

$b \rightarrow s\ell\ell$ anomalies from dynamical Yukawas

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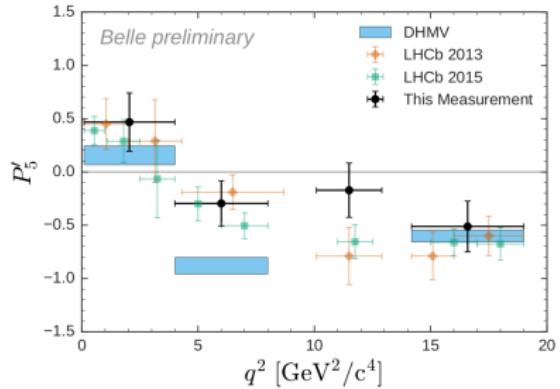
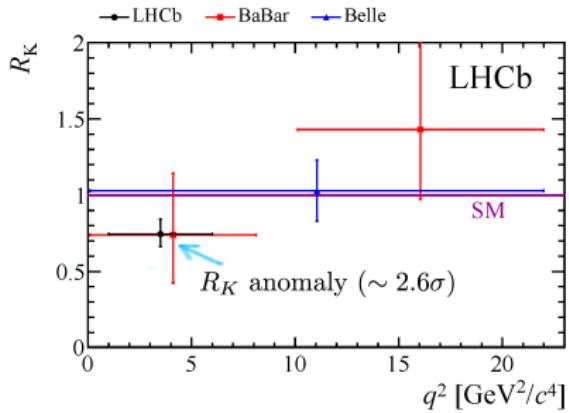
In collaboration with: Andreas Crivellin, Admir Greljo, and Gino Isidori

A bit of motivation

Experiment

The $b \rightarrow s\ell^+\ell^-$ anomalies

$(R_K, B \rightarrow K^*\mu^+\mu^-, B_s \rightarrow \phi\mu^+\mu^- \dots)$



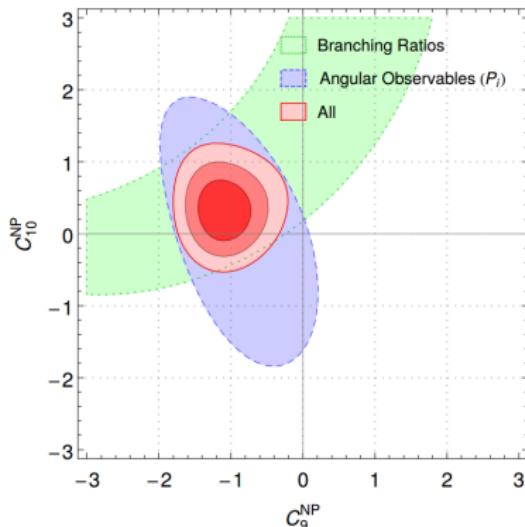
A bit of motivation

Experiment

The $b \rightarrow s\ell^+\ell^-$
anomalies

$(R_K, B \rightarrow K^*\mu^+\mu^-,$
 $B_s \rightarrow \phi\mu^+\mu^- \dots)$

See talk by Quim Matias



Descotes-Genon et al., JHEP 1606 (2016) 092

Allow for New Physics in muons

$$\mathcal{O}_9^\mu = (\bar{s}\gamma_\alpha P_L b)(\bar{\mu}\gamma^\alpha\mu)$$

$$\mathcal{O}_{10}^\mu = (\bar{s}\gamma_\alpha P_L b)(\bar{\mu}\gamma^\alpha\gamma_5\mu)$$

above **4 σ** pull w.r.t the SM hypothesis

A bit of motivation

$$M_{u,d,e} \sim \begin{matrix} & & \\ & & \\ & & \\ \begin{matrix} & & \\ & & \\ & & \end{matrix} & \begin{matrix} & & \\ & & \\ & & \end{matrix} & \begin{matrix} & & \\ & & \\ & & \end{matrix} \\ & & \\ & & \\ & & \end{matrix}$$

$$M_\nu \sim 0 \quad (\text{not very hierarchical})$$

$$V_{\text{CKM}} \sim \begin{matrix} & & & \\ & & & \\ & & & \\ \begin{matrix} & & & \\ & & & \\ & & & \\ & & & \end{matrix} & \begin{matrix} & & & \\ & & & \\ & & & \end{matrix} & \begin{matrix} & & & \\ & & & \\ & & & \end{matrix} \\ & & & \\ & & & \\ & & & \end{matrix}$$

$$U_{\text{PMNS}} \sim \begin{matrix} & & & & \\ & & & & \\ & & & & \\ \begin{matrix} & & & & \\ & & & & \\ & & & & \\ & & & & \end{matrix} & \begin{matrix} & & & & \\ & & & & \\ & & & & \end{matrix} & \begin{matrix} & & & & \\ & & & & \\ & & & & \end{matrix} & \begin{matrix} & & & & \\ & & & & \\ & & & & \end{matrix} \\ & & & & \\ & & & & \\ & & & & \end{matrix}$$

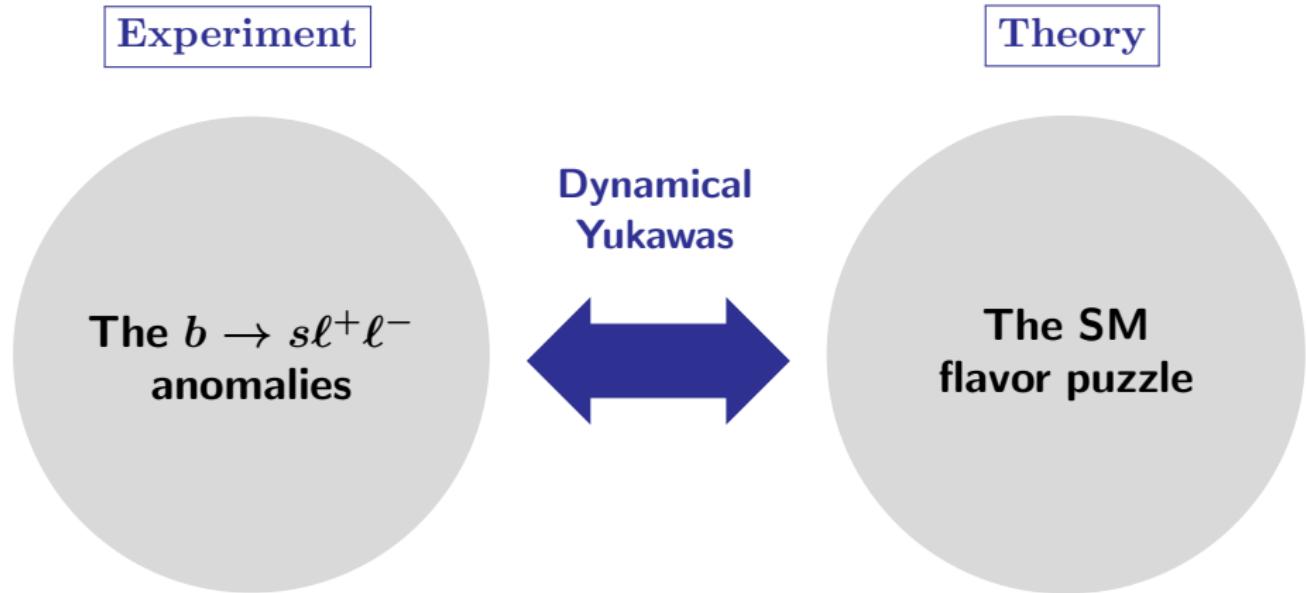
Theory

The SM flavor puzzle

Why these values? Why so different?

Maybe because neutrinos are Majorana?

A bit of motivation



See talks by Andreas, Giuliano, and Olcyr for other NP explanations of the anomalies

Dynamical Yukawa couplings

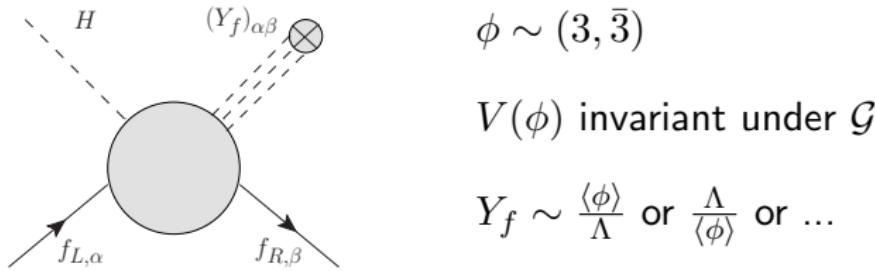
See also talk by Pablo Quilez

Anselm, Berezhiani, 96'; Berezhiani, Rossi, 01'; Alonso, Gavela, Isidori, Maiani, 13', ...

In the limit $Y_{u,d,e,\nu} \rightarrow 0$ (and 3 right-handed Majorana neutrinos):

$$\mathcal{G} = \mathbf{SU(3)_Q} \times \mathbf{SU(3)_D} \times \mathbf{SU(3)_U} \times \mathbf{SU(3)_\ell} \times \mathbf{SU(3)_E} \times \mathbf{\mathcal{O}(3)_{\nu_R}}$$

- Promote this symmetry to a local symmetry of nature
- Yukawas arise from dynamical fields:



- The vevs of the Yukawa flavons yield a sequential breaking of \mathcal{G} and can potentially explain the SM Yukawa structure

SM Yukawas from a minimum principle

Natural minima: Less dependent on specific tuning of the coefficients in the potential, as compared to generic minima

Alonso et al., JHEP 1311 (2013) 187

Quarks

$$\hat{Y}_{u(d)}^{(0)} = \text{diag}(0, 0, y_{t(b)})$$

$$V_{\text{CKM}}^{(0)} = \mathbb{1}$$

Leptons

$$\hat{Y}_e^{(0)} = \text{diag}(0, 0, y_\tau)$$

$$m_\nu^{(0)} = \frac{v^2}{M} \mathbb{1}$$

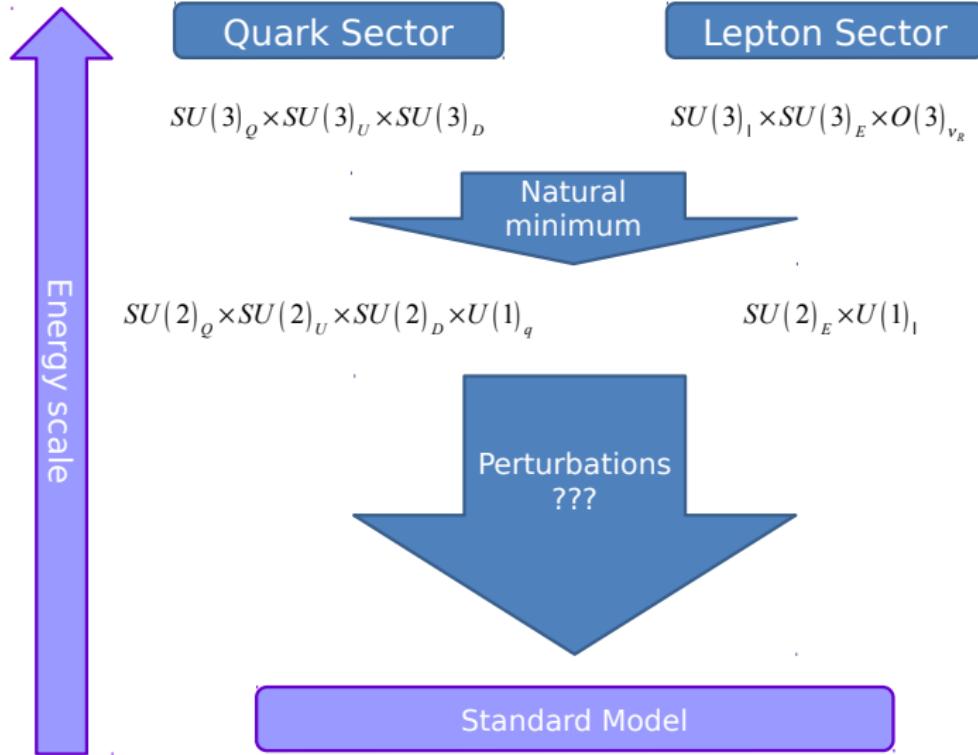
$$U_{\text{PMNS}}^{(0)}: \theta_{23} = \pi/4, \theta_{13} = 0, \\ \theta_{12} \text{ potentially large}$$

✓ Perturbations to this minima give the correct quantitative picture

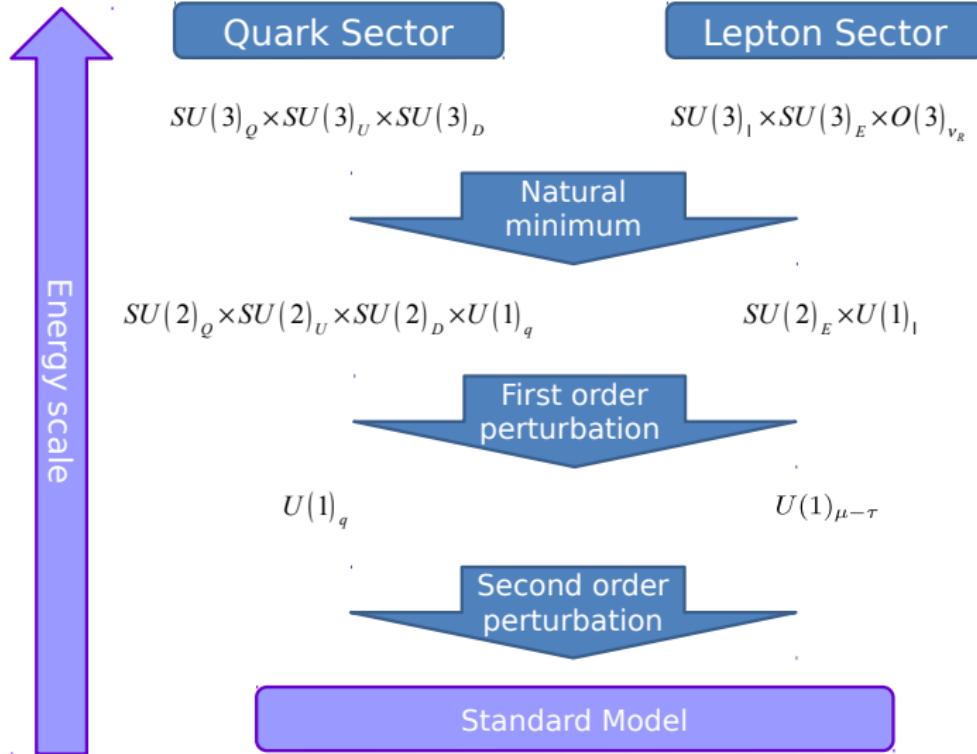
Alonso et al., JHEP 1311 (2013) 187

Fong, Nardi, Phys. Rev. D89 (2014) 036008

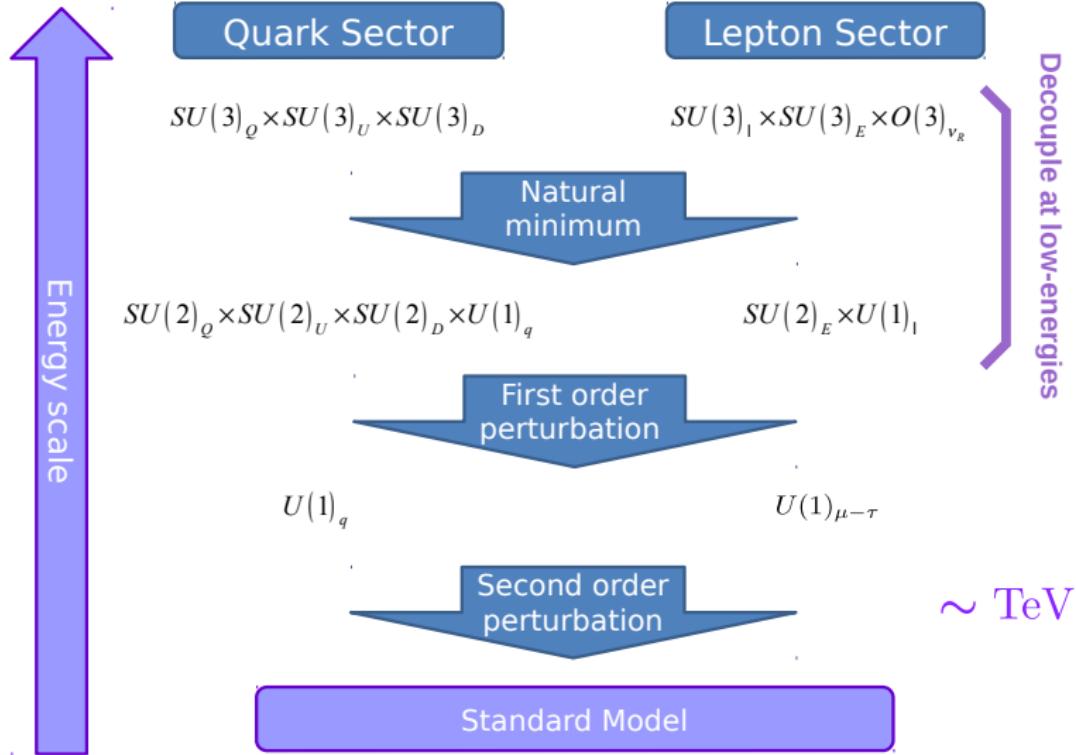
The big picture



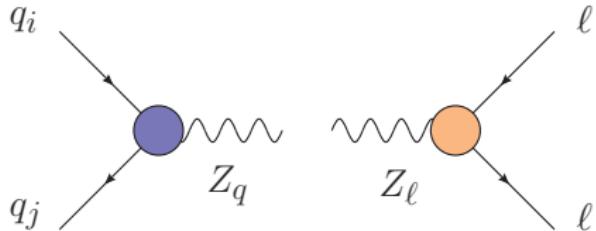
The big picture



The big picture



$\text{U}(1)_q \times \text{U}(1)_{\mu-\tau}$ couplings



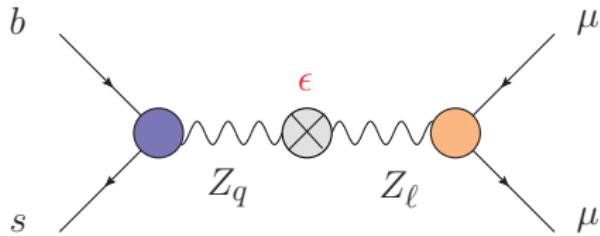
$$\text{(blue circle)} \propto g_q \left[\mathbf{V}_{ti} \mathbf{V}_{tj}^* - \delta_{ij} \frac{1}{3} \right]$$

(MFV-like FCNCs)

$$\text{(orange circle)} \propto g_\ell \text{ diag}(0, 1, -1)$$

Maximal LFNU (and no cLFV)

$\text{U}(1)_q \times \text{U}(1)_{\mu-\tau}$ couplings



$$\text{blue circle} \propto g_q V_{tb} V_{ts}^*$$

$$\text{orange circle} \propto g_\ell$$

To explain the $b \rightarrow s\ell^+\ell^-$ anomalies **both Z' should mix (mass mixing)**

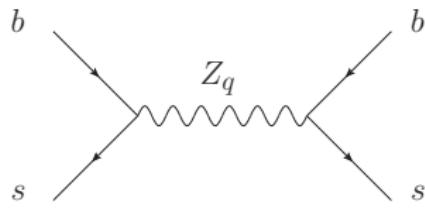
$$C_9^\mu|_{\text{NP}} = - \left(\frac{g_q \Lambda_v}{M_{Z_2}} \right) \left(\frac{g_\ell \Lambda_v}{M_{Z_1}} \right) \epsilon + \mathcal{O}(\epsilon^2)$$

ϵ mixing parameter

$$\Lambda_v \simeq 7 \text{ TeV}$$

Low-energy constraints: Estimates

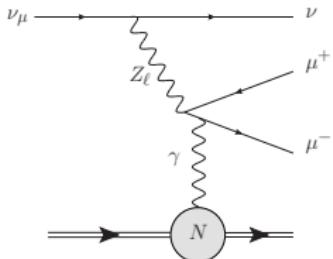
$B_s - \bar{B}_s$ mixing



Assuming up to 10% corrections

$$\left| \frac{g_q \Lambda_v}{M_{Z_q}} \right| \lesssim 0.7$$

Neutrino trident production



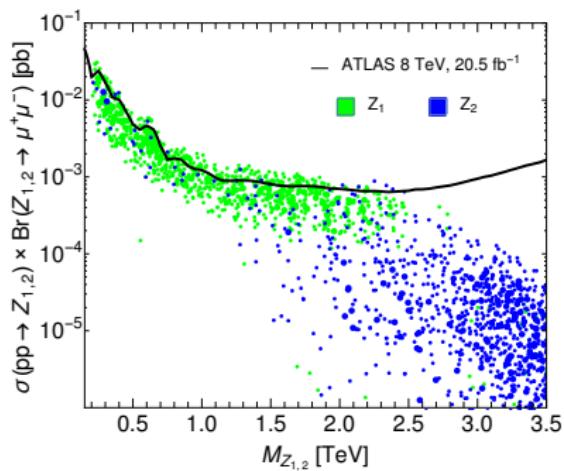
Allowing for 2σ deviations

Altmannshofer et al., Phys.Rev. D89 (2014) 095033

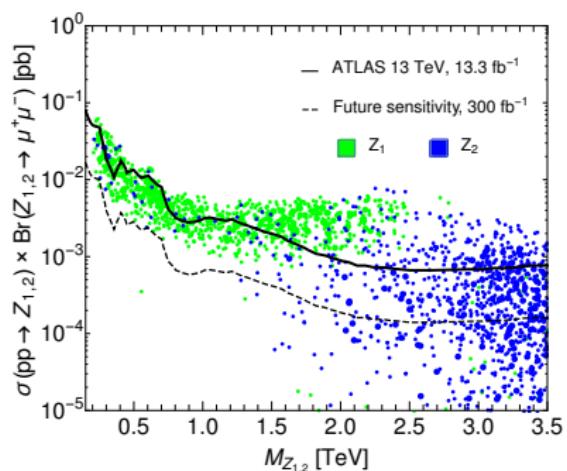
$$\left| \frac{g_\ell \Lambda_v}{M_{Z_\ell}} \right| \lesssim 12$$

$$C_9^\mu|_{\text{NP}} \simeq - \left(\frac{g_q \Lambda_v}{M_{Z_2}} \right) \left(\frac{g_\ell \Lambda_v}{M_{Z_1}} \right) \epsilon \stackrel{C_9^\mu|_{\text{NP}} \simeq -1}{\Longrightarrow} \epsilon \sim \mathcal{O}(0.1)$$

Direct searches at LHC: $pp \rightarrow Z' \rightarrow \mu^+ \mu^-$



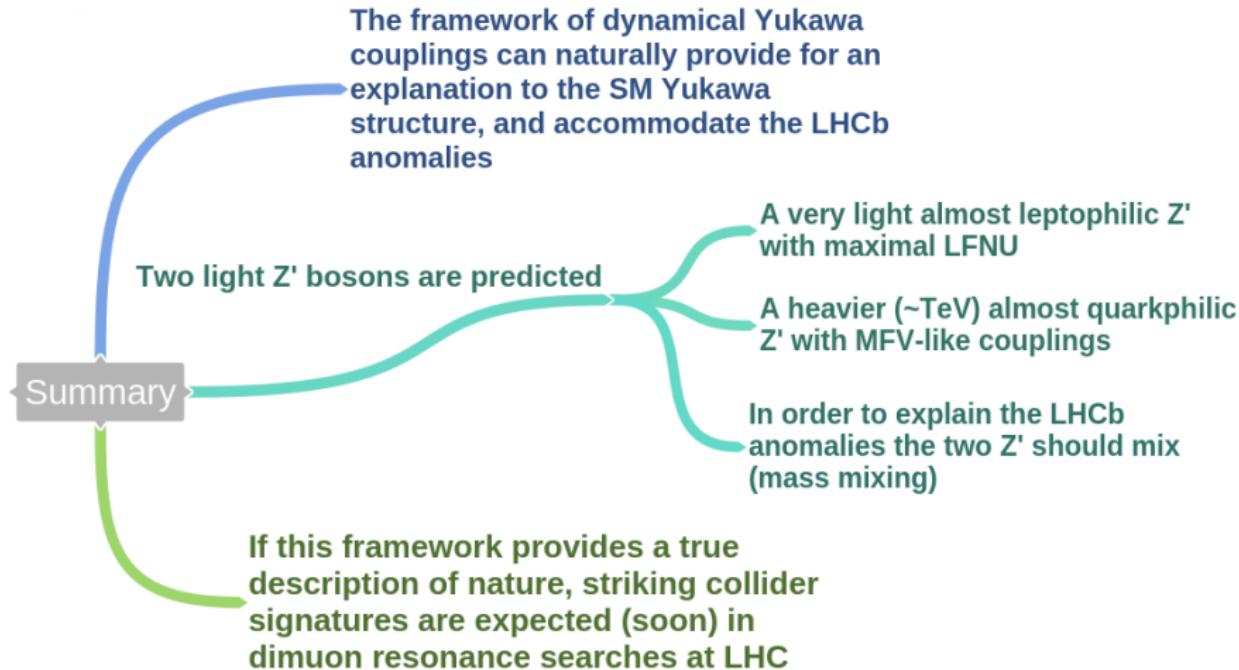
ATLAS Collab., Phys. Rev. D90 (2014) 052005



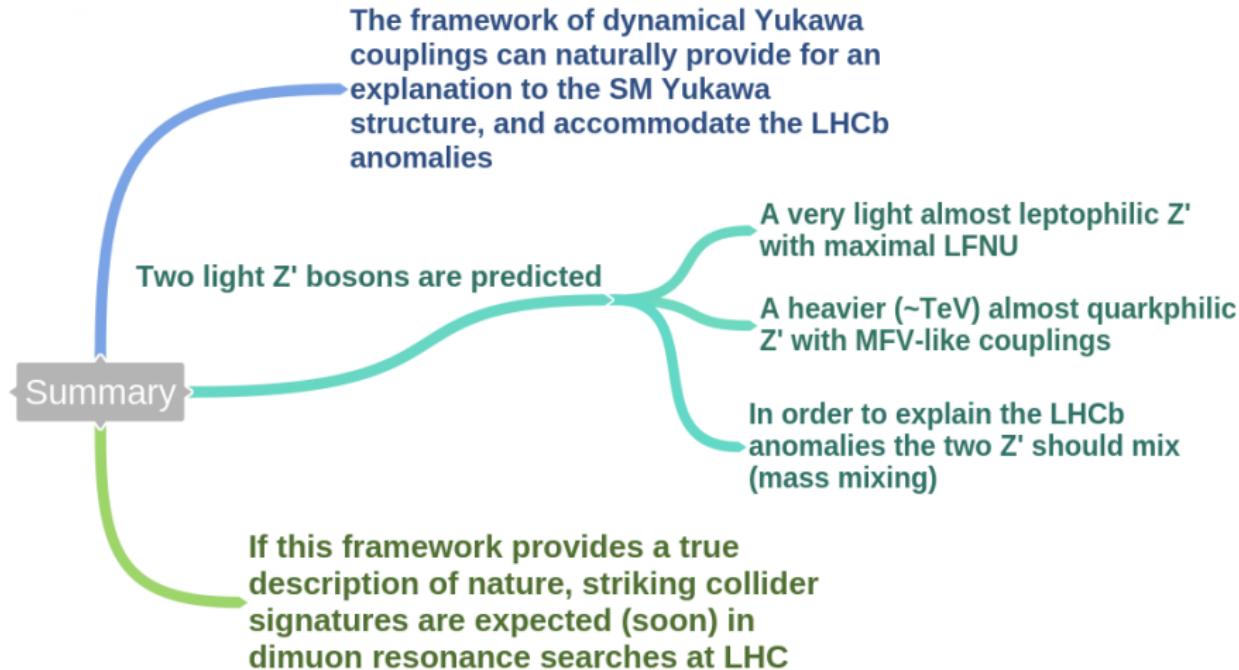
ATLAS-CONF-2016-045

We found the impact of present (and future) $Z' \rightarrow t\bar{t}$ and $Z' \rightarrow jj$ searches to be less relevant

So... summing up



So... summing up



Thanks!

Backup

SM Yukawas from a minimum principle

$$\frac{\partial V(Y_f)}{\partial Y_f} = 0 \quad V(Y_f) \text{ Invariant under the flavor group}$$

Natural extrema: Those that are less or not at all dependent from specific tuning of the coefficients in the potential, compared to the generic extrema

$$V(Y_f) = V(I_i[Y_f]) \quad \text{e.g. } I_1[Y_f] = \text{Tr}(Y_f^\dagger Y_f)$$

The space of Y_f has no boundaries but the one of $I_i[Y_f]$ does!

$$\frac{\partial V(Y_j)}{\partial Y_j} = \sum_i \frac{\partial V(I_i[Y_f])}{\partial I_i} J_{ij} = 0 \quad \text{Rank}(J) = R < N$$

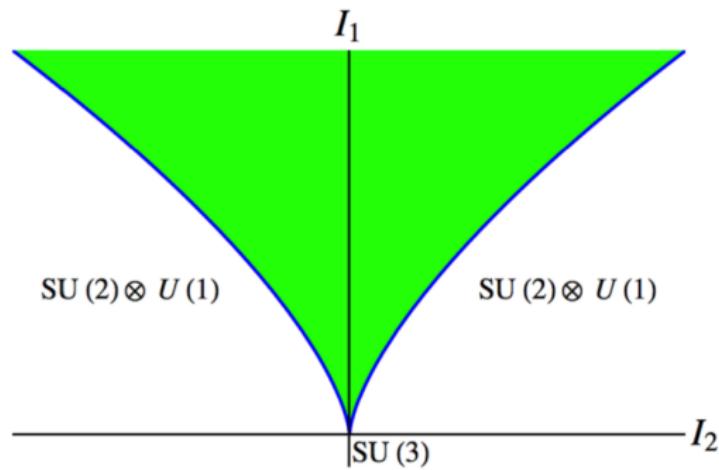
SM Yukawas from a minimum principle

Alonso et al., JHEP 1311 (2013) 187

Simplified flavor group: $SU(3)$

$$\bar{\Psi} M \Psi \implies M \rightarrow U M U^\dagger \quad M : 3 \times 3 \text{ (hermitic) matrix}$$

Invariants: $I_1 = \text{Tr}(M^2)$, $I_2 = \det(M)$



Natural minima perturbations

First order perturbations: High-scale

Quarks

$$\hat{Y}_{u(d)}^{(1)} = \begin{pmatrix} \epsilon_{u(d)}^{11} & \epsilon_{u(d)}^{12} & 0 \\ \epsilon_{u(d)}^{21} & \epsilon_{u(d)}^{22} & 0 \\ 0 & 0 & 0 \end{pmatrix}$$

Leptons

$$\begin{aligned}\hat{Y}_e^{(1)} &= \text{diag}(y_e, y_\mu, 0) \\ \hat{Y}_\nu^{(1)} &= 0\end{aligned}$$

Second order perturbations: \sim TeV scale

Quarks

$$\hat{Y}_{u(d)}^{(2)} = \begin{pmatrix} 0 & 0 & \delta_{u(d)}^1 \\ 0 & 0 & \delta_{u(d)}^2 \\ 0 & 0 & 0 \end{pmatrix}$$

Leptons

- Measured U_{PMNS}
- Quasi-degenerate neutrinos
- Absolute neutrino mass $m_0 \simeq 0.1\text{eV}$

We assume no RH FCNCs

Alonso et al., JHEP 1311 (2013) 187

An explicit model example

	SU(2) _Q	SU(2) _U	SU(2) _D	U(1) _q	SU(3) _c	SU(2) _L	U(1) _Y
q_{jL}	2	1	1	-1/2	3	2	1/6
u_{jR}	1	2	1	-1/2	3	1	2/3
d_{jR}	1	1	2	-1/2	3	1	-1/3
q_{3L}	1	1	1	1	3	2	1/6
t_R	1	1	1	1	3	1	2/3
b_R	1	1	1	1	3	1	-1/3
U_{jL}	1	2	1	-1/2	3	1	2/3
\mathcal{D}_{jL}	1	1	2	-1/2	3	1	-1/3
U_{jR}	2	1	1	-1/2	3	1	2/3
\mathcal{D}_{jR}	2	1	1	-1/2	3	1	-1/3
H	1	1	1	0	1	2	1/2
ϕ_u	2	2	1	0	1	1	0
ϕ_d	2	1	2	0	1	1	0
ϕ_{mix}	1	1	2	-3/2	1	1	0

Table I. Particle content for the quark sector. Particles added to the SM are shown in a gray background.

$$\begin{aligned} \mathcal{L} = & \mathcal{L}_{\text{kin}} - V(\phi_u, \phi_d, \phi_{\text{mix}}, \phi_e, \phi_\nu, H) \\ & + (y_t \overline{q}_{3L} \widetilde{H} t_R + y_b \overline{q}_{3L} H b_R + y_\tau \overline{\ell}_{3L} H \tau_R \\ & + \lambda_u \overline{q}_{iL} \widetilde{H} \mathcal{U}_{iR} + \lambda'_u \overline{\mathcal{U}_{iL}} (\phi_u)_{ij} \mathcal{U}_{jR} + M_u \overline{\mathcal{U}_{iL}} u_{iR} \\ & + \lambda_d \overline{q}_{iL} H \mathcal{D}_{iR} + \lambda'_d \overline{\mathcal{D}_{iL}} (\phi_d)_{ij} \mathcal{D}_{jR} + M_d \overline{\mathcal{D}_{iL}} d_{iR} \\ & + \lambda_{\text{mix}} \overline{\mathcal{D}_{iL}} (\phi_{\text{mix}})_i b_R + \lambda_{e1} \overline{\ell}_{1L} H \mathcal{E}_{1R} \\ & + \lambda_{e2} \overline{\ell}_{2L} H \mathcal{E}_{2R} + \lambda'_{e1} \overline{\mathcal{E}_{iL}} (\phi_e)_i \mathcal{E}_{1R} \\ & + \lambda'_{e2} \overline{\mathcal{E}_{iL}} (\widetilde{\phi}_e)_i \mathcal{E}_{2R} + M_e \overline{\mathcal{E}_{iL}} e_{iR} + h.c.) , \end{aligned}$$

	SU(2) _E	U(1) _l	SU(3) _c	SU(2) _L	U(1) _Y
ℓ_{jL}	1	δ_{j2}	1	2	-1/2
e_{jR}	2	1/2	1	1	-1
ℓ_{3L}	1	-1	1	2	-1/2
τ_R	1	-1	1	1	-1
\mathcal{E}_{jL}	2	1/2	1	1	-1
\mathcal{E}_{jR}	1	δ_{j2}	1	1	-1
H	1	0	1	2	1/2
ϕ_e	2	1/2	1	1	0
ϕ_ν	1	-1	1	1	0

Table II. Particle content for the lepton sector. Particles added to the SM are shown in a gray background.

Step II:

$$y_d^{(2)} = \frac{\lambda_d M_d}{\lambda'_d} V^\dagger \langle \phi_d \rangle^{-1}$$

Step III:

$$\begin{aligned} Y_d \xrightarrow{\langle \phi_{\text{mix}} \rangle} Y_d &= \begin{pmatrix} y_d^{(2)} & y_d^{\text{mix}} \\ 0 & y_b \end{pmatrix}, \\ y_d^{\text{mix}} &= y_d^{(2)} \frac{\lambda_{\text{mix}} \langle \phi_{\text{mix}} \rangle}{M_d}. \end{aligned}$$

Low-energy constraints: Global fit

