha\beta}\epsilon^{*\nu}p^\alpha p'^\beta \frac{2V(q^2)}{M_B+M_{K^*}} - i\left\{\epsilon^*_\mu(M_B+M_{K^*})A_1(q^2) - (p+p')_\mu(\epsilon^*\cdot p)\frac{A_2(q^2)}{M_B+M_{K^*}} - q_\mu(\epsilon^*\cdot q)\frac{2M_{K^*}}{q^2}\left[A_3(q^2)-A_0(q^2)\right]\right\}$
- $\langle K^*(p',\epsilon)|\bar{\mathbf{s}}\sigma_{\mu\nu}q^\nu(1+\gamma_5)\mathbf{b}|B(p)\rangle = i\epsilon_{\mu\nu\alpha\beta}\epsilon^{*\nu}p^\alpha p'^\beta T_1(q^2) + i\left[\epsilon^*_\mu(M_B-M_{K^*})A_1(q^2) - (p+p')_\mu(\epsilon^*\cdot q)\right]T_2(q^2) + (\epsilon^*\cdot q)\left[q_\mu - \frac{q^2}{M_B^2-M_{K^*}^2}(p+p')_\mu\right]T_3(q^2)$

K^* polarization 4-vector

$A_{0,1,2,3}(q^2)$, $V(q^2)$, $T_{1,2,3}(q^2)$ are *form factors* (FF). Actually they are not all independent, since:

$$A_3(q^2) = \frac{M_B+M_{K^*}}{2M_K^*}A_1(q^2) - \frac{M_B-M_{K^*}}{2M_K^*}A_2(q^2)$$

$$A_3(0) = A_0(0)$$

$$T_1(0) = T_2(0)$$

$B \to K^*$ form factors (Light-Cone Sum Rules)

The independent form factors $F = V, A_0, A_1, A_{12}, T_1, T_2, T_{23}$ are parametrized by LCSR[3]:

$$F(q^2) = \frac{1}{1 - q^2/M_{B^*}^2} \sum_{k=0}^{2} \alpha_k(F)[z(q^2) - z(0)]^k$$

mass of lightest resonance

$$z(t) = \frac{\sqrt{t_+ - t} - \sqrt{t_+ - t_0}}{\sqrt{t_+ - t} + \sqrt{t_+ - t_0}}$$

with: $\begin{cases} t_\pm = (M_B \pm M_{K^*})^2 \\ t_0 = t_+(1 - \sqrt{1 - t_-/t_+}) \end{cases}$

F	M_{B^*} (GeV)	$\alpha_0(F)$	$\alpha_1(F)$	$\alpha_2(F)$
V	5.415	0.38 ± 0.03	-1.17 ± 0.26	2.42 ± 1.53
A_0	5.366	0.37 ± 0.03	-1.37 ± 0.26	0.13 ± 1.63
A_1	5.829	0.30 ± 0.03	0.39 ± 0.19	1.19 ± 1.03
A_{12}	5.829	0.27 ± 0.02	0.53 ± 0.13	0.48 ± 0.66
T_1	5.415	0.31 ± 0.03	-1.01 ± 0.19	1.53 ± 1.64
T_2	5.829	0.31 ± 0.03	0.50 ± 0.17	1.61 ± 0.80
T_{23}	5.829	0.67 ± 0.06	1.32 ± 0.22	3.82 ± 2.20

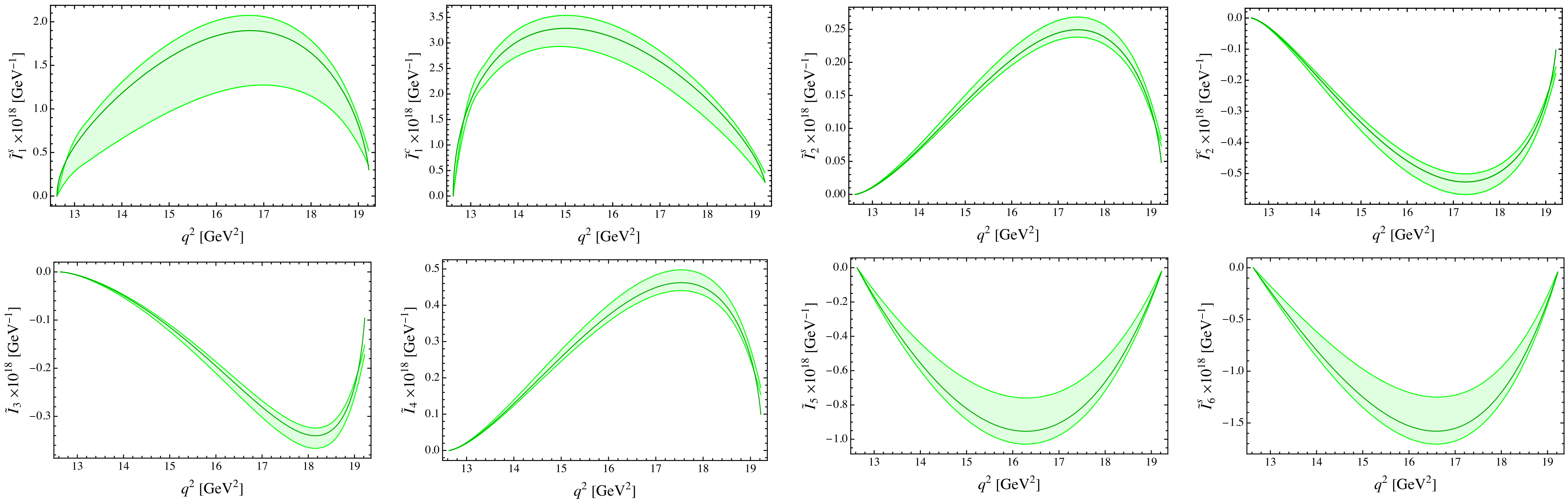
Finally A_2 & T_3 are obtained from:

$$A_{12} = \frac{(M_B + M_{K^*})^2(M_B^2 - M_{K^*}^2 - q^2)A_1(q^2) - \lambda(q^2, M_B^2, M_{K^*}^2)A_2(q^2)}{16 M_B M_{K^*}(M_B + M_{K^*})}$$

$$T_{23} = \frac{(M_B - M_{K^*})^2(M_B^2 + 3M_{K^*}^2 - q^2)T_2(q^2) - \lambda(q^2, M_B^2, M_{K^*}^2)T_3(q^2)}{8 M_B M_{K^*}(M_B - M_{K^*})}$$

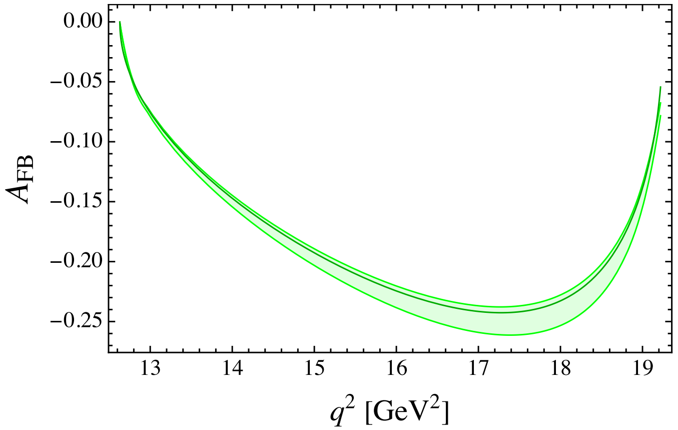
[3] Bharucha, Straub, Zwicky [JHEP 08(2016)098]

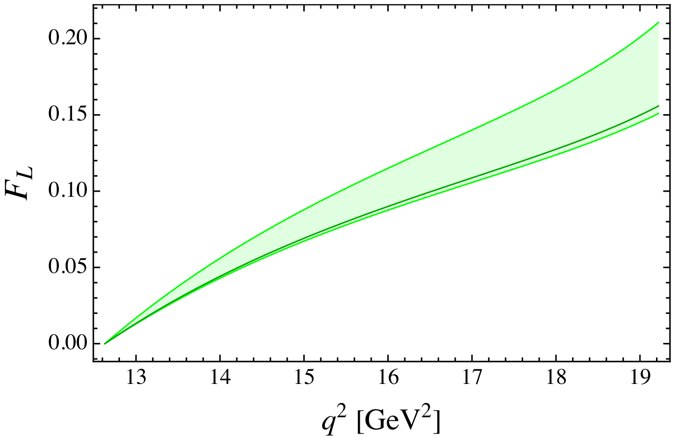
$B^0 \to K^{*0}\,\tau^-\tau^+$ angular analysis – angular coefficients (@1 TeV)



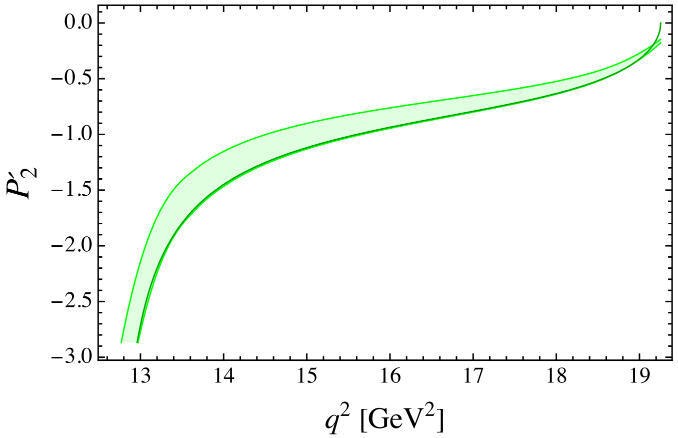
NP deviations (light green band) from SM central value (green line)

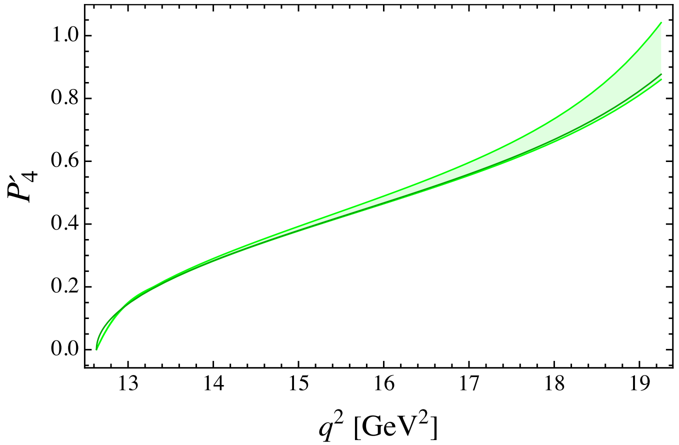
$B^0 \to K^{*0}\,\tau^-\tau^+$ angular analysis – observables (@1 TeV)

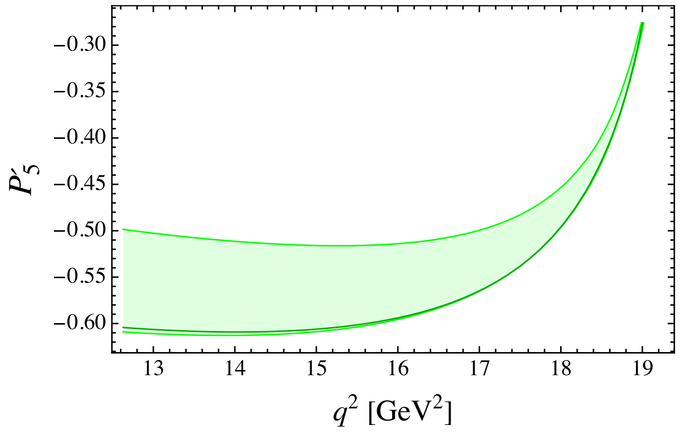




No experimental data available yet







NP deviations (light green band) from SM central value (green line)