Theoretical Models for combined explanations of the B-physics anomalies

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[*University of Zürich*]

- Introduction [*From the SMEFT to UV models*]
- LFU anomalies & Flavor symmetries [*The* $U(2)^n$ *case*]
- Simplified models: The Return of the Leptoquark
- Non-universal gauge interactions [*The* PS^3 *hypothesis*]
- Conclusions

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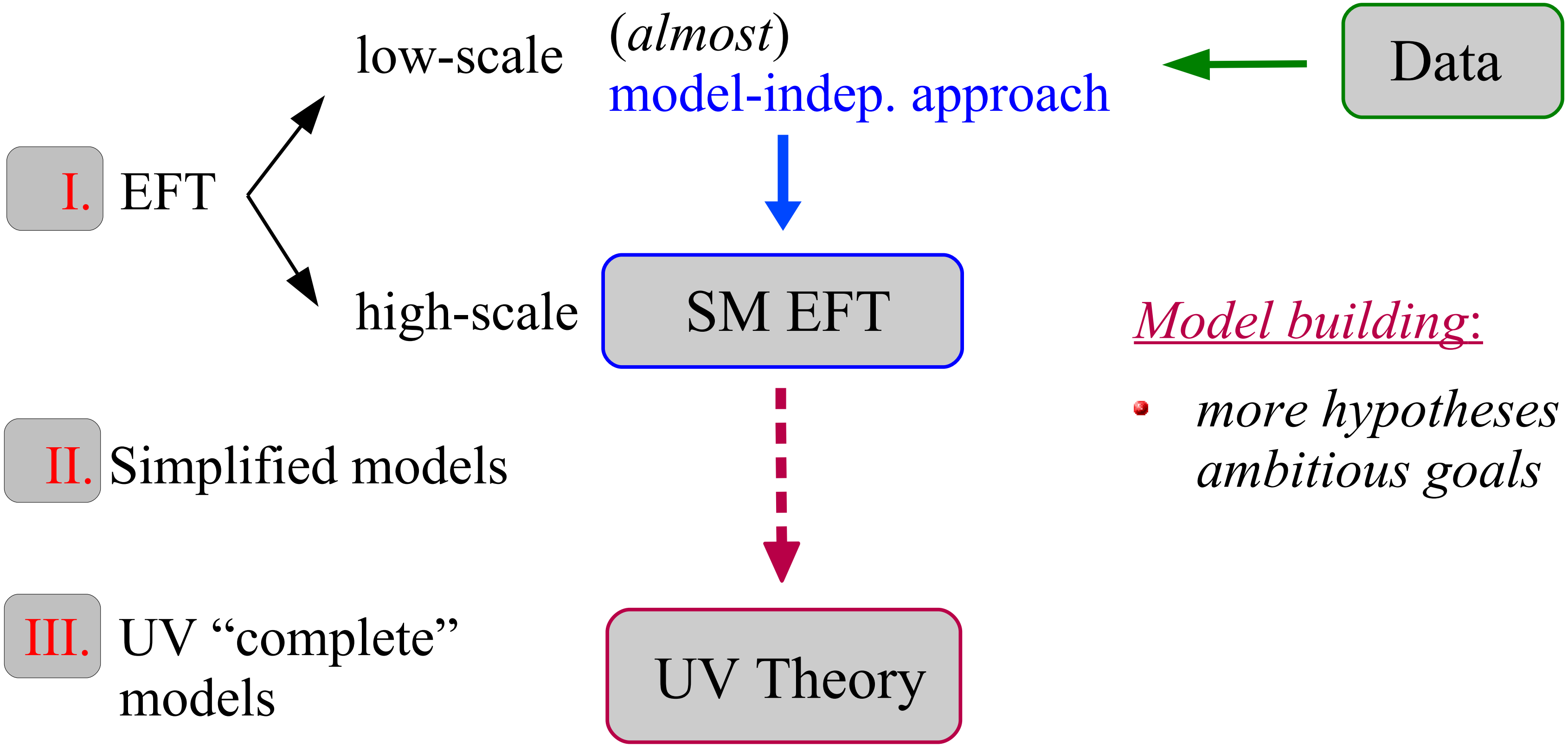
Introduction

We can adopt different theoretical approaches to describe the anomalies:



I. EFT

low-scale

(*almost*)
model-indep. approach

Data

high-scale

SM EFT

II. Simplified models

III. UV "complete" models

UV Theory

Model building:

- *more hypotheses & more ambitious goals*

Introduction

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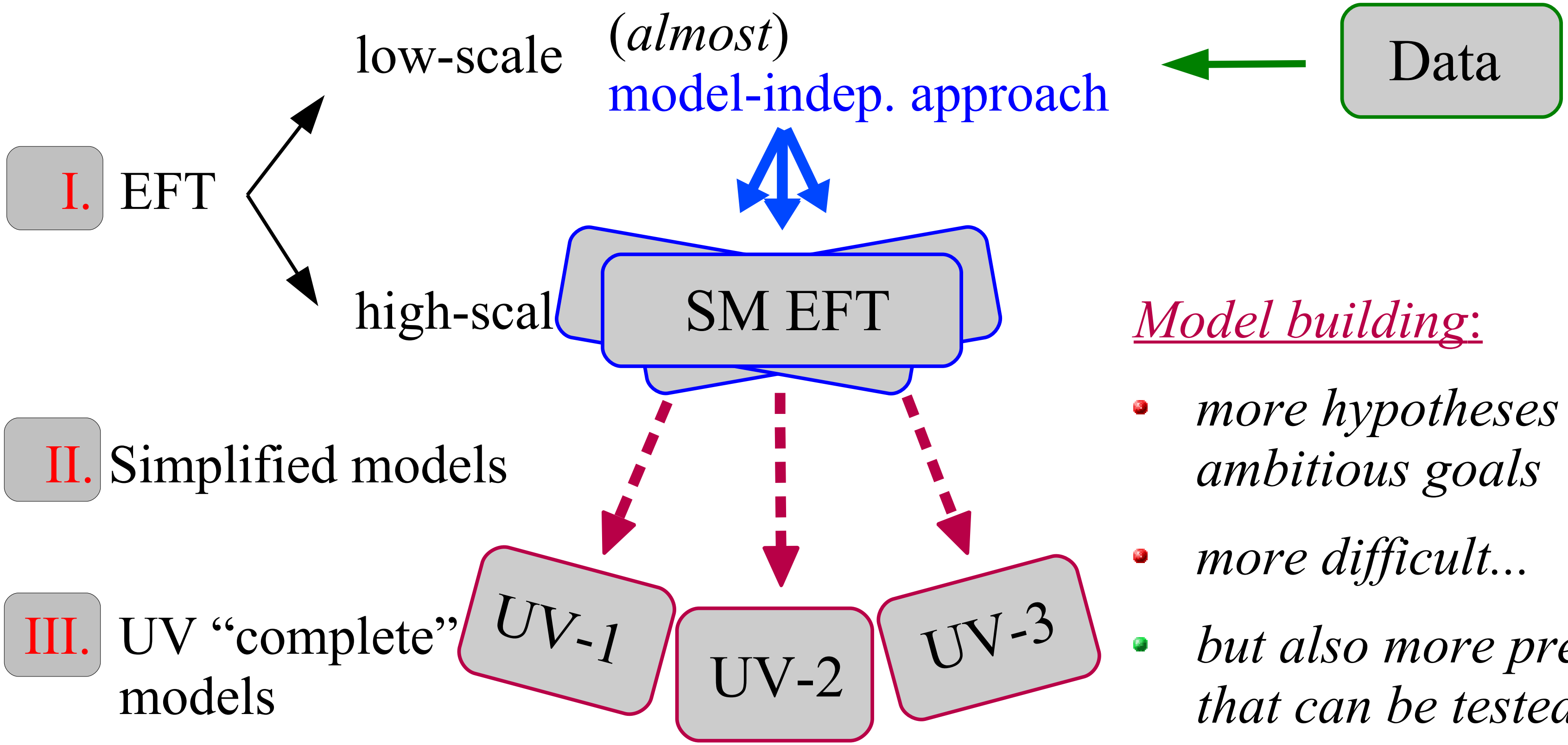

I. EFT

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SM EFT

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III. UV "complete" models

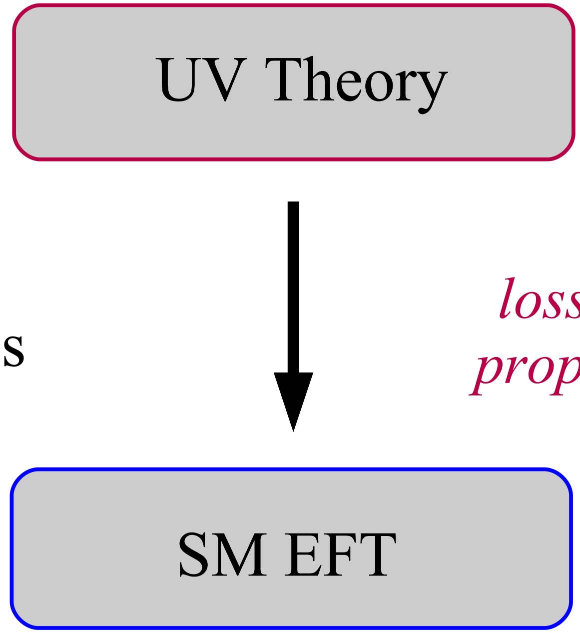
Model building:

- *more hypotheses & more ambitious goals*
- *more difficult...*
- *but also more predictions that can be tested against data !*

Goals (↔ "*quality measure*") of the model-building attempts (*while waiting more data...*):

- Solve the anomalies with no/small fine tuning with other data
- Link the solutions of the anomalies to solutions of existing SM problems

Introduction



UV Theory

Integrate out the high-energy modes

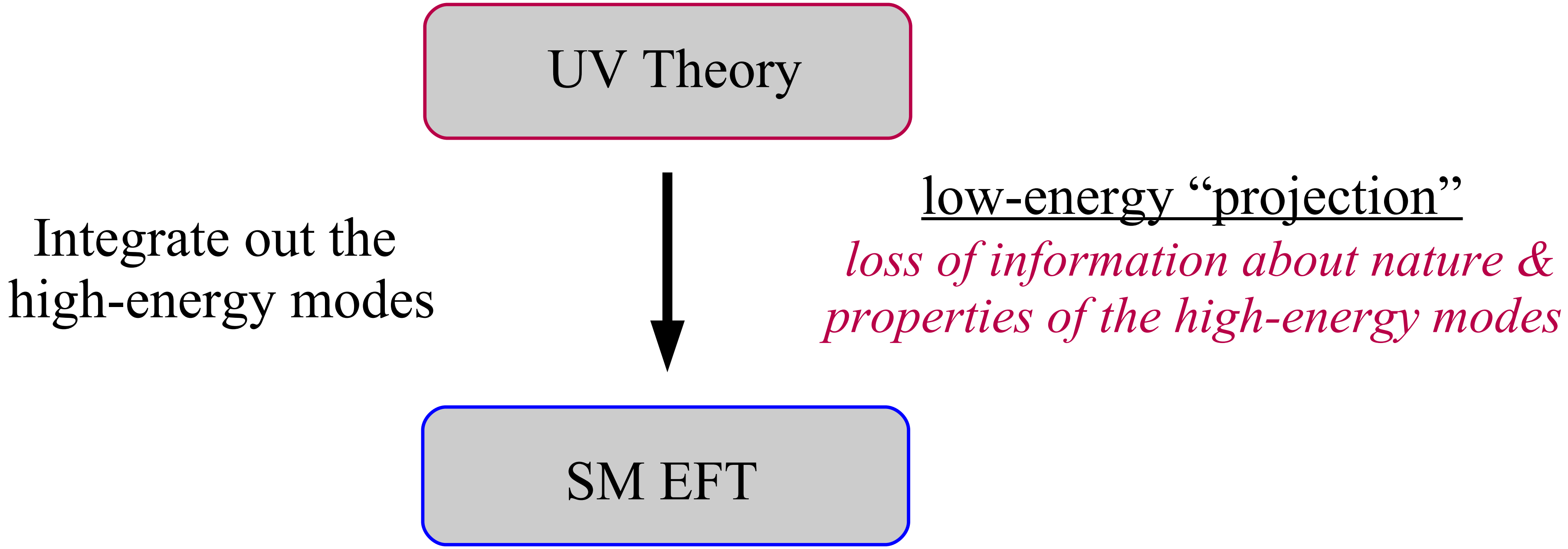
low-energy “projection”

loss of information about nature & properties of the high-energy modes

SM EFT

Reconstructing the UV theory from its low-energy limit is a very difficult problem with no unique solution [*~ 35 years from the Fermi Theory to the GSW model...*]

Introduction



UV Theory

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SM EFT

Reconstructing the UV theory from its low-energy limit is a very difficult problem with no unique solution [*~ 35 years from the Fermi Theory to the GSW model...*]

- The light fields appearing in the EFT are often superposition of the fundamental fields [*N.B.: true also for weak theories & gauge fields:* $A_\mu = c_\theta B_\mu + s_\theta W_\mu$]
- Many global symmetries of the EFT could by accidental low-energy properties
- The most interesting hints on UV dynamics comes from *un-natural features* of the EFT... [→ that's why we would like to link the anomalies to existing SM probl.]

Introduction

UV Theory

"trivial" low-energy projection

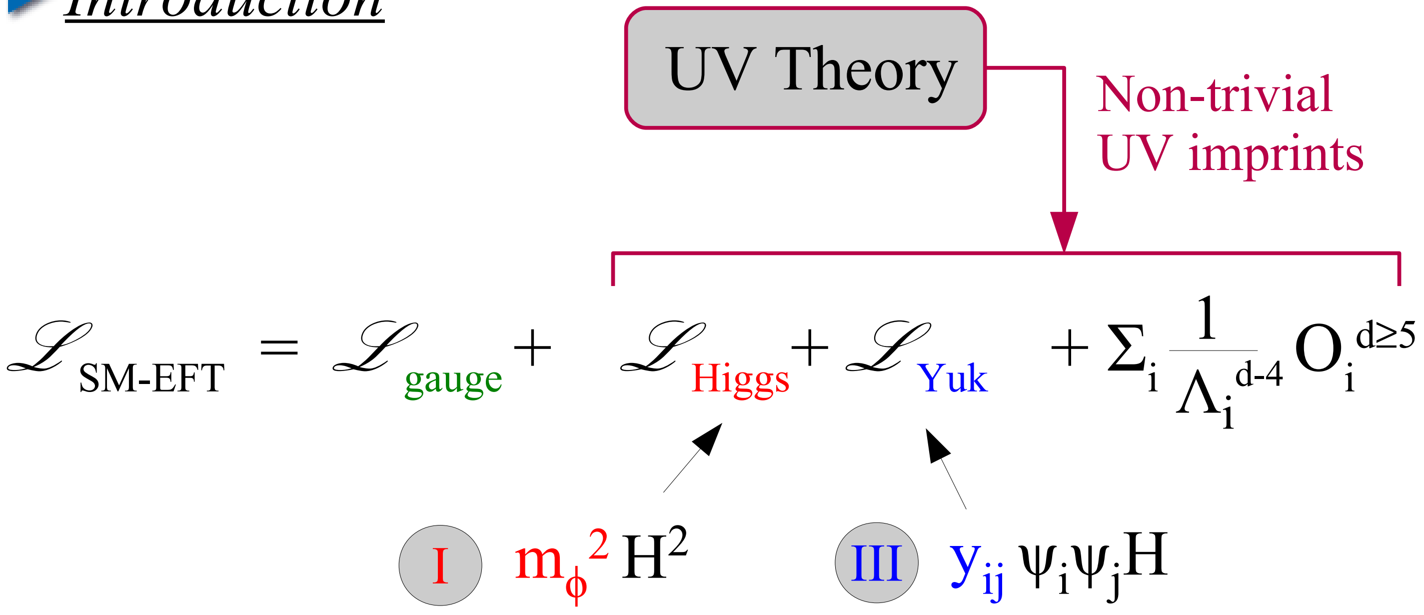
$$\mathscr{L}_{\text{SM-EFT}} = \mathscr{L}_{\text{gauge}} + \mathscr{L}_{\text{Higgs}} + \mathscr{L}_{\text{Yuk}} + \Sigma_i \frac{1}{\Lambda_i^{d-4}} O_i^{d\geq 5}$$

Structure fully dictated by

- Number of light fields
- Their charges under long-range interactions

Contains only "natural" O(1) couplings

Introduction



UV Theory

Non-trivial UV imprints

$$\mathscr{L}_{\text{SM-EFT}} = \mathscr{L}_{\text{gauge}} + \overbrace{\mathscr{L}_{\text{Higgs}} + \mathscr{L}_{\text{Yuk}} + \sum_i \frac{1}{\Lambda_i^{d-4}} O_i^{d\geq 5}}$$

I $m_\phi{}^2 H^2$

III $y_{ij}\, \psi_i \psi_j H$

$\Lambda_{t,W,H} >$ (few) TeV II

$\Lambda_{CP,\,F} > 10^{2\text{-}4}$ TeV IV

not a real problem:

$\Lambda_L \sim 10^{14}$ TeV

$\Lambda_B > 10^{15}$ TeV

- Hierarchy problem (II vs. I): $m_\phi \ll \Lambda_{t,W,H}$
- SM Flavor problem (III): $y_e \ll y_t$ [N.B.: 5 orders of magnitude !]
- NP Flavor problem (IV vs. I): $m_\phi \ll \Lambda_{CP,\,F}$

Introduction

$$\mathcal{L}_{\text{SM-EFT}} = \mathcal{L}_{\text{gauge}} + \overbrace{\mathcal{L}_{\text{Higgs}} + \mathcal{L}_{\text{Yuk}} + \Sigma_i \frac{1}{\Lambda_i^{d-4}} O_i^{d\geq 5}}^{\text{Non-trivial UV imprints}} \quad \left[\begin{array}{l} \Lambda_{t,W,H} > \text{(few) TeV} \quad \text{II} \\ \Lambda_{CP,\,F} > 10^{2-4}\ \text{TeV} \quad \text{IV} \end{array} \right.$$

$$\text{I} \quad m_\phi^2 H^2 \nearrow \mathcal{L}_{\text{Higgs}} \qquad \text{III} \quad y_{ij}\, \psi_i \psi_j H \nwarrow \mathcal{L}_{\text{Yuk}}$$

The MFV "solution" (popular in the *pre-LHC era*):

- The genuine hierarchy problem is not too severe → expect NP at TeV scale
- Postpone the solution of III to very high scale, and assume no other sources of flavor-breaking at low-energies → TeV scale NP is flavor-blind

Try to separate the two problems & postpone the Flavor one

Introduction

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From high-pT searches we now know that
if there is any NP at the TeV scale, then for sure it is not flavor universal...

Introduction

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The path of flavor non-universal interactions (not so popular *yet*...):

- The hierarchical structure of the SM Yukawa couplings is a clear indication that all the new degrees of freedom are coupled in a non-universal way to SM fermion families → expect TeV scale NP coupled mainly to 3rd gen.
- Genuine hierarchy problem less severe for NP coupled mainly to 3rd gen.

We should not give up & should not try to separate the two problems

Introduction

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$$\left[\begin{array}{l} \Lambda_{t,W,H} > \text{(few) TeV} \\ \boxed{\Lambda_{LFU} \sim \text{few TeV}} \\ \Lambda_{CP,\,F} > 10^{2\text{-}4}\text{ TeV} \end{array}\right.$$

The path of flavor non-universal interactions (not so popular *yet*...):

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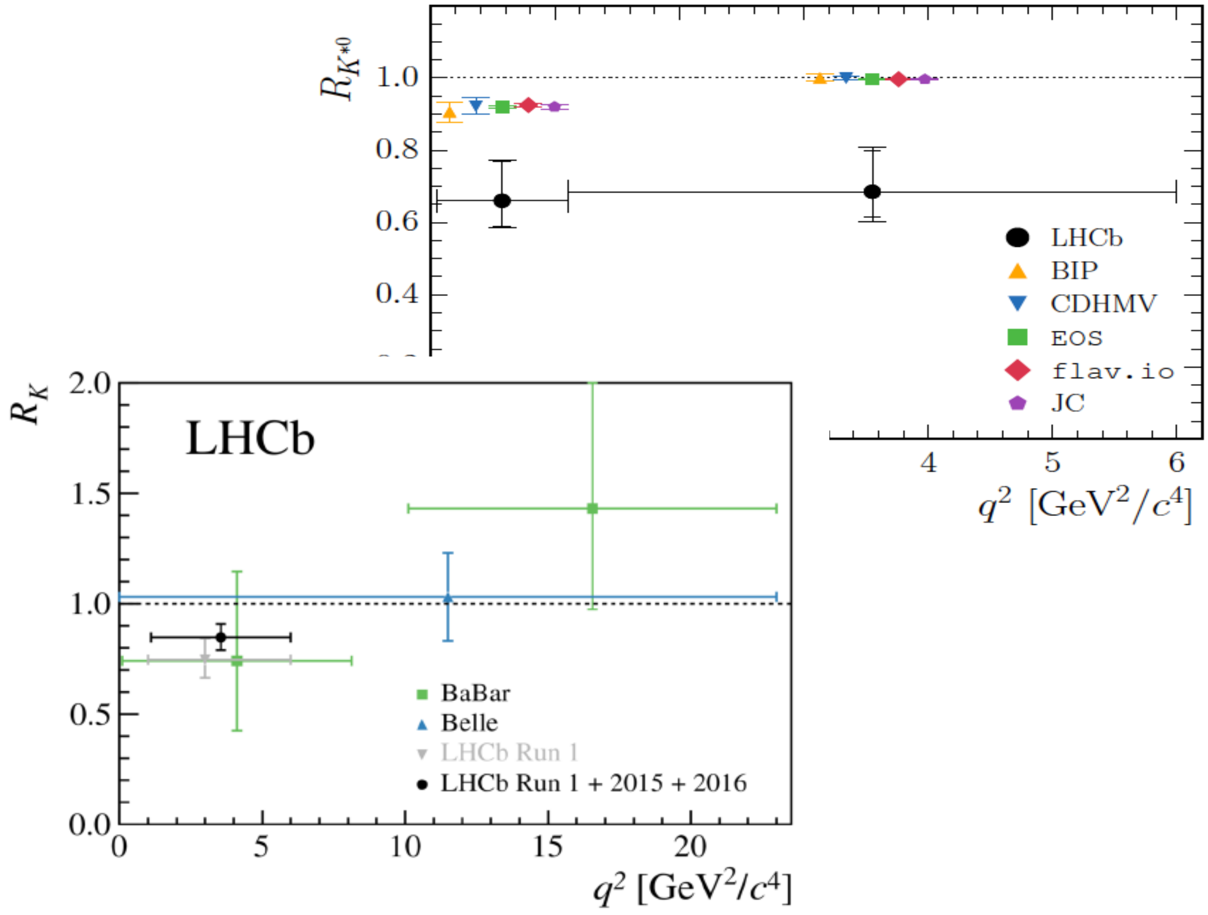
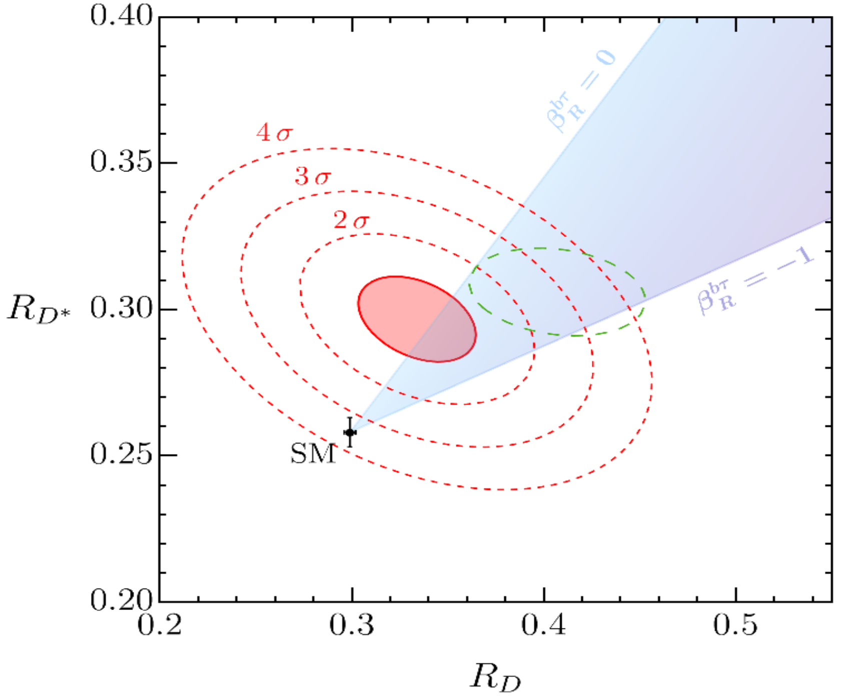
This is the path that seems to be indicated by the recent hints of Lepton Flavor non Universality in semi-leptonic B decays

LFU anomalies & Flavor symmetries





On the LFU anomalies

Recent data show some convincing evidences of Lepton Flavor Universality violations

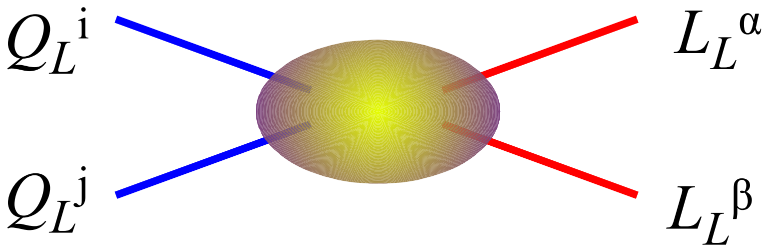
- $b \to c$ charged currents: τ vs. light leptons (μ, e) [R_D, R_{D*}]
- $b \to s$ neutral currents: μ vs. e [R_K, R_{K*} (+ P_5 *et al.*)]

IF taken together... this is probably the largest "coherent" set of deviations from the SM we have ever seen...

As we shall see, putting them together in a consistent way is quite non-trivial, but is "re-warding" from the model-building point of view

On the LFU anomalies

- Anomalies are seen only in semi-leptonic (quark×lepton) operators
- We definitely need non-vanishing left-handed current-current operators although other contributions are also possible



Bhattacharya *et al.* '14
Alonso, Grinstein, Camalich '15
Greljo, GI, Marzocca '15
(+many others...)

- Large coupling [*competing with SM tree-level*] in bc → $l_3\ \nu_3$ [R_D, R_{D^*}]
- Small coupling [*competing with SM loop-level*] in bs → $l_2\ l_2$ [R_K, R_{K^*}, ...]

↓

$T_{ij\alpha\beta} = (\delta_{i3}\times\delta_{3j})\times(\delta_{\alpha 3}\times\delta_{3\beta})$ + small terms for 2nd (& 1st) generations →

Link to pattern of the Yukawa couplings !

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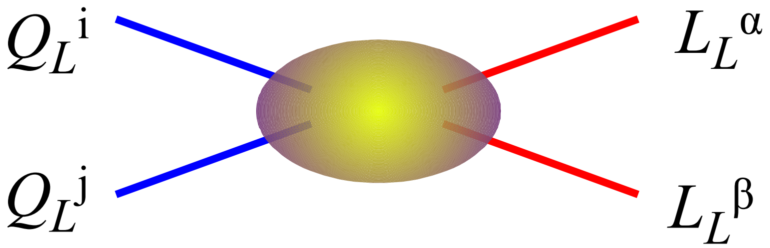

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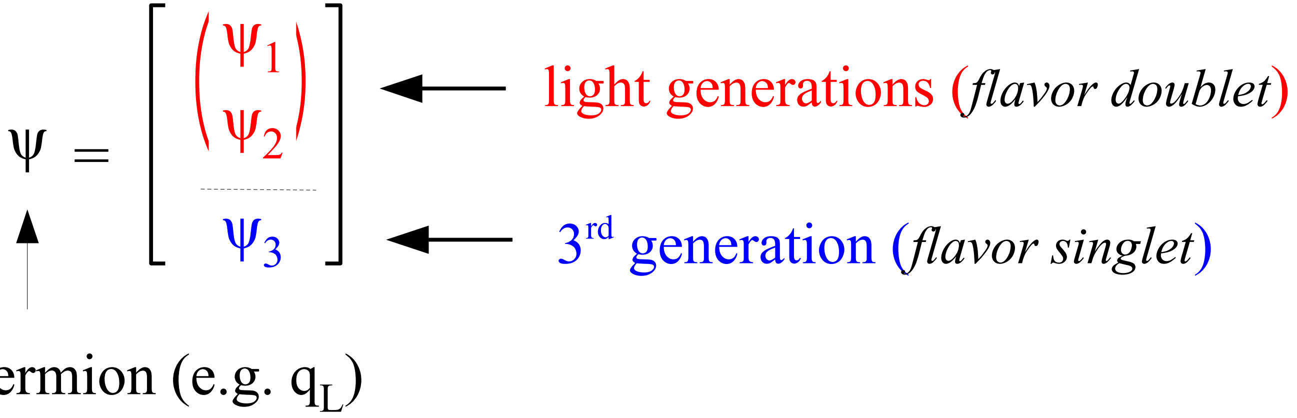
Long list of constraints [FCNCs + semi-leptonic b decays + π, K, τ decays + EWPO]

↓

Essential role of *flavor symmetries*, not only to explain the pattern of the anomalies, but also to “protect” against too large effects in other low-energy observables

LFU anomalies & the U(2)^n *flavor symmetry*

A very good candidate to address both these issues (link with the origin of the Yukawa couplings + compatibility with other low-energy data) is a chiral flavor symmetry of the type U(2)^n



$$\psi = \left[\begin{array}{c} \begin{pmatrix} \psi_1 \\ \psi_2 \end{pmatrix} \\ \hdashline \psi_3 \end{array}\right]$$

….with suitable (small) symmetry-breaking terms, related to the structures observed in the SM Yukawa couplings

Barbieri, G.I., Jones-Perez, Lodone, Straub, '11

NB: This flavor symmetry does not need to be a "fundamental" symmetry, it could well be an "accidental" symmetry, resulting from non-universal interactions that distinguish the 3rd family

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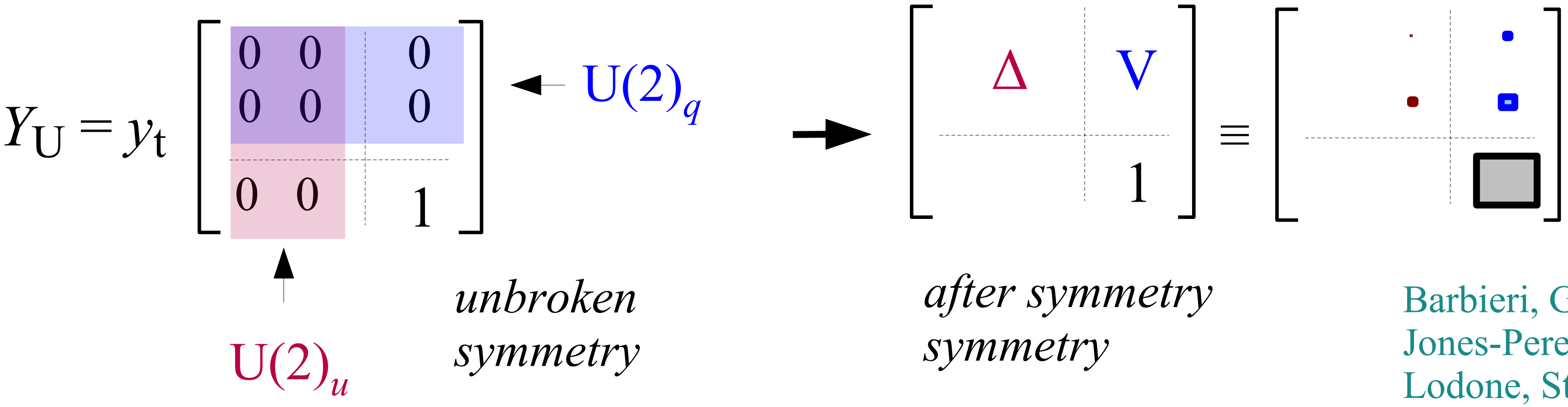
E.g. up-sector: $U(2)_q \times U(2)_u$



$$Y_U = y_t \left[\begin{array}{cc|c} 0 & 0 & 0 \\ 0 & 0 & 0 \\ \hline 0 & 0 & 1 \end{array}\right] \longrightarrow \left[\begin{array}{c|c} \Delta & V \\ \hline & 1 \end{array}\right] \equiv$$

Barbieri, G.I., Jones-Perez, Lodone, Straub, '11

Main idea: the same symmetry-breaking pattern control the mixing 3rd → 1st ,2nd gen. for the NP responsible for the anomalies

$$|V| \approx |V_{ts}| = 0.04$$
$$|\Delta| \approx y_c = 0.006$$

N.B.: this symmetry & symmetry-breaking pattern was proposed well-before the anomalies appeared [*it is not ambulance chasing...!*]

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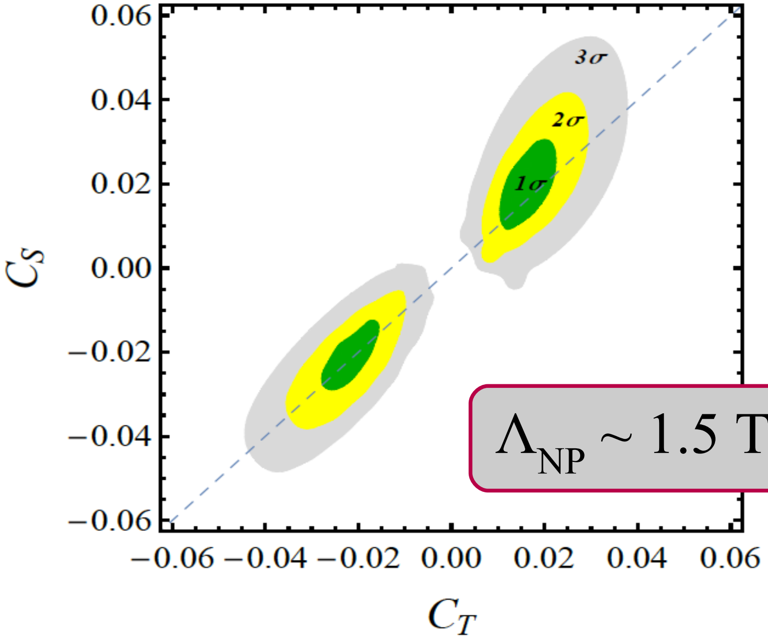
↓

An EFT based on the following two hypothesis:

- $U(2)_q \times U(2)_l$ chiral flavor symmetry
- NP in left-handed semi-leptonic operators only [*at the high-scale*]

provides an excellent fit to the data

Buttazzo, Greljo, GI, Marzocca, '17



$\Lambda_{NP} \sim 1.5$ TeV

LFU anomalies & the $\mathrm{U(2)^n}$ *flavor symmetry*

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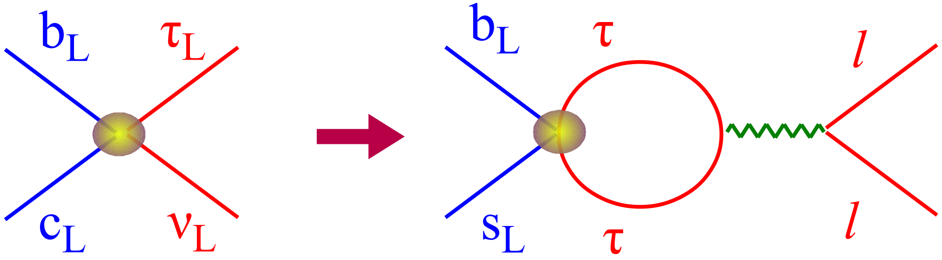
The latest data have made this picture even more consistent:

I. Higher NP scale given smaller central value of $b \to c$ anomaly

II. Rising "evidence" of LFU contribution to C_9, naturally expected in this framework:

Alguero *et al.* '19
Aebischer *et al.* '19



Crivellin, Greub, Muller, Saturnino '19

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II. Rising "evidence" of LFU contribution to C_9.

III. Rising "evidence" of a suppression of BR($B_s \to \mu\mu$), naturally expected by $\Delta C_9 = -\Delta C_{10}$

Greljo, GI, Marzocca, '15

$$BR(B_s \to \mu\mu)_{SM} = (3.66 \pm 0.14) \times 10^{-9}$$

Beneke et al. '19

$$BR(B_s \to \mu\mu)_{exp} = (2.72 \pm 0.34) \times 10^{-9}$$

ATLAS+CMS+LHCb '19

$\boxed{2.6\sigma}$

▶ *LFU anomalies & the* U(2)^n *flavor symmetry*

N.B.: The flavor symmetry hypothesis alone + chiral structure allow us to make very interesting predictions for low-energy observables

→ talk by C. Cornella

E.g.:

I. [*flavor*]:

$$\frac{A(b\to d\, ll)_{SM+NP}}{A(b\to s\, ll)_{SM+NP}} = \frac{A(b\to d\, ll)_{SM}}{A(b\to s\, ll)_{SM}} \qquad \frac{A(b\to u\, l\nu)_{SM+NP}}{A(b\to c\, l\nu)_{SM+NP}} = \frac{A(b\to u\, l\nu)_{SM}}{A(b\to c\, l\nu)_{SM}}$$

II. [*chiral structure*]:

$$R_\phi(B_s) \approx R_{\pi K}(B) \approx R(\Lambda_b)_\Lambda \approx R(\Lambda_b)_{pK} \approx \ldots \approx R_K$$

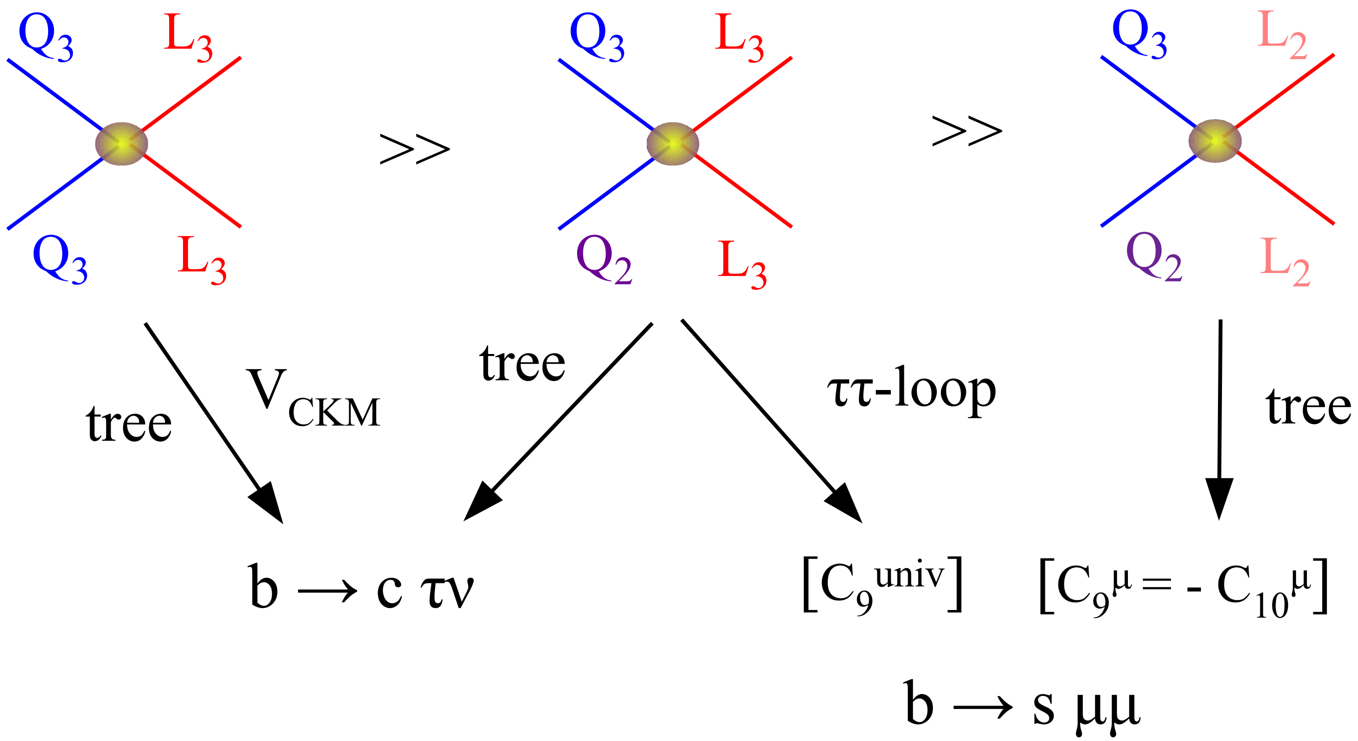
exact in the limit where $(C_{10}+C_9)_{SM} / (C_{10}-C_9)_{SM} \to 0$

$$A_{SM} = (C_{10}+C_9)_{SM} \langle Q_9+Q_{10} \rangle \left[\, 1 \underset{<5\%}{\swarrow}{+} \frac{(C_{10}-C_9)_{SM}}{(C_{10}+C_9)_{SM}} \frac{\langle Q_9-Q_{10}\rangle}{\langle Q_9+Q_{10}\rangle} + \text{other ops...} \right]$$

LFU anomalies & the $U(2)^n$ *flavor symmetry*

N.B.: The flavor symmetry hypothesis alone + chiral structure allow us to make very interesting predictions for low-energy observables

N.B.: This consistent flavor symmetry hypothesis tell us that the connection between charged & neutral-current anomalies is not trivial:



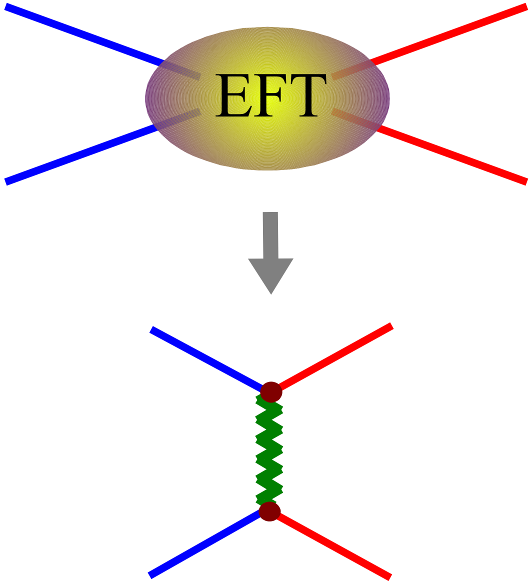
Q_3 L_3 Q_3 L_3 >> Q_3 L_3 Q_2 L_3 >> Q_3 L_2 Q_2 L_2

tree V_{CKM} tree ττ-loop tree

$b \to c\,\tau\nu$ $[C_9^{univ}]$ $[C_9^{\mu} = - C_{10}^{\mu}]$

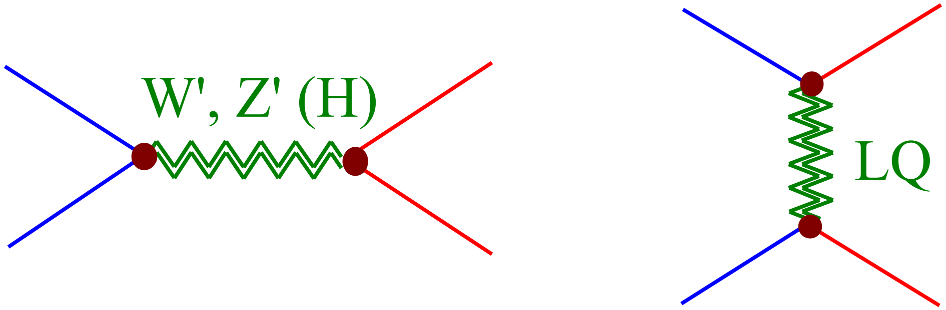
$b \to s\,\mu\mu$

Simplified models: the return of the Leptoquark



General considerations

Which tree-level mediators can generate the effective operators required for a successful EFT fit? Not many possibilities...



N.B.: Given the effective low-scale of NP, we are naturally lead to simplified models with tree-level leading mediators

These simplified models are not meant to be complete UV models, but rather a "tool" to connect

- low- vs. high-energy phenomenology,
- disconnected sectors of the EFT (e.g. semi-leptonic vs. $\Delta F=2$ ops.)

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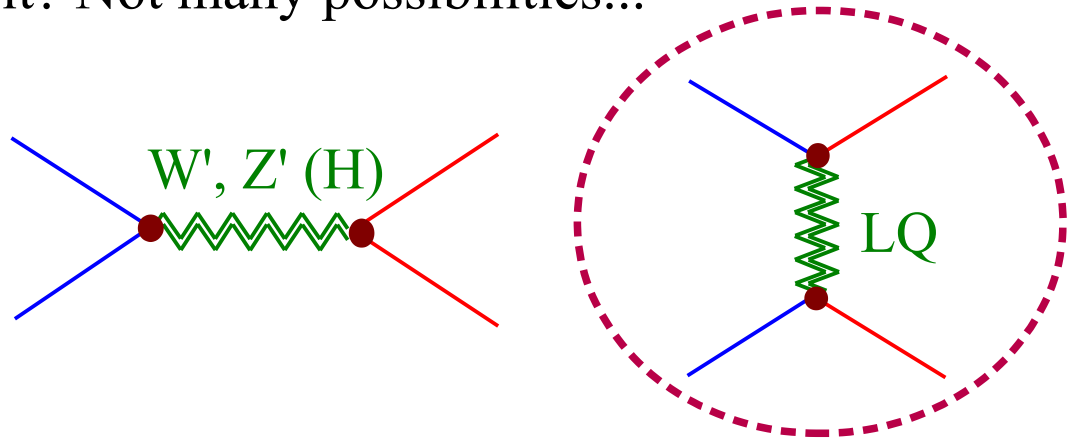
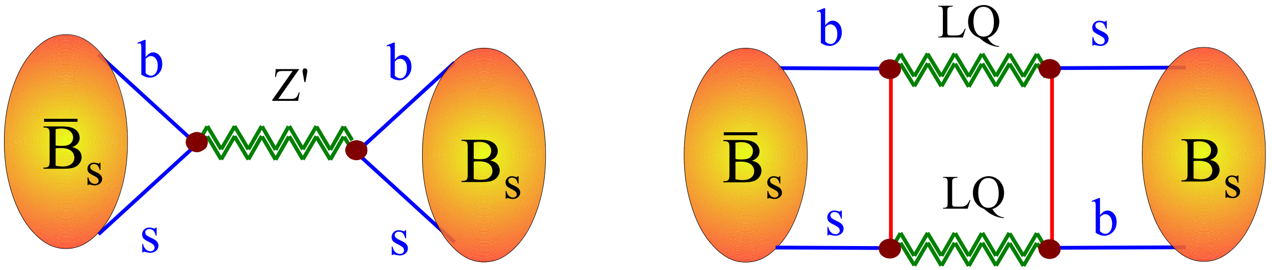


LQ (both scalar and vectors) have two general strong advantages with respect to the other mediators:

I. ΔF=2 &
$\tau \to l\nu\nu$

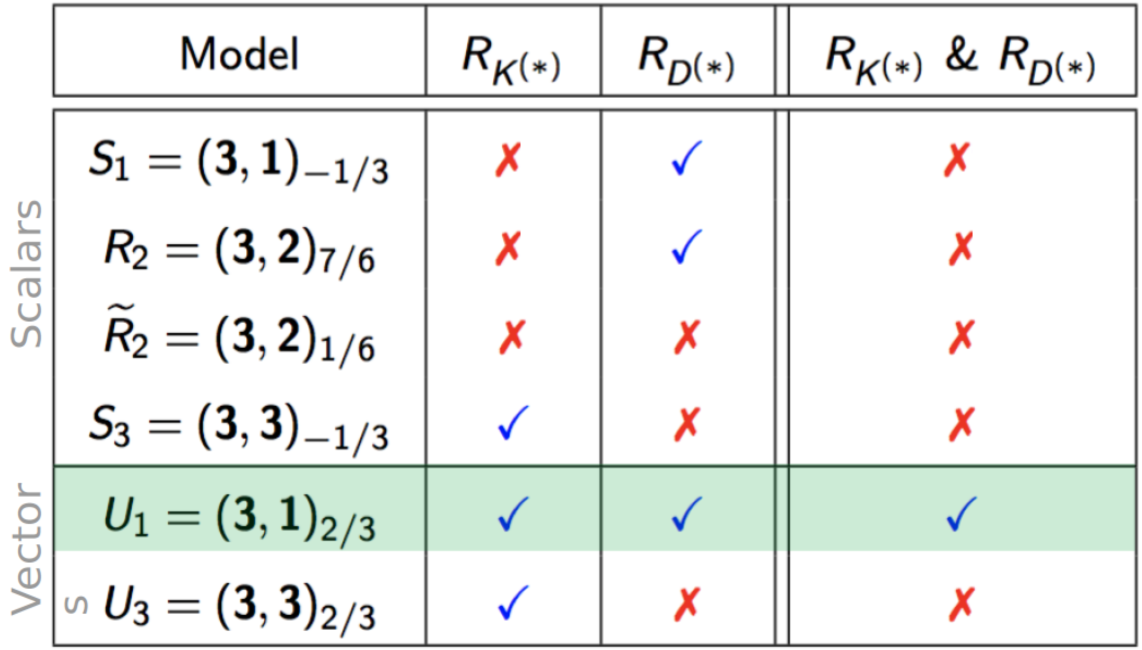


II. Direct searches:

3rd gen. LQ are also in better shape as far as direct searches are concerned (*contrary to Z'...*).

▸ *General considerations*

Which LQ explain which anomaly?

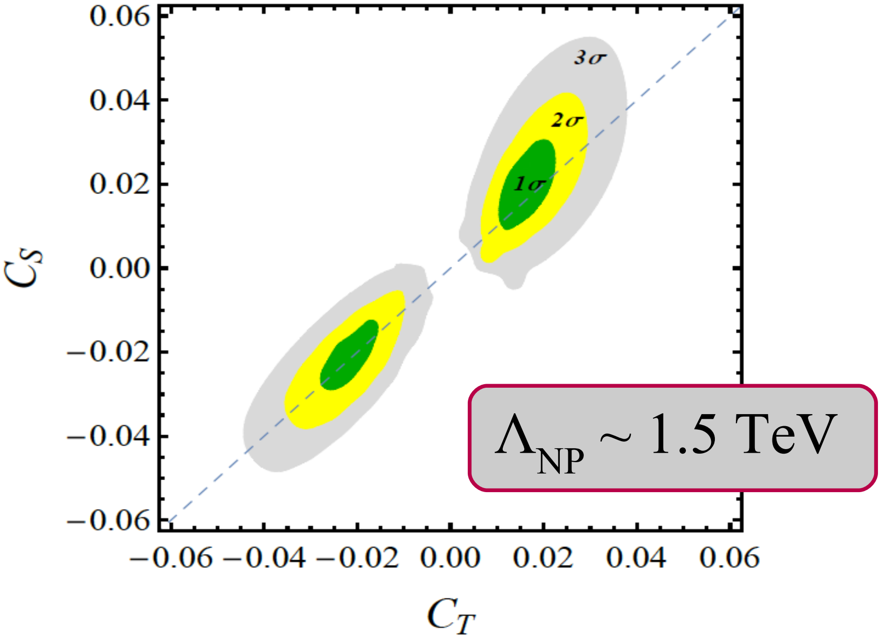


	Model	$R_{K^{(*)}}$	$R_{D^{(*)}}$	$R_{K^{(*)}}$ & $R_{D^{(*)}}$
Scalars	$S_1 = (\mathbf{3}, \mathbf{1})_{-1/3}$	✗	✓	✗
	$R_2 = (\mathbf{3}, \mathbf{2})_{7/6}$	✗	✓	✗
	$\widetilde{R}_2 = (\mathbf{3}, \mathbf{2})_{1/6}$	✗	✗	✗
	$S_3 = (\mathbf{3}, \mathbf{3})_{-1/3}$	✓	✗	✗
Vectors	$U_1 = (\mathbf{3}, \mathbf{1})_{2/3}$	✓	✓	✓
	$U_3 = (\mathbf{3}, \mathbf{3})_{2/3}$	✓	✗	✗

Angelescu, Becirevic, DAF, Sumensari [1808.08179]

There is one clear winner [U_1]...

Buttazzo, Greljo, GI, Marzocca, '17



$\Lambda_{\rm NP} \sim 1.5$ TeV

▸ *General considerations*

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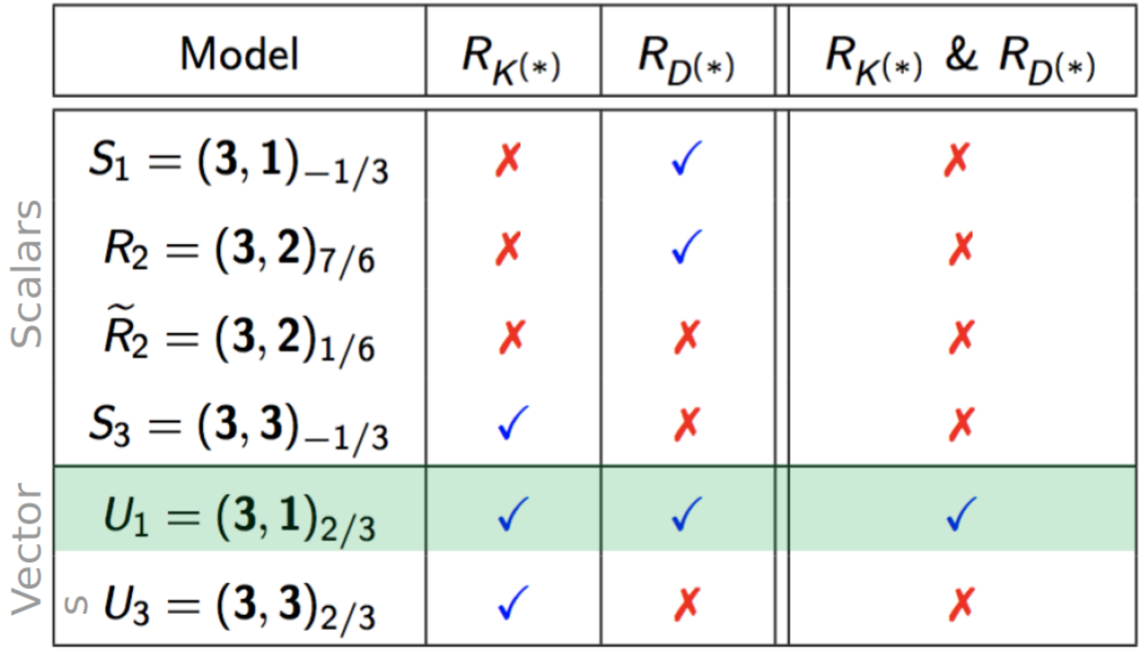

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Vectors	$U_1 = (\mathbf{3}, \mathbf{1})_{2/3}$	✓	✓	✓
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There is one clear winner [U_1]...

...but the single-mediator case is definitely an over simplification [*as we learned in the last ~ 2 years...*]

3 interesting options:

- U_1 + colorless-vectors

Being a massive vector, U_1 requires an appropriate UV compl. → always accompanied by (at least) a Z'

Alonso, Grinstein, Camalich '15
Barbieri, GI , Pattori, Senia '15
\+ wide literature

- S_1 & S_3

Good option for the EFT “pure-LH” solution

Crivellin, Muller, Ota '17
Buttazzo *et al.* '17
Marzocca '18

- R_2 & S_3

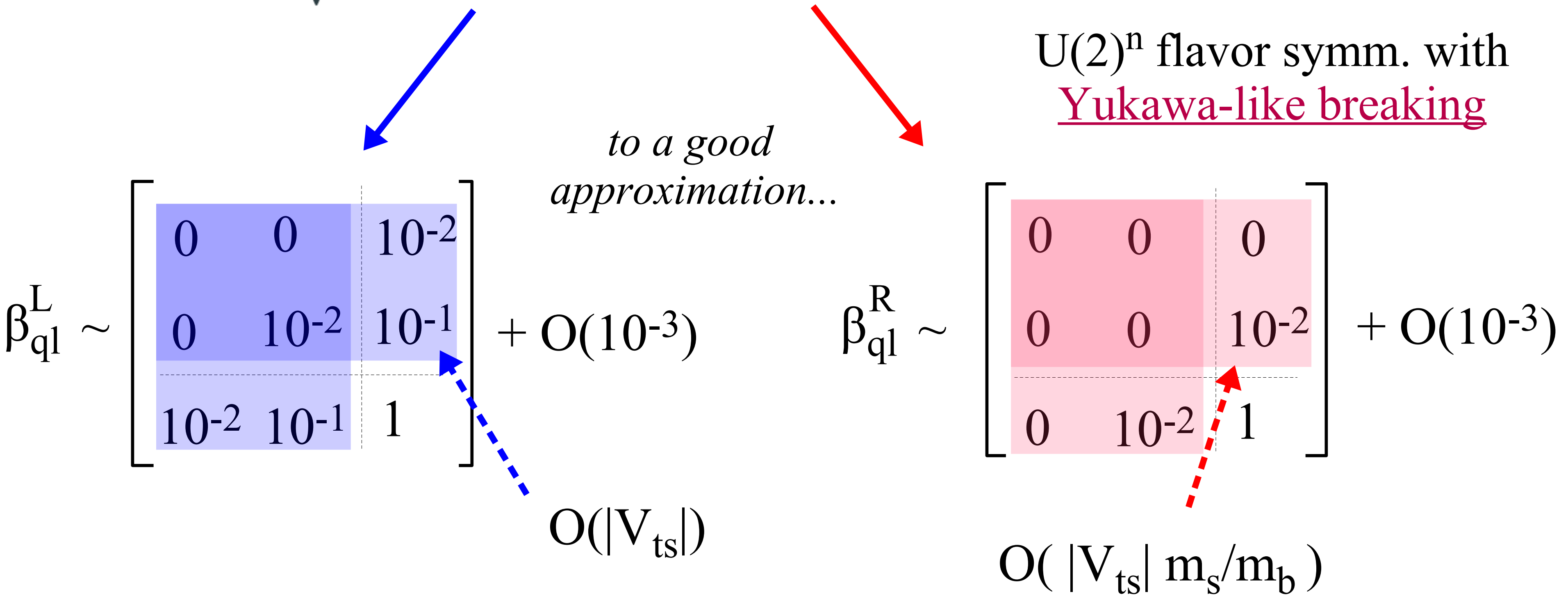
GUT-inspired option for EFT solution including also RH currents

Becirevic *et al.* '18

A "consistent" simplified model for the U_1

- Initial attempts focused on LQ with few, purely LH couplings.
  However, the quantum numbers of the U_1 allow both RH and LH currents.
- A consistent reduction in the number if free parameters is achieved with the help of the flavor symmetry:

$$\mathscr{L} \supset \frac{g_U}{\sqrt{2}} U_1^\mu \left[\beta^L_{i\alpha}(\bar q^i_L \gamma_\mu \ell^\alpha_L) - \beta^R_{i\alpha}(\bar d^i_R \gamma_\mu e^\alpha_R)\right] + \mathrm{h.c.}$$



U(2)^n flavor symm. with Yukawa-like breaking

to a good approximation...

$$\beta^L_{ql} \sim \left[\begin{array}{cc|c} 0 & 0 & 10^{-2} \\ 0 & 10^{-2} & 10^{-1} \\ \hline 10^{-2} & 10^{-1} & 1 \end{array}\right] + O(10^{-3})$$

$$\beta^R_{ql} \sim \left[\begin{array}{cc|c} 0 & 0 & 0 \\ 0 & 0 & 10^{-2} \\ \hline 0 & 10^{-2} & 1 \end{array}\right] + O(10^{-3})$$

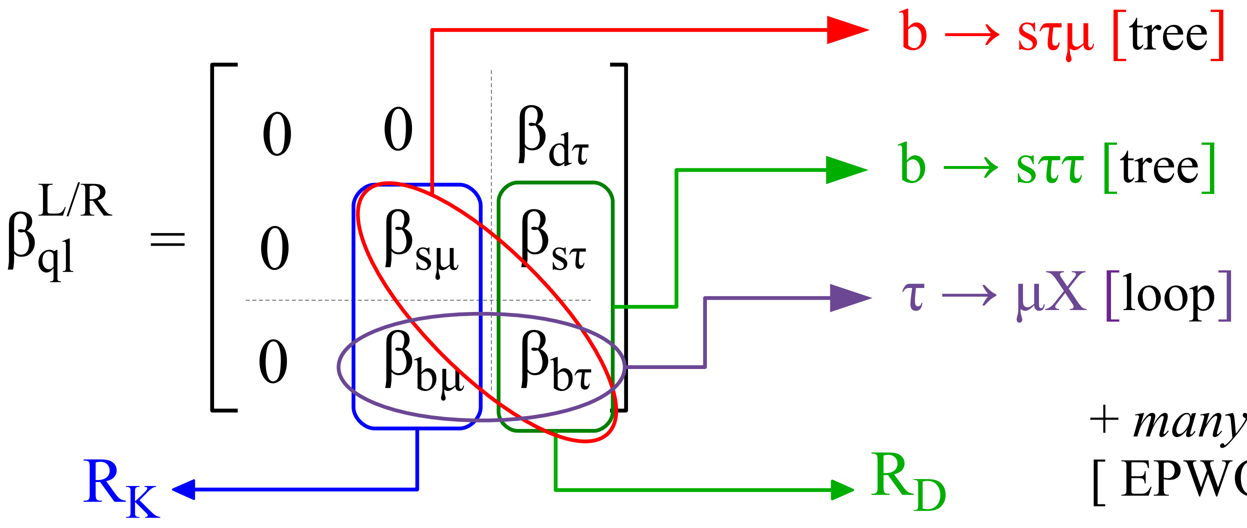
$O(|V_{ts}|)$

$O(\, |V_{ts}|\, m_s/m_b \,)$

A "consistent" simplified model for the U_1

- Initial attempts focused on LQ with few, purely LH couplings.
  However, the quantum numbers of the U_1 allow both RH and LH currents.
- A consistent reduction in the number if free parameters is achieved with the help of the flavor symmetry:

$$\mathcal{L} \supset \frac{g_U}{\sqrt{2}} U_1^\mu \left[\beta^L_{i\alpha}\,(\bar q^i_L \gamma_\mu \ell^\alpha_L) - \beta^R_{i\alpha}\,(\bar d^i_R \gamma_\mu e^\alpha_R)\right] + \mathrm{h\,.\,c\,.}$$



$$\beta_{ql}^{L/R} = \begin{bmatrix} 0 & 0 & \beta_{d\tau} \\ 0 & \beta_{s\mu} & \beta_{s\tau} \\ 0 & \beta_{b\mu} & \beta_{b\tau} \end{bmatrix}$$

$b \to s\tau\mu$ [tree]

$b \to s\tau\tau$ [tree]

$\tau \to \mu X$ [loop]

R_K

R_D

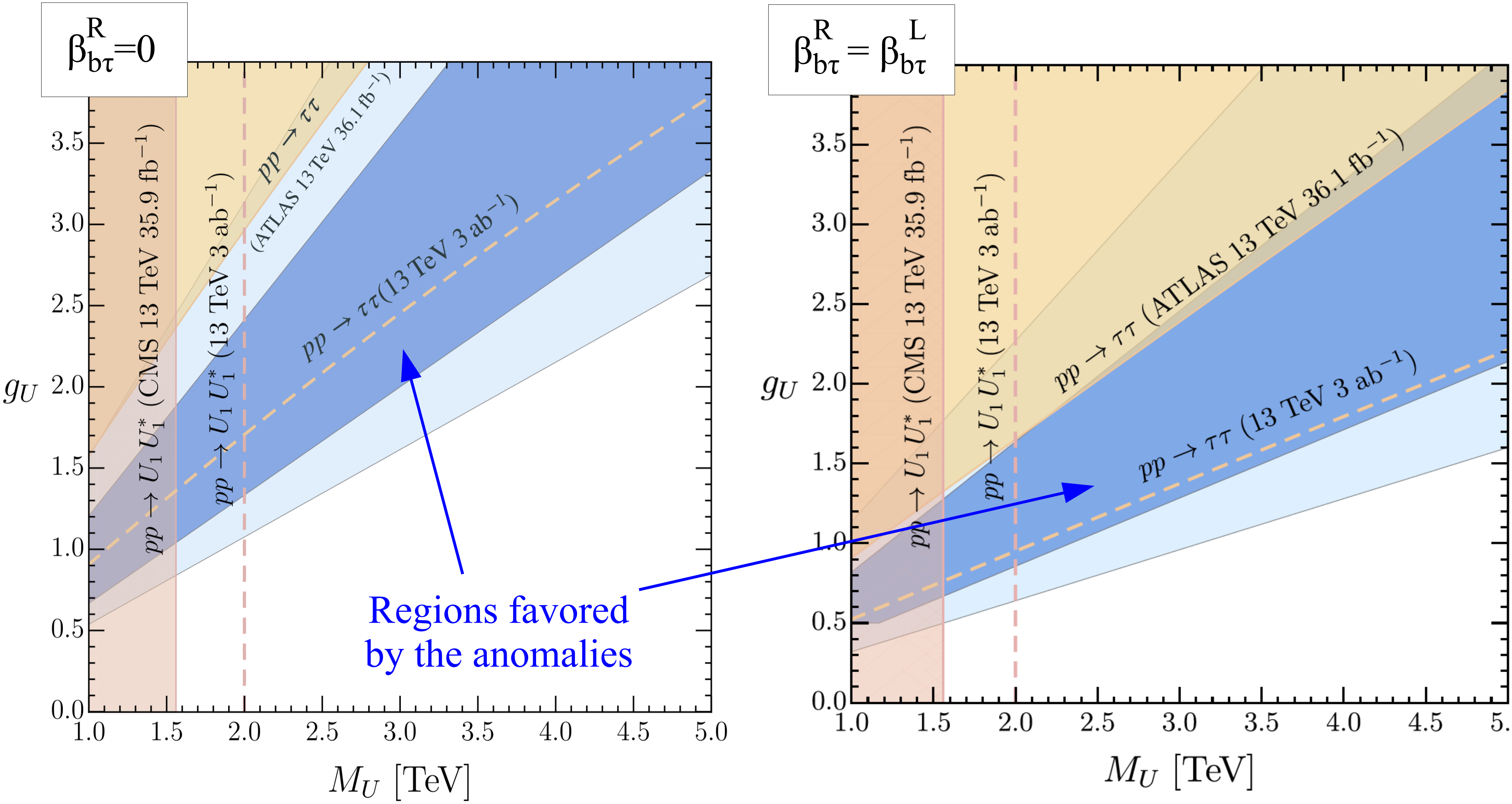
+ *many other effects*
[EPWO, LFU in τ's...]

The presence of the (motivated) extra coupling leads to a series of interesting effects at both low- and high-energies

Bordone, Cornella, Fuentes-Martin, GI, '18
Cornella, Fuentes-Martin, GI, '19

▸ *A "consistent" simplified model for the* U_1

The presence of RH couplings leads to significant differences at high-p_T:



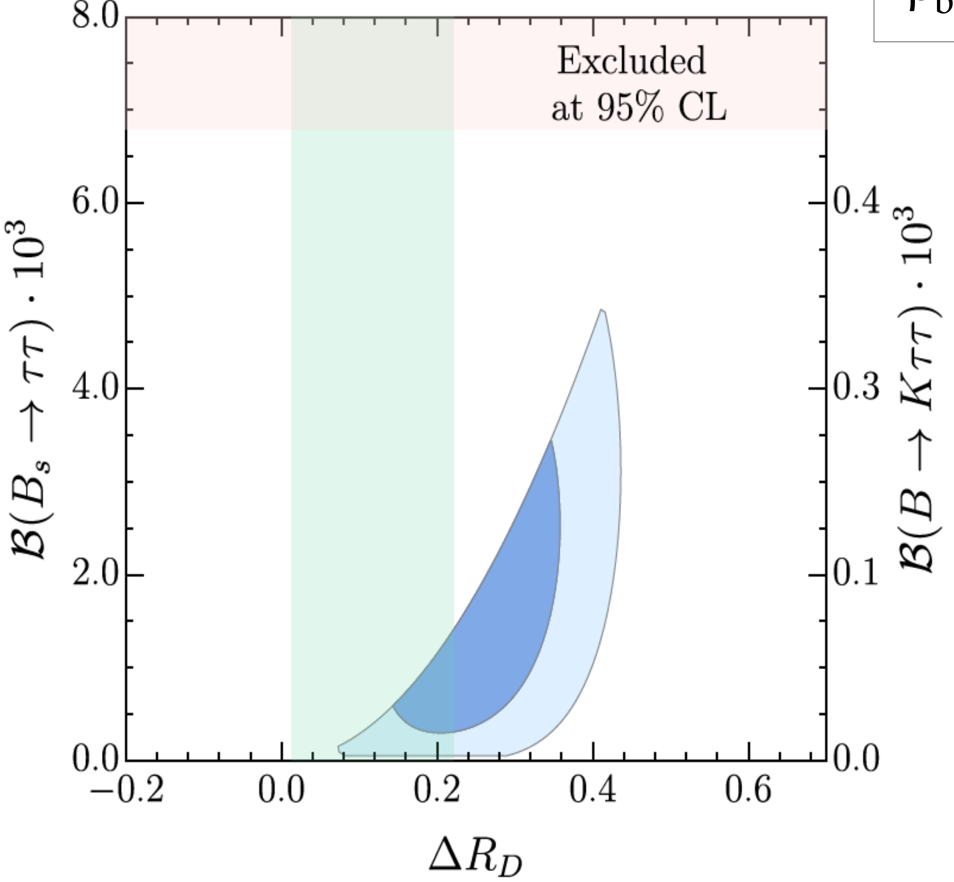
Regions favored by the anomalies

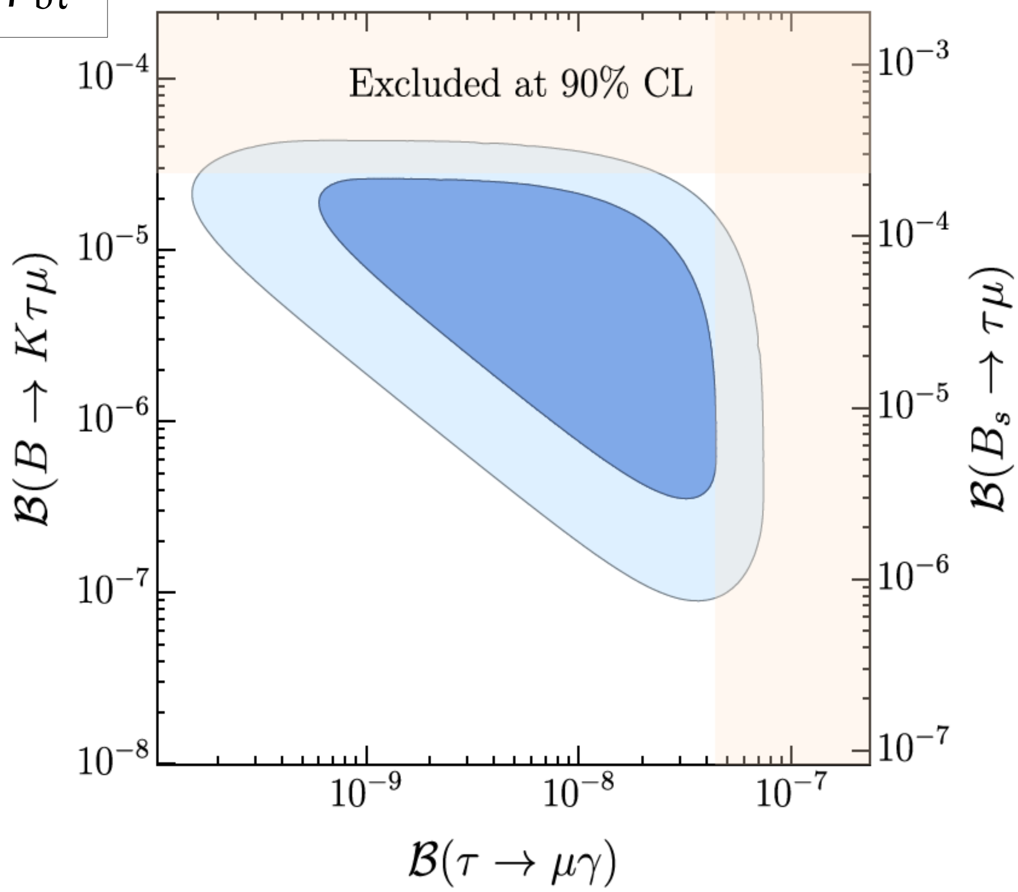
Baker, Fuentes-Martin, GI, König, '19

▸ *A "consistent" simplified model for the* U_1

Probably the most striking signature of large RH couplings is the (unavoidable) large enhancement of the helicity-suppressed B(B→ ττ) & B(B→ τμ):

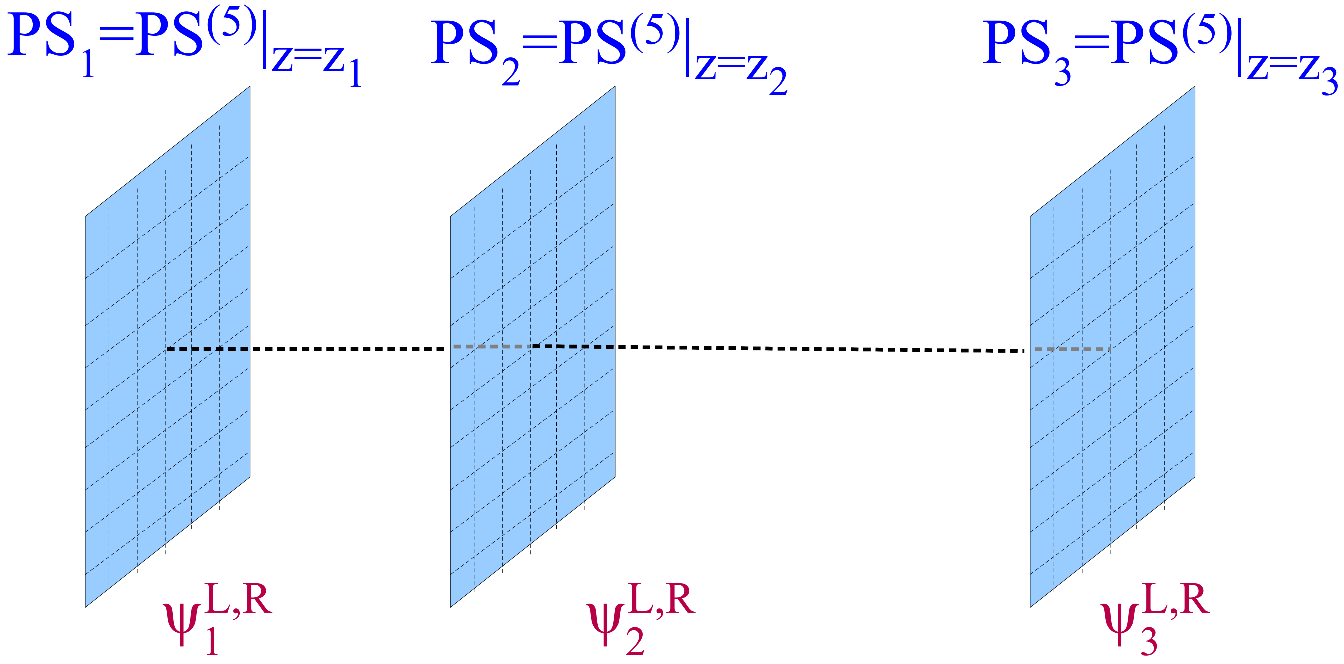
$$\beta^R_{b\tau} = \beta^L_{b\tau}$$





Cornella, Fuentes-Martin, GI, '19

Non-universal gauge interactions & the PS^3 hypothesis



Toward a UV completion: the PS^3 *hypothesis*

Starting observation: the gauge theory proposed in the 70's to unify quarks and leptons by Pati & Salam predicts a massive vector LQ with the correct quantum numbers to fit the anomalies:

Pati-Salam group: $SU(4) \times SU(2)_L \times SU(2)_R$

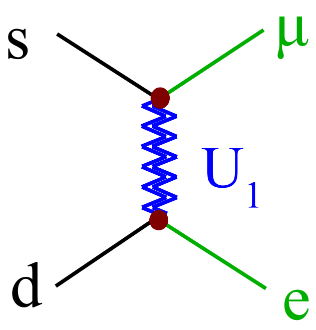
Fermions in SU(4):

$$\begin{bmatrix} Q_L^\alpha \\ Q_L^\beta \\ Q_L^\gamma \\ L_L \end{bmatrix} \quad \begin{bmatrix} Q_R^\alpha \\ Q_R^\beta \\ Q_R^\gamma \\ L_R \end{bmatrix}$$

Main Pati-Salam idea:
Lepton number as "the 4th color"

The massive LQ [U_1] arise from the breaking $SU(4) \to SU(3)_C \times U(1)_{B-L}$

The problem of the "original PS model" are the strong bounds on the LQ couplings to 1st & 2nd generations [e.g. $M > 200$ TeV from $K_L \to \mu e$]



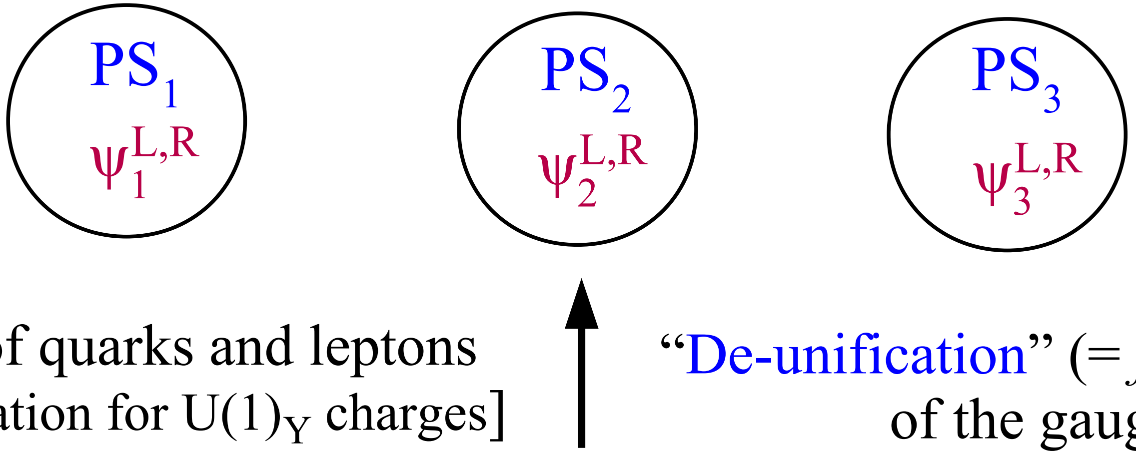
Interesting recent attempts to solve this problem adding extra fermions and/or modifying the gauge group [Calibbi, Crivellin, Li, '17; Di Luzio, Greljo, Nardecchia, '17]

▶ *The* PS^3 *model*

$$[\ \mathrm{PS}\ ]^3 = [\ SU(4) \times SU(2)_L \times SU(2)_R\ ]^3$$

Bordone, Cornella,
Fuentes-Martin, GI, '17

Main idea: at high energies the 3 families are charged under 3 independent gauge groups (*gauge bosons carry a flavor index !*)



UV

PS_1 $\psi_1^{L,R}$

PS_2 $\psi_2^{L,R}$

PS_3 $\psi_3^{L,R}$

Unification of quarks and leptons
[natural explanation for $U(1)_Y$ charges]

"De-unification" (= *flavor deconstruction*)
of the gauge symmetry

SM

IR

Q_i, u_i, d_i, L_i, e_i

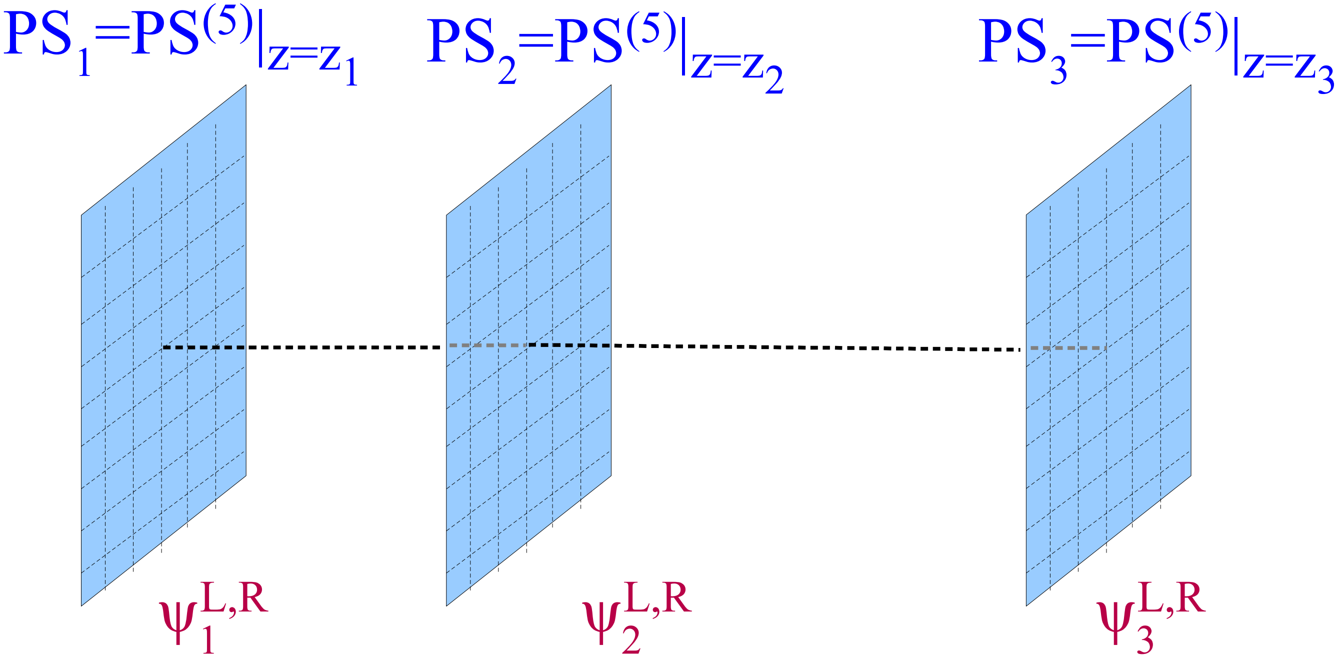
Key advantages:

- Light LQ coupled mainly to 3rd gen.
- Accidental $U(2)^5$ flavor symmetry
- Natural structure of SM Yukawa couplings

- *The* PS^3 *model*

$$[\,\mathrm{PS}\,]^3 = [\,\mathrm{SU(4)}\times\mathrm{SU(2)}_L\times\mathrm{SU(2)}_R\,]^3$$

Bordone, Cornella, Fuentes-Martin, GI, '17



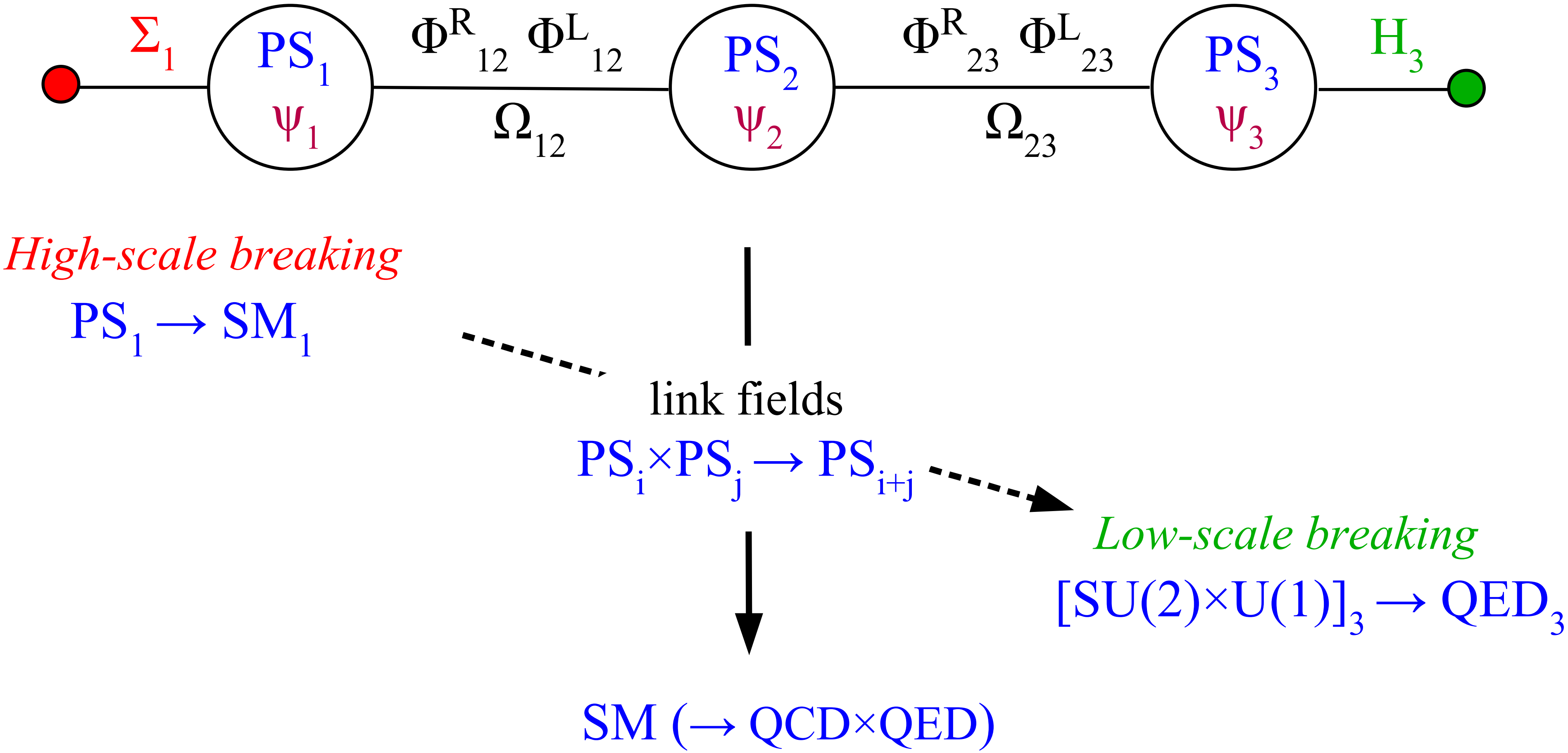
Unification
of quarks and leptons

"De-unification"
(= *flavor deconstruction*)
of the gauge symmetry

This construction can find a "natural" justification in the context of models with extra space-time dimensions

The 4D description is apparently more complex, but it allow us to derive precise low-energy phenomenological signatures (*4D renormalizable gauge model*)

The PS^3 *model*



High-scale breaking

$PS_1 \rightarrow SM_1$

link fields

$PS_i \times PS_j \rightarrow PS_{i+j}$

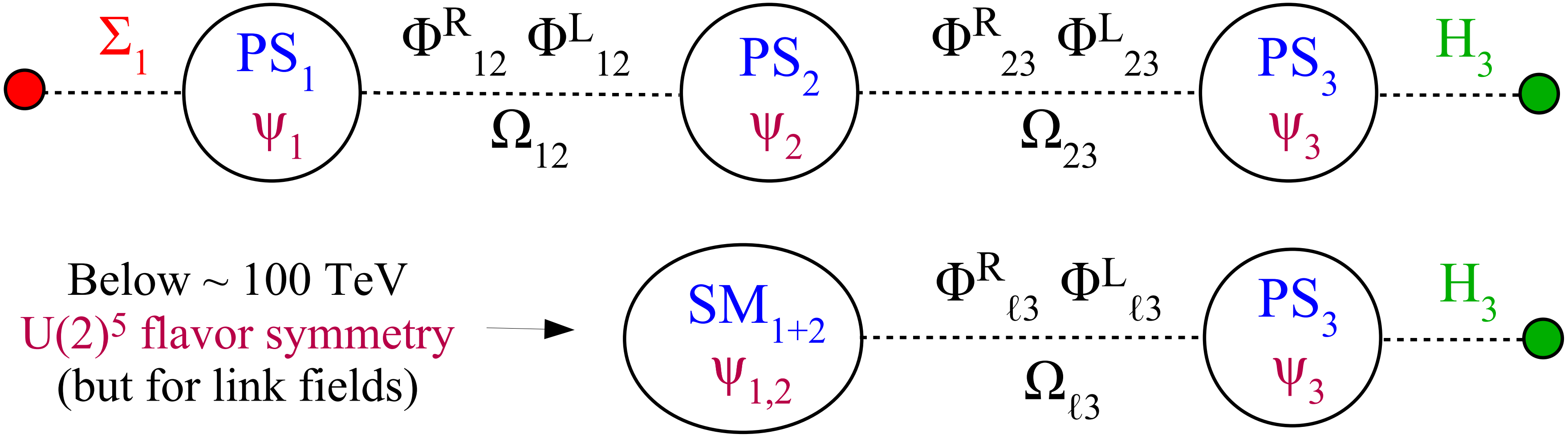
Low-scale breaking

$[SU(2)\times U(1)]_3 \rightarrow QED_3$

SM (→ QCD×QED)

- The breaking to the diagonal SM group occurs via appropriate “link” fields, responsible also for the generation of the hierarchy in the Yukawa couplings.
- The 2-3 breaking gives a TeV-scale LQ [+ Z' & G'] coupled mainly to 3rd gen., as in the “4321” model [Di Luzio, Greljo, Nardecchia, '17]

The PS^3 *model*

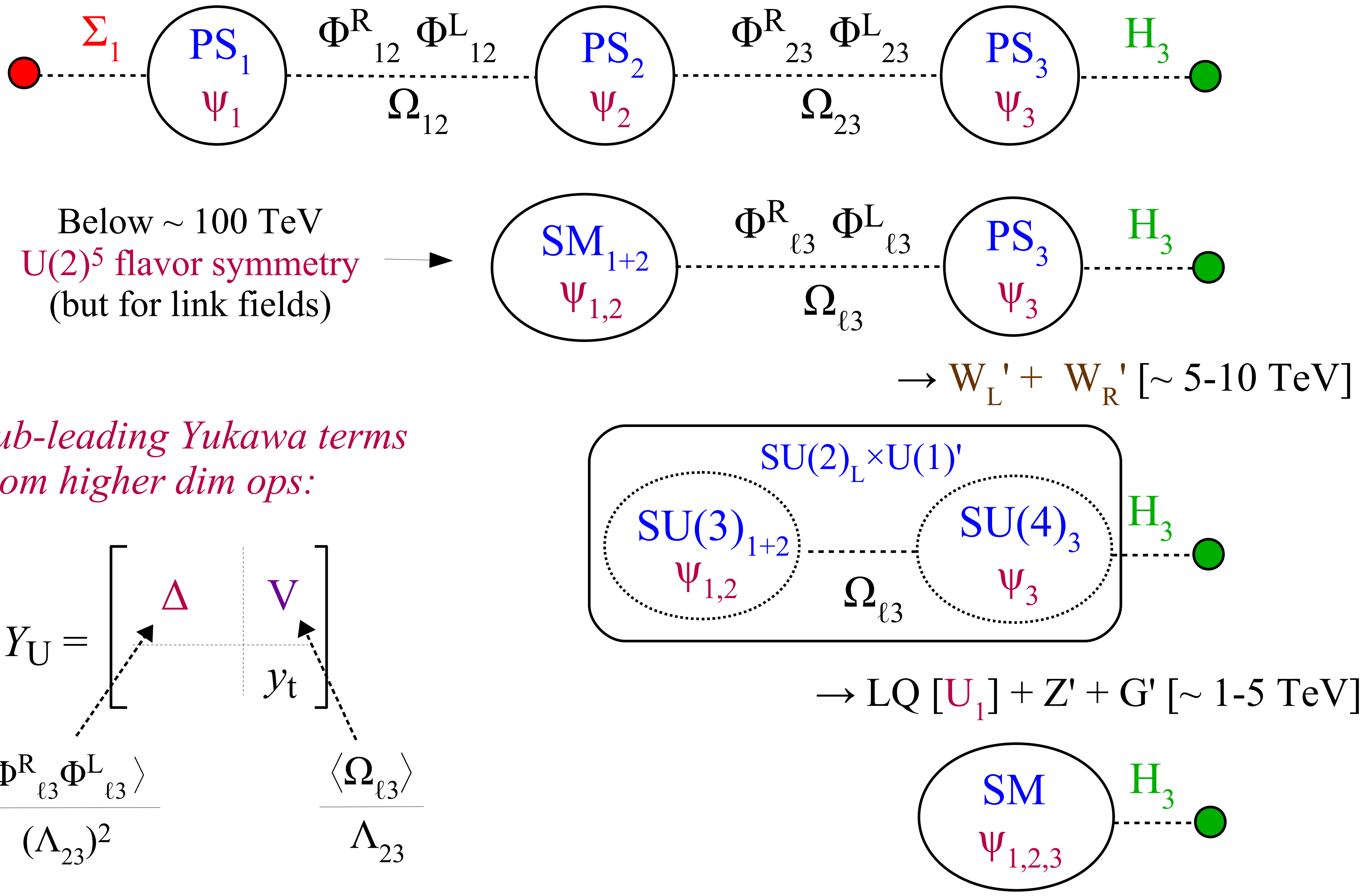


Below ~ 100 TeV
U(2)^5 flavor symmetry
(but for link fields)

Leading flavor structure:

- Yukawa coupling for 3rd gen. only
- "Light" LQ field (from PS$_3$) coupled only to 3rd gen.
- U(2)^5 symmetry protects flavor-violating effects on light gen.

The PS^3 *model*



Σ_1 — PS_1, ψ_1 — $\Phi^R{}_{12}$ $\Phi^L{}_{12}$, Ω_{12} — PS_2, ψ_2 — $\Phi^R{}_{23}$ $\Phi^L{}_{23}$, Ω_{23} — PS_3, ψ_3 — H_3

Below ~ 100 TeV
U(2)^5 flavor symmetry
(but for link fields)

SM_{1+2}, $\psi_{1,2}$ — $\Phi^R{}_{\ell 3}$ $\Phi^L{}_{\ell 3}$, $\Omega_{\ell 3}$ — PS_3, ψ_3 — H_3

→ $W_L' + W_R'$ [~ 5-10 TeV]

$SU(2)_L \times U(1)'$

$SU(3)_{1+2}$, $\psi_{1,2}$ — $\Omega_{\ell 3}$ — $SU(4)_3$, ψ_3 — H_3

→ LQ [U_1] + Z' + G' [~ 1-5 TeV]

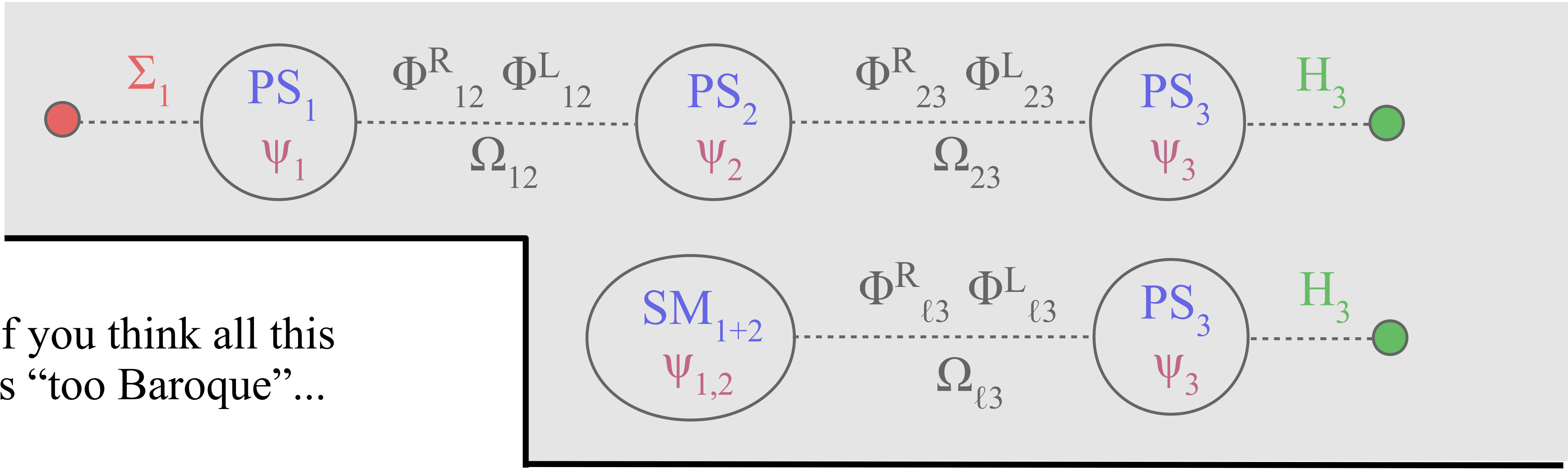
SM, $\psi_{1,2,3}$ — H_3

Sub-leading Yukawa terms from higher dim ops:

$$Y_U = \begin{bmatrix} \Delta & V \\ & y_t \end{bmatrix}$$

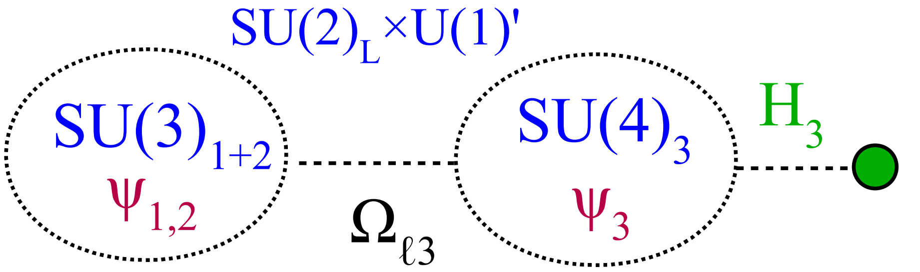
$$\frac{\langle \Phi^R{}_{\ell 3} \Phi^L{}_{\ell 3} \rangle}{(\Lambda_{23})^2} \qquad \frac{\langle \Omega_{\ell 3} \rangle}{\Lambda_{23}}$$

The PS^3 *model*



If you think all this
is “too Baroque”...

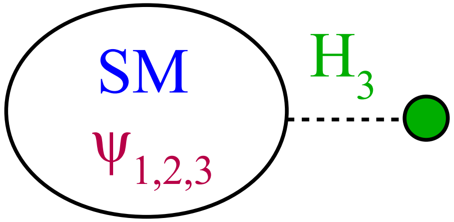
...we can start here:
4321 (*flavor non-universal*) model:



$$Y_U = \left[\begin{array}{c|c} \Delta & V \\ \hline & y_t \end{array}\right]$$

$$\frac{\langle \Omega_{\ell 3} \rangle}{\Lambda_{23}}$$

→ LQ [U_1] + Z' + G' [~ 1-5 TeV]



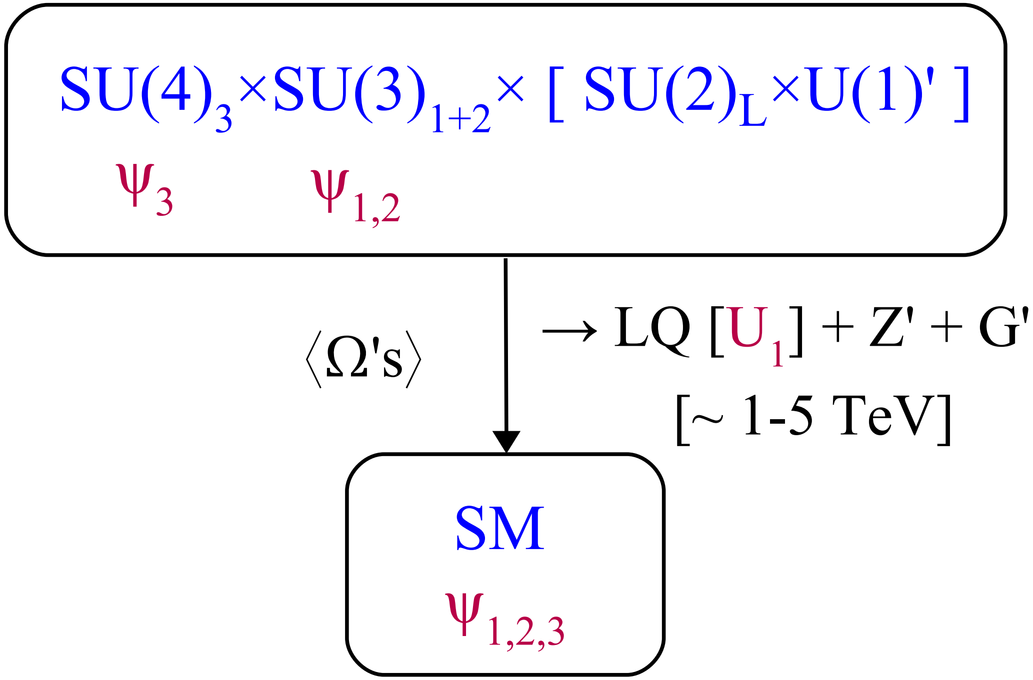
The PS^3 model

Present collider and low-energy pheno are all controlled by the last-step in the breaking chain [4321 → SM]

Despite the apparent complexity, the construction is highly constrained

Renormalizable structure (no d>5 ops) achieved with vector-like fermions

Field	$SU(4)$	$SU(3)'$	$SU(2)_L$	$U(1)'$
$q_L'^i$	$\mathbf{1}$	$\mathbf{3}$	$\mathbf{2}$	$1/6$
$u_R'^i$	$\mathbf{1}$	$\mathbf{3}$	$\mathbf{1}$	$2/3$
$d_R'^i$	$\mathbf{1}$	$\mathbf{3}$	$\mathbf{1}$	$-1/3$
$\ell_L'^i$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{2}$	$-1/2$
$e_R'^i$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	-1
ψ_L'	$\mathbf{4}$	$\mathbf{1}$	$\mathbf{2}$	0
ψ_u'	$\mathbf{4}$	$\mathbf{1}$	$\mathbf{1}$	$1/2$
ψ_d'	$\mathbf{4}$	$\mathbf{1}$	$\mathbf{1}$	$-1/2$
χ_L^i	$\mathbf{4}$	$\mathbf{1}$	$\mathbf{2}$	0
χ_R^i	$\mathbf{4}$	$\mathbf{1}$	$\mathbf{2}$	0
H_1	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{2}$	$1/2$
H_{15}	$\mathbf{15}$	$\mathbf{1}$	$\mathbf{2}$	$1/2$
Ω_1	$\bar{\mathbf{4}}$	$\mathbf{1}$	$\mathbf{1}$	$-1/2$
Ω_3	$\bar{\mathbf{4}}$	$\mathbf{3}$	$\mathbf{1}$	$1/6$
Ω_{15}	$\mathbf{15}$	$\mathbf{1}$	$\mathbf{1}$	0



$\mathrm{SU}(4)_3 \times \mathrm{SU}(3)_{1+2} \times [\ \mathrm{SU}(2)_L \times \mathrm{U}(1)'\ ]$

Ψ_3 $\Psi_{1,2}$

$\langle \Omega\text{'s} \rangle$

$\rightarrow$ LQ [U_1] + Z' + G'

[~ 1-5 TeV]

SM

$\Psi_{1,2,3}$

We can reproduce all the positive features the simplified model

+

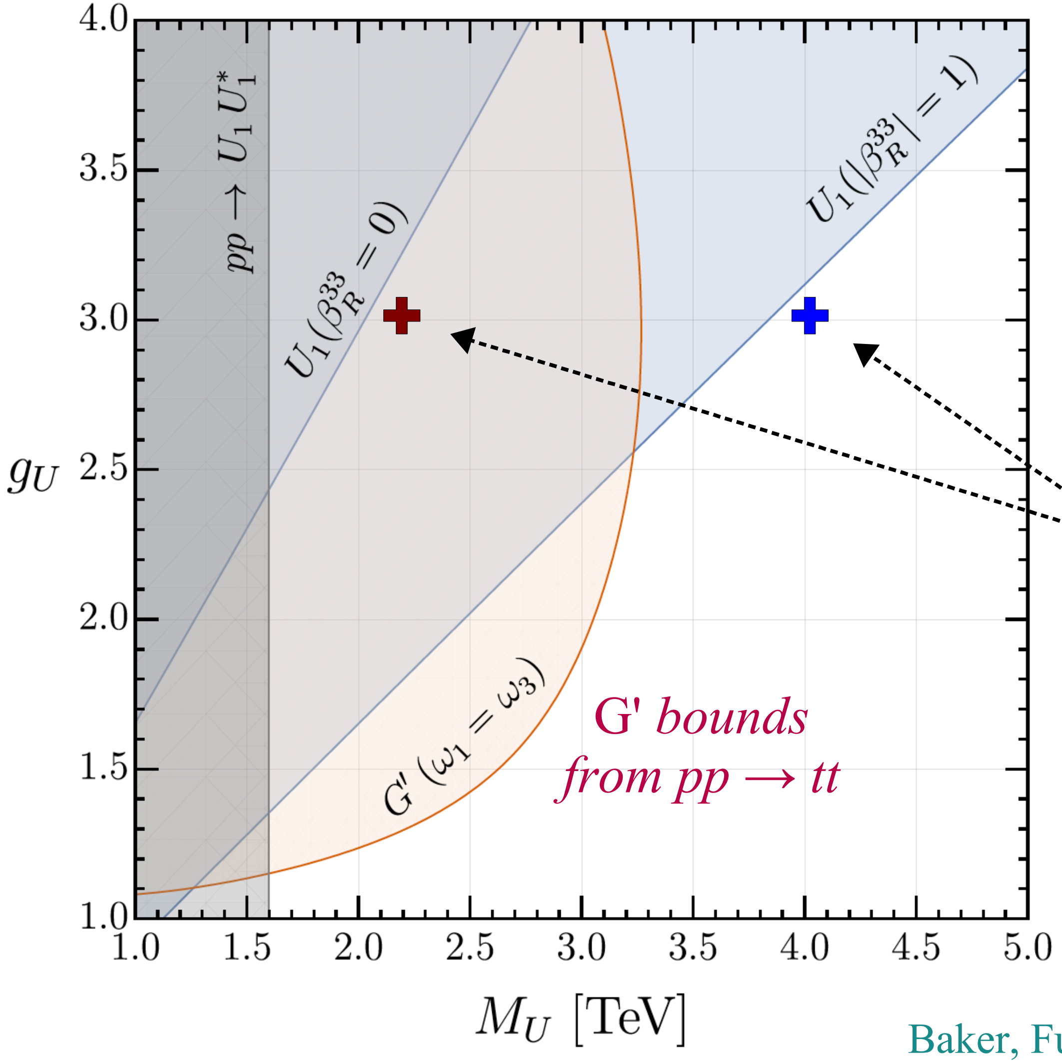
Calculability of ΔF=2 processes

[*in agreement with present data in large area of param. space*]

Greljo, Stefanek, '18; Di Luzio *et al.* '18; Cornella, Fuentes-Martin, GI, '19

The PS^3 *model*

A key difference between the simplified model and this complete UV model is the high-pT phenomenology, which now involves more states



The bounds on the coloron are less relevant in PS^3 vs. the case of a pure LH coupled U_1

Same U_1
contrib. to R_D

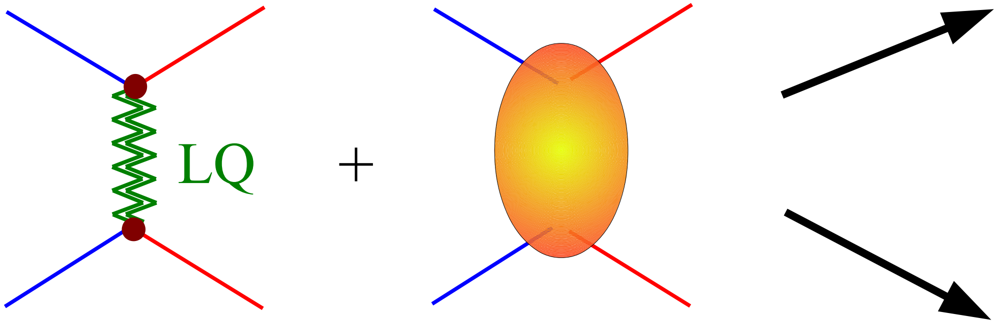
Baker, Fuentes-Martin, GI, König, '19

▶ *The* PS^3 *model*

A further important difference is that in a complete UV model we can compute precisely higher-order (quantum) corrections → *fully predictive framework*

Recent complete analysis of the leading NLO effects of $O(\alpha_4/\pi)$ on the four-fermion operators

Fuentes-Martin, GI, König, Selimovic, '19



20-40% enhancement of the low-energy 4-fermion ops. compared to tree-level (*at fixed on-shell coupl.*)

=> *weaker high-energy constraints*

Unavoidable breaking of the tree-level relation $C^{(1)} = C^{(3)}$ for semilept. ops. (at ~10% level)

=> *unavoidable BSM contrib. to* $B(B \to K^{(*)}\nu\nu)$ [10-100% vs. SM]

Conclusions

- The "B-physics anomalies" provide a concrete demonstration of the high discovery potential of flavor physics. Even if they will go away, they have been very beneficial in shaking some prejudices in model building and in (re-)opening new interesting directions.
  - If interpreted as NP signals, both set of anomalies are not in contradiction among themselves & with existing low- & high-energy data.
    Taken together, they point to NP coupled mainly to 3rd generation, with a flavor structure connected to that appearing in the SM Yukawa couplings.
  - Simplified models with LQ states seem to be favored. Among them, the U_1 case stands for simplicity & phenomenological success.
    The PS^3 model is an interesting example of (a class of) UV framework(s) which could host it, and could help to shed light on "old" SM problems.
- To understand if any of the two statements above is correct...

… we desperately need more data !!!!!