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New Physics at LHC and fluxed GUTs

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Outline of the talk

1. Experimental Facts
2. Explanations with new particles
3. F-GUTs and Non-Universal $U(1)$'s
4. Conclusions

$\mathcal{A}$

Experimental Facts

▲ Lepton Flavour Universality (LFU) Violation ▲

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Beyond the **Standard Model**

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Evidence (?)

$\Downarrow$

Anomalous B-decays at LHC

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Tension with Lepton Flavour Universality (LFU) in SM

LFU

(*brief reminder*)

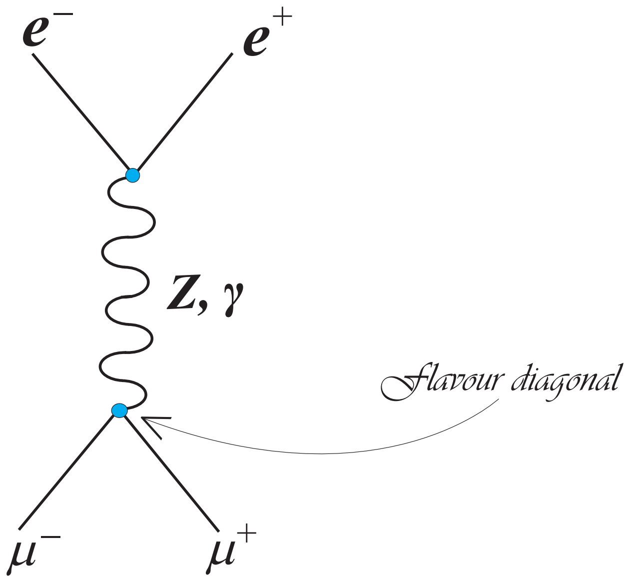
▲ **Standard Model**:

EW couplings of leptons to neutral gauge bosons:

Flavour Independent

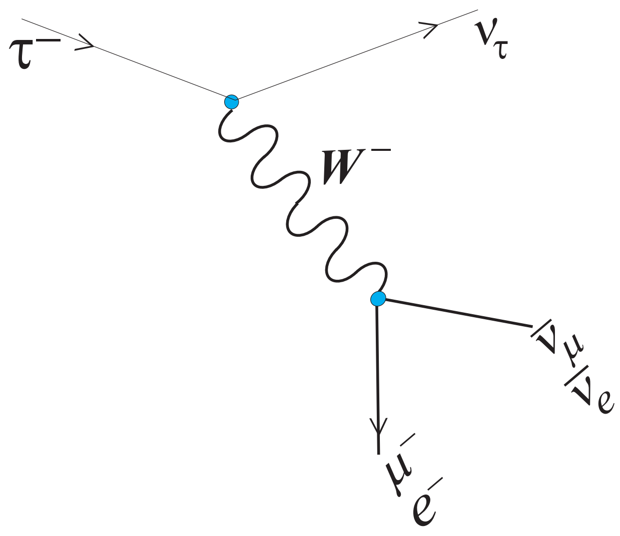
examples:

- *Involving neutral bosons* : $e^+e^- \to Z \to \mu^+\mu^-$



- *Involving* $W^{\pm}$ *(at tree level...)*

$$\Gamma(\tau^- \to \mu^- + \bar{\nu}_\mu + \nu_\tau) = \Gamma(\tau^- \to e^- + \bar{\nu}_e + \nu_\tau)$$



Both cases are in agreement with experimental measurements

Focusing on Z

▲ Z gauge boson of broken symmetry

$\Rightarrow$ *in principle no reason to prevent* $FCNC$*s*

but

... in $\mathcal{SM}$, there are no $FCNC$s at tree-level!

explanation

Z connects fermions with same **charge** Q and **Colour**

$$Q = T_3 + Y$$

All quarks with same Q, have the same T_3 and Y.

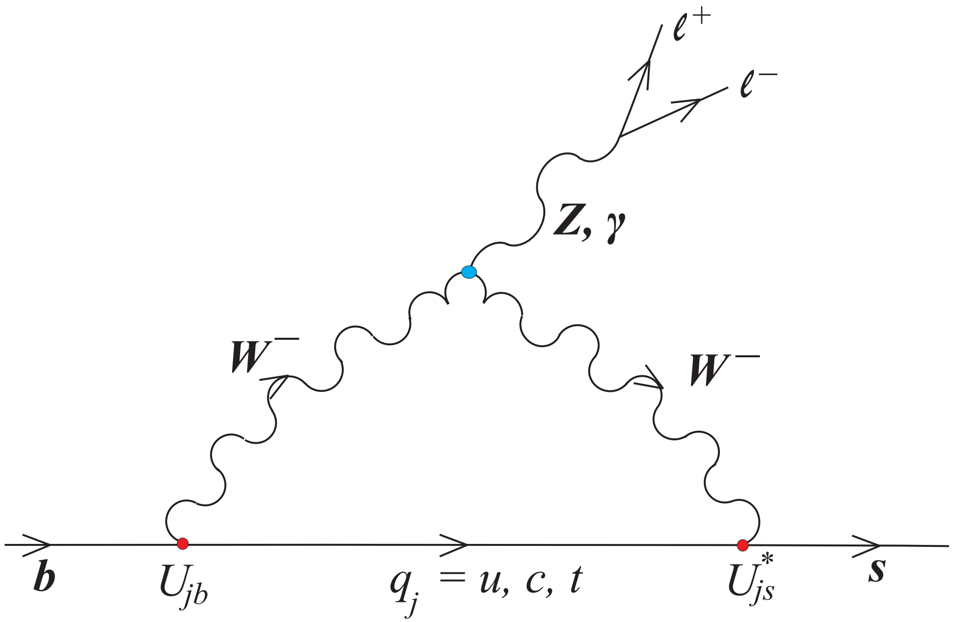
All couple with the same strength (Universal)

$$g^{Zff} = g\cos\theta_W T_3 - g'\sin\theta_W Y$$

B-meson decays

in SM occur due to flavour violating transition

$$b \to s + \gamma$$



▲ $Z\ell^+\ell^-$ *vertex* $\to$ *flavour independent* $\to$ $\ell^+\ell^-$ same flavour

▲ b u W *vertex* $\to$ *flavour violating* (*CKM* mixing.)

$\Rightarrow$ **Suitable candidate reactions** to test LFU:

$$b \to s\ell^+\ell^-, \quad \ell = e, \mu, \tau$$

b-quarks are found in B mesons such as $B^+ = \bar{b}u$ and $B^0 = \bar{b}d$;

$$B^+ \quad \to \quad K^+\ell^+\ell^-$$

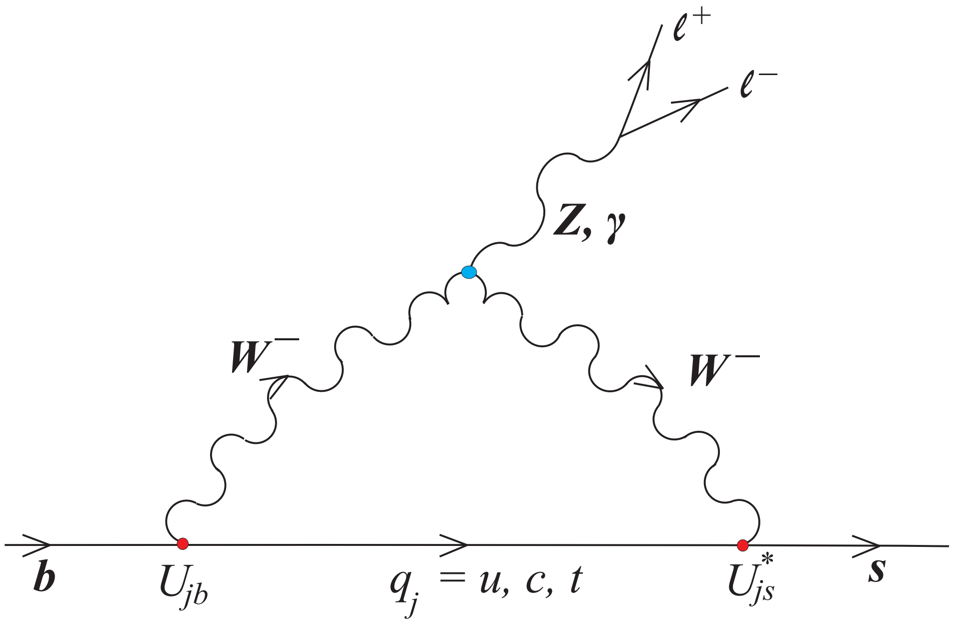
$$B^0 \quad \to \quad K^{*0}\ell^+\ell^-$$

remarks

(K^{*0} *reconstructed in the final state* $K^+\pi^-$)

In Flavour changing (only) processes, BRs of neutral currents suppressed compared to charged ones...

$$Br(B^- \to K^{*-}\ell^+\ell^-) \sim 5 \times 10^{-7}, \quad Br(B^- \to D^0\ell\bar{\nu}) \sim 2.3\%$$



▲ *Lepton Flavour Universality* at Z vertex ⇒

Ratios of branching ratios in SM: expected to be ~ 1:

$$R_{X_{ij}} = \frac{\mathrm{BR}(B \to X^+ \ell_i^+ \ell_i^-)}{\mathrm{BR}(B \to X^+ \ell_j^+ \ell_j^-)} \approx 1$$

$i, j = e, \mu, \tau;\ X = K^+, K^0, \cdots$ but ! →

pp collision data at ~ 8 TeV, 2011-2012

LHCb experimental evidence *in tension* with SM:

$$R_K = \frac{\mathrm{BR}(B \to K^+\mu^+\mu^-)}{\mathrm{BR}(B \to K^+e^+e^-)} = 0.745 \pm 0.09(stat) \pm 0.036(syst)$$

integrated over $1\mathrm{GeV}^2 < q^2 < 6\ \mathrm{GeV}^2$ (dilpeton invariant mass^2)

$$R_{K^*} = \frac{\mathrm{BR}(B \to K^*\mu^+\mu^-)}{\mathrm{BR}(B \to K^*e^+e^-)} \approx \begin{cases} 0.660 & (2m_\mu)^2 < q^2 < 1.1\mathrm{GeV}^2 \\ 0.685 & 1.1\mathrm{GeV}^2 < q^2 < 6\mathrm{GeV}^2 \end{cases}$$

▲ Both ratios → deficit in same direction! ▲

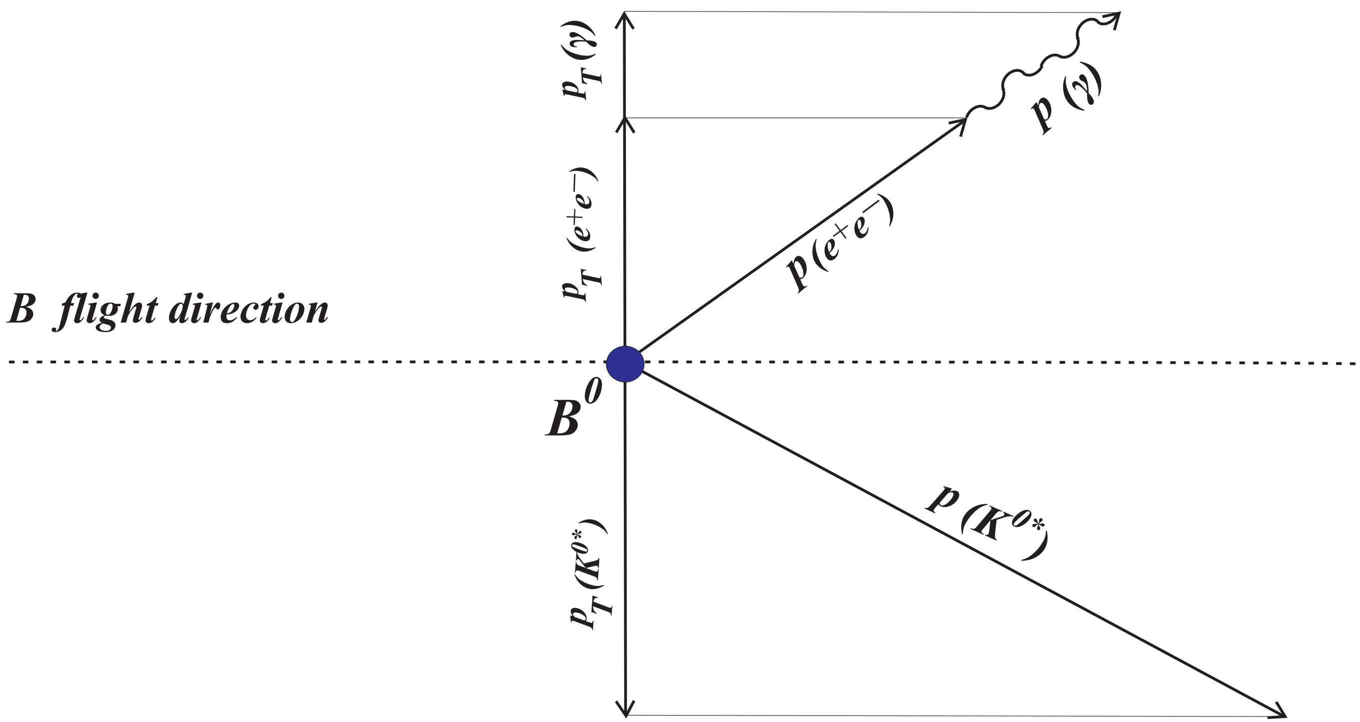
▲ Unexplained in SM ▲

experimental data … against expectations?…

▲ LHCb more efficient for $B \to K^*\mu^+\mu^-$

▲ $B \to K^*e^+e^-$: significant reduction due to bremsstrahlung

Bremsstrahlung effect recovery (evaluation of p_T difference):
(LHCb 1705.05802)



Other deviations

1) ▲ *based on transition* $b \to c$:

$$R_{D^*}{}^{exp} = \frac{\mathrm{BR}(B \to D^* \tau \nu_\tau)}{\mathrm{BR}(B \to D^* \ell \nu_\ell)} \approx 0.321, \quad R_{D^*}{}^{SM} = 0.252$$

2) ▲ Deficit of differential branching fraction $B_s \to \phi \mu^+ \mu^-$:

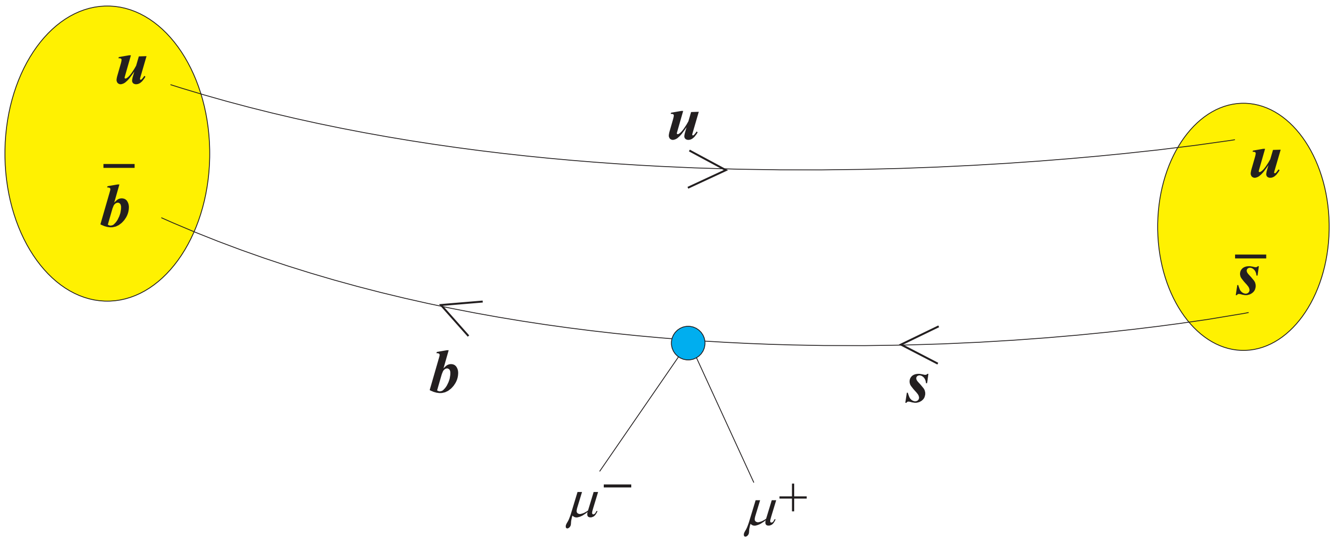
$$\frac{d\mathcal{B}(B_s^0 \to \phi \mu^+ \mu^-)}{dq^2} \;\; ; (\phi \to K^+ K^-)$$

$(B_s = \bar{b}s, \phi = \bar{s}s)$

New Physics *solution to the puzzle...required!*

Generate new contributions to the process :

$$B \to K\,\mu^-\mu^+$$



Observation: a new physics interaction discriminating μ, e ratios in B decays, induces new sources of lepton flavour violation

Effective Hamiltonian *approach*

SM & BSM contributions parametrised in terms of the

$$\mathcal{H}_{eff} = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \frac{\alpha}{4\pi} \sum_k \left(C_k(\mu) \mathcal{O}_k(\mu) + C'_k(\mu) \mathcal{O}'_k(\mu) \right)$$

$C_k(\mu)$: *Dimensionless parameters in* $\mathcal{H}_{eff} \rightarrow$ *Wilson coefficients (... depend on masses, couplings and various constants)*

$\mathcal{O}_n(\mu)$: *semi-leptonic operators related to the fields* ℓ, b, s

LHCb data in B-decay anomalies

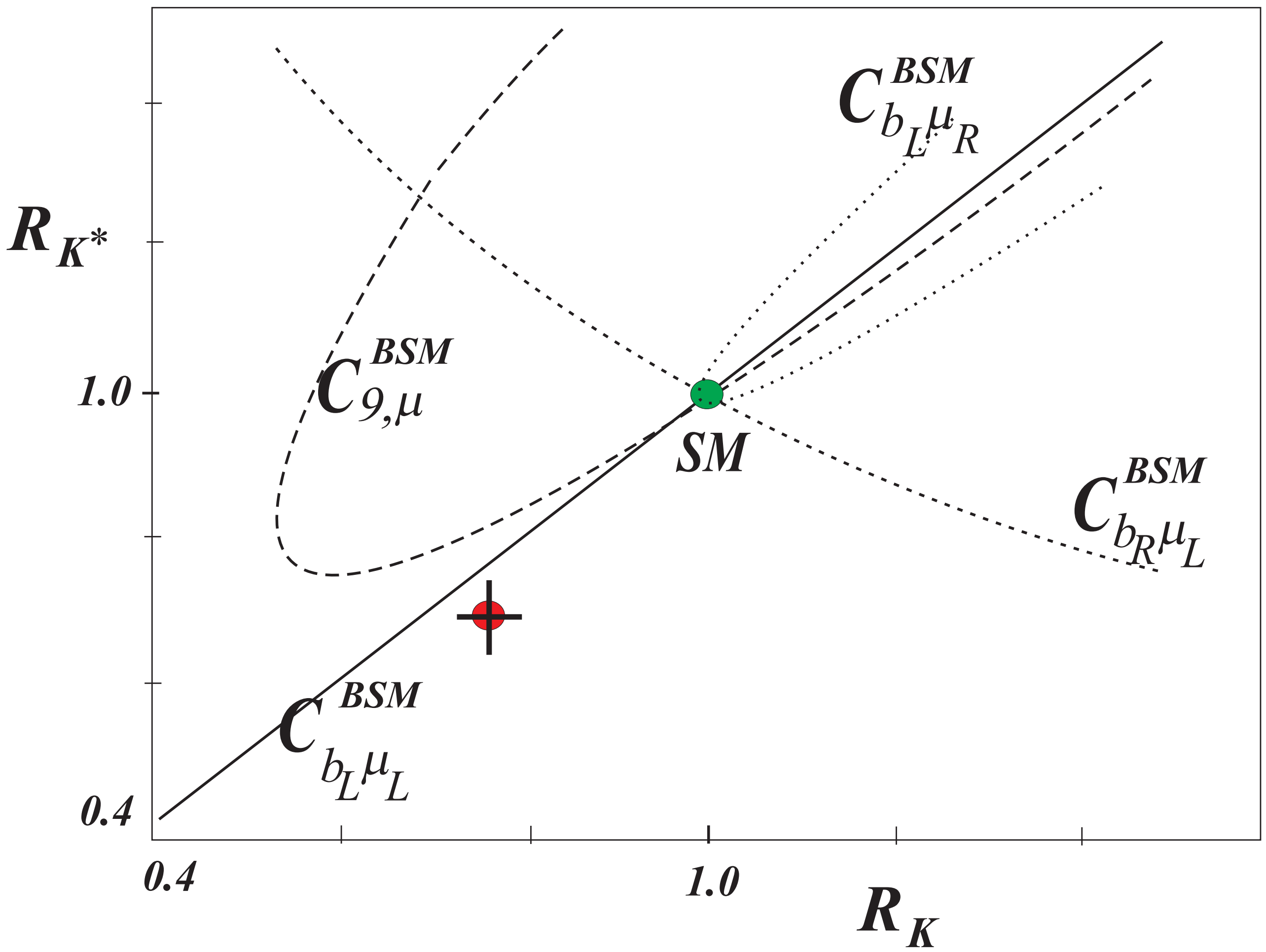
are in accordance with contributions from the following semi-leptonic operators:

$$\begin{aligned}
\mathcal{O}_9 &= \bar{s}\gamma_\lambda P_L b \bar{\ell}\gamma^\lambda \ell \\
\mathcal{O}_9' &= \bar{s}\gamma_\lambda P_R b \, \bar{\ell}\gamma^\lambda \ell \\
\mathcal{O}_{10} &= \bar{s}\gamma_\lambda P_L b \, \bar{\ell}\gamma^\lambda \gamma_5 \ell \\
\mathcal{O}_{10}' &= \bar{s}\gamma_\lambda P_R b \, \bar{\ell}\gamma^\lambda \gamma_5 \ell
\end{aligned} \tag{1}$$

$P_L = \frac{1}{2}(1-\gamma_5),\ P_R = \frac{1}{2}(1+\gamma_5)$

Wilson coefficients:

$$C_k(\mu) = C_k(\mu)^{SM} + C_k(\mu)^{BSM}$$



correlations of R_K/R_{K^*} deviations and the corresponding chiral operators generated by New Physics in the μ sector (based on 1704.05438)

Possible Solutions

▲ $\mathcal{A}$: **Negative** New Physics contributions 25% to C_9.

$$C_9{}^{NP} \approx -1.07$$

▲ $\mathcal{B}$: Contributions along the $SU(2)$-invariant direction
$C_9 = -C_{10}$, ($V - A$-type)

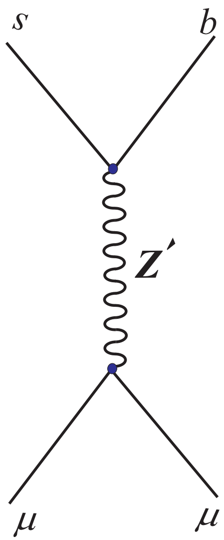
$$C_9{}^{NP} \approx -0.53, \; C_{10}{}^{NP} \approx 0.53$$

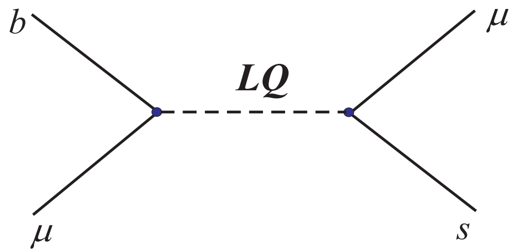
BSM Extensions involve:

▲ 1.) Z' neutral gauge boson
(*coupled differently to 3rd family and/or vectorlike fields*)
▲ 2.) New Particles (Leptoquarks...) (*1709.00692*)

Graphs:

Z' boson and Leptoquark contributions to $b \to s\mu^+\mu^-$





focus in present talk:

Z' contribution to $B^+ \to K^+\mu^+\mu^-$ (*see e.g. 1511.07447*)

... assuming a toy example of Z' *current: (1511.07447)*

$$J'^{0}_{\lambda} = g_\mu\,\bar{\mu}\gamma_\lambda\mu + g_t\,\bar{t}\gamma_\lambda P_L t + g_q\bar{q}\gamma_\lambda P_L q$$

$$+(g_t - g_q)\,V^*_{ts}V_{tb}\,\bar{s}\gamma_\lambda P_L b + \cdots$$

g_q *couplings taken equal for* $q = u, d, c, s$ *to suppress FCNC*

Then:

$$C_9^{NP} = -\frac{\pi g_\mu (g_t - g_q)}{2\sqrt{2}G_F M^2_{Z'} c^2_W \alpha} \approx -\frac{\pi g_\mu (g_t - g_q)}{c^2_W \left(\frac{M_{Z'}}{2\,\mathrm{TeV}}\right)^2}$$

$\rightarrow$ **promising!** *since* $C_9^{NP} \sim -1$ for:

- **reasonable** values of g_t, g_q, g_μ, and
- new neutral boson mass $M_{Z'} \sim$ few TeV.

thus... minimal requirement:

... Z' explains the anomalous B-decays if :

Z' couplings to 2^{nd} and 3^{rd} families are different!

or

... in the presence of a heavier vector-like family ...

$\mathcal{B}$

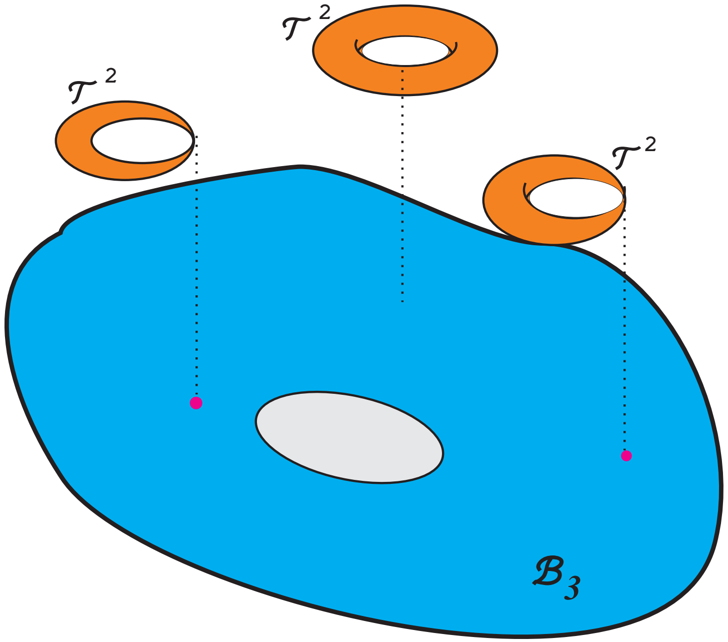
F-theory model building

...practical and local

F-theory *6-d compact manifold*

elliptically fibered with equation describing a torus:

$$y^2 = x^3 + f(z)\, x + g(z)$$



Topol. and geom. properties depend on $f(z), g(z)$

GUT Models from F-Theory

BASIC INGREDIENTS

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- **geometric singularities** $\rightleftarrows$ **gauge symmetries**

  (*Elliptic fibration admits* E_8 *and its subgroups*)
- **topology and fluxes** $\rightleftarrows$ **low energy properties**

A Class of 'semi-local' constructions

▲▼ *The role of* the manifold: ▲▼

▲ candidate GUT embedded in maximal exceptional group:

$$\mathcal{E}_8 \to \mathbf{G_{GUT}} \times \mathcal{C}$$

Assuming a Manifold with $SU(5)$ divisor:

$$\begin{aligned} \mathcal{E}_8 &\to SU(5) \times SU(5)_\perp \\ &\to SU(5) \times U(1)^4 \end{aligned}$$

Matter descends from the Adjoint:

$$248 \to (24,1) + (1,24) + (10,5) + (\bar{5},10) + (\bar{5},\overline{10}) + (5,\overline{10})$$

$SU(5)_\perp \rightarrow$: *locally described by Cartan roots:*

$$t_i \;=\; SU(5)_\perp - \text{roots} \rightarrow \;\; \sum_{i=1}^{5} t_i = 0$$

$$SU(5)_\perp = \begin{pmatrix} t_1 & 0 & 0 & 0 & 0 \\ 0 & t_2 & 0 & 0 & 0 \\ 0 & 0 & t_3 & 0 & 0 \\ 0 & 0 & 0 & t_4 & 0 \\ 0 & 0 & 0 & 0 & t_5 \end{pmatrix}$$

effective theory representations transform according to:

$$(10, 5) \;\;\rightarrow\;\; 10_{t_i}$$

$$(\overline{5}, 10) \;\;\rightarrow\;\; \overline{5}_{t_i+t_j}$$

The role of fluxes:

Three important implications

- $SU(5)$ Chirality
- $SU(5)$ Symmetry Breaking

(fluxes act as the surrogate of the Higgs vev)

- **Splitting of $SU(5)$-reps**

Two types of fluxes:

i) M_{10}, M_5: (*associated with* $U(1)_\perp$ *'s*)

determine the chirality of complete $10, 5 \in SU(5)$

ii) N_Y: *(turned on along* $U(1)_Y \in SU(5)$*)*

... **split** $SU(5)$*-representations*

$SU(5)$ chirality from $U(1)_\perp$ Flux

$U(1)_\perp$–Flux on SM reps $\in$ **10**'s:

$$\#10 - \#\overline{10} = \left\{ \begin{array}{l} n_{(3,2)_{\frac{1}{6}}} - n_{(\bar{3},2)_{-\frac{1}{6}}} \\ n_{(\bar{3},1)_{-\frac{2}{3}}} - n_{(3,1)_{\frac{2}{3}}} \\ n_{(1,1)_1} - n_{(1,1)_{-1}} \end{array} \right\} = M_{10}$$

$U(1)_\perp$– Flux on SM reps $\in$ **5**'s:

$$\#5 - \#\overline{5} = \left\{ \begin{array}{l} n_{(3,1)_{-\frac{1}{3}}} - n_{(\bar{3},1)_{\frac{1}{3}}} \\ n_{(1,2)_{\frac{1}{2}}} - n_{(1,2)_{-\frac{1}{2}}} \end{array} \right\} = M_5$$

SM chirality form Hypercharge Flux

$U(1)_Y$ –**Flux**-splitting of **10**'s:

$$\begin{aligned} n_{(3,2)_{\frac{1}{6}}} - n_{(\bar{3},2)_{-\frac{1}{6}}} &= M_{10} \\ n_{(\bar{3},1)_{-\frac{2}{3}}} - n_{(3,1)_{\frac{2}{3}}} &= M_{10} - N_{Y_{10}} \\ n_{(1,1)_{1}} - n_{(1,1)_{-1}} &= M_{10} + N_{Y_{10}} \end{aligned}$$

$U(1)_Y$– **Flux**-splitting of **5**'s:

$$\begin{aligned} n_{(3,1)_{-\frac{1}{3}}} - n_{(\bar{3},1)_{\frac{1}{3}}} &= M_{5} \\ n_{(1,2)_{\frac{1}{2}}} - n_{(1,2)_{-\frac{1}{2}}} &= M_{5} + N_{Y_{5}} \end{aligned}$$

For the Higgs 'curve' in particular:

Hyper-Flux Doublet-Triplet splitting :

$U(1)_Y-$ **Flux**-splitting of $\mathbf{5_{H_u}}$:

$$
\begin{aligned}
n_{(3,1)_{-\frac{1}{3}}} - n_{(\bar{3},1)_{\frac{1}{3}}} &= M_5 = 0 \\
n_{(1,2)_{\frac{1}{2}}} - n_{(1,2)_{-\frac{1}{2}}} &= M_5 + N_{Y_5} = 0 + 1 = 1 \ (H_u)
\end{aligned}
$$

$U(1)_Y-$ **Flux**-splitting of $\mathbf{\bar{5}_{H_d}} \rightarrow$:

$$
\begin{aligned}
n_{(3,1)_{-\frac{1}{3}}} - n_{(\bar{3},1)_{\frac{1}{3}}} &= M_5 = 0 \\
n_{(1,2)_{\frac{1}{2}}} - n_{(1,2)_{-\frac{1}{2}}} &= M_5 + N_{Y_5} = 0 - 1 = -1 \ (H_d)
\end{aligned}
$$

$\swarrow \quad \searrow$

General Property

by virtue of Hyperflux, members of the same family, may no longer be components of the same 5-plet

Fluxes and Anomaly Cancellation

M_j, N_{Y_j} subject to geometry/anomaly cancellation restrictions

Anomaly cancellation

$$\mathcal{A}_{SU(3)^2-U(1)},\ \mathcal{A}_{SU(2)^2-U(1)},\ \mathcal{A}_{U(1_Y)^2-U(1)}$$

$$\mathcal{A}_{U(1_Y)-U(1)^2}$$

equivalent to geometric constraints * : ($q_n = n$-irrep $U(1)$ *'charge'*)

$$\begin{aligned} \sum_{\Sigma_{10}} q_{10_j} N_{10_j} + \sum_{\Sigma_5} q_{5_i} N_{5_i} &= 0 \\ 3\sum_{\Sigma_{10}} q_{10_j}^2 N_{10_j} + \sum_{\Sigma_5} q_{5_i}^2 N_{5_i} &= 0 \end{aligned} \tag{2}$$

* (*see works of Dudas-Palti, Marsano, Weigand,...*)

$\mathcal{C}$

Anomalies of B decays

Proposed interpretations within **F-GUTs**

Interpretation in F-theory GUTs

- Z' must couple differently to 3^{rd} family (or a new vectorlike one).
- $\to$ ... scenario naturally realised in an F-theory framework

$$E_8 \supset SU(5) \times SU(5)_\perp \to SU(5) \times U(1)_\perp^4$$

Cartan generators $\Leftrightarrow$ $U(1)_\perp$

$$H_1 = \frac{1}{2}\text{diag}(1, -1, 0, 0, 0),$$

$$H_2 = \frac{1}{2\sqrt{3}}\text{diag}(1, 1, -2, 0, 0),$$

$$H_3 = \frac{1}{2\sqrt{6}}\text{diag}(1, 1, 1, -3, 0),$$

$$H_4 = \frac{1}{2\sqrt{10}}\text{diag}(1, 1, 1, 1, -4),$$

MONODROMIES

Physics and Geometry

... t_i obey a 5^{th}-degree polynomial

$$\sum_{k=0}^{5} b_k s^{5-k} = 0$$

with b_k 'transmitting' topological properties to effective model

... ...

minimum condition (Monodromy)

$$Z_2 : \; t_1 \leftrightarrow t_2 \Rrightarrow U(1)_{\perp}^{4} \rightarrow U(1)_{\perp}^{3}$$

...breaks one $U(1)_{\perp}$ generator...

$$H_1 \quad = \quad \frac{1}{2}\mathrm{diag}(1, -1, 0, 0, 0),$$

A Z' with Non-Universal Gauge-Lepton couplings

M. Crispim-Romão, S.F. King, G.K.L.

Assumed Model: $SU(5)$ *with* $t_1 \leftrightarrow t_2$ *monodromy*

choosing convenient basis for $U(1)_i$*'s* $\perp$ *to* $SU(5)_{GUT}$:

$$E_8 \rightarrow E_6 \times U(1)_\perp^2 \quad (3)$$

$$\rightarrow SO(10) \times U(1)_\psi \times U(1)_\perp^2 \quad (4)$$

$$\rightarrow SU(5) \times U(1)_\chi \times U(1)_\psi \times U(1)_\perp^2. \quad (5)$$

Unbroken generators after *imposing a* Z_2 *monodromy* :

$$Q_\chi \propto \mathrm{diag}[-1,-1,-1,-1,4] \in E_6$$

$$Q_\psi \propto \mathrm{diag}[1,1,1,-3,0] \in E_6$$

$$Q_\perp \propto \mathrm{diag}[1,1,-2,0,0] \in E_8, \notin E_6$$

▲ $U(1)'$ must be combination of unbroken generators:

$$Q = c_1 Q_\chi + c_2 Q_\chi + c_3 Q_\perp$$

▲ must respect anomaly cancellation conditions.

Additional Conditions on c_i coeffs and M_{10_j}, M_{5_i} :

$$c_1^2 + c_2^2 + c_3^2 = 1, \; \sum_j M_{10_j} = -\sum_i M_{5_i} = 3$$

▲ 3rd family Q'_3 differently charged under $U(1)'$

▲ preferably $Q'_1 = Q'_2$ in quark sector (to suppress FCNCs)

Results: **Plenty of solutions:**

▲ cases with an additional $5 + \bar{5}$ a pair

▲ cases with an additional $10 + \overline{10}$

▲ models with complete vector-like family $(10 + \overline{10}) + (5 + \bar{5})$

Example:

Curve Name	$\sqrt{10}\,Q_3$	SM content
5_{H_u}	$\frac{3}{2}$	H_u
5_1	-1	L
5_2	$\frac{3}{2}$	H_d
5_3	$\frac{1}{4}$	L
5_4	-1	d^c
5_5	$-\frac{9}{4}$	$d^c + L$
5_6	$\frac{1}{4}$	d^c
10_t	$-\frac{3}{4}$	$Q + 2u^c$
10_2	$\frac{7}{4}$	$-$
10_3	-$\frac{3}{4}$	$Q + 2e^c$
10_4	$\frac{1}{2}$	$Q + u^c + e^c$

... MSSM + Vector Family

Curve Name	Weights	Q'	SM Content
5_{H_u}	$-2t_1$	$-\frac{1}{2}$	H_u
5_1	$t_1 + t_3$	$-\frac{1}{4}$	L
5_2	$t_1 + t_4$	$\frac{1}{2}$	H_d
5_3	$-t_1 - t_5$	0	$\overline{d^c}$
5_4	$t_3 + t_4$	$-\frac{1}{4}$	$3d^c + 2L$
5_5	$t_3 + t_5$	$-\frac{3}{4}$	$d^c + L$
5_6	$-t_4 - t_5$	0	$\overline{L}$
10_t	t_1	$\frac{1}{4}$	$2Q + 3u^c + e^c$
10_2	t_3	$-\frac{1}{2}$	$Q + u^c + e^c$
10_3	t_4	$\frac{1}{4}$	$Q + 2e^c$
10_4	$-t_5$	$\frac{1}{4}$	$\overline{Q} + \overline{u^c} + \overline{e^c}$

$\mathcal{D}$

$\searrow \cdots \swarrow$

SUMMING UP...

$\nearrow \cdots \nwarrow$

Anomalous B decays (*if true*) :

$\Downarrow\Downarrow\Downarrow$

will shake the foundations of SM

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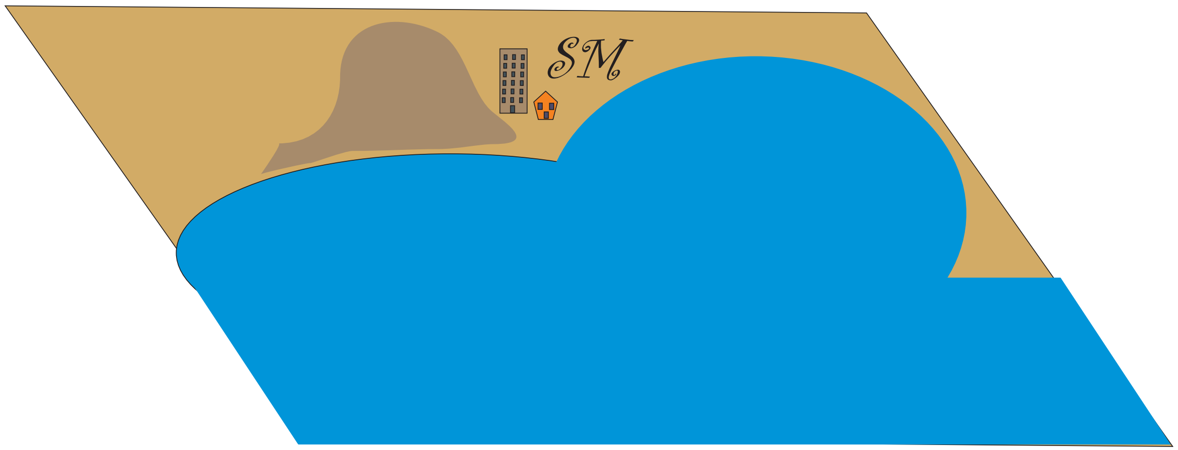
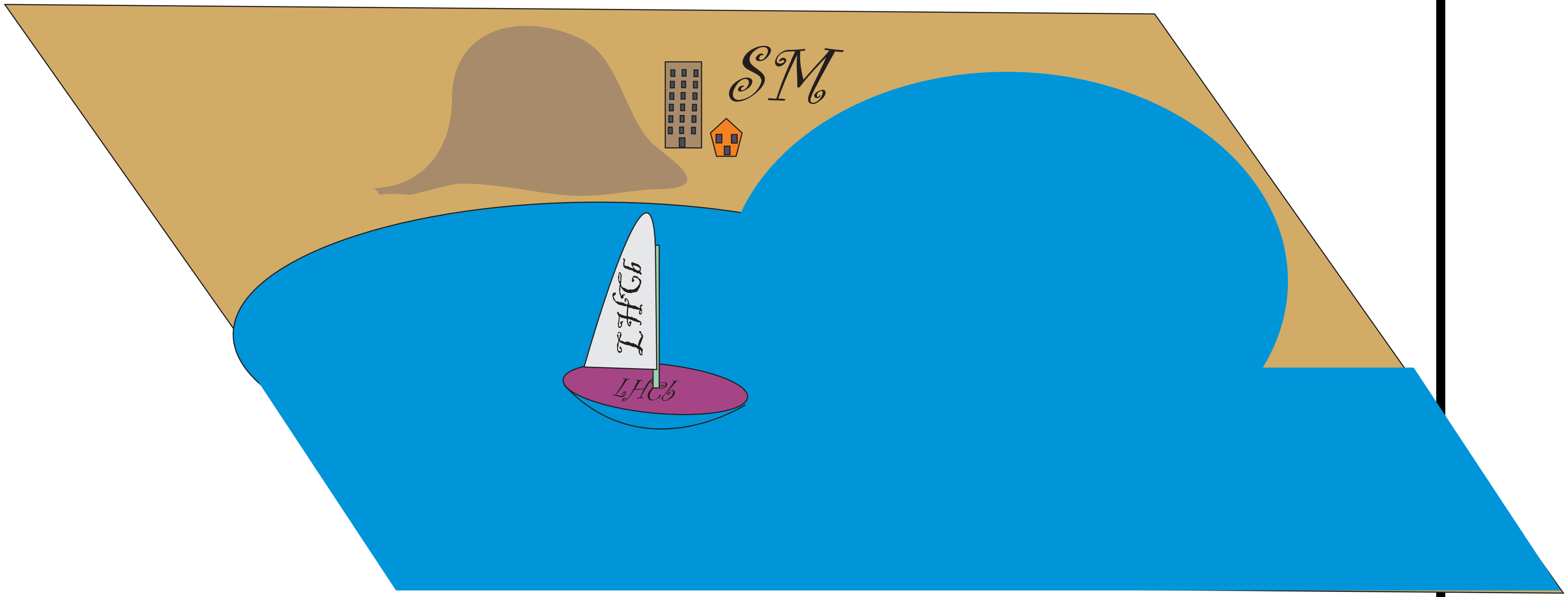
...in Greece, bewildered sailors having problems in navigation used to say...

either the coastline is wrongly aligned...(SM)



... or we are sailing the wrong direction($LHCb$)



⇓

but...

String Theory GUTs are rich enough to accommodate:

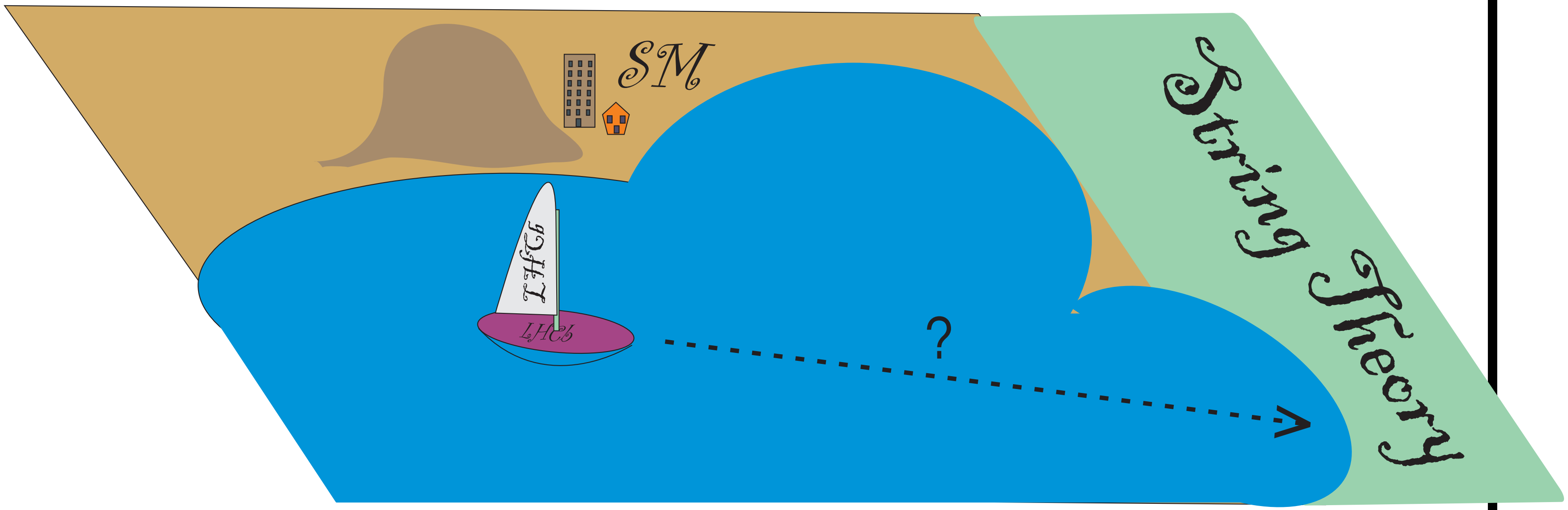
Viable models for New Physics

...Z''s with non-universal couplings to fermions

...vectorlike families

... and more...

so, the question is



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to sail, or not to sail?...

THANK YOU