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

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outline

- the zoo of flavour anomalies
- ABCD model: correlations between quark and lepton observables
- summary

based on:
P. Colangelo, D. Milillo, FDF
arXiv:2506.02552

Flavour Physics: direct vs indirect searches complementarity

direct searches at colliders

- New particles directly produced on-shell
- Identified through their decay modes

Exp: push the collider energy as much as possible

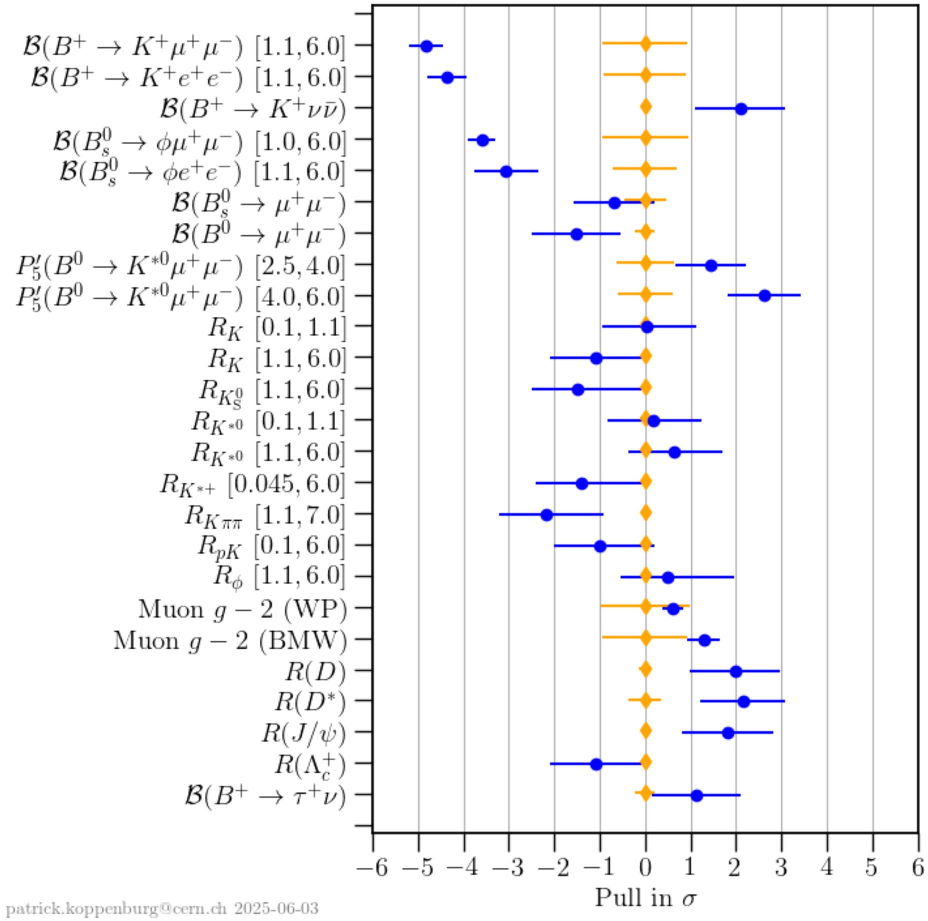
searches through quantum effects

- New particles contribute as virtual states
- Deviations from SM predictions can emerge
- Might be sensitive to large mass scales (e.g. new massive mediators)

Exp: Push the intensity as much as possible

Flavour physics
unique opportunities to look for BSM
intimate connection of flavour with the Higgs sector

Flavour anomalies



- loop induced (rare)
- tree level decays
- puzzling quantities (V_{cb}, V_{ub}, ε'/ε, $(g-2)_\mu$)

- correlated pattern of deviations from SM predictions?
- common origin of the anomalies?

  ex. V_{cb}, V_{ub} puzzles correlated with observed anomalies in tree-level modes?

➢ look for new modes/observables/correlations

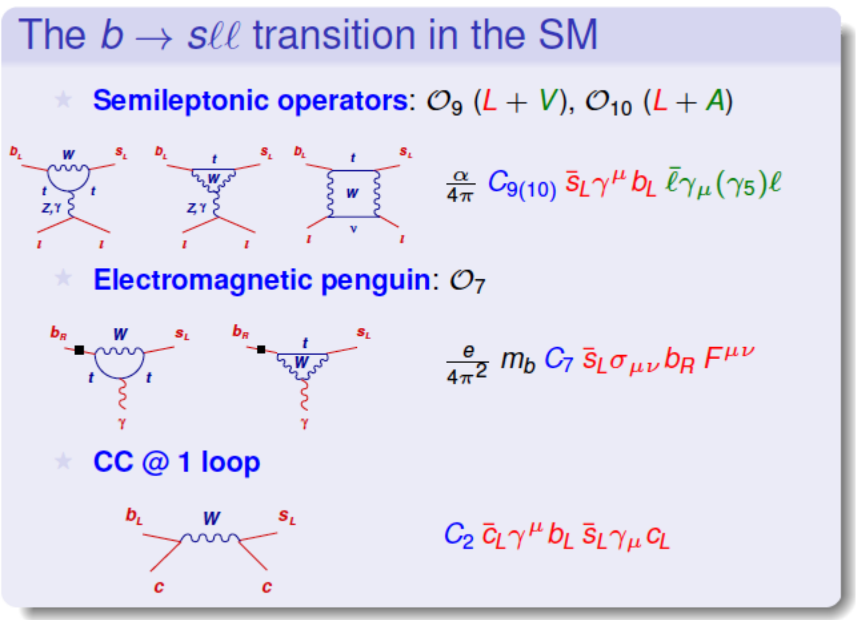
➢ look also for processes forbidden in SM: LFV decays $\tau \to 3\mu$, $\mu \to e\gamma$ …

Flavour anomalies: loop-induced modes

$b \to s\,\ell\,\bar{\ell}$

$$H^{\rm eff} = -4\frac{G_F}{\sqrt{2}}V_{tb}V_{ts}^* \left\{ C_1 O_1 + C_2 O_2 + \sum_{i=3,..,6} C_i O_i + \sum_{i=7,..,10} [C_i O_i + C_i' O_i'] \right\}$$

credit J. Camalich



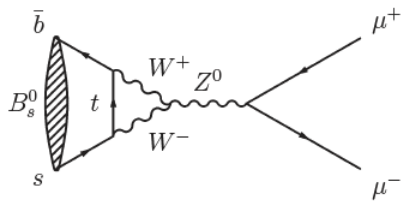
NP: i) new operators

ii) modified Wilson coefficients

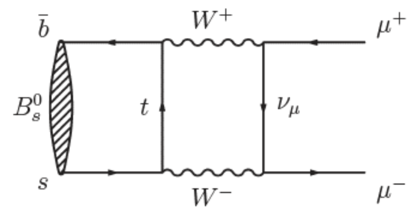
iii) new phases

Flavour anomalies: loop-induced modes

$B_s \to \ell_1^- \ell_2^+$



(a)



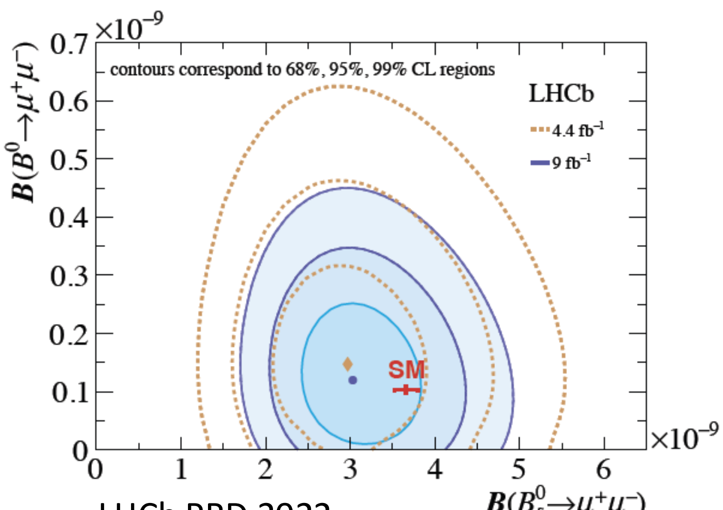
(b)

$$\bar{\mathcal{B}}(B_s \to \ell_1^- \ell_2^+) = \frac{\tau_{B_s}}{(1-y_s)} \frac{G_F^2 \alpha^2 |\lambda_{ts}^*|^2 f_{B_s}^2}{64\pi^3 m_{B_s}^3} \lambda^{1/2}(m_{B_s}^2, m_{\ell_1}^2, m_{\ell_2}^2)$$
$$\times \left\{ |C_9 - C_9'|^2 (m_{\ell_1} - m_{\ell_2})^2 \left[m_{B_s}^2 - (m_{\ell_1} + m_{\ell_2})^2 \right] \right.$$
$$\left. + |C_{10} - C_{10}'|^2 (m_{\ell_1} + m_{\ell_2})^2 \left[m_{B_s}^2 - (m_{\ell_1} - m_{\ell_2})^2 \right] \right\}$$

a single parameter

$$\langle 0 | \bar{s} \gamma_\mu \gamma_5 b | B_s(p) \rangle = i\, f_{B_s} p_\mu$$

SM:
only C_{10}



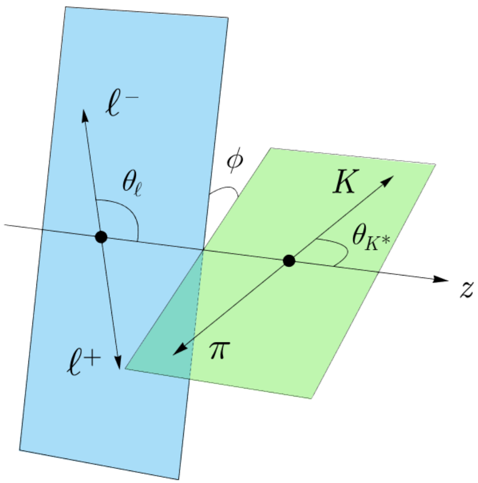
LHCb PRD 2022

Flavour anomalies: loop-induced modes

$\bar{B}^0 \to \bar{K}^{*0} \ell_1^- \ell_2^+$

fully differential decay rate

$$\frac{d^4\Gamma(\bar{B}^0 \to \bar{K}^{*0}(K\pi)\ell_1^-\ell_2^+)}{dq^2\, d\cos\theta_\ell\, d\cos\theta_{K^*}\, d\phi} = \frac{9}{32\pi} I(q^2, \theta_\ell, \theta_{K^*}, \phi)$$



$$\begin{aligned} I(q^2, \theta_\ell, \theta_{K^*}, \phi) = {} & I_1^s(q^2)\sin^2\theta_{K^*} + I_1^c(q^2)\cos^2\theta_{K^*} + \left[I_2^s(q^2)\sin^2\theta_{K^*} + I_2^c(q^2)\cos^2\theta_{K^*}\right]\cos 2\theta_\ell \\ & + I_3(q^2)\sin^2\theta_{K^*}\sin^2\theta_\ell\cos 2\phi + I_4(q^2)\sin 2\theta_{K^*}\sin 2\theta_\ell\cos\phi \\ & + I_5(q^2)\sin 2\theta_{K^*}\sin\theta_\ell\cos\phi \\ & + \left[I_6^s(q^2)\sin^2\theta_{K^*} + I_6^c(q^2)\cos^2\theta_{K^*}\right]\cos\theta_\ell + I_7(q^2)\sin 2\theta_{K^*}\sin\theta_\ell\sin\phi \\ & + I_8(q^2)\sin 2\theta_{K^*}\sin 2\theta_\ell\sin\phi + I_9(q^2)\sin^2\theta_{K^*}\sin^2\theta_\ell\sin 2\phi\,. \end{aligned} \tag{51}$$

$\bar{B}^0 \to \bar{K}^{*0} \ell_1^- \ell_2^+$

fully differential decay rate

$$\frac{d^4\Gamma(\bar{B}^0 \to \bar{K}^{*0}(K\pi)\ell_1^-\ell_2^+)}{dq^2\, d\cos\theta_\ell\, d\cos\theta_{K^*}\, d\phi} = \frac{9}{32\pi} I(q^2, \theta_\ell, \theta_{K^*}, \phi)$$

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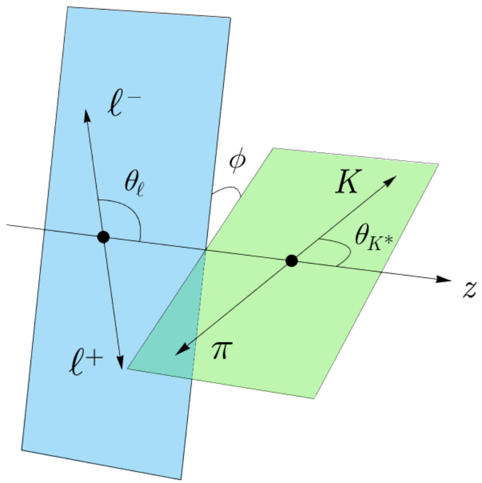

angular coefficient functions
- depend on q^2
- depend on the Wilson coefficients
- encode possible NP effects

Flavour anomalies: loop-induced modes

$\bar{B}^0 \to \bar{K}^{*0} \ell_1^- \ell_2^+$

fully differential decay rate

$$\frac{d^4\Gamma(\bar{B}^0 \to \bar{K}^{*0}(K\pi)\ell_1^-\ell_2^+)}{dq^2\, d\cos\theta_\ell\, d\cos\theta_{K^*}\, d\phi} = \frac{9}{32\pi} I(q^2, \theta_\ell, \theta_{K^*}, \phi)$$

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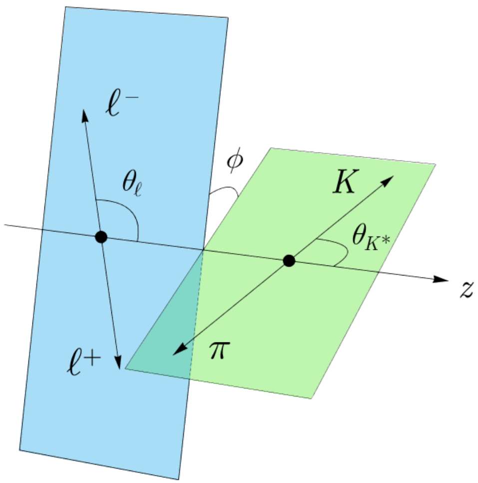


define:

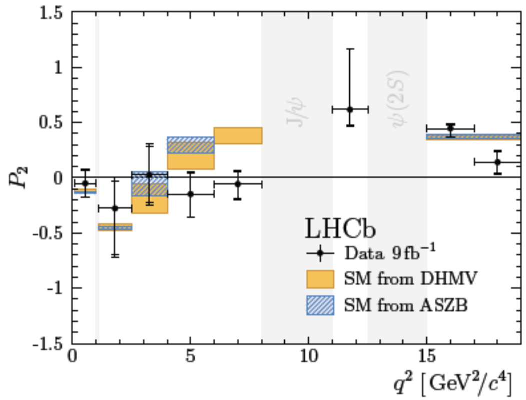
CP- conjugated mode

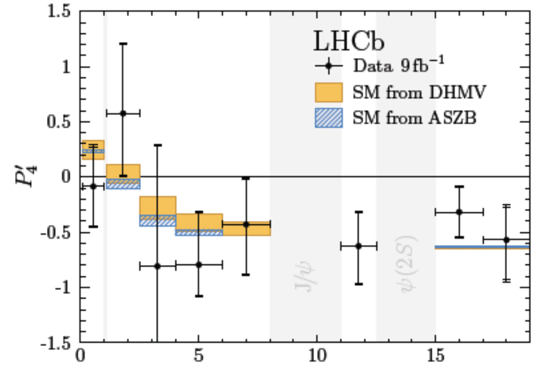
$$S_i^{(a)}(q^2) = \left(I_i^{(a)}(q^2) + \bar{I}_i^{(a)}(q^2)\right) / \left(d\Gamma/dq^2 + d\bar{\Gamma}/dq^2\right)$$

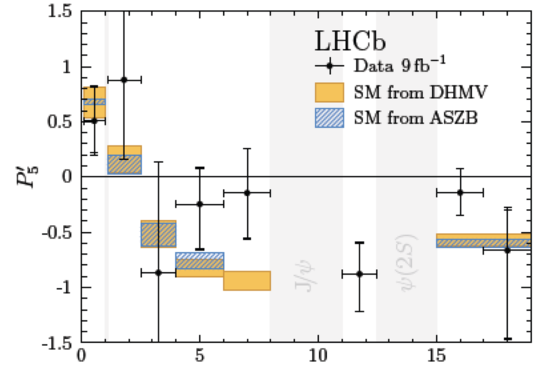
starting point to build *clean* observables

Flavour anomalies: loop-induced modes

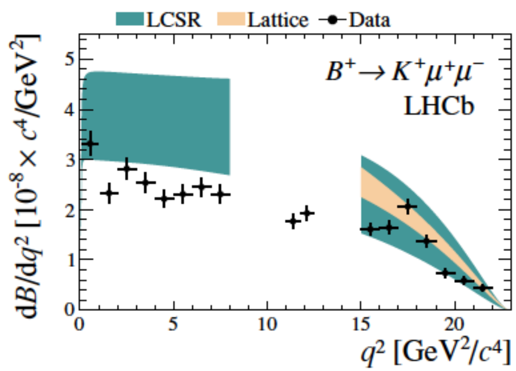
angular distributions in $B \to K^* \mu^+ \mu^-$

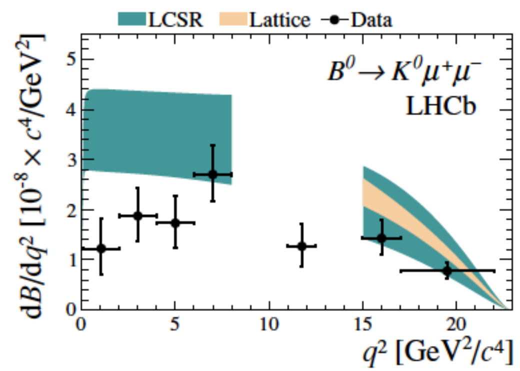


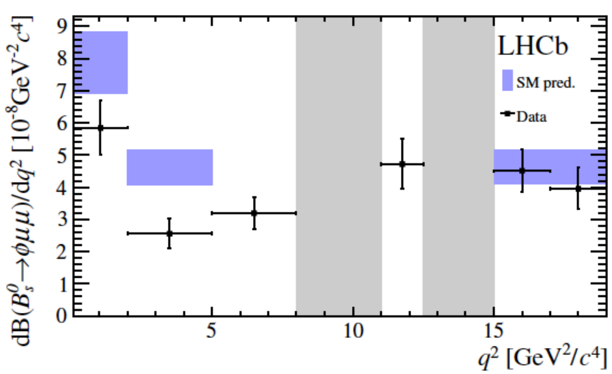


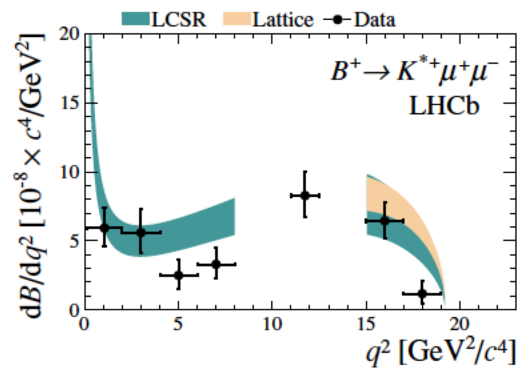


branching ratios in $b \to s \mu^+ \mu^-$









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Two approaches to BSM

1. Bottom-up (Standard Model Effective Field Theory-SMEFT)

- mainly driven by experiment
- SM as an effective low energy theory
- investigate NP effects without specifying the NP extension
- correlations among flavour observables

2. Top-down

- consider specific NP scenarios
- predict flavour observales, compare the results
- discriminate among the models

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Two approaches to BSM

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U(1)' anomaly free extension of the SM: ABCD Model

Minimal extension of the SM gauge group:

$$SU(3)_c \otimes SU(2)_L \otimes U(1)_Y \otimes U(1)'$$

- new abelian group
- new neutral gauge boson Z'
- new coupling g_Z
- new quantum number: *z*-hypercharge

interaction with SM fermions (+ right-handed ν) in the flavour basis

$$\mathcal{L}_{\rm int}^{Z'} = \sum_{i,j} \left[(\Delta_L^{\psi})^{ij}\, \bar{\psi}_L^i\, \gamma^\mu\, \psi_L^j + (\Delta_R^{\psi})^{ij}\, \bar{\psi}_R^i\, \gamma^\mu\, \psi_R^j \right] Z'_\mu$$

$$(\Delta_{L(R)}^{\psi})^{ij} = g_{Z'}\, z_{\psi_{L(R)}}\, \delta^{ij}$$

J. **A**ebischer, A.J. **B**uras, M. **C**erdà-Sevilla, F**D**F
JHEP 02 (2020) 183

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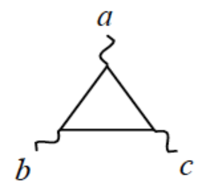
U(1)' anomaly free extension of the SM: ABCD Model

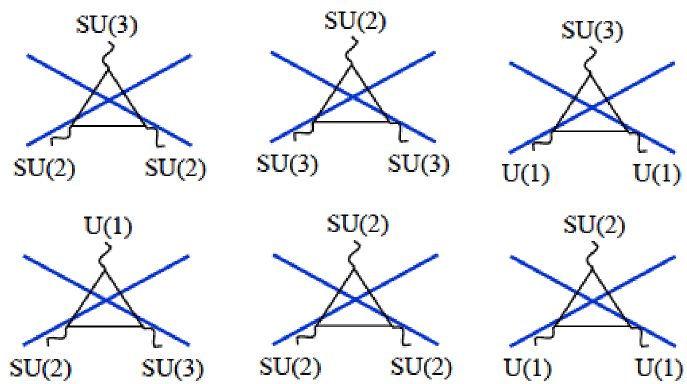
SM

anomalous graphs

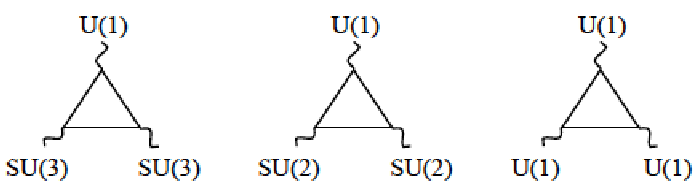


$\propto \; \mathrm{Tr}\big[\mathbf{T}_a\{\mathbf{T}_b, \mathbf{T}_c\}\big]$

generators



SU(N): $\mathrm{Tr}[T_a]=0$



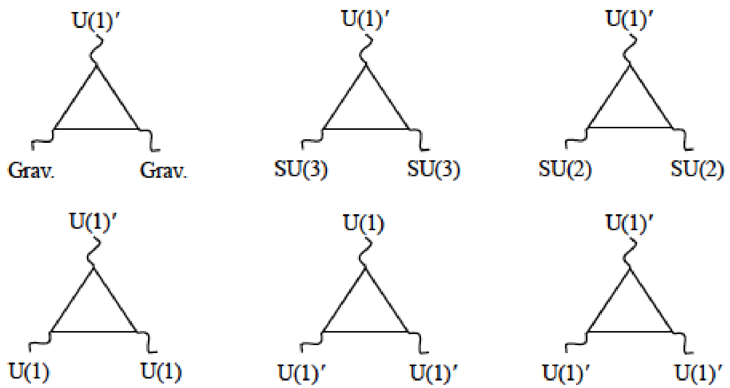
$$\begin{cases} A_{331} = 2y_q - y_u - y_d = 0 \;\checkmark \\ A_{221} = 3y_q + y_\ell = 0 \;\checkmark \\ A_{111} = 3(2y_q^3 - y_u^3 - y_d^3) + 2y_\ell^3 - y_e^3 = 0 \;\checkmark \end{cases}$$

- ✓ anomaly free
- ✓ gauge anomalies cancel within each fermion generation
  - → universality of gauge boson couplings to the three generations

U(1)' anomaly free extension of the SM: ABCD Model

SM+U(1)'

new triangle graphs
gauge anomaly cancellation → *z*- hyper charges cannot be arbitrary
→ solve anomaly cancellation equations (ACE)



$$f^i = q_L^i,\, u_R^i,\, d_R^i,\, \ell_L^i,\, e_R^i,\, \nu_R^i$$

$$z_f = \sum_{i=1,2,3} z_{f_i}$$

$$z_f^{(2)} = \sum_{i=1,2,3} z_{f_i}^2$$

$$z_f^{(3)} = \sum_{i=1,2,3} z_{f_i}^3$$

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

U(1)' anomaly free extension of the SM: ABCD Model

ABCD assumption:

$$f^i = q_L^i,\, u_R^i,\, d_R^i,\, \ell_L^i,\, e_R^i,\, \nu_R^i$$

$$z_{f_i} = y_f + \epsilon_i$$

SM hypercharges:
generation-independent

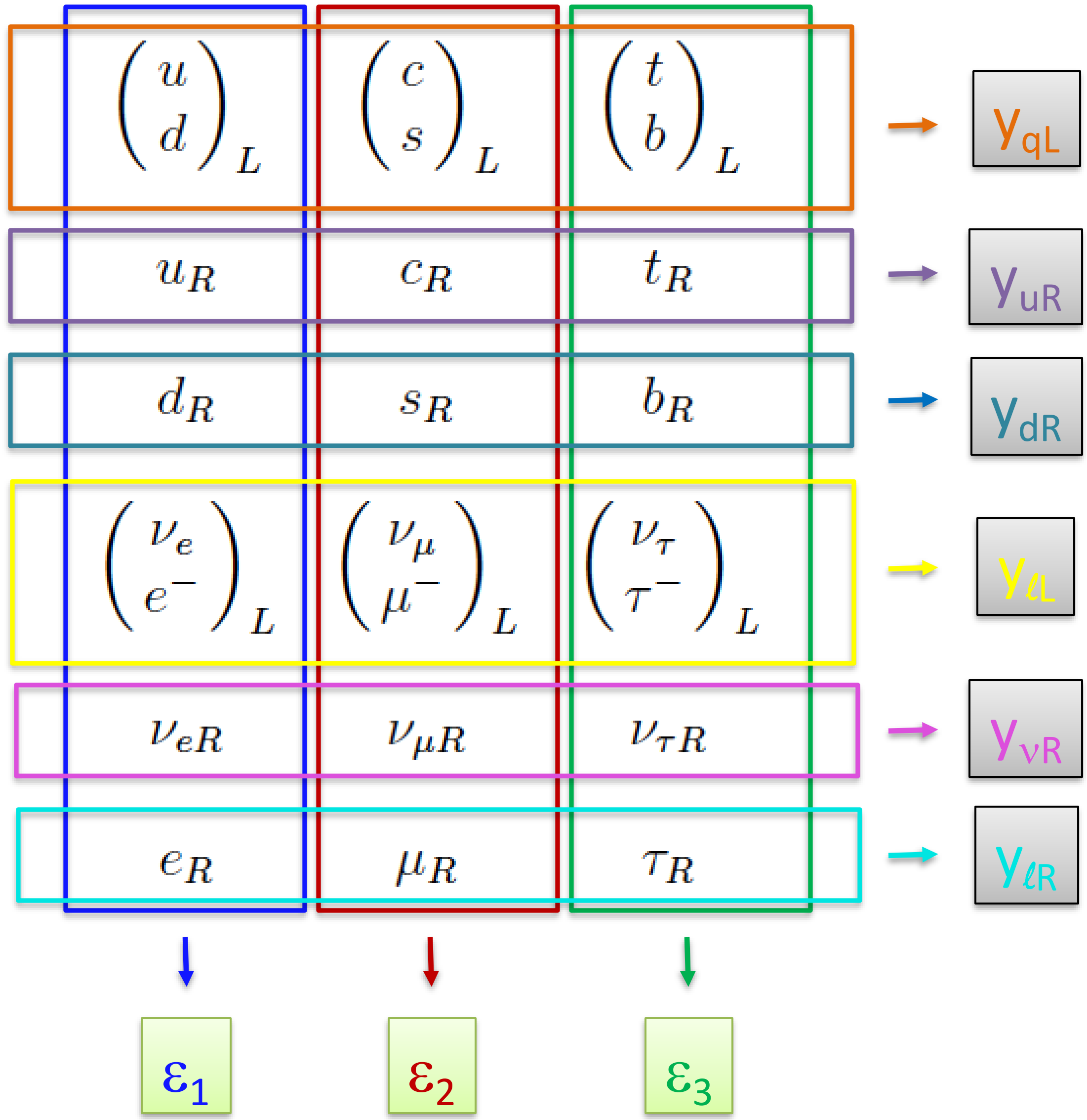
- NP parameters
- rational numbers
- generation dependent

Solution to the ACE:

$$\epsilon = \sum_{i=1}^{3} \epsilon_i = 0$$

only two ε independent

U(1)' anomaly free extension of the SM: ABCD Model



U(1)' anomaly free extension of the SM: ABCD Model

Implication for correlations:

Couplings to Z' of quark and leptons in the same generation governed by the same ε

ABCD Model: rotation to mass eigenstates

rotation matrices

$$(\hat{M}_\psi)_D = (\hat{V}_L^\psi)^\dagger \hat{M}_\psi \hat{V}_R^\psi$$

diagonal mass matrix

$(\psi^1_{L(R)},\, \psi^2_{L(R)}\,,\, \psi^3_{L(R)})$

same quantum numbers

$$\mathcal{L}_{\rm int}^{Z'} = \sum_{i,j} \left[(\Delta_L^\psi)^{ij}\, \bar{\psi}_L^i\, \gamma^\mu\, \psi_L^j + (\Delta_R^\psi)^{ij}\, \bar{\psi}_R^i\, \gamma^\mu\, \psi_R^j \right] Z'_\mu$$

$$(\Delta_L^\psi)^{ij} = g_{Z'} [(V_L^\psi)^\dagger \hat{Z}_L^\psi V_L^\psi]^{ij}$$

$$(\Delta_R^\psi)^{ij} = g_{Z'} [(V_R^\psi)^\dagger \hat{Z}_R^\psi V_R^\psi]^{ij}$$

rotation matrices enter the couplings

ABCD Model: rotation to mass eigenstates

rotation matrices

$$(\hat{M}_\psi)_D = (\hat{V}_L^\psi)^\dagger \hat{M}_\psi \hat{V}_R^\psi$$

diagonal mass matrix

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$$(\Delta_L^\psi)^{ij} = g_{Z'}[(V_L^\psi)^\dagger \hat{Z}_L^\psi V_L^\psi]^{ij}$$

$$(\Delta_R^\psi)^{ij} = g_{Z'}[(V_R^\psi)^\dagger \hat{Z}_R^\psi V_R^\psi]^{ij}$$

rotation matrices enter the couplings

Z' can mediate FCNC at tree level!

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ABCD Model: rotation to mass eigenstates

$$(\hat{M}_\psi)_D = (\hat{V}_L^\psi)^\dagger \hat{M}_\psi \hat{V}_R^\psi$$

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$$(\Delta_L^\psi)^{ij} = g_{Z'}[(V_L^\psi)^\dagger \hat{Z}_L^\psi V_L^\psi]^{ij}$$

$$(\Delta_R^\psi)^{ij} = g_{Z'}[(V_R^\psi)^\dagger \hat{Z}_R^\psi V_R^\psi]^{ij}$$

rotation matrices enter the couplings

Z’ can mediate FCNC at tree level!

Z’ can mediate Lepton Flavour Violating (LFV) modes at tree level!

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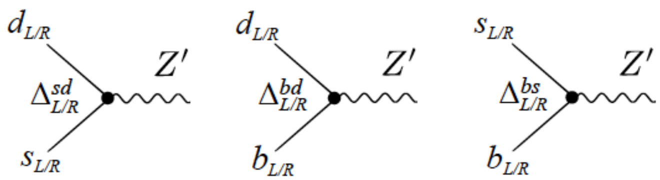
ABCD Model: final couplings

down quarks:

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

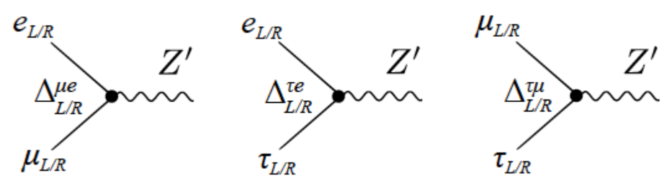
(CKM) (CKM-like)



charged leptons:

$$\Delta^{ij}_{e_L} = g_z \sum_k \epsilon_k U_{ik} U^*_{jk} \qquad \Delta^{ij}_{e_R} = g_z \sum_k \epsilon_k (U^e_R)^*_{ki} (U^e_R)_{kj}$$

(PMNS) (CKM-like)



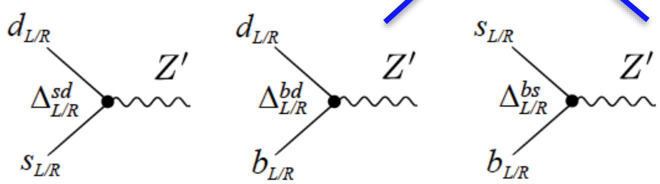
- Assumptions on Z' couplings to fermions → various possible scenarios

ABCD Model: scenario A

down quarks:

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

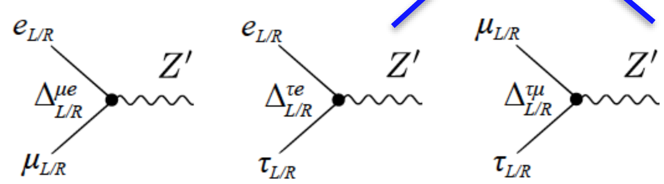
$$\Delta^{ij}_{d_R} = g_z \sum_k \epsilon_k (V^d_R)^*_{ki} (V^d_R)_{kj}$$ (CKM-like)



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)



- Assumptions on Z' couplings to fermions → various possible scenarios
- Appealing, the simplest one:

  flavour violating couplings only for LH fermions (scenario A)

ABCD Model: parameter space

$$(g_{Z'},\, M_{Z'},\, \epsilon_1,\, \epsilon_2,\, |V_{cb}|,\, |V_{ub}|) \longrightarrow \begin{cases} |V_{cb}| \in [|V_{cb}|_{exc},\, |V_{cb}|_{inc}] \\ |V_{ub}| \in [|V_{ub}|_{exc},\, |V_{ub}|_{inc}] \end{cases}$$

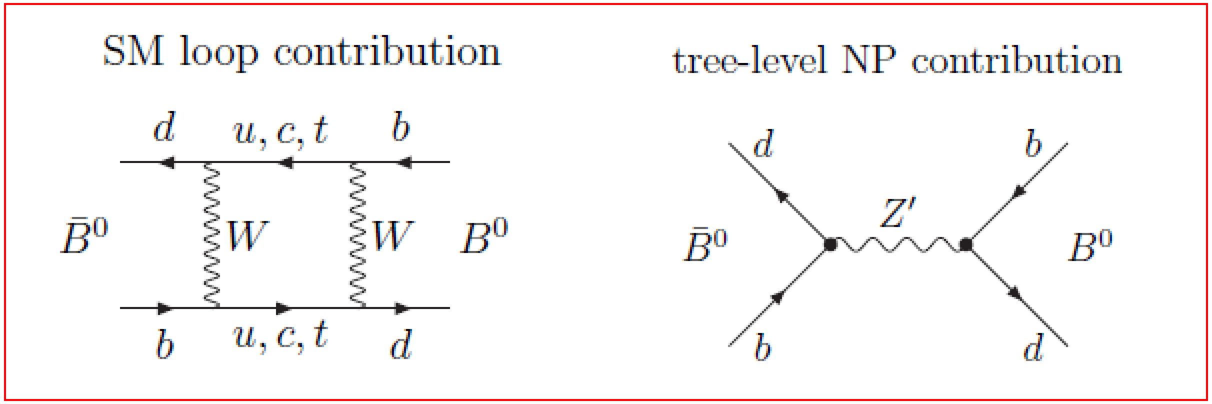
NP parameters

$M_{Z'} = 1$ TeV $\quad M_{Z'} = 3$ TeV

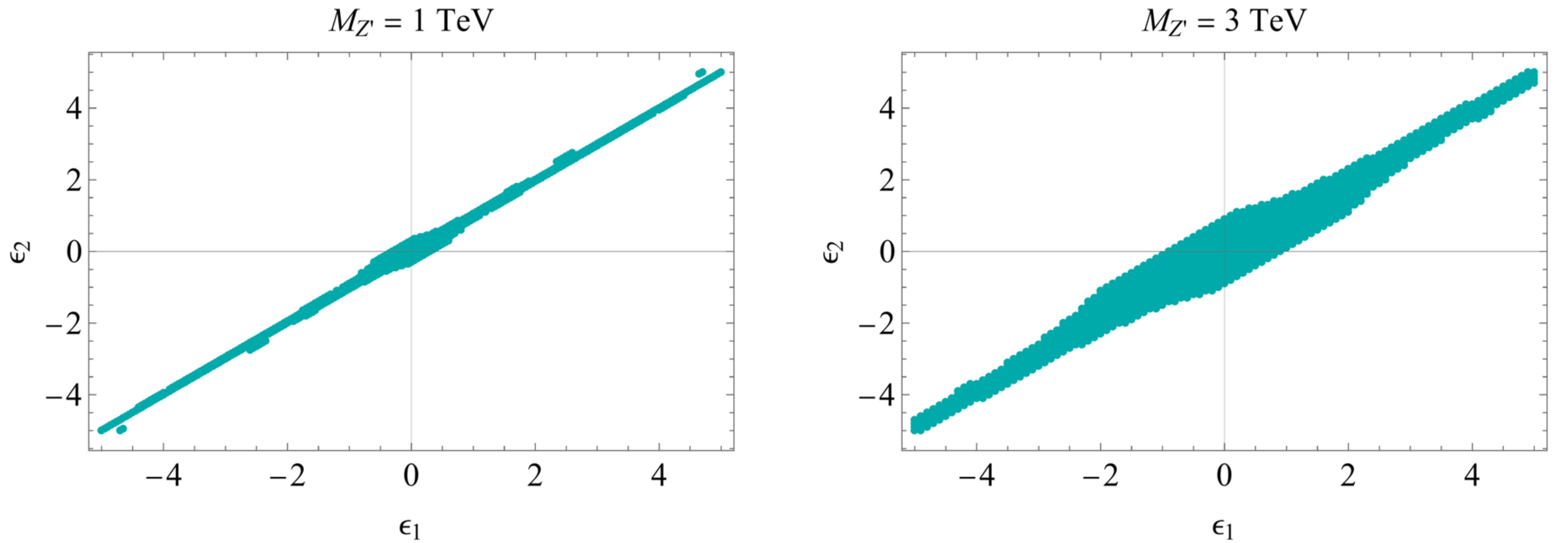
fixed from ΔF=2 observables:

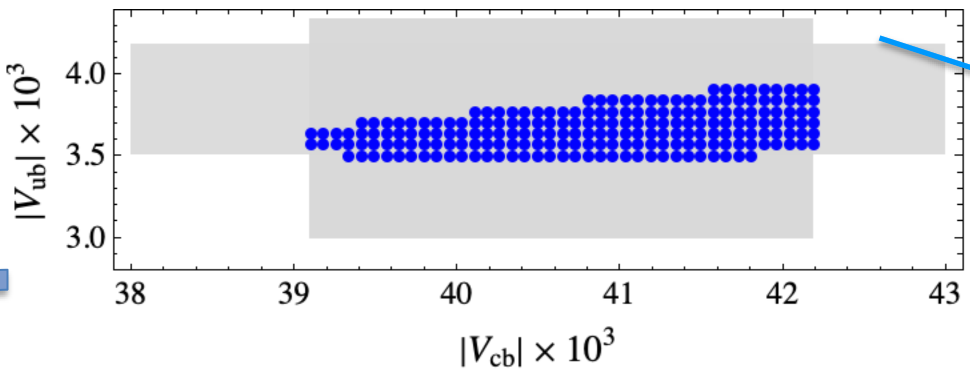
$\bar{B}_d - B_d$ system	ΔM_d	$(0.5069 \pm 0.0019)\ \text{ps}^{-1}$
	$S_{\psi K_S}$	0.709 ± 0.011
$\bar{B}_s - B_s$ system	ΔM_s	$(17.765 \pm 0.004)\ \text{ps}^{-1}$
	$S_{\psi\phi}$	0.051 ± 0.046
$K^0 - \overline{K^0}$ system	ΔM_K	$(0.0059 \pm 0.0015)\ \text{ps}^{-1}$
	ε_K	$(2.25 \pm 0.25) \times 10^{-3}$

Example of NP contribution:



ABCD Model: parameter space





excluded values of $|V_{ub}|_{incl}$

gray regions: initial ranges

$$|V_{cb}| \in [|V_{cb}|_{exc},\ |V_{cb}|_{inc}]$$

$$|V_{ub}| \in [|V_{ub}|_{exc},\ |V_{ub}|_{inc}]$$

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ABCD Model: rare B decays

$b \to s\, \ell_1^- \ell_2^+$

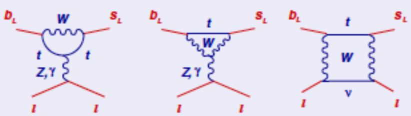
$$H^{\rm eff} = -4 \frac{G_F}{\sqrt{2}} V_{tb} V_{ts}^* \left\{ C_1 O_1 + C_2 O_2 + \sum_{i=3,..,6} C_i O_i + \sum_{i=7,..,10} [C_i O_i + C_i' O_i'] \right\}$$

opposite chirality absent in scenario A

credit J. Camalich

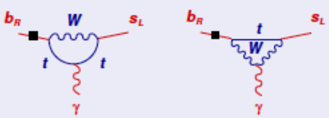
The $b \to s\ell\ell$ transition in the SM

- **Semileptonic operators**: $\mathcal{O}_9$ $(L+V)$, $\mathcal{O}_{10}$ $(L+A)$



$$\frac{\alpha}{4\pi} C_{9(10)}\, \bar{s}_L \gamma^\mu b_L\, \bar{\ell}\gamma_\mu(\gamma_5)\ell$$

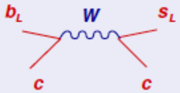
- **Electromagnetic penguin**: $\mathcal{O}_7$



$$\frac{e}{4\pi^2} m_b C_7\, \bar{s}_L \sigma_{\mu\nu} b_R F^{\mu\nu}$$

no contribution to LFV modes

- **CC @ 1 loop**

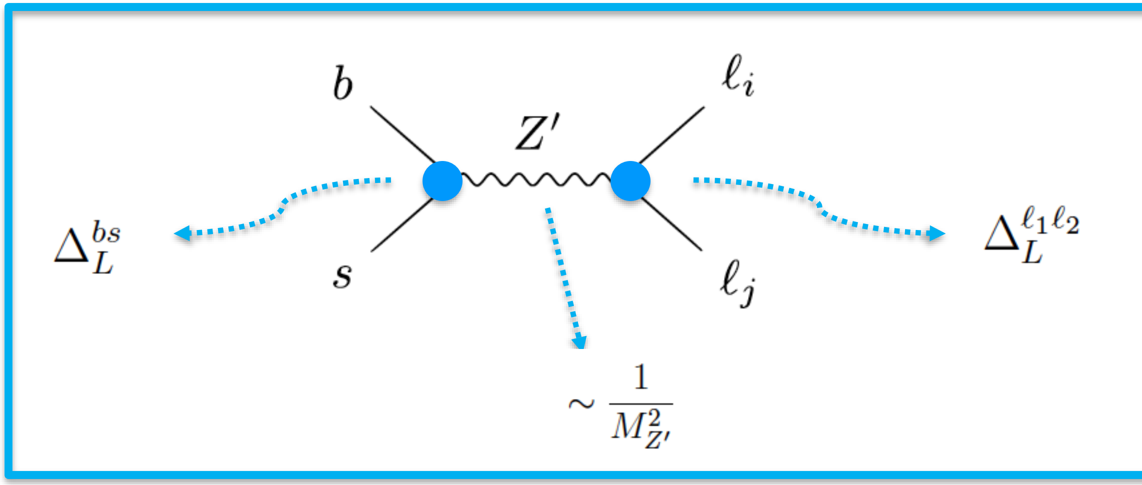


$$C_2\, \bar{c}_L \gamma^\mu b_L\, \bar{s}_L \gamma_\mu c_L$$

ABCD Model: rare B decays

ABCD:

- Tree level Z' exchange
- Wilson coefficients modified
- lepton-flavour dependent



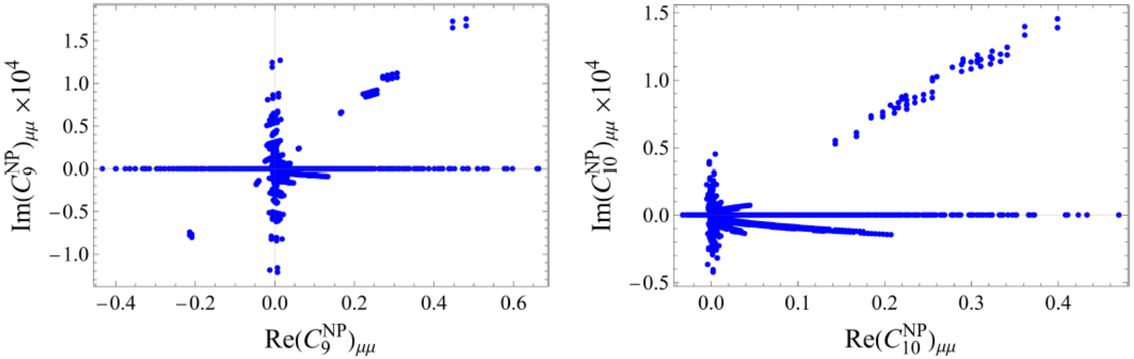
$$\left(C_{9(10)}\right)_{\ell_i\ell_j} = C_{9(10)}^{SM}\delta_{ij} + \left(C_{9(10)}^{\rm NP}\right)_{\ell_i\ell_j}$$

$$(C_9^{NP})_{\ell_1\ell_2} \propto -\frac{1}{M_{Z'}^2}\left(\Delta_L^{bs}\right)^*\Delta_V^{\ell_1\ell_2}\,, \qquad (C_{10}^{NP})_{\ell_1\ell_2} \propto -\frac{1}{M_{Z'}^2}\left(\Delta_L^{bs}\right)^*\Delta_A^{\ell_1\ell_2}$$

ABCD Model: rare B decays

Lepton Flavour Conserving (LFC) case

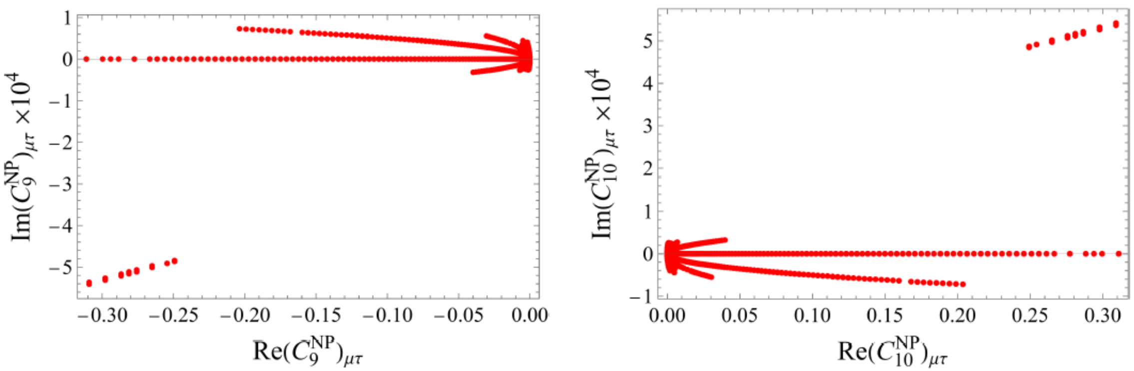
P. Colangelo, D. Milillo, FDF, arXiv:2506.02552



compare to:

$C_9^{\mathrm{SM}} = 4.273$ $\qquad$ $C_{10}^{\mathrm{SM}} = -4.166$

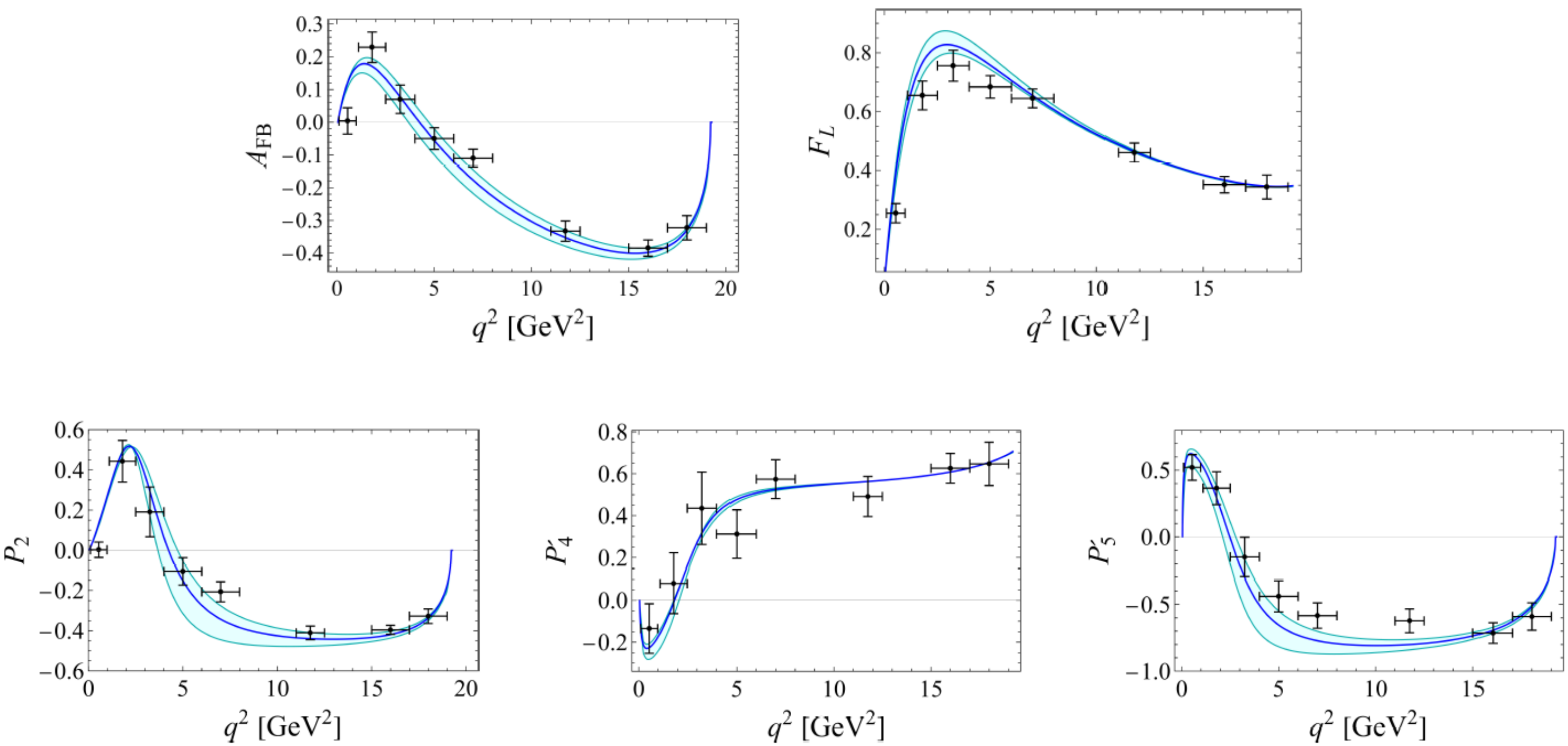
Lepton Flavour Violating (LFV) case



- imaginary parts tiny
- LFC : real parts can reach O(10%) SM value → possible deviations in observables
- LFV : real parts might produce observable effects

ABCD Model: LFC B decays

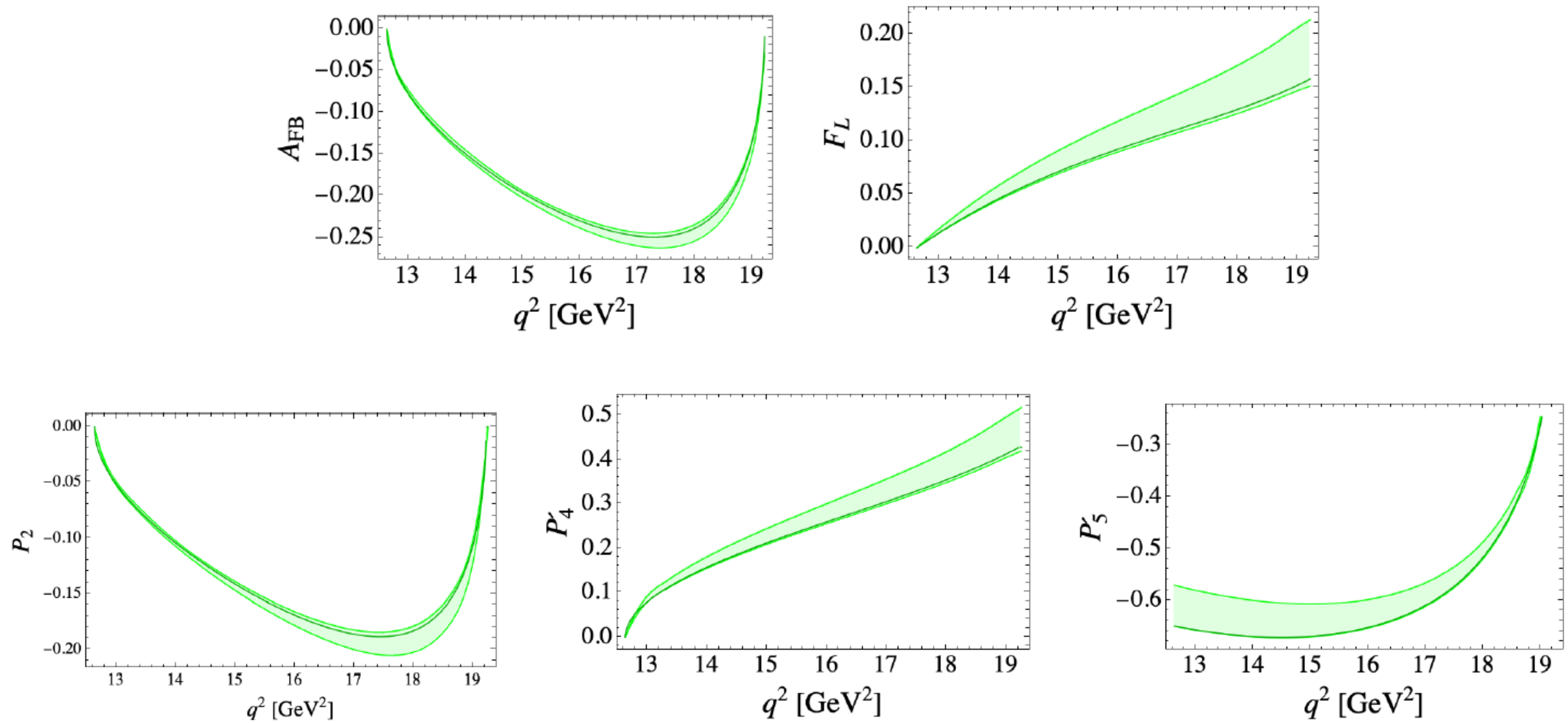
$\bar{B}^0 \to \bar{K}^{*0}\mu^+\mu^-$



possible small deviations wrt SM

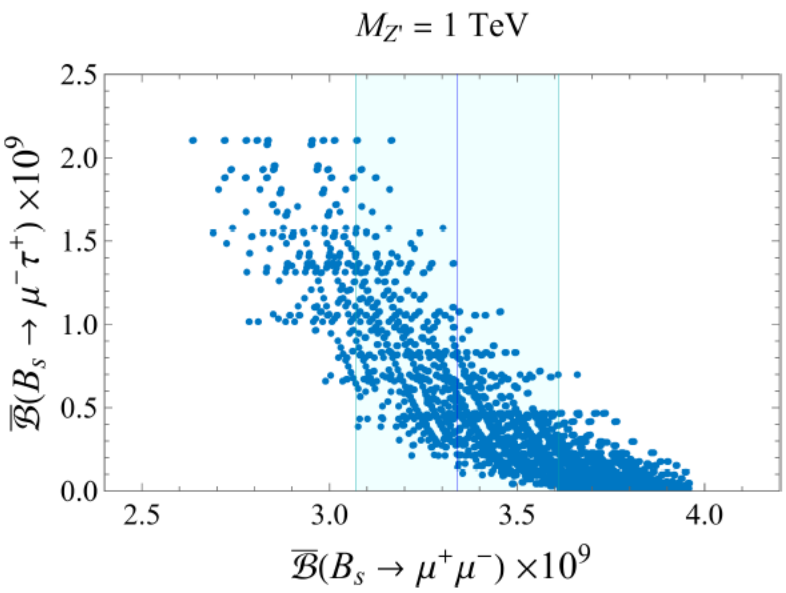
ABCD Model: LFC B decays

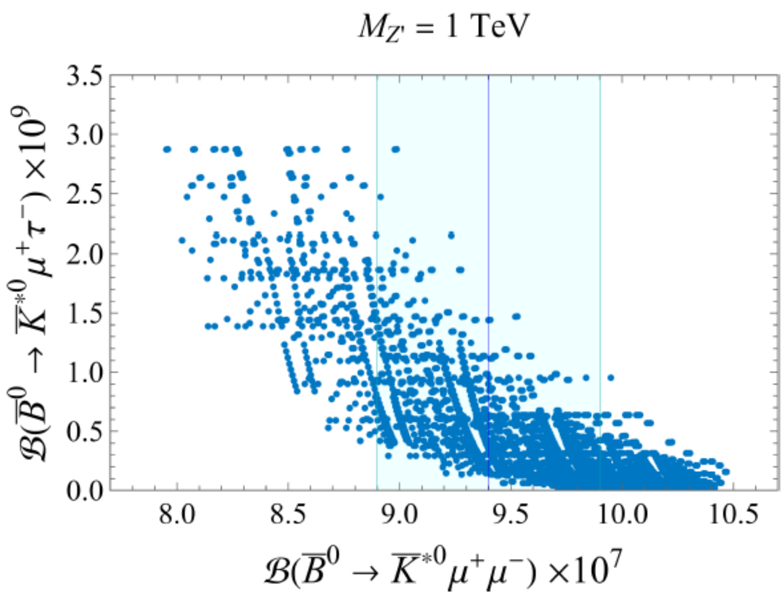
$\bar{B}^0 \to \bar{K}^{*0}\tau^+\tau^-$



possible small deviations wrt SM

Correlations between LFV land LFC decays





- LFV modes constrained by the corresponding LFC ones
- branching ratios O(10^{-9}) in the reach of future experiments

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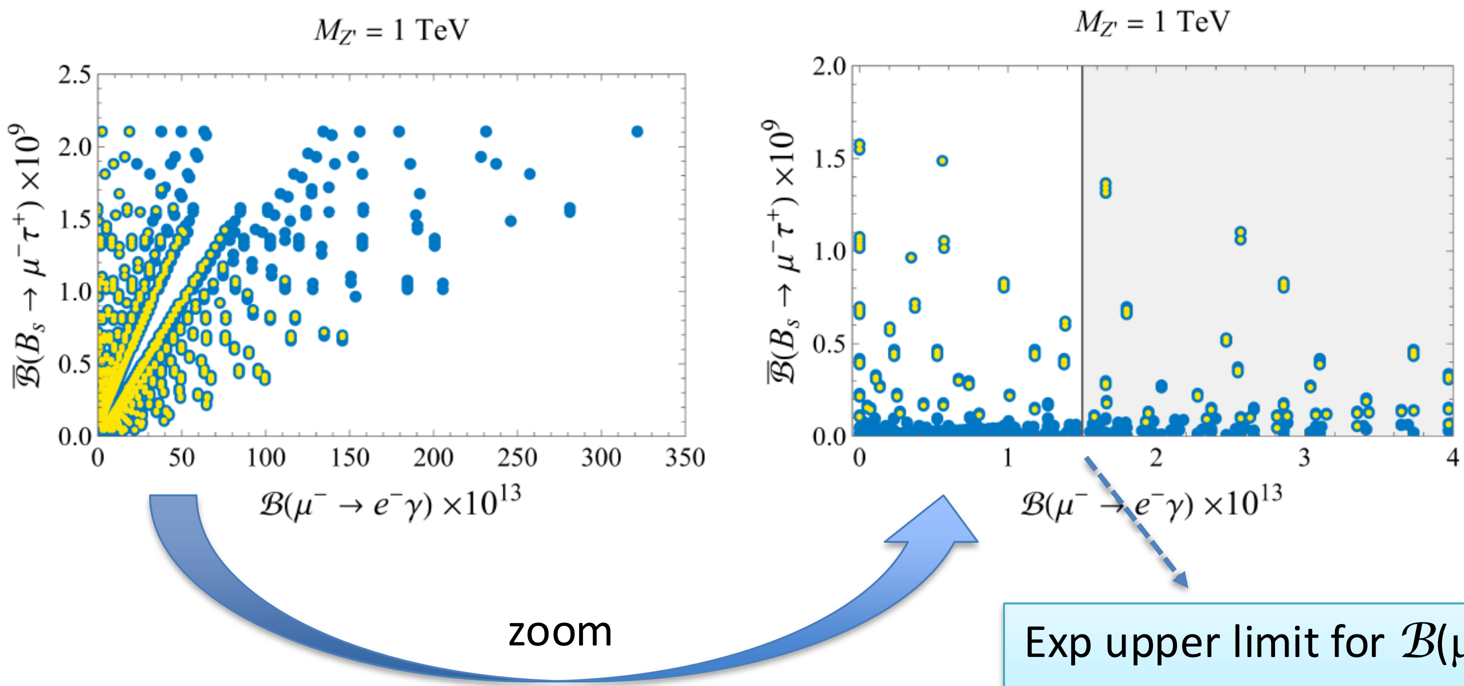
LFV rare B decays vs leptonic decays

ABCD: Z' couplings of quarks and leptons related
➢ correlations between quark and lepton observables

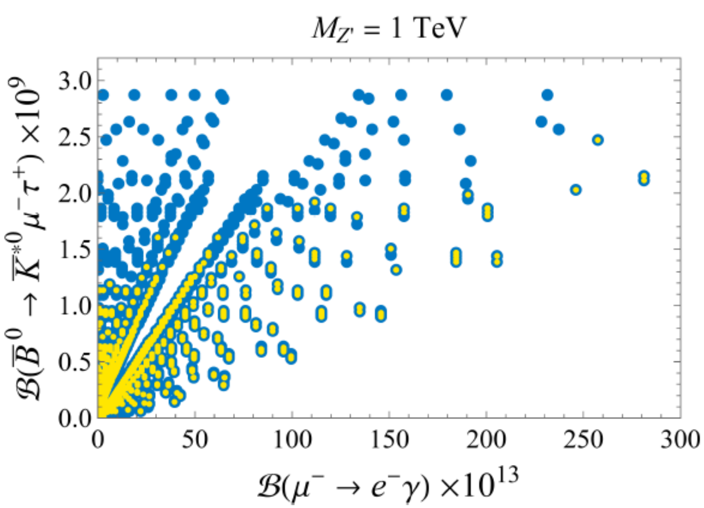


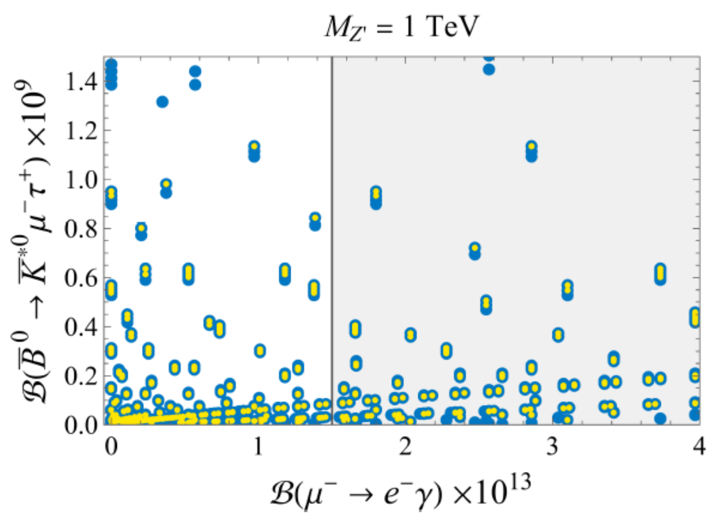
Exp upper limit for $\mathcal{B}(\mu^- \to e^- \gamma)$

constrains $\mathcal{B}(B_s \to \mu^- \tau^+)$

LFV rare B decays vs leptonic decays

ABCD: Z' couplings of quarks and leptons related
➢ correlations between quark and lepton observables





zoom

Exp upper limit for $\mathcal{B}(\mu^- \to e^- \gamma)$

constrains $\mathcal{B}(B^0 \to K^{*0} \mu^- \tau^+)$

LFV rare B decays vs leptonic decays

Summary

	LFV mode	$\mathcal{B}\times 10^9$	$\mathcal{B}^{(1)}\times 10^9$	$\mathcal{B}^{(2)}\times 10^9$	experiment
$M_{Z'} = 1$ TeV	$B_s \to \tau^+\mu^-$	$0.00 \div 2.10$	$0.00 \div 2.10$	$0.00 \div 1.60$	$< 4.2 \times 10^{-5}$ [28]
	$\bar{B}^0 \to \bar{K}^{*0}\tau^+\mu^-$	$0.00 \div 2.90$	$0.00 \div 2.90$	$0.00 \div 1.15$	$< 1.0 \times 10^{-5}$ [28]
	$B_s \to \phi\tau^+\mu^-$	$0.00 \div 3.43$		$0.00 \div 2.60$	$< 1.0 \times 10^{-5}$ [79]
$M_{Z'} = 3$ TeV	$B_s \to \tau^+\mu^-$	$0.00 \div 2.30$	$0.00 \div 1.50$	$0.00 \div 0.14$	$< 4.2 \times 10^{-5}$ [28]
	$\bar{B}^0 \to \bar{K}^{*0}\tau^+\mu^-$	$0.00 \div 3.10$	$0.00 \div 2.00$	$0.00 \div 0.20$	$< 1.0 \times 10^{-5}$ [28]
	$B_s \to \phi\tau^+\mu^-$	$0.00 \div 3.70$		$0.00 \div 0.25$	$< 1.0 \times 10^{-5}$ [79]

constrained by LFC modes

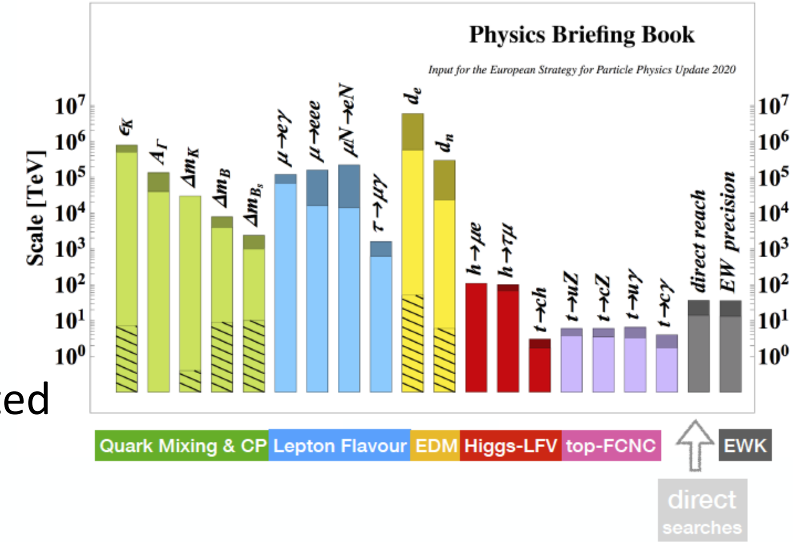
constrained by $\mathcal{B}(\mu^- \to e^- \gamma)$

Main message:
LFV quarks and lepton observables in the reach of future experiments

P. Colangelo, D. Milillo, FDF, arXiv:2506.02552

Conclusions

Flavour physics may access high scales



Understanding the anomalies requires

- Control over theory uncertainty
- Explore other modes where anomalies are expected
- Work out correlations

ABCD model:

- ➢ large deviations have not been found in SM allowed modes
  → mutual action of quark and lepton sectors

- ➢ LFV processes predicted in the reach of future experiments
  → SM forbidden: smoking gun for NP