Old and recent puzzles in Flavor Physics

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- Introduction [*Open problems, common lore, recent hopes*]
- On the recent "anomalies" in B-physics
- Bottom-up approaches to describe the anomalies
- Speculations on UV completions
- Possible future implications
- Conclusions

▶ Introduction

The Standard Model has proven to be successful over an unprecedented range of energies. However, despite all its phenomenological successes, this Theory has some deep unsolved problems (*hierarchy problem*, *flavor pattern*, *neutrino masses*, *dark-matter*, U(1) *charges*,…)

⬇

The SM should be regarded as an *effective theory*, i.e. the limit –*in the accessible range of energies and effective couplings*– of a more fundamental theory, with new degrees of freedom

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↓

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"*Common lore*" (I) :

$$\mathscr{L}_{\rm SM} = \mathscr{L}_{\rm gauge}(A_a, \psi_i) + \mathscr{L}_{\rm Higgs}(\phi, A_a, \psi_i)$$

↑

Understanding what stabilizes the Higgs sector (*hierarchy problem*)
is the natural "avenue" to discover New Physics

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The SM should be regarded as an *effective theory*, i.e. the limit –*in the accessible range of energies and effective couplings*– of a more fundamental theory, with new degrees of freedom

But we must admit that, so far, we have very little clues about the validity range of this effective theory...

We need to search for New Physics with a broad spectrum perspective

Key (unique) role of Flavor Physics

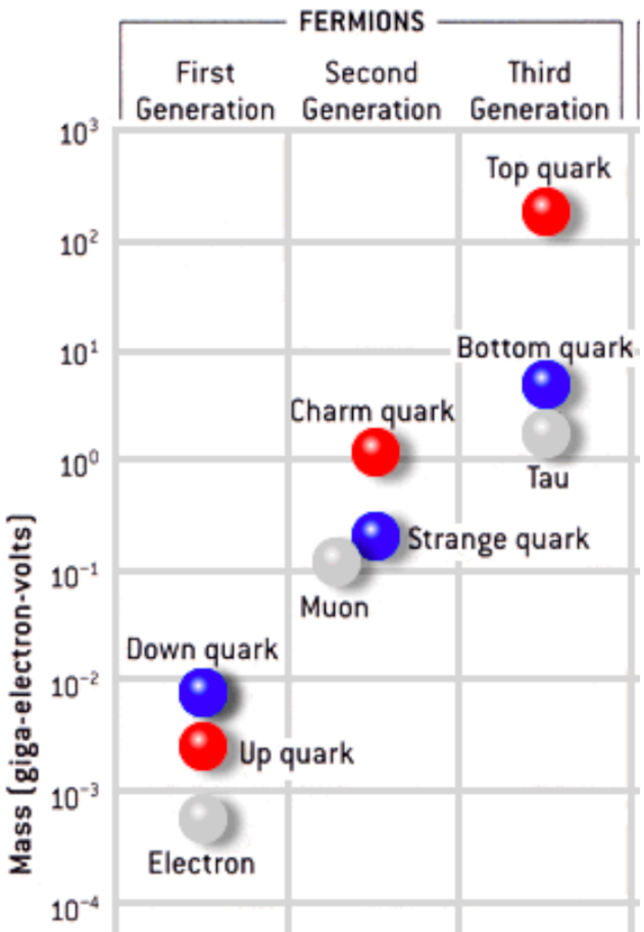
- Identify symmetries and symmetry-breaking patterns beyond those present in the SM
- Probe physics at energy scales not directly accessible at accelerators

The Flavor structure of the SM

$$\mathscr{L}_{\rm SM} = \mathscr{L}_{\rm gauge}(A_{\rm a}, \psi_{\rm i}) + \mathscr{L}_{\rm Higgs}(\phi, A_{\rm a}, \psi_{\rm i})$$

3 identical replica of the basic fermion family $[\psi = Q_L, u_R, d_R, L_L, e_R] \Rightarrow$ huge flavor-degeneracy $[\ \mathrm{U}(3)^5$ global symmetry $]$

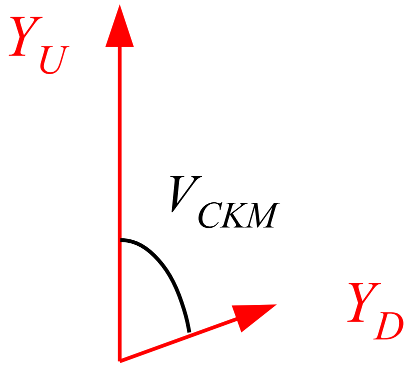
Within the SM the flavor-degeneracy is broken only by the Yukawa interaction:



$$\bar{L}_L^{\,i}\, Y_L^{ik}\, e_R^{\,k}\, \phi + h.c. \rightarrow \bar{l}_L^{\,i}\, M_L^{ii}\, l_R^{\,i} + \ldots$$

$$\bar{Q}_L^{\,i}\, Y_D^{ik}\, d_R^{\,k}\, \phi + h.c. \rightarrow \bar{d}_L^{\,i}\, M_D^{ik}\, d_R^{\,k} + \ldots$$

$$\bar{Q}_L^{\,i}\, Y_U^{ik}\, u_R^{\,k}\, \phi_c + h.c. \rightarrow \bar{u}_L^{\,i}\, M_U^{ik}\, u_R^{\,k} + \ldots$$

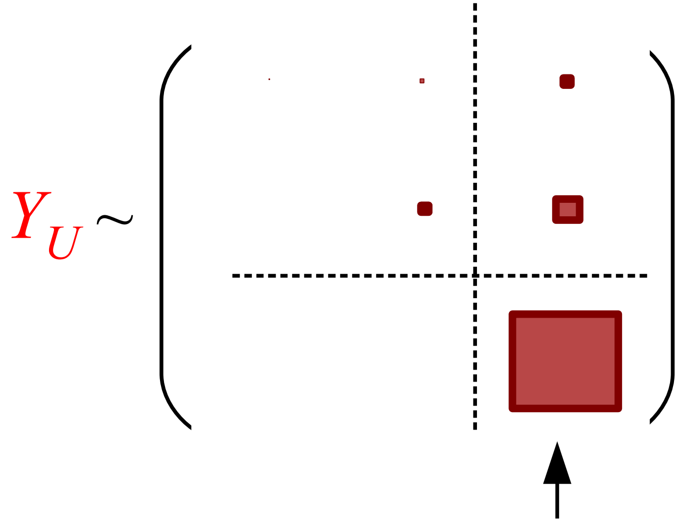


The Flavor structure of the SM

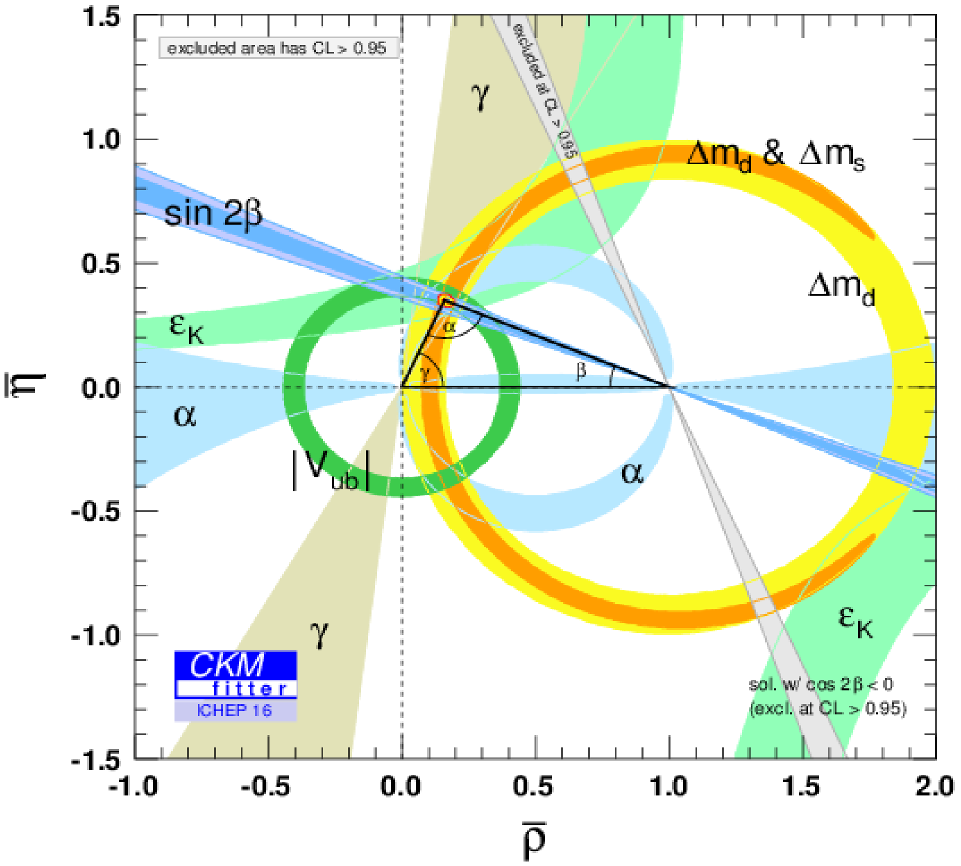
Altogether, the SM flavor (Yukawa) sector is characterized by 13 parameters:
[3 lepton masses + 6 quark masses + 3+1 CKM parameters]

Which do not look at all accidental...

....and which are determined with high accuracy



$$y_t = \frac{\sqrt{2}\, m_t}{<\phi>} \approx 1$$



The “old” flavor puzzle…

The Flavor structure of the SM and beyond...

Given the SM is an effective theory, we should ask the following question:
Are there other sources of flavor symmetry breaking [beside the SM Yukawas] ?

$$\mathscr{L}_{\text{eff}} = \mathscr{L}_{\text{SM}} + \sum_n \frac{c_n}{\Lambda^2} O_n^{d=6}$$

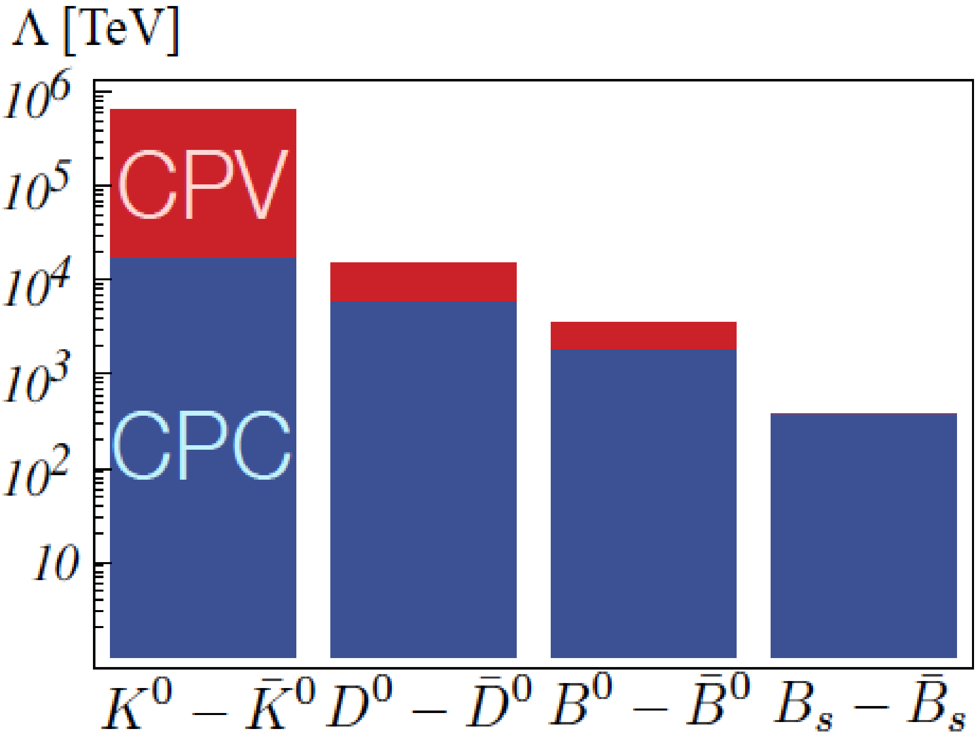
Possible large impact on rare flavor-changing processes, such as meson-antimeson mixing

So far (*almost*) everything fits well with the SM→ Strong limits on NP

“*Common lore*” (II) :

The flavor structures are generated at some very heavy energy scale

→ *No chance to probe their dynamical origin*



The Flavor structure of the SM and beyond...

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$$\mathscr{L}_{\rm eff} = \mathscr{L}_{\rm SM} + \frac{1}{\Lambda} O^{d=5}_{\nu\text{-mass}} + \sum_{n} \frac{c_n}{\Lambda^2} O^{d=6}_{n}$$

Actually *neutrino masses* provide a clear indication of BSM physics & flavor structures beyond the SM Y's

However, if interpreted in terms of

High-scale see-saw, with no intermediate scales down to the Fermi scale

Also neutrino masses leads to confirmation of

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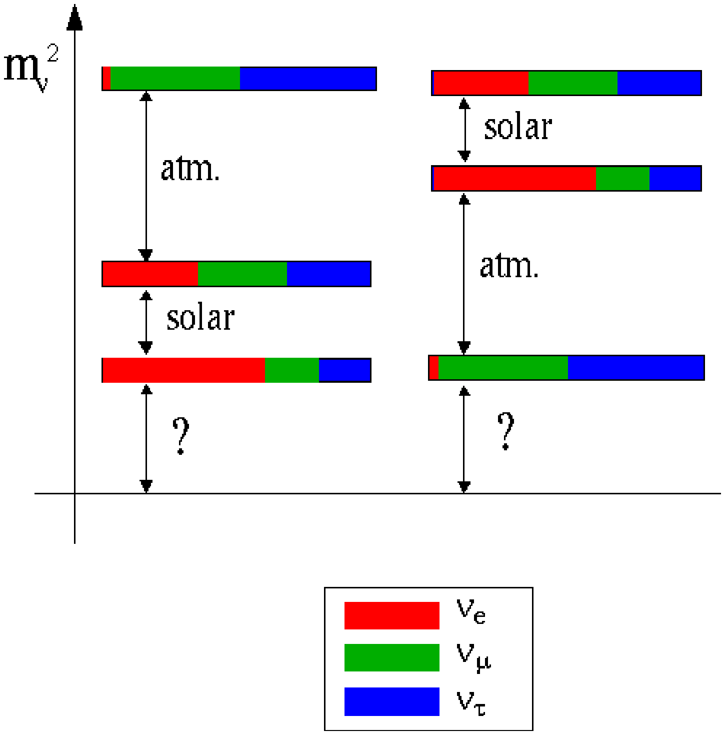


The Flavor structure of the SM and beyond...

This point of view is challenged by the recent "anomalies" in B physics, i.e. the observation of a different (*non-universal*) behavior of different lepton species in specific semi-leptonic processes:

- $b \rightarrow c$ charged currents: τ vs. light leptons (μ, e)
- $b \rightarrow s$ neutral currents: μ vs. e

IF taken together... this is probably the largest "coherent" set of NP effects in present data...

The "new" flavor puzzle...

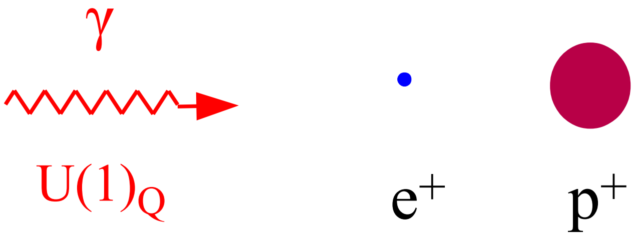
What is particularly interesting, is that these anomalies are challenging an assumption (Lepton Flavor Universality), that we gave for granted for many years (*without many good theoretical reasons...*)

⬇

Interesting shift of paradigm
(*in flavor physics, but possibly also beyond*)

A digression on LFU

Suppose we could test matter only with long wave-length photons...



We would conclude that these two particles are "identical copies" but for their mass ...

▶ *A digression on LFU*

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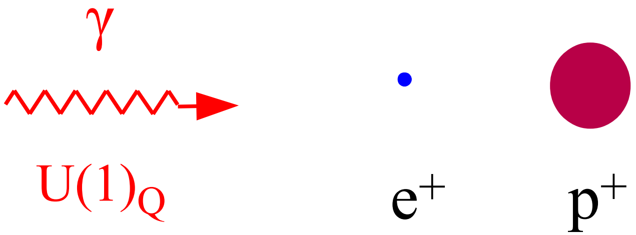

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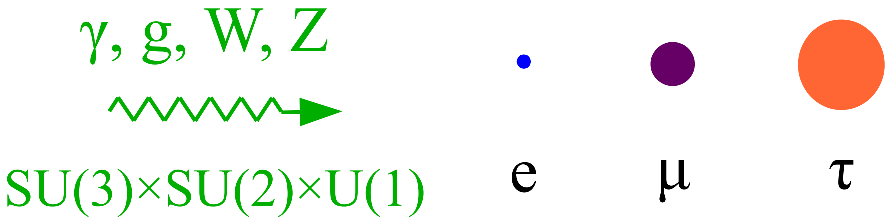
That's exactly the same (misleading) argument we use to infer LFU...



These three (families) of particles seems to be "identical copies" but for their mass ...

The SM quantum numbers of the three families could be an "accidental" low-energy property: the different families may well have a very different behavior at high energies, as signaled by their different mass

A digression on LFU

So far, the vast majority of BSM model-building attempts

- Concentrate only on the Higgs hierarchy problem
- Postpone (ignore) the flavor problem, implicitly assuming the 3 families are "identical" copies (but for Yukawa-type interactions)

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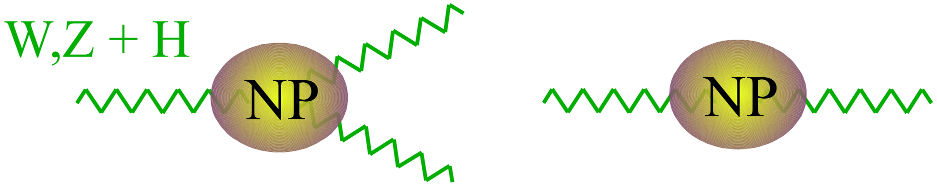
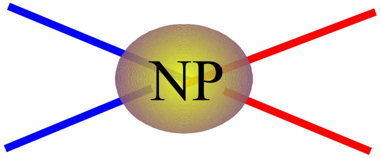


large (*more interesting…*)



small (*less interesting…*)

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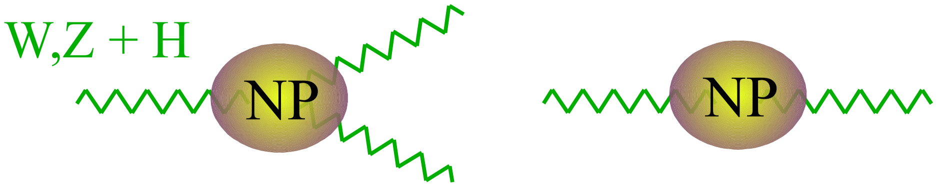
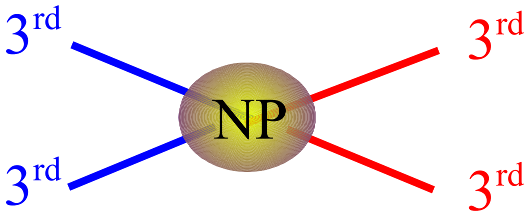
The recent flavor anomalies seem to suggest a shift of paradigm:

- We should not ignore the flavor problem [→ *new (non-Yukawa) interactions at the TeV scale distinguishing the different families*]
- A (very) different behavior of the 3 families (with special role for 3rd gen.) *may be the key to solve/understand also the gauge hierarchy problem*





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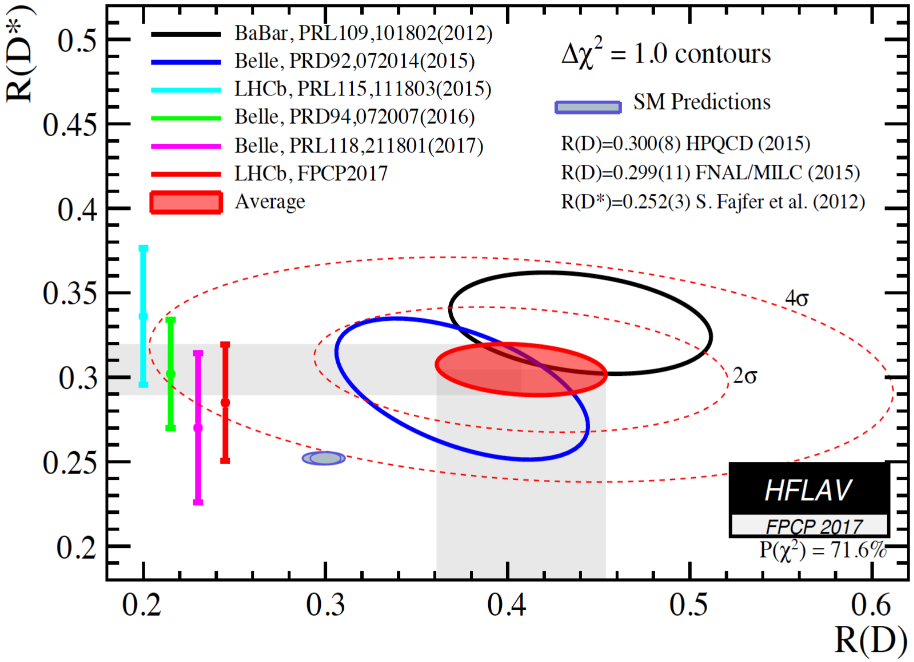
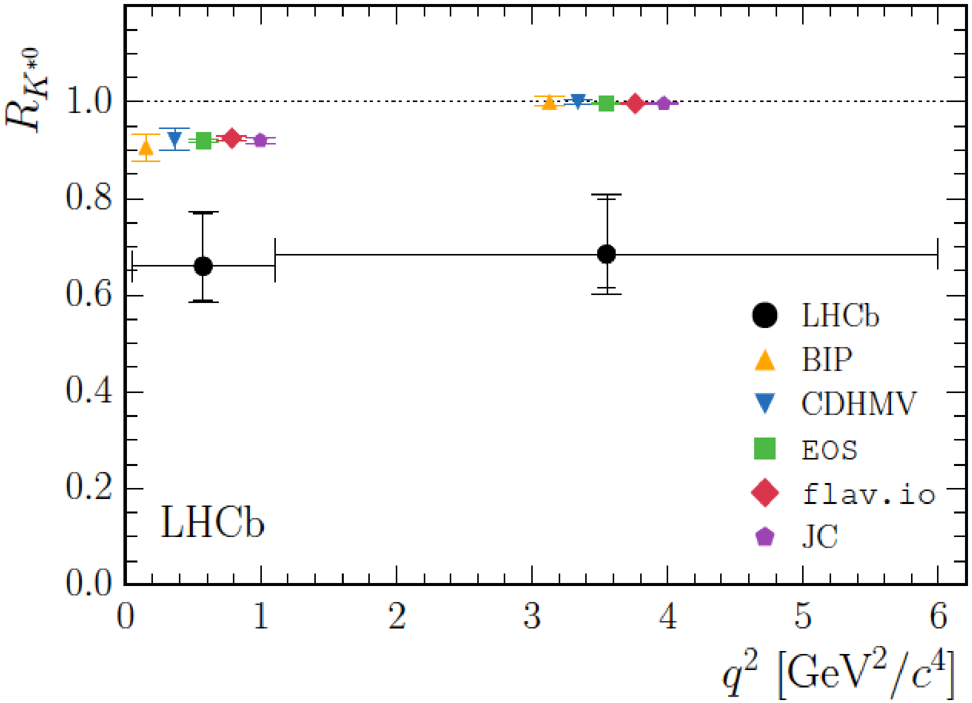
And if we are lucky... these anomalies may help us to shed light on another key problem of the SM that we have postponed (*somehow forgotten...*) for a long time:

- The quantization of U(1) charges and the possible (*natural...*) quark-lepton unification

And possibly help us to reconcile the apparently very different Yukawa and neutrino flavor structures...

On the recent B-physics anomalies



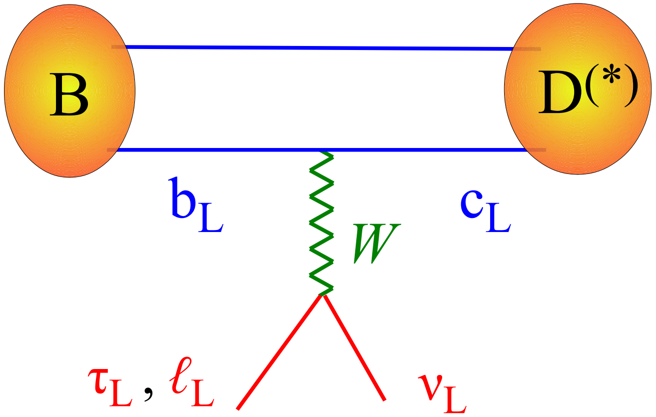


$B \to D^{(*)} \tau\nu$ [Babar, Belle, LHCb]

Test of Lepton Flavor Universality in charged currents
[τ vs. light leptons (μ, e)]:

$$R(X) = \frac{\Gamma(B \to X\tau\bar{\nu})}{\Gamma(B \to X\ell\bar{\nu})}$$

X = D or D*



- SM prediction quite solid: hadronic uncertainties cancel (*to large extent*) in the ratio and deviations from 1 in R(X) expected only from phase-space differences

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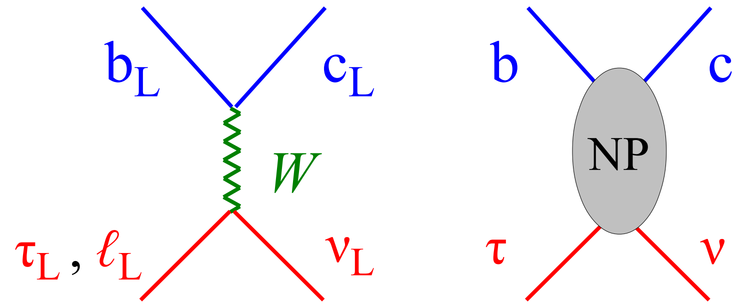

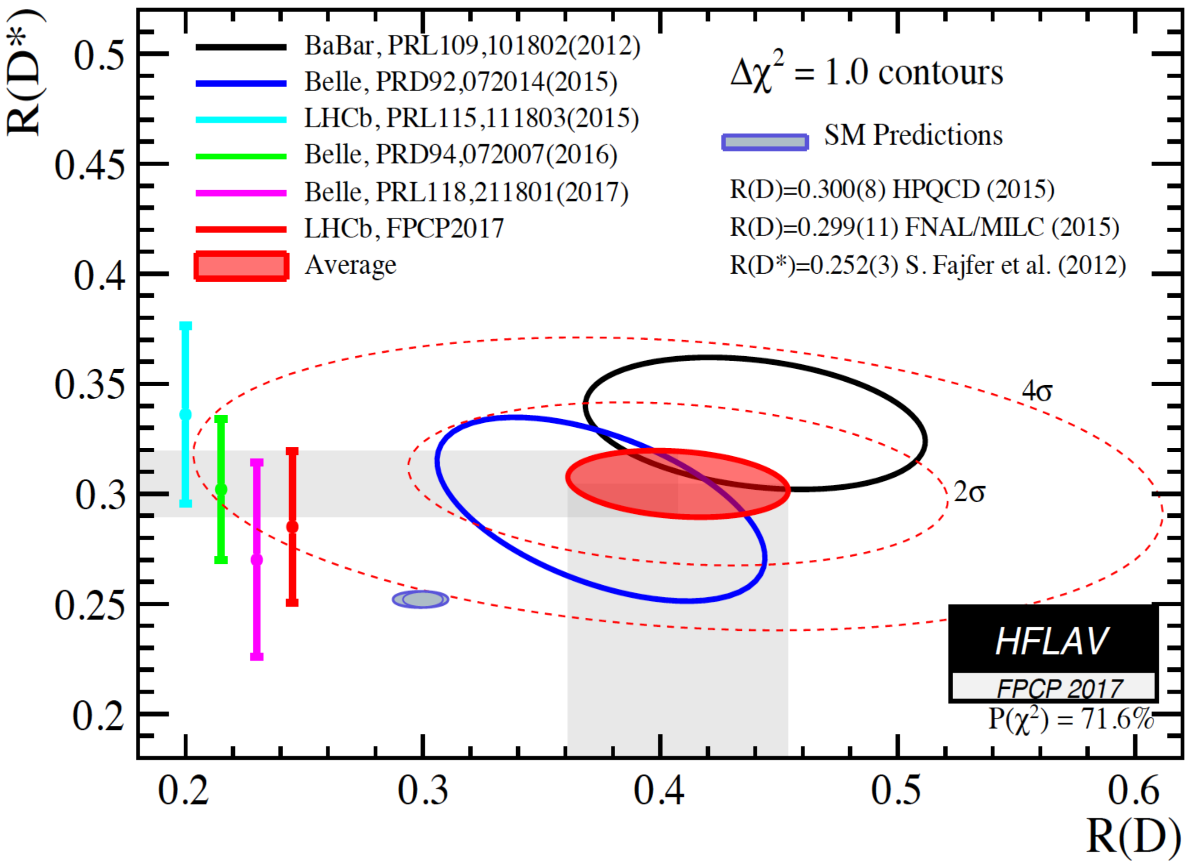

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- Consistent results by 3 different exps. → 3.6–3.9σ excess over SM (*D* + *D**)

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Test of LFU in charged currents
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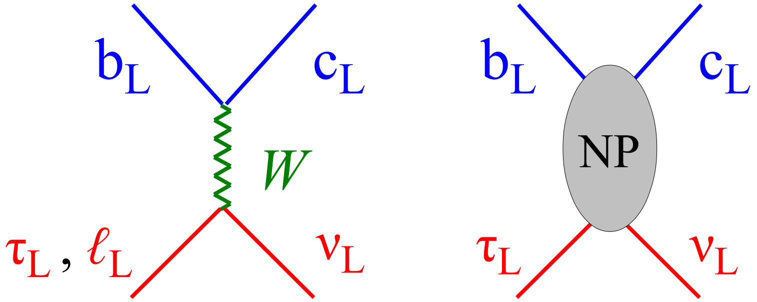

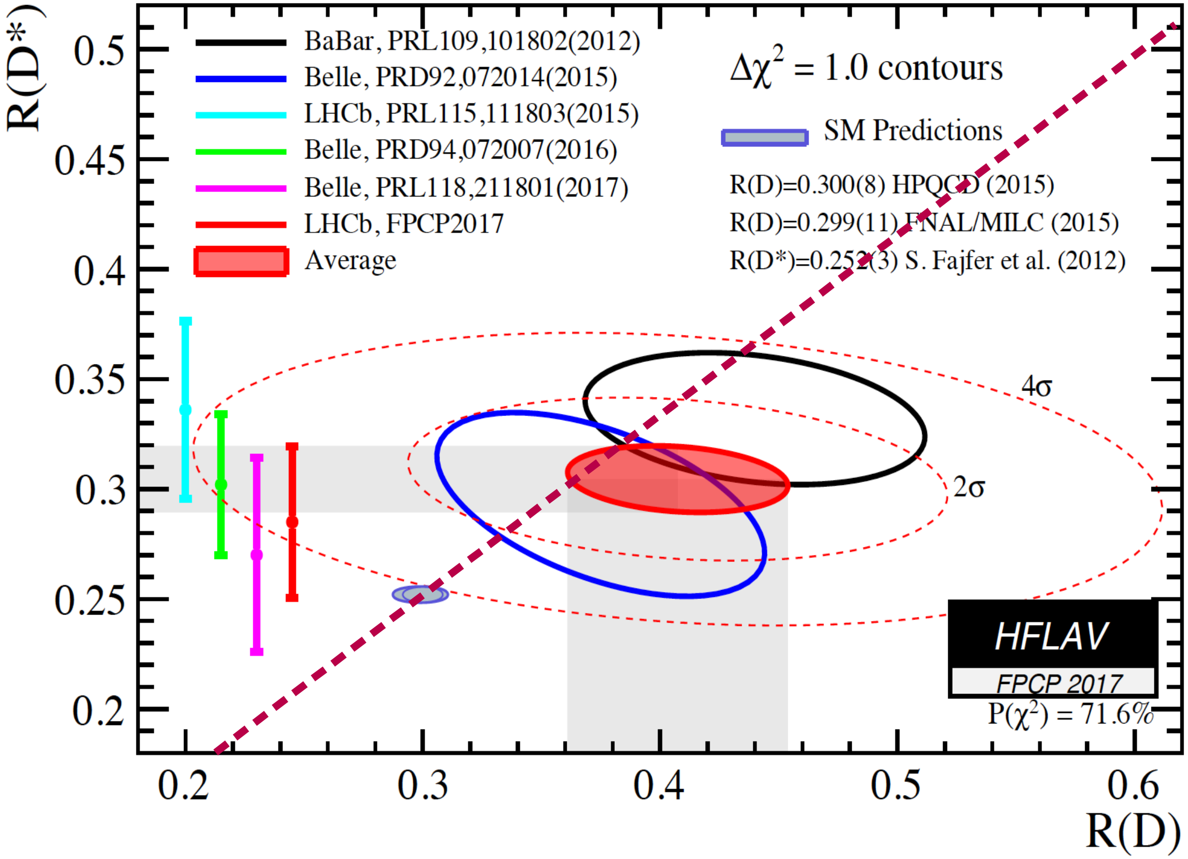

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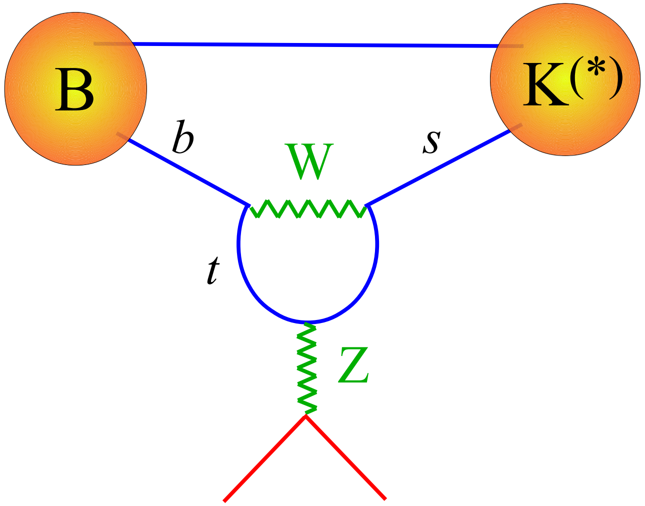
- Consistent results by 3 different exps. → 3.6–3.9σ excess over SM (*D* + *D**)
- The two channels are well consistent with a universal enhancement (~30%) of the SM $b_L \to c_L \tau_L \nu_L$ amplitude

Anomalies in B → $K^{(*)}$ μμ / ee [LHCb]

- The largest anomaly is the one [*observed in 2013 and confirmed with higher statistics n 2015*] in the P_5' [B → K^*μμ] angular distribution.
- Less significant correlated anomalies present also in other B → K^*μμ obs. and also in other b→sμμ channels [→ overall smallness of all BR(B → Hadron + μμ)]

N.B.: b → s *ll* transitions are Flavor Channing Neutral Current amplitudes

- No SM tree-level contribution
- Strong suppression within the SM because of CKM hierarchy
- Sizable hadronic uncertainties in the rates



Anomalies in $B \to K^{(*)} \mu\mu$ / ee [LHCb]

- The largest anomaly is the one in the P_5' [$B \to K^* \mu\mu$] angular distribution.
- Less significant correlated anomalies present also in other $B \to K^* \mu\mu$ obs.
- But also in this case the most interesting effects are the deviations from the SM in appropriate μ/e "clean" LFU ratios:

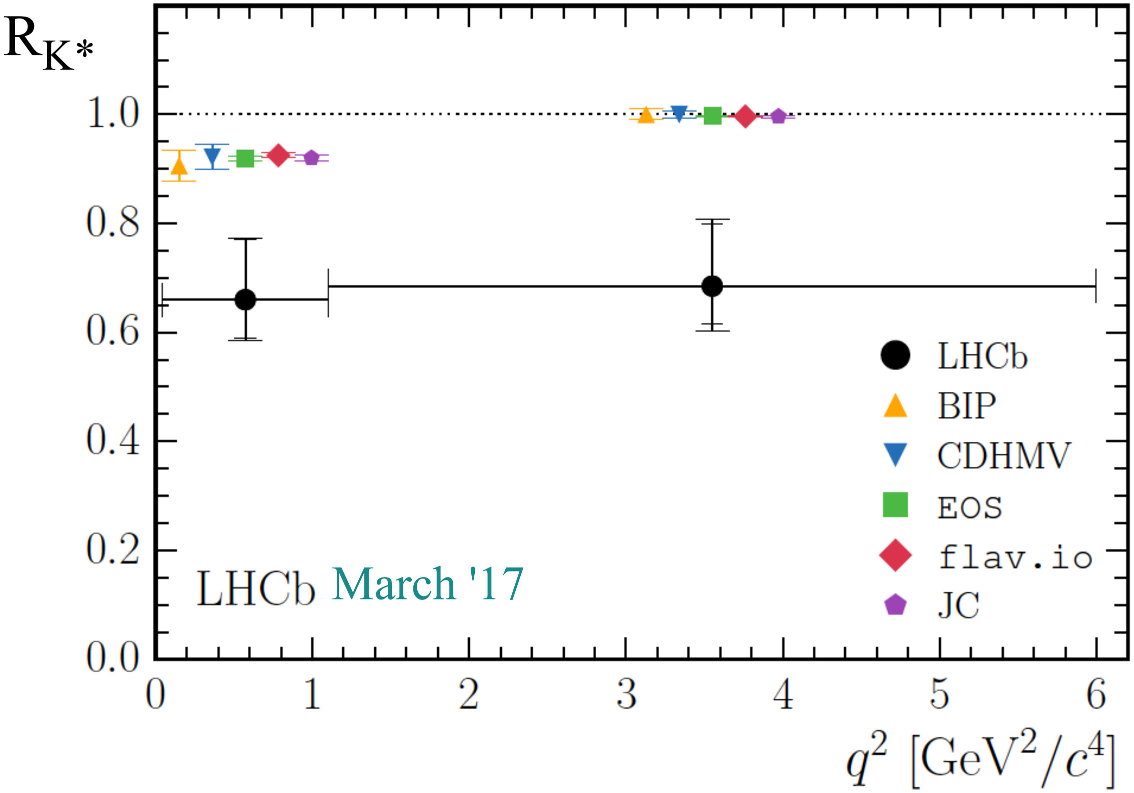
$$R_H = \frac{\int d\Gamma(B \to H\,\mu\mu)}{\int d\Gamma(B \to H\,ee)}$$

R_K [1-6 GeV^2] = 0.75 ± 0.09

LHCb, '14

(vs. 1.00±0.01 SM)

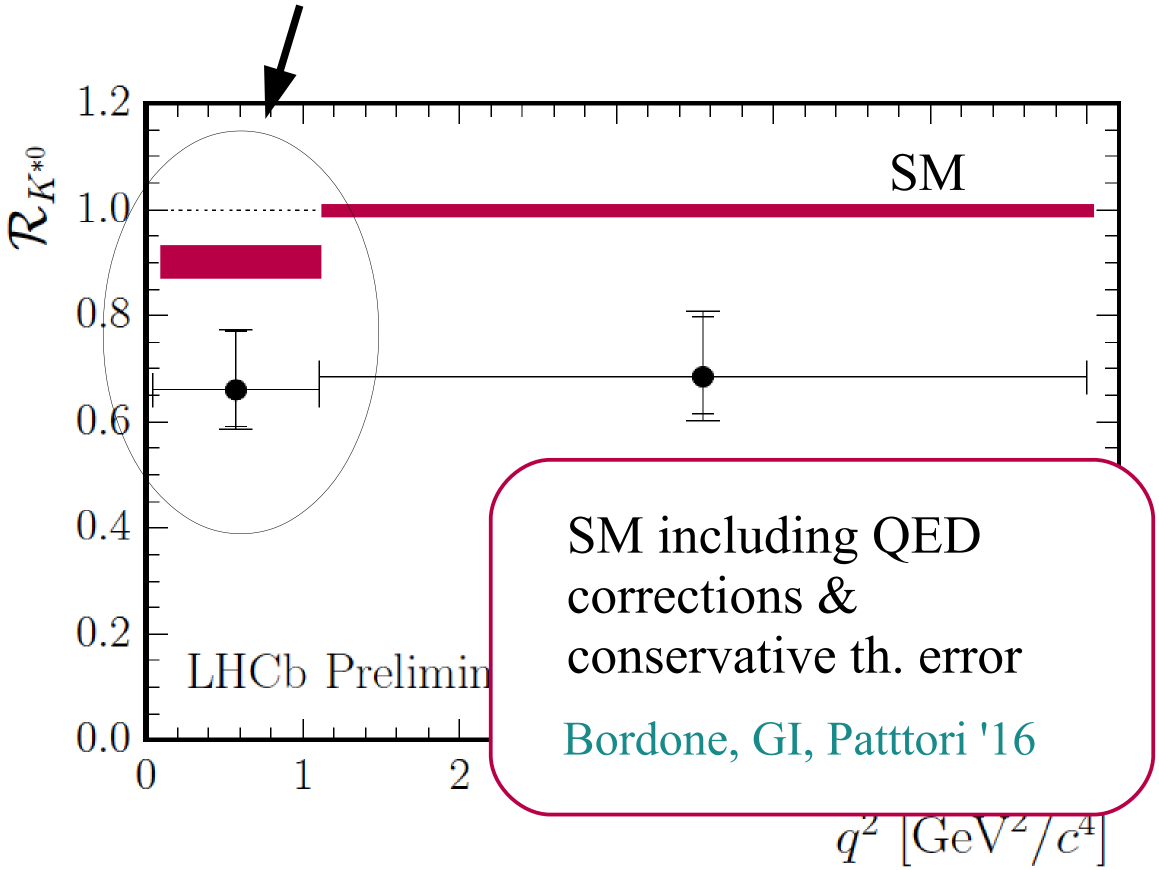
Overall significance ~ 3.8σ
(*LFU ratios only*)



Anomalies in $B \to K^{(*)} \mu\mu$ / ee [LHCb]

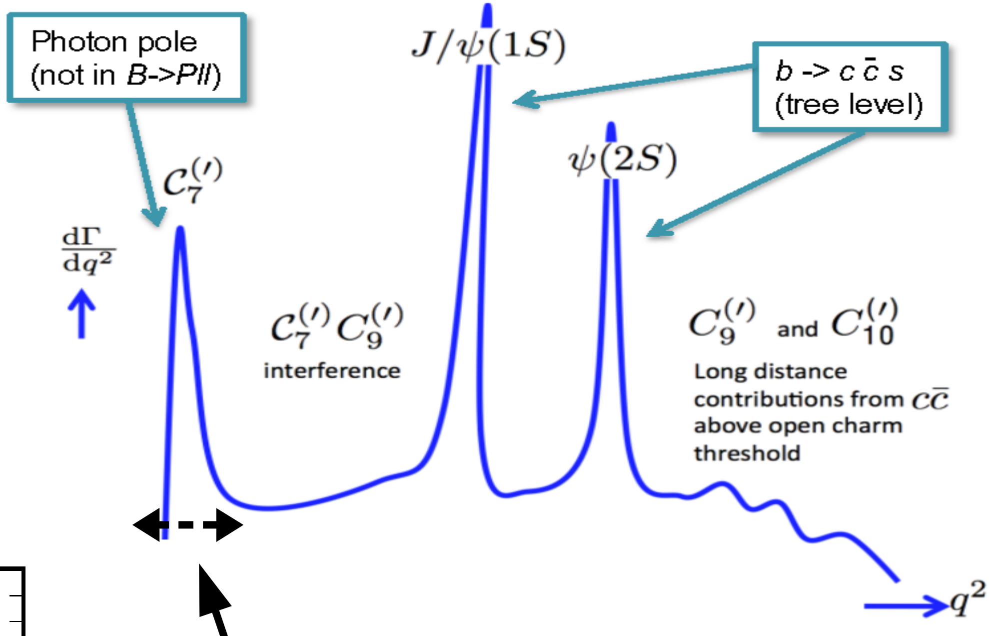
Technical note: I don't think we should be too worried about the low-q^2 bin...

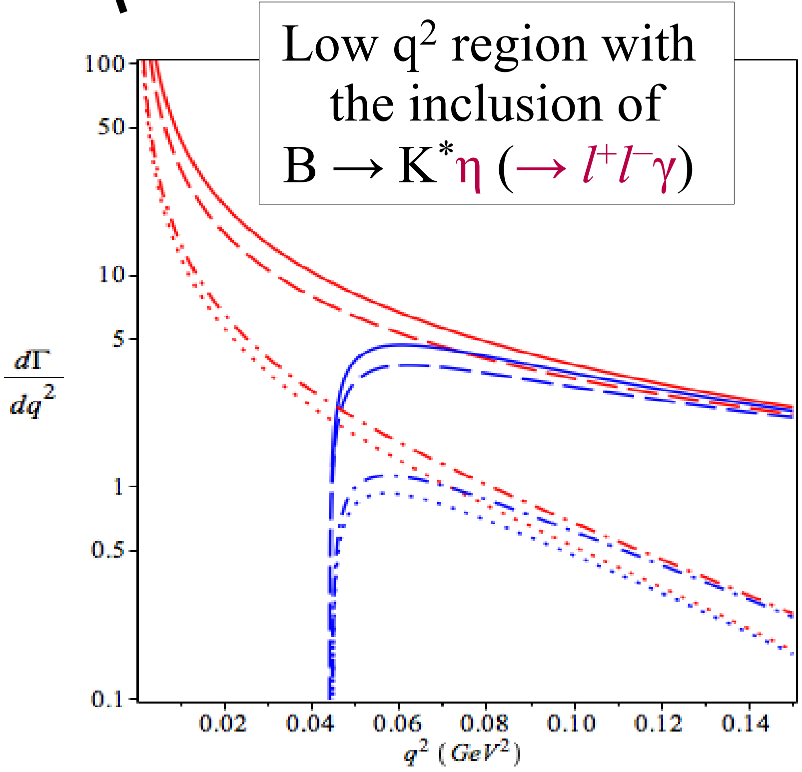
"dangerous" choice of the bin starting from the di-muon threshold



SM including QED corrections & conservative th. error

Bordone, GI, Patttori '16





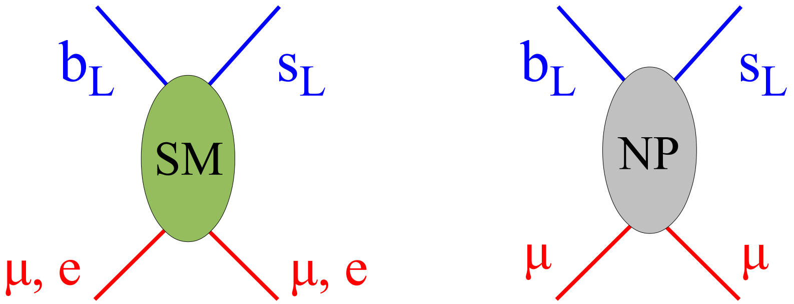
Low q^2 region with the inclusion of $B \to K^* \eta$ ($\to l^+ l^- \gamma$)

Anomalies in B → $K^{(*)}$ μμ / ee [LHCb]

Several groups performed global fits of all the available b→sll observables

Descotes-Genon, Matias, Virto '13, '15
Capdevila *et al.* '17; D'Amico *et al.* '17
Altmannshofer & Straub '13, '15
Ciuchini *et al.* '17; Hurth *et al.* '16, '17
Many others...

No consensus on the significance of the non-LFU observables, but full agreement on the main aspects:

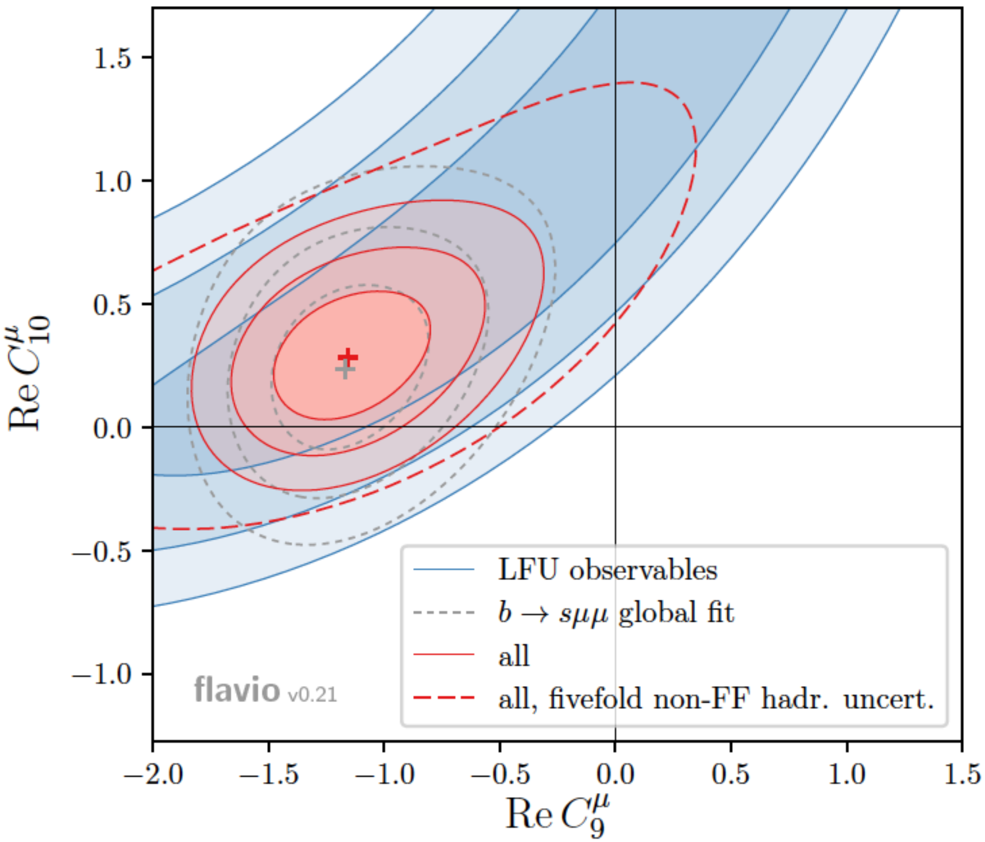


- All effects well described by NP of short-distance origin only in b→sμμ and (& not in ee)
- LH structure on the quark side:

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

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

Altmannshofer, Stangl, Straub '17



Bottom-up approaches to describe the anomalies [*from EFT to simplified models*]

Bottom-up approaches to describe the anomalies

These recent results have stimulated a lot of theoretical activity
(*not particularly instructive to discuss all NP proposals...*)

What I will discuss next is a bottom-up approach made of three main steps:

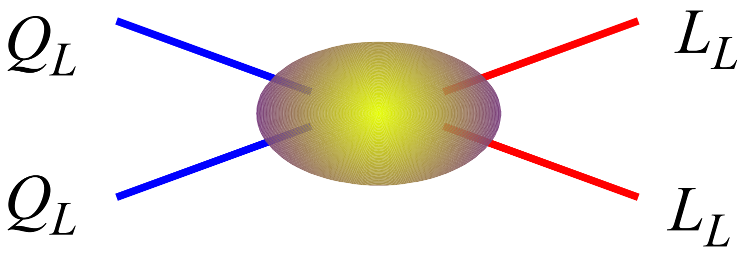
Generic EFT approach
↓
Simplified Dynamical Models
↓
High-energy behavior and UV completion

The main guide will be the attempt to describe both LFU effects within the same framework and, while "going up" in energies (and assumptions), check the consistency with

- other low-energy data
- high-pT physics

EFT-type considerations

- Anomalies are seen only in semi-leptonic (quark×lepton) operators
- Data largely favor non-vanishing left-handed current-current operators [*the Fermi-like* $\mathrm{SU(2)_L}$ *triplet contributes to both charged & neutral curr.*], although other contributions are also possible



Bhattacharya *et al.* '14
Alonso, Grinstein, Camalich '15
Greljo, GI, Marzocca '15
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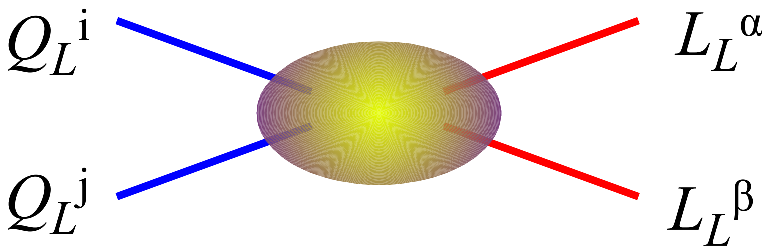

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(+many others...)

- Large coupling (competing with SM tree-level) in bc → $l_3\, \nu_3$
- Small non-vanishing coupling (competing with SM FCNC) in bs → $l_2\, l_2$

$$\downarrow$$

$$\Lambda_{ij\alpha\beta} = (\delta_{i3}\times\delta_{3j})\times(\delta_{\alpha3}\times\delta_{3\beta}) \quad +$$

small terms for 2nd (& 1st) generations →

Link to pattern of the Yukawa couplings !

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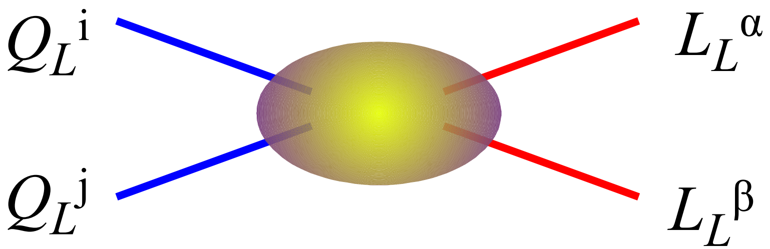
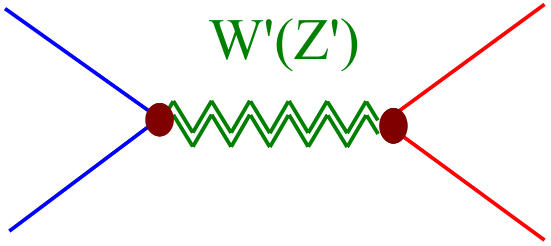
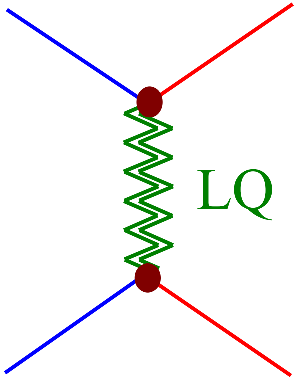




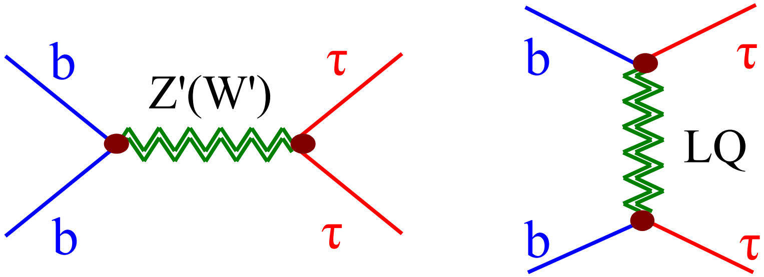


Two classes of (tree-level) mediators, giving rise to different correlations among the anomalies, other low-energy observables, and high-p_T physics

EFT-type considerations

Three main problems identified in the recent literature (*driven mainly by R_D*...):

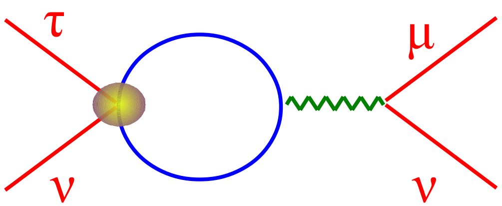
I. *high-p_T constraints*



[low naïve EFT scale: $\Lambda \sim 700$ GeV]

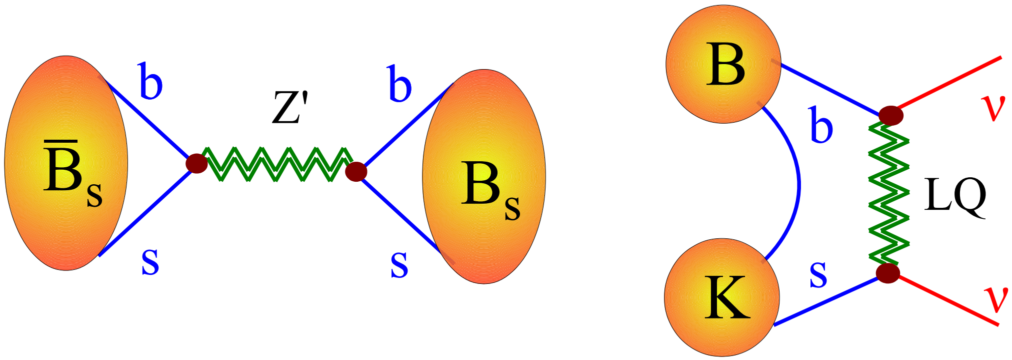
Faroughy, Greljo, Kamenik '16

II. *radiative constraints*



Feruglio, Paradisi, Pattori '16

III. *flavor bounds*



Greljo, GI, Marzocca '15
Calibbi, Crivellin, Ota, '15
(+many others...)

- *EFT-type considerations* [*The* U(2)^n *flavor symmetry*]

A solution to all these "*combination*" problems + natural link with the origin of the Yukawa couplings, is provided by a suitable EFT based on the hypothesis of an approximate $U(2)_q \times U(2)_l$ flavor symmetry

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- A brief detour: U(2)^{n} flavor symmetries (acting on light generations)

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

Quark sector: $U(2)^3 = U(2)_q \times U(2)_u \times U(2)_d$

$$Y_U = y_t \left[\begin{array}{c|c} 0 & 0 \\ \hline 0 & 1 \end{array}\right] \longleftarrow U(2)_q$$

$$\uparrow$$

$U(2)_u$

unbroken symmetry

$$\mathscr{L}_{\text{Yukawa}} = Q_L^{\,i}\, Y_U^{ij}\, U_R^{\,j}\, \phi \;+ \ldots$$

> The exact symmetry limit is good starting point for the SM spectrum ($m_u=m_d=m_s=m_c=0$, $V_{CKM}=1$)

EFT-type considerations [*The* U(2)^n *flavor symmetry*]

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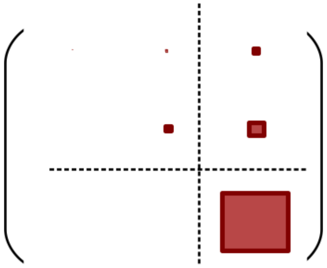
$$Y_U = y_t \begin{bmatrix} 0 & 0 \\ 0 & 1 \end{bmatrix} \to \begin{bmatrix} 0 & V \\ 0 & 1 \end{bmatrix} \to \begin{bmatrix} \Delta & V \\ 0 & 1 \end{bmatrix} \equiv$$



unbroken symmetry

leading breaking

final breaking

Minimal breaking to reproduce SM Yukawa couplings:

$$|V| \approx |V_{ts}| = 0.04$$

$$|\Delta| \approx y_c = 0.006$$

- The assumption of a single leading breaking ensures an effective protection of FCNCs → consistency with CKM fits
- Large NP effects possible for 3rd generation

▸ *EFT-type considerations* [*“The Zurich's guide”*]

A solution to all these “*combination*” problems + natural link with the origin of the Yukawa couplings, is provided by a suitable EFT based on the hypothesis of an approximate $U(2)_q \times U(2)_l$ flavor symmetry

+

Assumption of NP in left-handed semi-leptonic operators only [*high-scale matching*]

Buttazzo, Greljo, GI, Marzocca, '17

“*The Zürich's Guide*”

↓

$$\mathcal{L}_{\rm eff} = \mathcal{L}_{\rm SM} - \frac{1}{v^2}\underline{\lambda^q_{ij}}\,\underline{\lambda^\ell_{\alpha\beta}}\left[\underline{C_T}\,(\bar{Q}^i_L\gamma_\mu\sigma^a Q^j_L)(\bar{L}^\alpha_L\gamma^\mu\sigma^a L^\beta_L) + \underline{C_S}\,(\bar{Q}^i_L\gamma_\mu Q^j_L)(\bar{L}^\alpha_L\gamma^\mu L^\beta_L)\right]$$

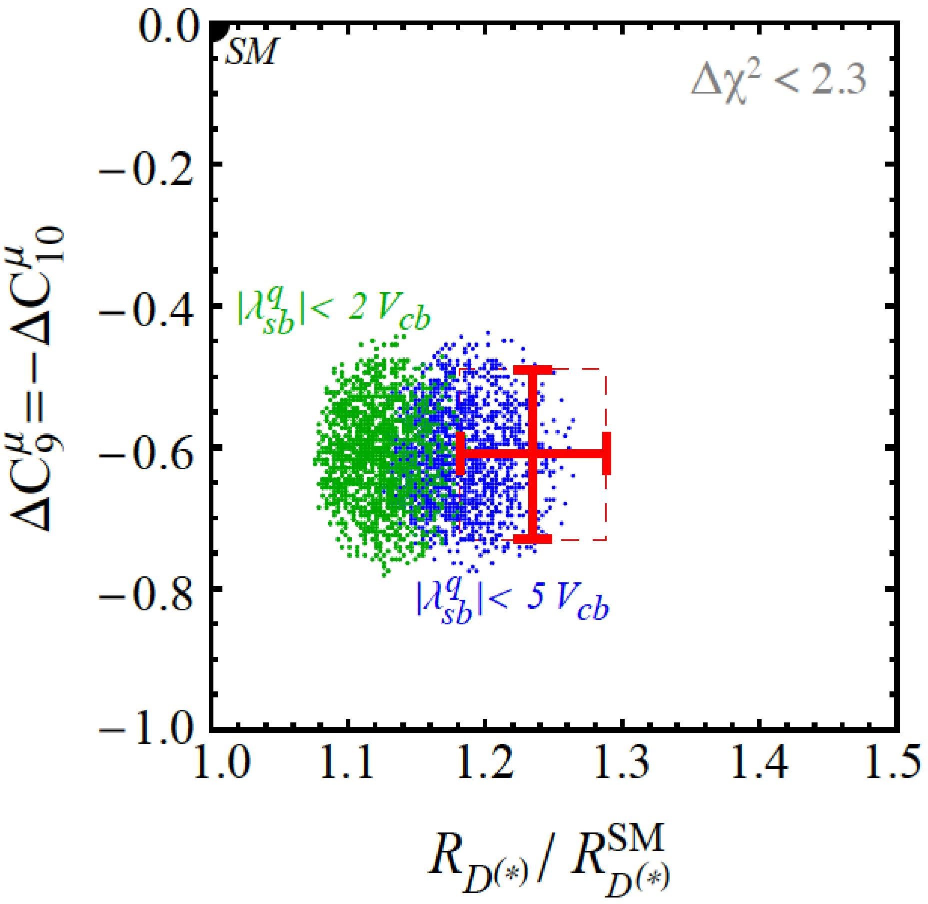
four free parameters...

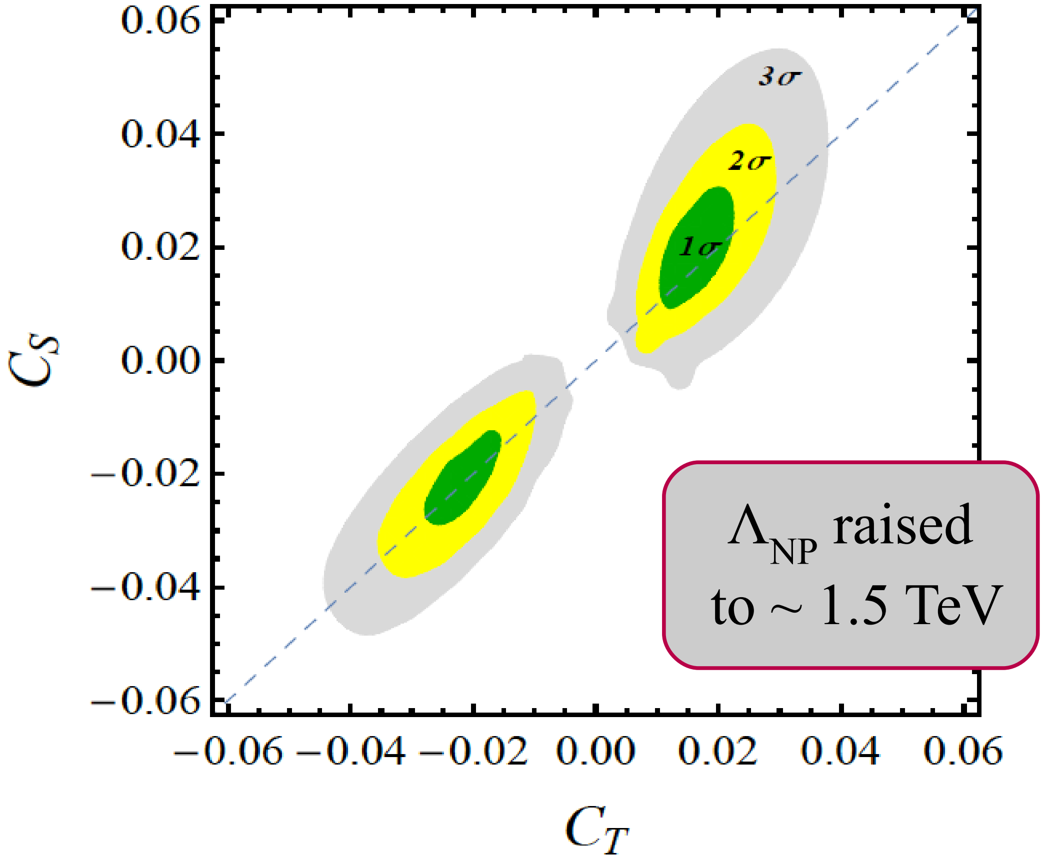
C_T, C_S
$\lambda_{bs} = O(V_{cb})$
$\lambda_{\mu\mu} = O(|V_{\tau\mu}|^2)$

...and a long list of constraints
[FCNC and CC semi-leptonic processes, tau decays, EWPO]

- *EFT-type considerations* [*"The Zurich's guide"*]

Excellent fit to both anomalies, passing all existing constraints with no fine tuning





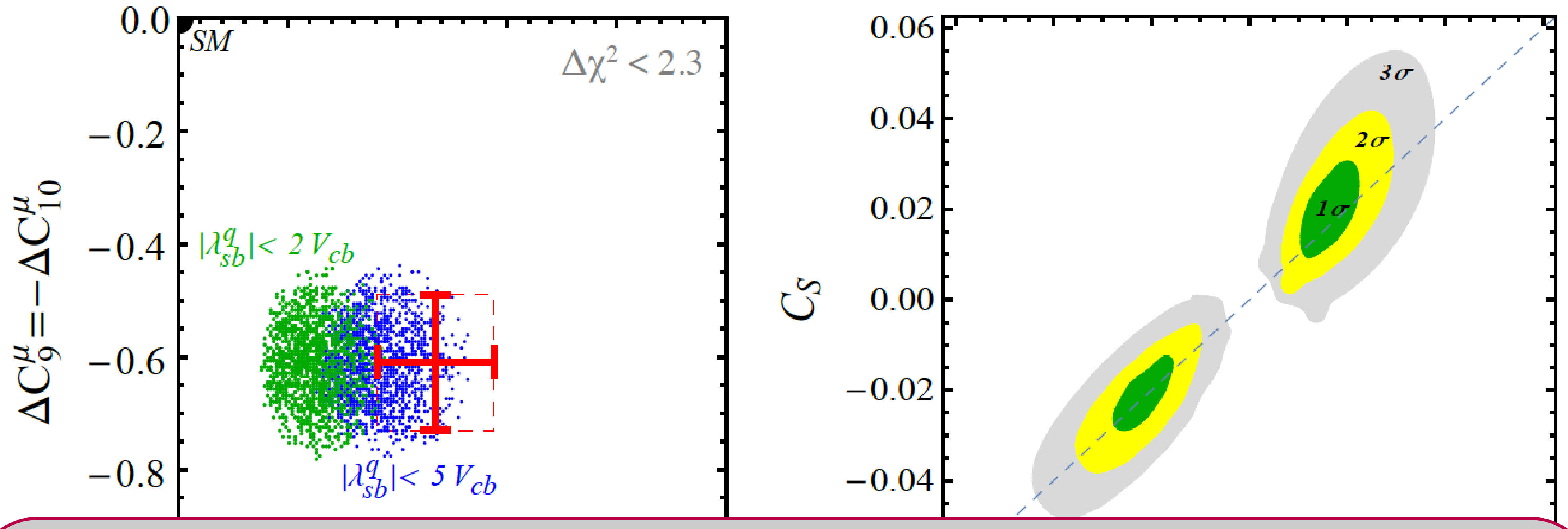
Λ_{NP} raised to ~ 1.5 TeV

Key features compared to previous analyses:

- $SU(2)_L$ *singlet & triplet operators*
- *Flavor symmetry*
- *Deviation from "pure-mixing"*
- $O(V_{cb})$ *misalignment to b-quark mass basis*

EFT-type considerations [*"The Zurich's guide"*]

Excellent fit to both anomalies, passing all existing constraints with no fine tuning



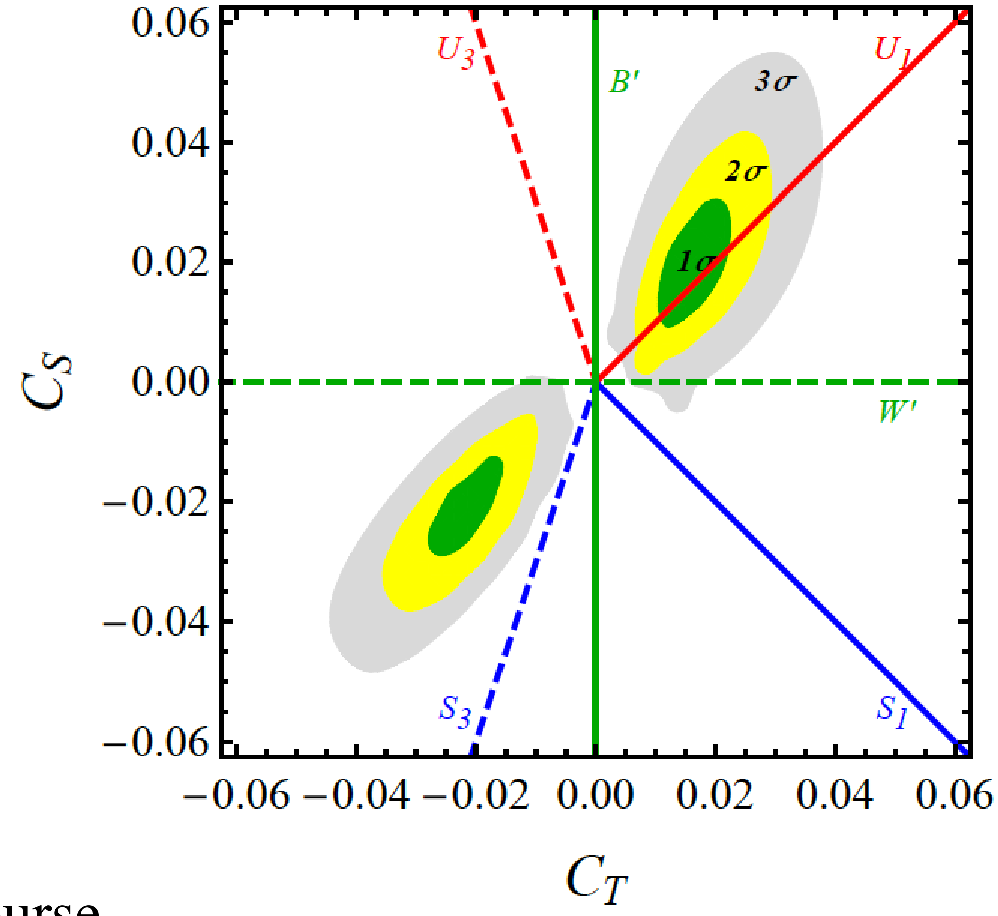
- The virtue of this EFT approach is the demonstration that is possible to find a "combined" (*motivated*) explanation of the two set of anomalies. Very useful in identifying implications in other low-energy measurements [→ *more later...*]
- The EFT solution is not unique [e.g. sub-leading RH currents can be added], but large variations are possible only if the R_D anom. goes away completely

- ***Simplified dynamical models*** [*"The Return of the LeptoQuark"...*]

If we ask which tree-level mediators can generate the effective operators required by the EFT fit, we have not many possibilities...

Three main options
(*for the combined explanation*):

	SU(2)$_L$ singlet	SU(2)$_L$ triplet
Vector LQ:	U_1	U_3
Scalar LQ:	S_1	S_3
Colorless vector:	B'	W'



The U_1 option fits quite nicely... but of course models with more than one mediators are possible

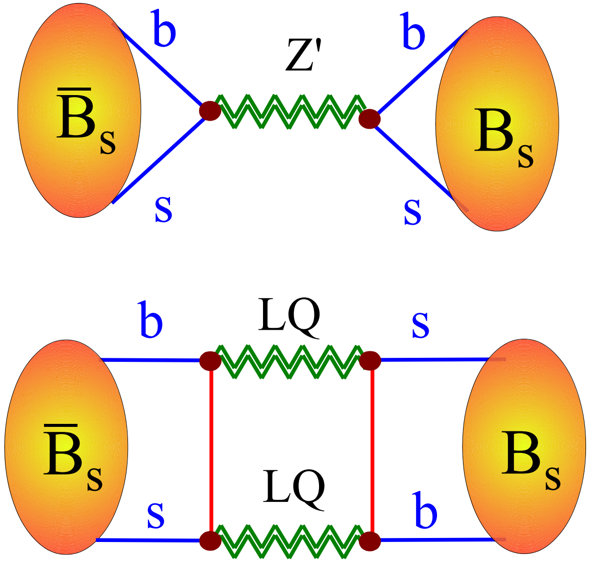
▸ *Simplified dynamical models* [*"The Return of the LeptoQuark"...*]

If we ask which tree-level mediators can generate the effective operators required by the EFT fit, we have not many possibilities...

Three main options
(*for the combined explanation*):

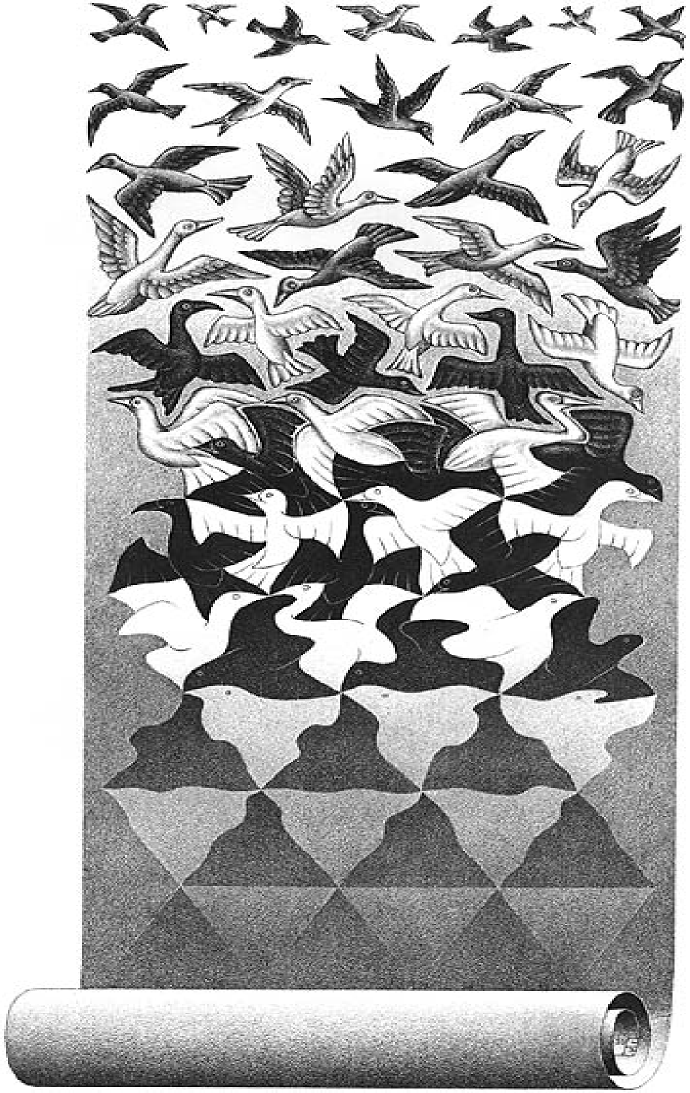
	$SU(2)_L$	
	singlet	triplet
Vector LQ:	$\boxed{U_1}$	U_3
Scalar LQ:	S_1	S_3
Colorless vector:	B'	W'

LQ (both scalar and vectors) have an additional clear advantage concerning constraints from non-semilpetonic processes:



Similarly, 3rd gen. LQ are in very good shape also as far as direct searches are concerned (*contrary to Z'...*):

Speculations on UV completions



Speculations on UV completions

Two main approaches

Non-perturbative
TeV-scale dynamics
[*non-renormalizable models*]

- Scalar LQ as PNG

  Gripaios, '10
  Gripaios, Nardecchia, Renner, '14
  Marzocca '18

- Vector LQ (or W',Z') as techni-fermion resonances

  Barbieri *et al.* '15, Buttazzo *et al.* '16
  Barbieri, Murphy, Senia, '17
  Blanke, Crivellin, '17

- W', Z' as Kaluza-Klein excitations [*e.g. from warped extra dim.*]

  Megias, Quiros, Salas '17
  Megias, Panico, Pujolas, Quiros '17

Perturbative
TeV-scale dynamics
[*renormalizable models*]

- Renormalizable models with scalar mediators [*LQ, but also RPV-SUSY*]

  Hiller & Schmaltz, '14
  Becirevic *et al.* '16, Fajfer *et al.* '15-'17
  Dorsner *et al.* '17
  Crivellin, Muller, Ota '17
  Altmannshofer, Dev, Soni, '17
  + ...

- Gauge models

  Cline, Camalich '17
  Calibbi, Crivellin, Li, '17
  Assad, Fornal, Grinstein, '17
  Di Luzio, Greljo, Nardecchia, '17
  Bordone, Cornella, Fuentes-Martin, GI, '17
  + ...

Speculations on UV completions

In the following I will now concentrate on one (class of) option(s) that I find particularly interesting.

Starting observation: the Pati-Salam model predicts a massive vector LQ with the correct quantum numbers to fit the anomalies (*best single mediator*):

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

Fermions in SU(4): $\begin{bmatrix} Q_L^{\alpha} \\ Q_L^{\beta} \\ Q_L^{\gamma} \\ L_L \end{bmatrix}$ $\begin{bmatrix} Q_R^{\alpha} \\ Q_R^{\beta} \\ Q_R^{\gamma} \\ L_R \end{bmatrix}$ LQ [U_1] from $SU(4) \rightarrow SU(3)_c$

The problem of the “original PS model” are the strong bounds on the LQ couplings to 1st & 2nd generations [e.g. $M > 100$ TeV from $K_L \rightarrow \mu e$].

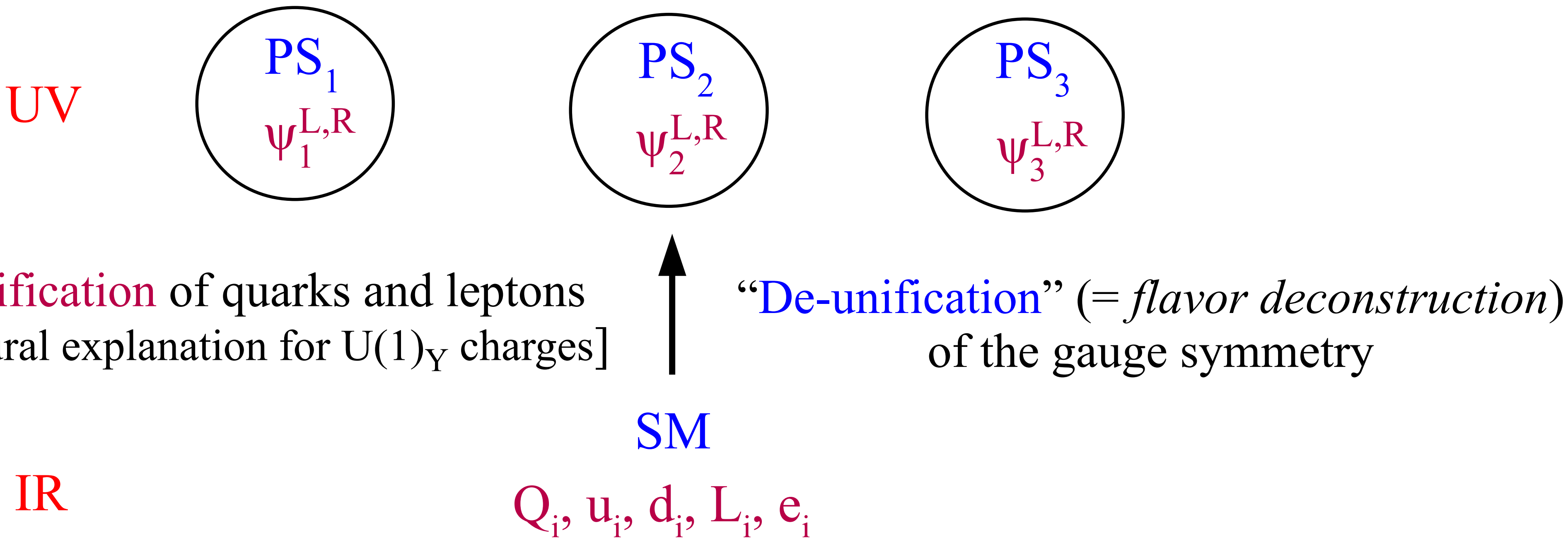
Interesting recent attempts to solve this problem adding extra fermions and/or modifying the gauge group [Calibbi, Crivellin, Li, '17; Di Luzio, Greljo, Nardecchia, '17]

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 !*)



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

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

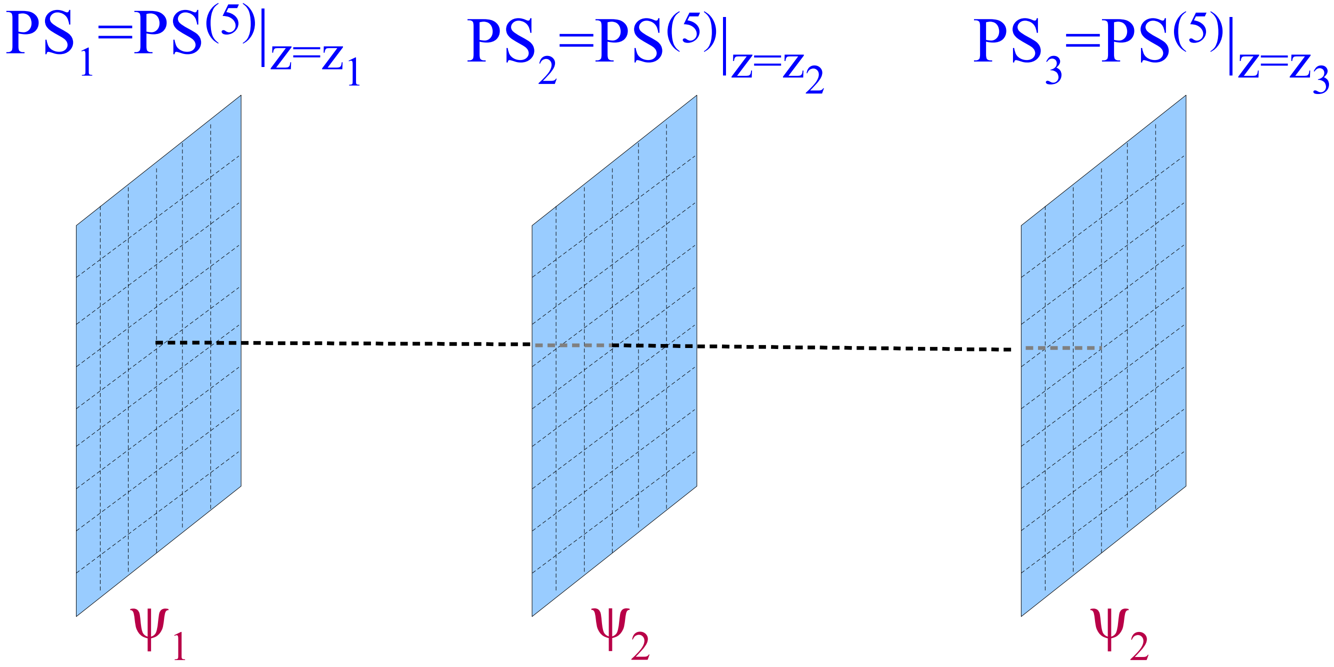
Key advantages:

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

▶ *The* PS^3 *model*

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

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



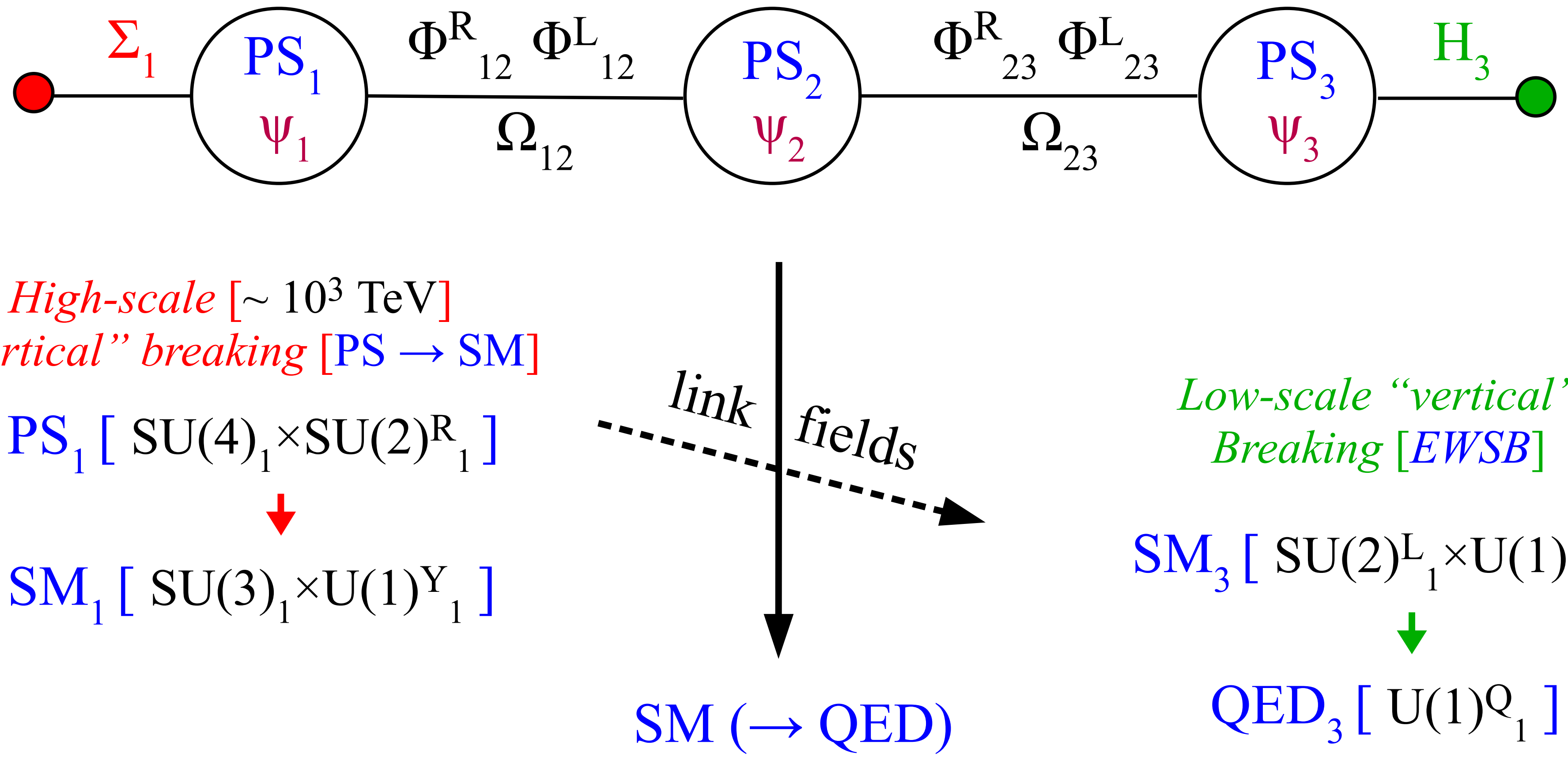
Unification
of quarks and leptons

"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 [~ 10^3 TeV]
"vertical" breaking [PS → SM]

PS_1 [$SU(4)_1 \times SU(2)^R_1$]

SM_1 [$SU(3)_1 \times U(1)^Y_1$]

SM (→ QED)

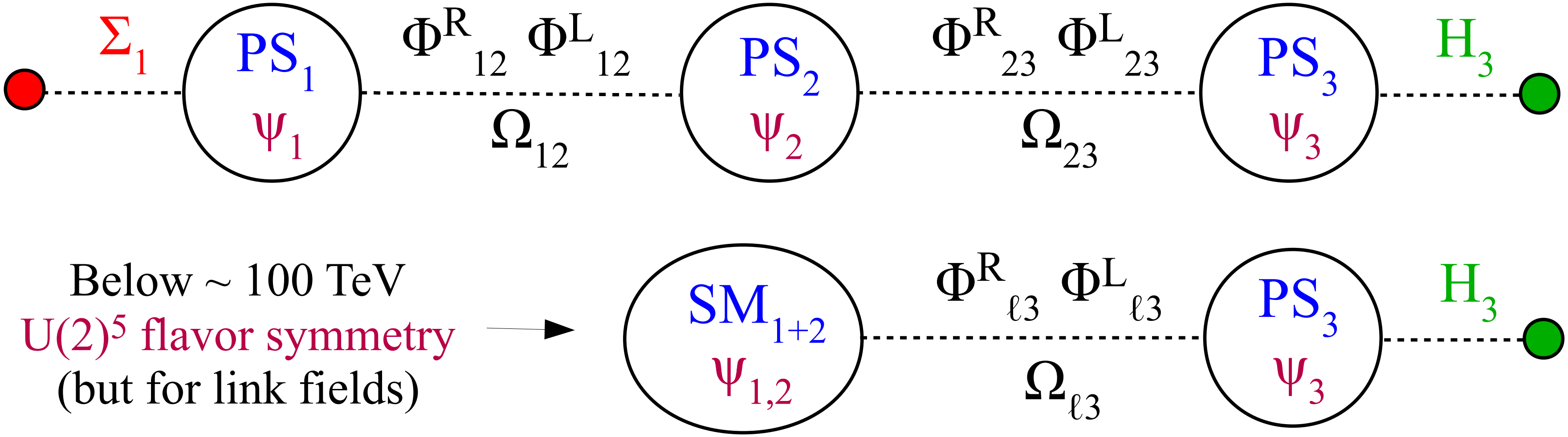
Low-scale "vertical"
Breaking [*EWSB*]

SM_3 [$SU(2)^L_1 \times U(1)^Y_1$]

QED_3 [$U(1)^Q_1$]

- 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. [similar to "4321" (Di Luzio et al. '17) but "natural" flavor structure: no ad-hoc mixings]

The PS^3 *model*

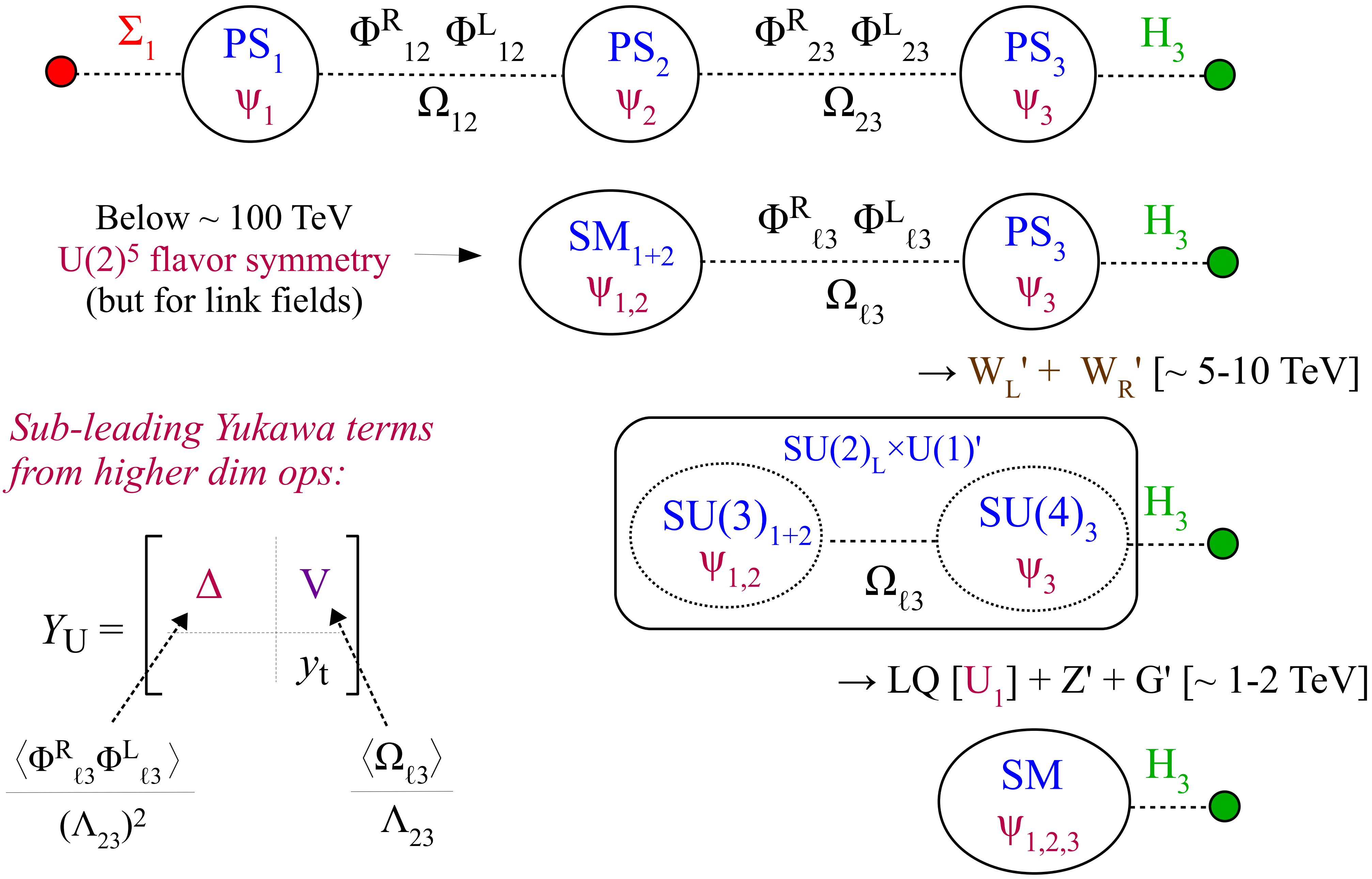


Below ~ 100 TeV
U(2)^5 flavor symmetry
(but for link fields)

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 — Φ^R_{12} Φ^L_{12} Ω_{12} — PS$_2$ ψ_2 — Φ^R_{23} Φ^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)$_L$×U(1)'

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

→ LQ [U_1] + Z' + G' [~ 1-2 TeV]

SM $\psi_{1,2,3}$ — H_3

Sub-leading Yukawa terms from higher dim ops:

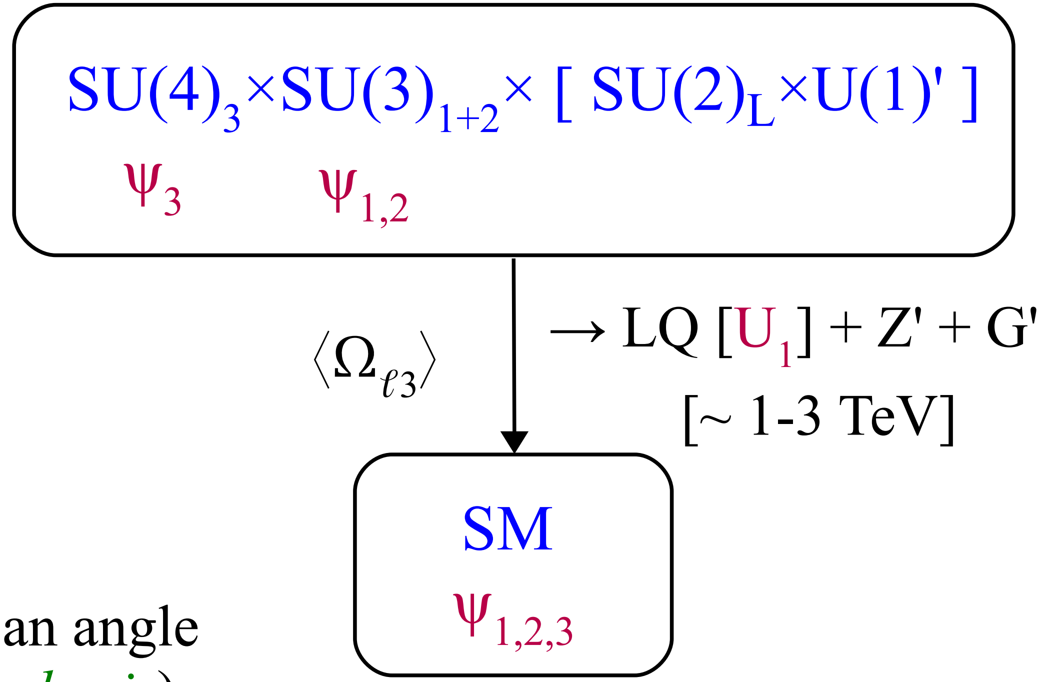
$$Y_U = \begin{bmatrix} \Delta & V \\ & y_t \end{bmatrix}$$

$$\frac{\langle \Phi^R_{\ell 3} \Phi^L_{\ell 3} \rangle}{(\Lambda_{23})^2} \qquad \frac{\langle \Omega_{\ell 3} \rangle}{\Lambda_{23}}$$

The PS^3 *model*

Collider phenomenology and flavor anomalies are controlled by the last-but one step in the breaking chain.

Despite the apparent complexity, the construction is highly constrained:



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

ψ_3 $\psi_{1,2}$

$\langle \Omega_{\ell 3} \rangle$

→ LQ [U_1] + Z' + G'

[~ 1-3 TeV]

SM

$\psi_{1,2,3}$

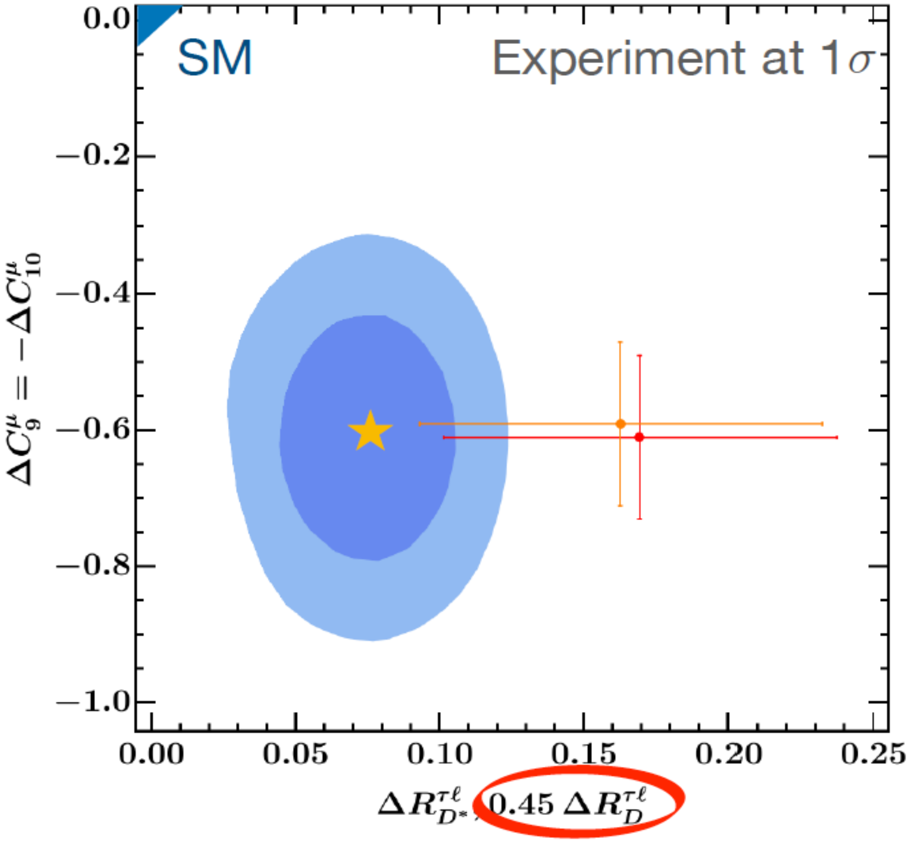
Quark flavor structure determined up to an angle (→ *degree of alignment to d-quark mass basis*)

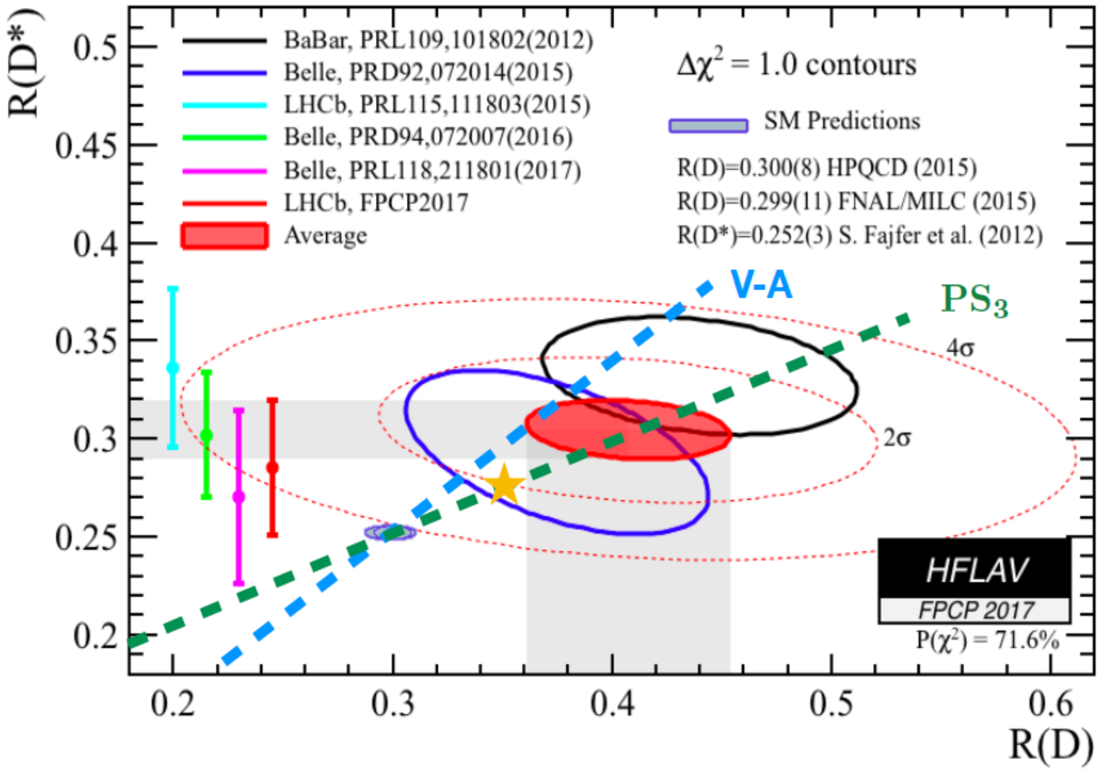
Key difference to all existing pheno models: unsupressed b_R-τ_R coupling of the LQ

The PS^3 *model*

Collider phenomenology and flavor anomalies are controlled by the last-but one step in the breaking chain.

Despite the apparent complexity, the construction is highly constrained





The fit to low-energy data is very good

(*although slightly smaller NP effects in* R_D, *mainly because of radiative constraints*)

- ΔF=2 constraints imply 5-10% alignment to d-quark mass basis

Possible future implications

“It is very difficult to make predictions,
especially about the future”

[attributed to Niels Bohr]

Implications for low-energy flavor physics

If the anomalies are due to NP, we should expect to see several other BSM effects in low-energy observables

Main message: "super-reach" flavor program for LHCb, but also other flavor physics facilities (Belle-II, Kaons, CLFV)

- This program is essential to determine the flavor structure of the new sector
- Correlations among low-energy obs. can be studied by means of EFT

Implications for low-energy flavor physics

If the anomalies are due to NP, we should expect to see several other BSM effects in low-energy observables

E.g.: correlations among down-type FCNCs [*using the results of* U(2)-*based EFT*]:

	$\mu\mu$ (ee)	$\tau\tau$	$\nu\nu$	$\tau\mu$	μe
$b \to s$	R_K, R_{K^*} O(20%)	$B \to K^{(*)} \tau\tau$ → 100×SM	$B \to K^{(*)} \nu\nu$ O(1)	$B \to K \tau\mu$ $\to \sim 10^{-6}$	$B \to K \mu e$???
$b \to d$	$B_d \to \mu\mu$ $B \to \pi \mu\mu$ $B_s \to K^{(*)} \mu\mu$ O(20%) [$R_K=R_\pi$]	$B \to \pi \tau\tau$ → 100×SM	$B \to \pi \nu\nu$ O(1)	$B \to \pi \tau\mu$ $\to \sim 10^{-7}$	$B \to \pi \mu e$???
$s \to d$	*long-distance pollution*	*NA*	$K \to \pi \nu\nu$ O(1)	*NA*	$K \to \mu e$???

Implications for low-energy flavor physics

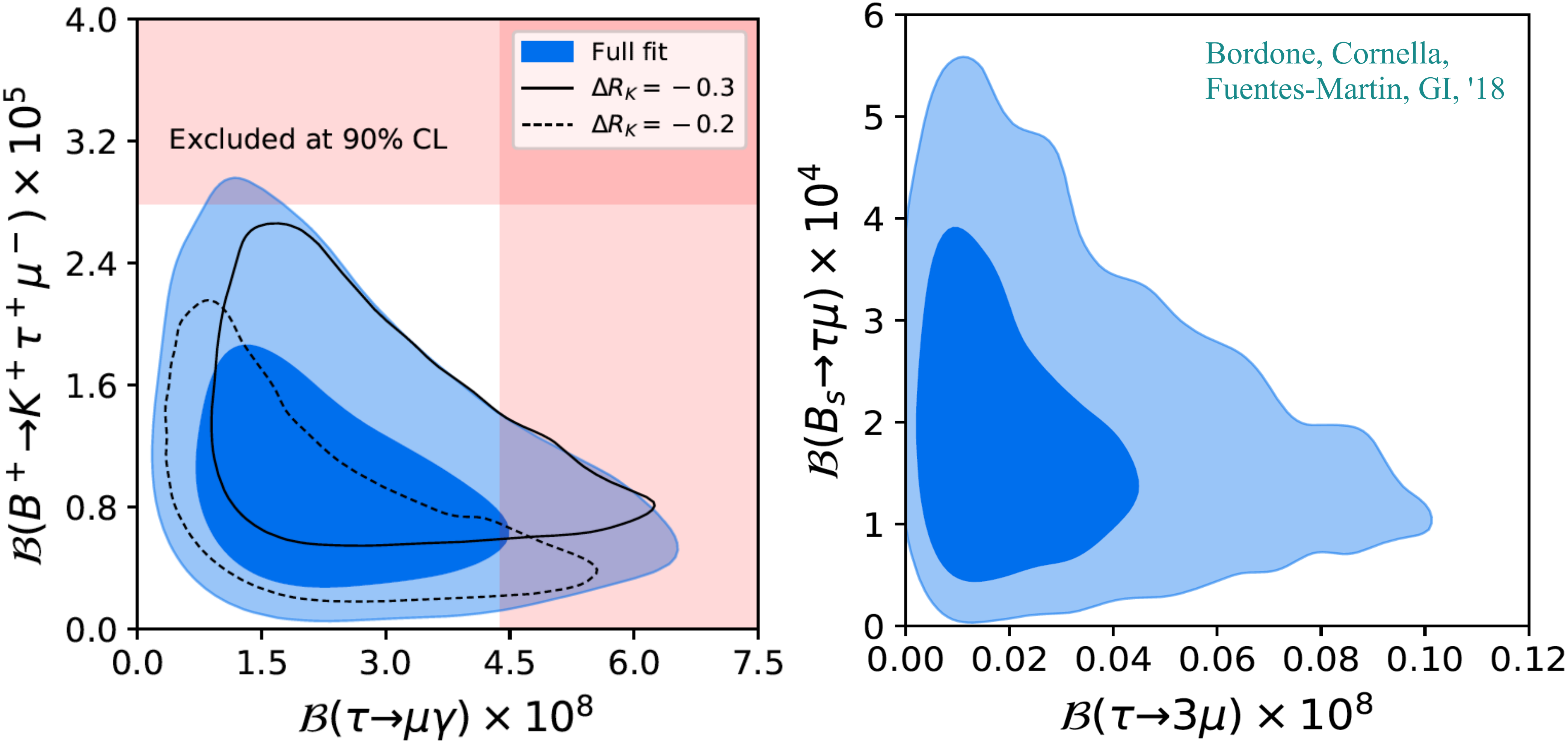
The low-energy observables with large uncertainties are those mediated by four-quark or four-leptons effective operators (*larger model-dependence in connecting them to the semi-leptonic operators, hence to the anomalies*)

However, in many explicit constructions, the effects are close to present bounds:

- Meson mixing
  - O(1-10%) deviations from SM in ΔM_{Bs} & ΔM_{Bd}
  - O(0.1%) CPV violation D-D mixing
- LFV decays
  - $\tau \to 3\mu$ & $\tau \to \mu\gamma$ can be close to their exp. bounds
  - LFV B decays, $B_s \to \tau\mu$ or $B \to K\tau\mu$ could also be within the reach

Implications for low-energy flavor physics

E.g: expectation of LFV processes in the PS^3 model:



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

$$\left(\frac{\Delta R_D}{0.2}\right)^2 \left(\frac{\Delta R_K}{0.3}\right)^2 \approx 3\left[\frac{\mathcal{B}(B \to K\tau^+\mu^-)}{3\times 10^{-5}}\right]\left[\frac{\mathcal{B}(\tau \to \mu\gamma)}{5\times 10^{-8}}\right] \approx \left[\frac{\mathcal{B}(B_s \to \tau^\pm\mu^\mp)}{2\times 10^{-4}}\right]\left[\frac{\mathcal{B}(\tau \to \mu\gamma)}{5\times 10^{-8}}\right]$$

Implications for high-p_T physics

Some general considerations:

Independently of the details of the UV models, the anomalies (and particularly $R_{D(*)}$) point to NP in the ball-park of direct searches @ LHC

This NP could have escaped detection so far only under specific circumstances (*that are fulfilled by the proposed UV completions*):

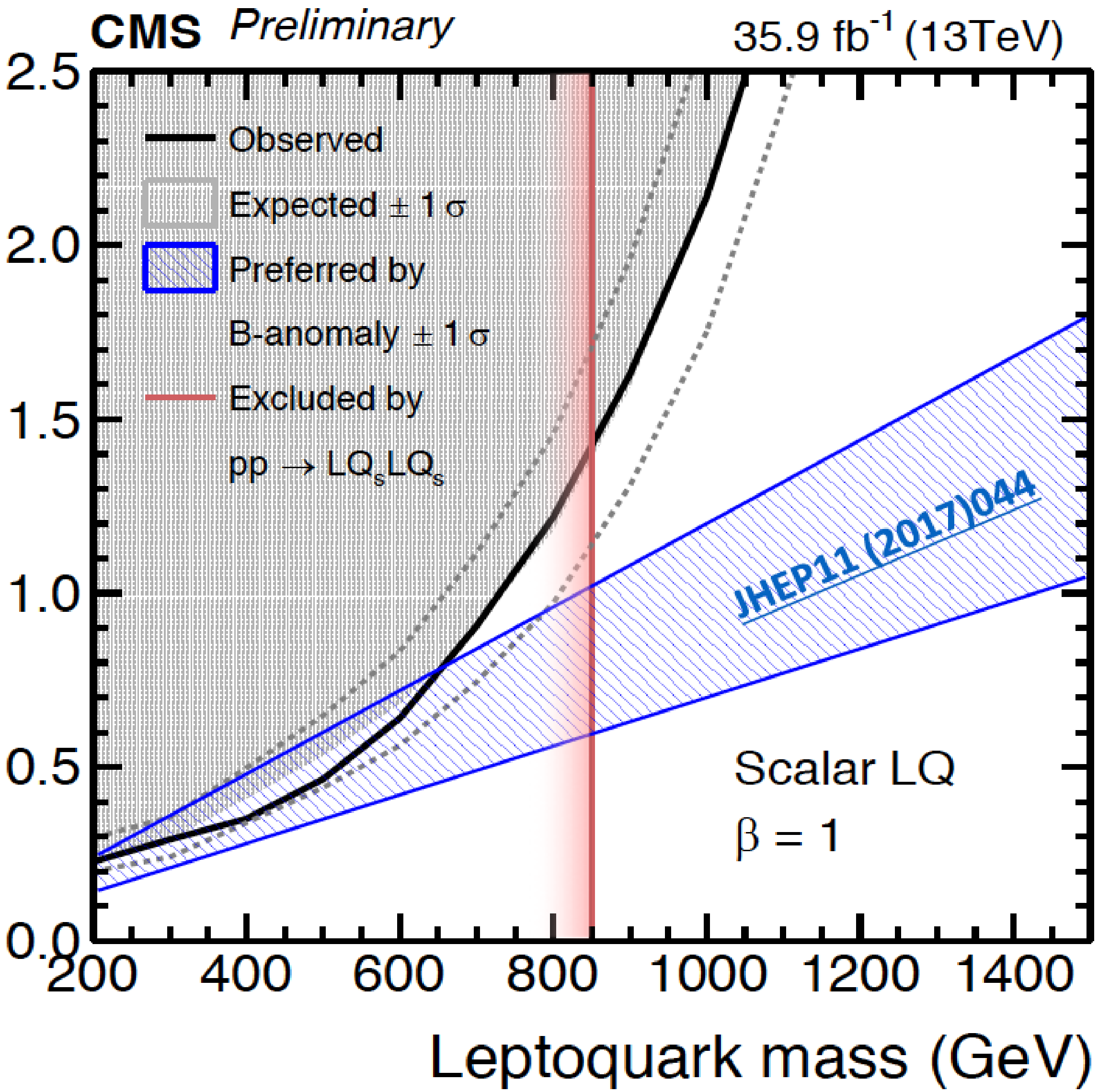
- Coupled mainly to 3rd generation (→ *no large coupl. to proton valence quarks*)
- No narrow peaks in dilepton pairs (*including tau pairs*)

⬇

Significant room for improvement for the corresponding searches @ HL-LHC
But only HE-LHC would be able to rule out all reasonable models

Implications for high-p_T physics

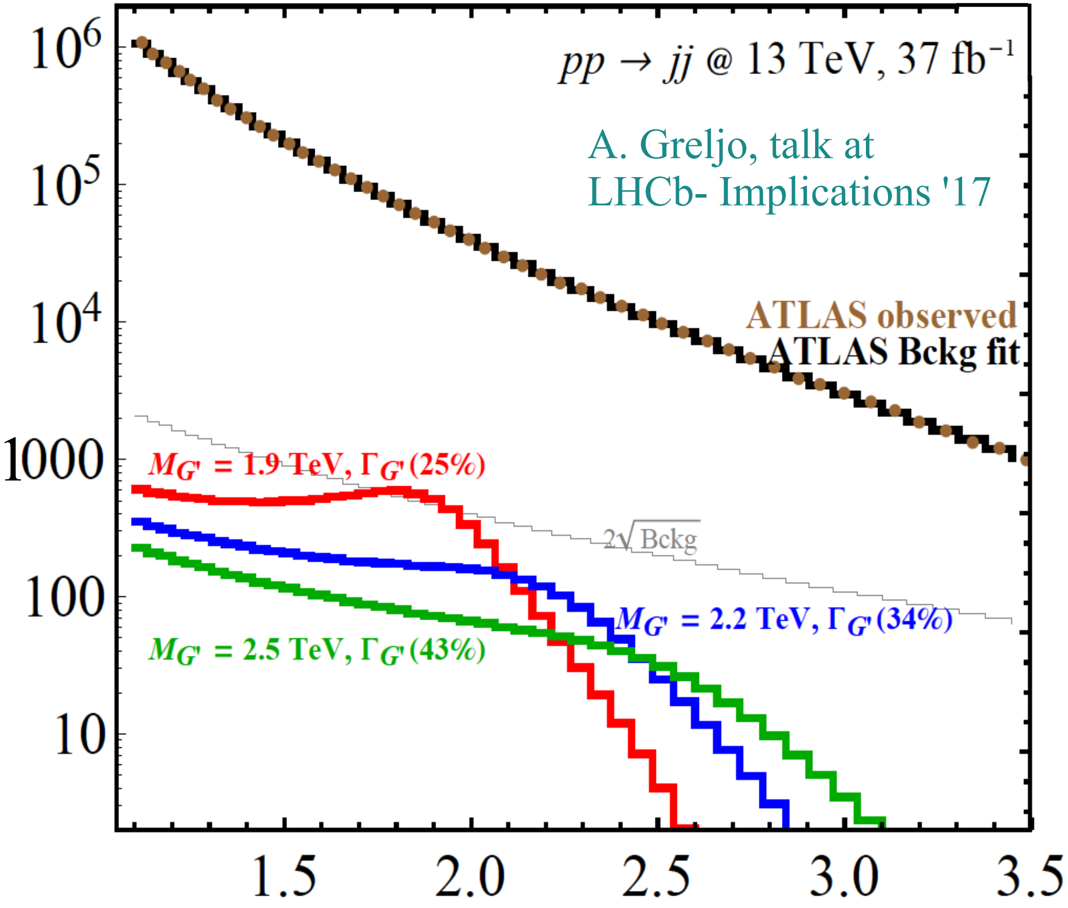
E.g.: Pair vs. Single scalar LQ production @CMS:



Implications for high-p_T physics & neutrino physics

In specific models, such at the PS^3 or the “4321”, the TeV-scale phenomenology involve (several) additional states not directly involved in the anomalies

E.g.: I. The “Coloron”



E.g.: II. TeV-scale RH neutrinos

General prediction of TeV-scale PS-like models, where small neutrino masses occurs via the *inverse see-saw*

↓

Deviations from PMNS unitarity correlated to the B-physics anomalies in the 10^{-6}-10^{-5} range [Greljo, Stefanek '18]

Consistent with (*but not far from…*) present bounds [Antusch, Fischer '15]

Conclusions

- If these ~~LFU~~ anomalies were confirmed, it would be a fantastic discovery, with far-reaching implications

- 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 out 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. However, realistic UV for these models naturally imply a much richer spectrum of states at the TeV scale (*and possibly above...*).

- The PS^3 model I have presented is particularly interesting as example of the change of paradigm in model building that these anomalies could imply.
  But many points/possible-variations remains to be clarified/explored...

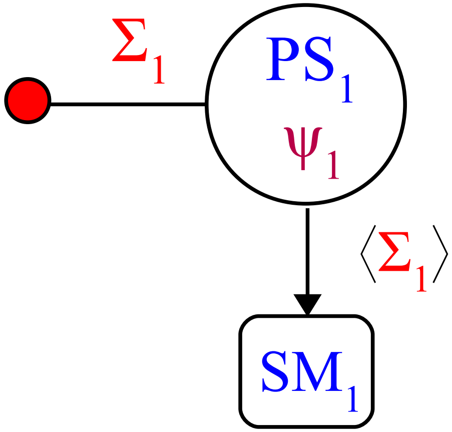
↓

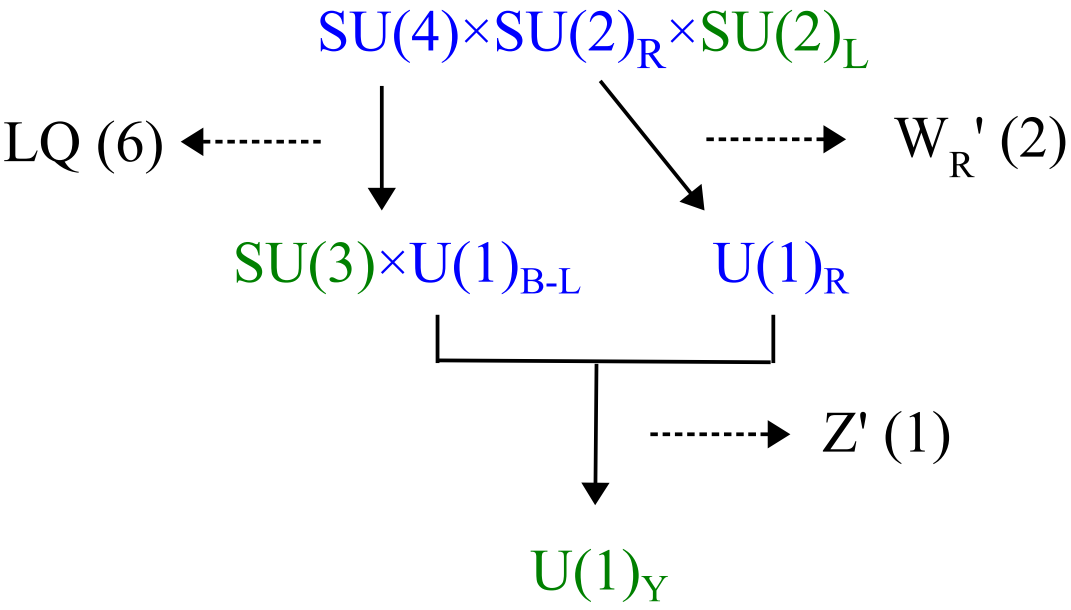
A lot of fun ahead of us...

(both on the exp., the pheno, and model-building point of view)


Backup

Symmetry breaking pattern in PS^3

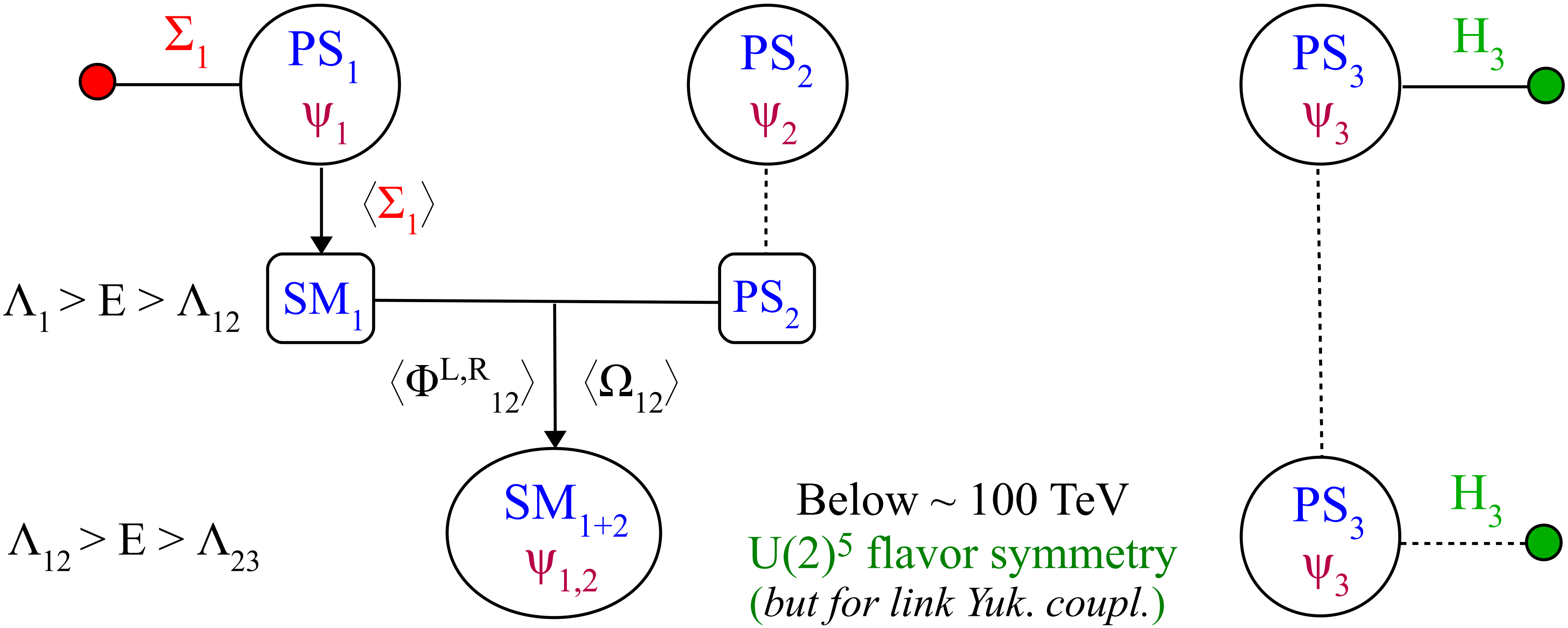




High-scale [~ 10^3 TeV]
"vertical" breaking [PS → SM]

$$PS_1 \, [\, SU(4)_1\times SU(2)^R_1 \,]$$
$$\downarrow$$
$$SM_1 \, [\, SU(3)_1\times U(1)^Y_1 \,]$$

Symmetry breaking pattern in PS^3



Σ_1 PS_1 ψ_1 PS_2 ψ_2 PS_3 ψ_3 H_3

$\langle \Sigma_1 \rangle$

$\Lambda_1 > E > \Lambda_{12}$ SM_1 PS_2

$\langle \Phi^{L,R}{}_{12} \rangle$ $\langle \Omega_{12} \rangle$

$\Lambda_{12} > E > \Lambda_{23}$ SM_{1+2} $\psi_{1,2}$

Below ~ 100 TeV
U(2)^5 flavor symmetry
(*but for link Yuk. coupl.*)

PS_3 ψ_3 H_3

$\Phi^L{}_{12} \sim (1,2,1)_1 \times (1,2,1)_2$ VEV $\rightarrow$ $SU(2)^L{}_{1+2}$

$\Phi^R{}_{12} \sim (1,1,2)_1 \times (1,1,\underline{2})_2$ VEV $\rightarrow$ $SU(2)^R{}_{1+2}$

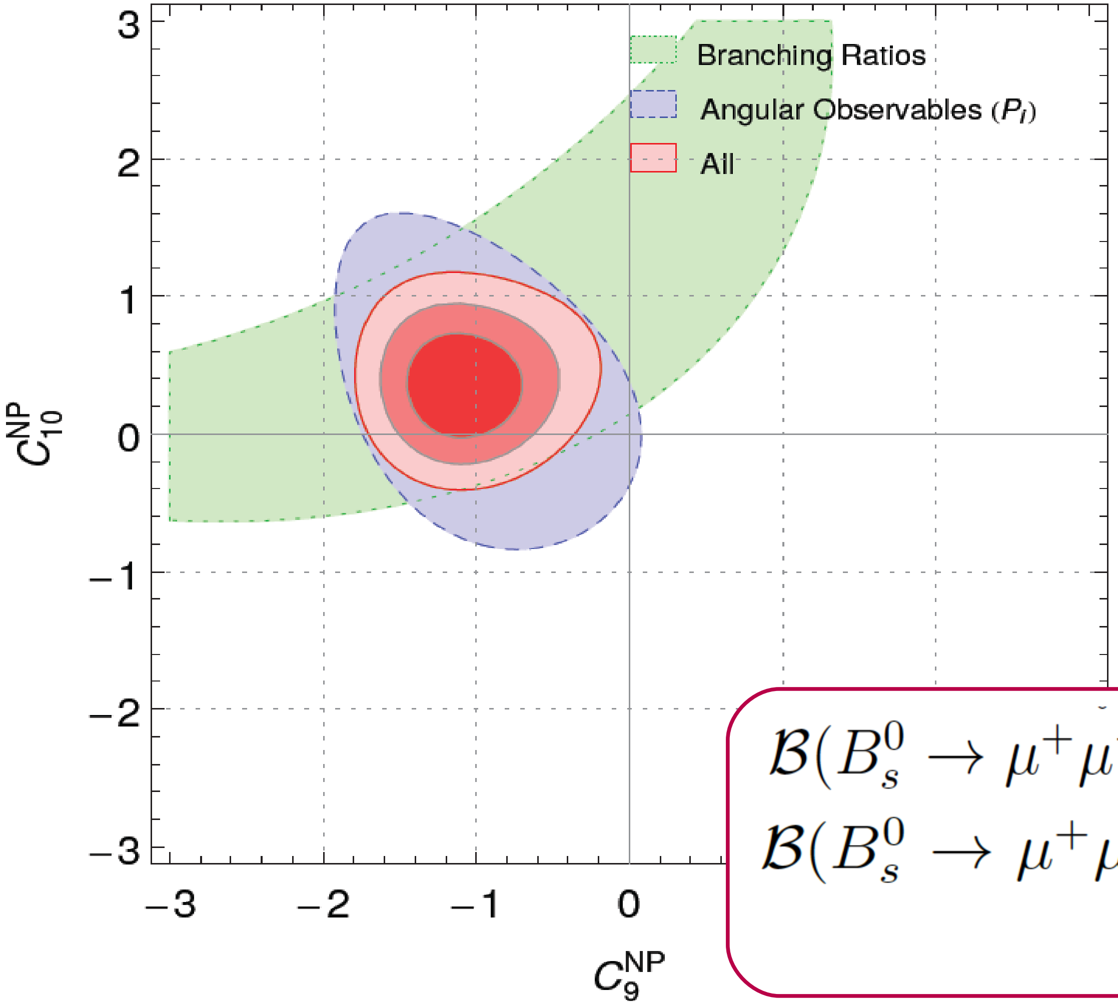
$\Omega_{12} \sim (4,2,1)_1 \times (\underline{4},\underline{2},1)$ VEV $\rightarrow$ $SU(4)_{1+2}$ & $SU(2)^L{}_{1+2}$

Anomalies in B → $K^{(*)}$ μμ / ee [LHCb]

Pro NP:

- Reduced tension in all the observables with a unique fit of non-standard short-distance Wilson coefficients

Descotes-Genon, Matias, Virto '13, '15
Altmannshofer & Straub '13, '15
Beaujean, Bobeth, van Dyk '13
Horgan *et al.* '13



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

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

Consistency with smallness of BR(B_s →μμ) for C_9 = - C_{10}

$$\mathcal{B}(B_s^0 \to \mu^+\mu^-)_{\rm SM} = (3.66 \pm 0.23) \times 10^{-9}$$

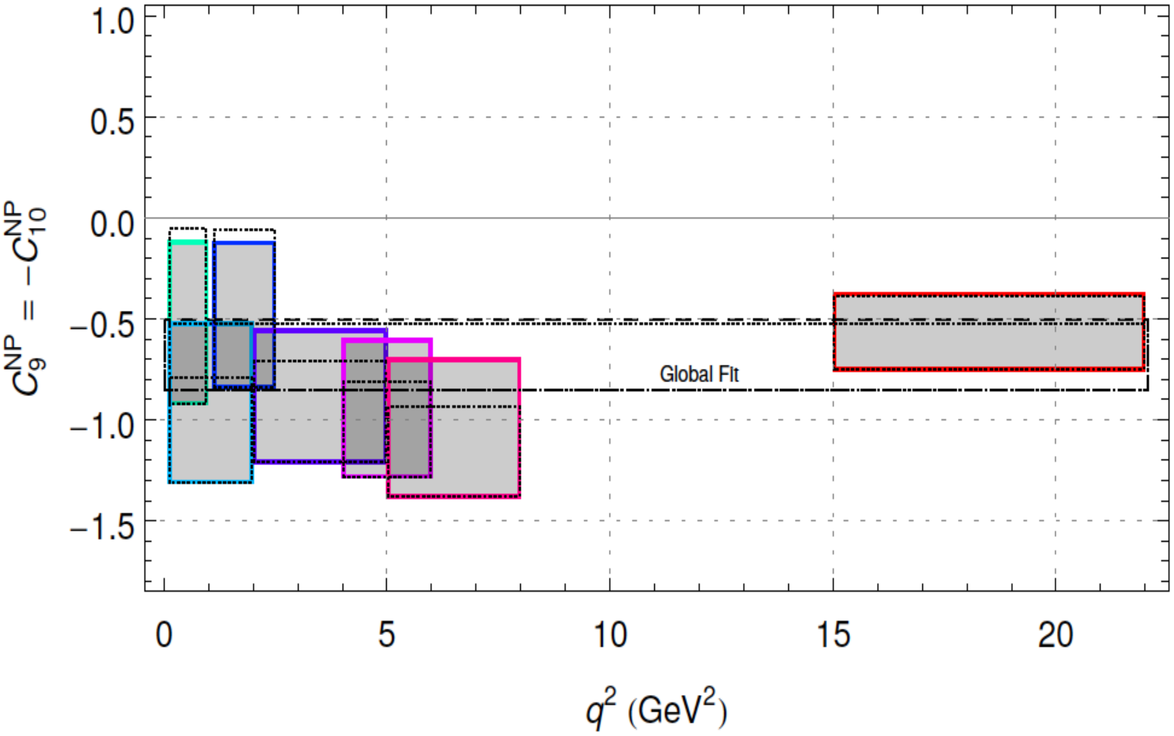
$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) = (2.8\,^{+0.7}_{-0.6}) \times 10^{-9}$$

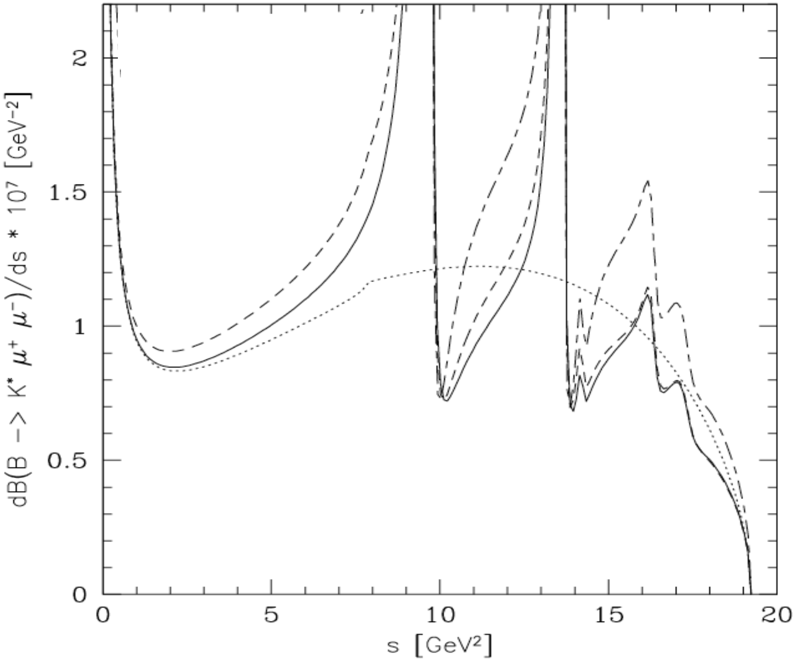
LHCb + CMS

Anomalies in B → $K^{(*)}$ μμ / ee [LHCb]

Pro NP:

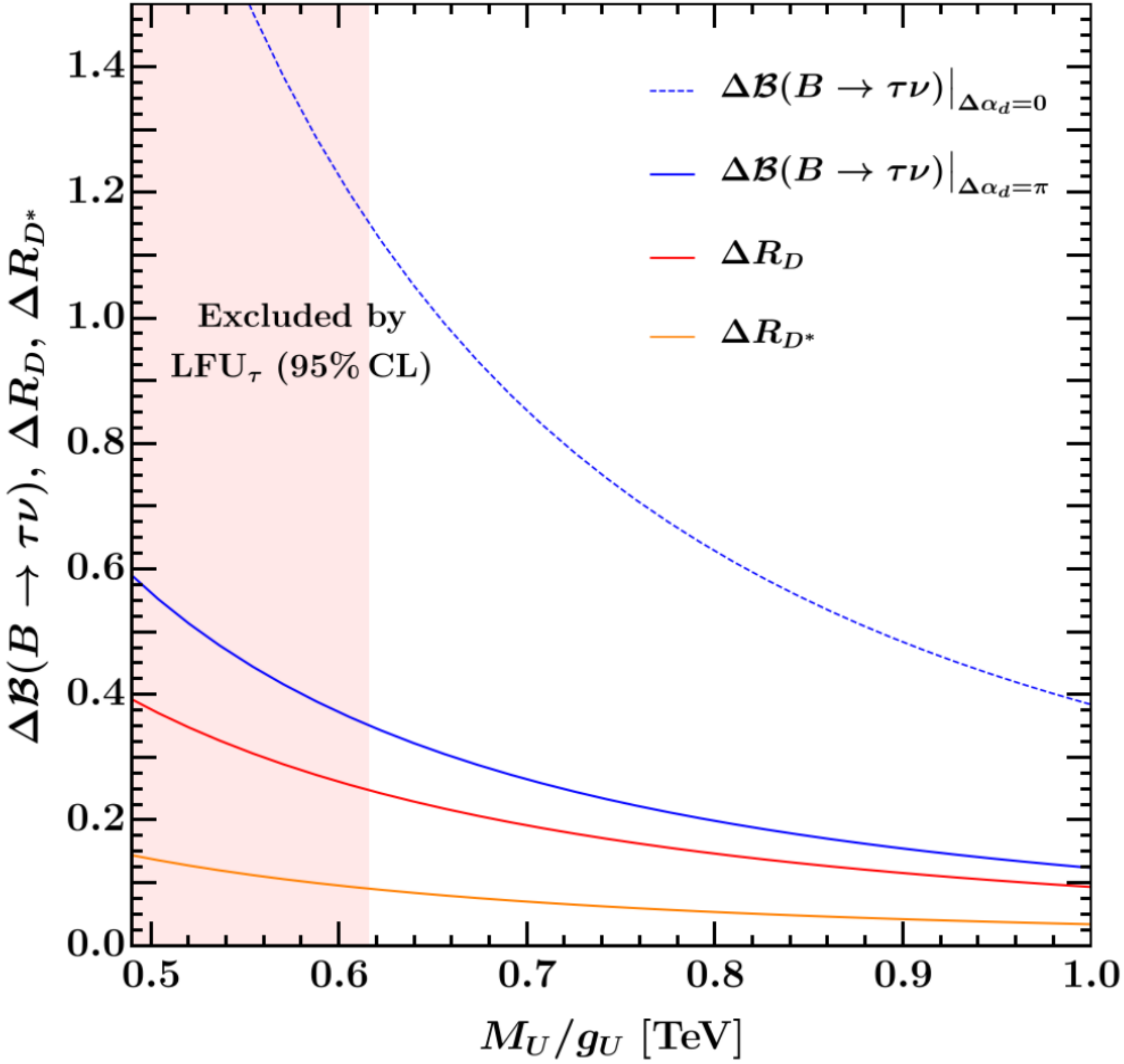
- Reduced tension in all the observables with a unique fit of non-standard short-distance Wilson coefficients

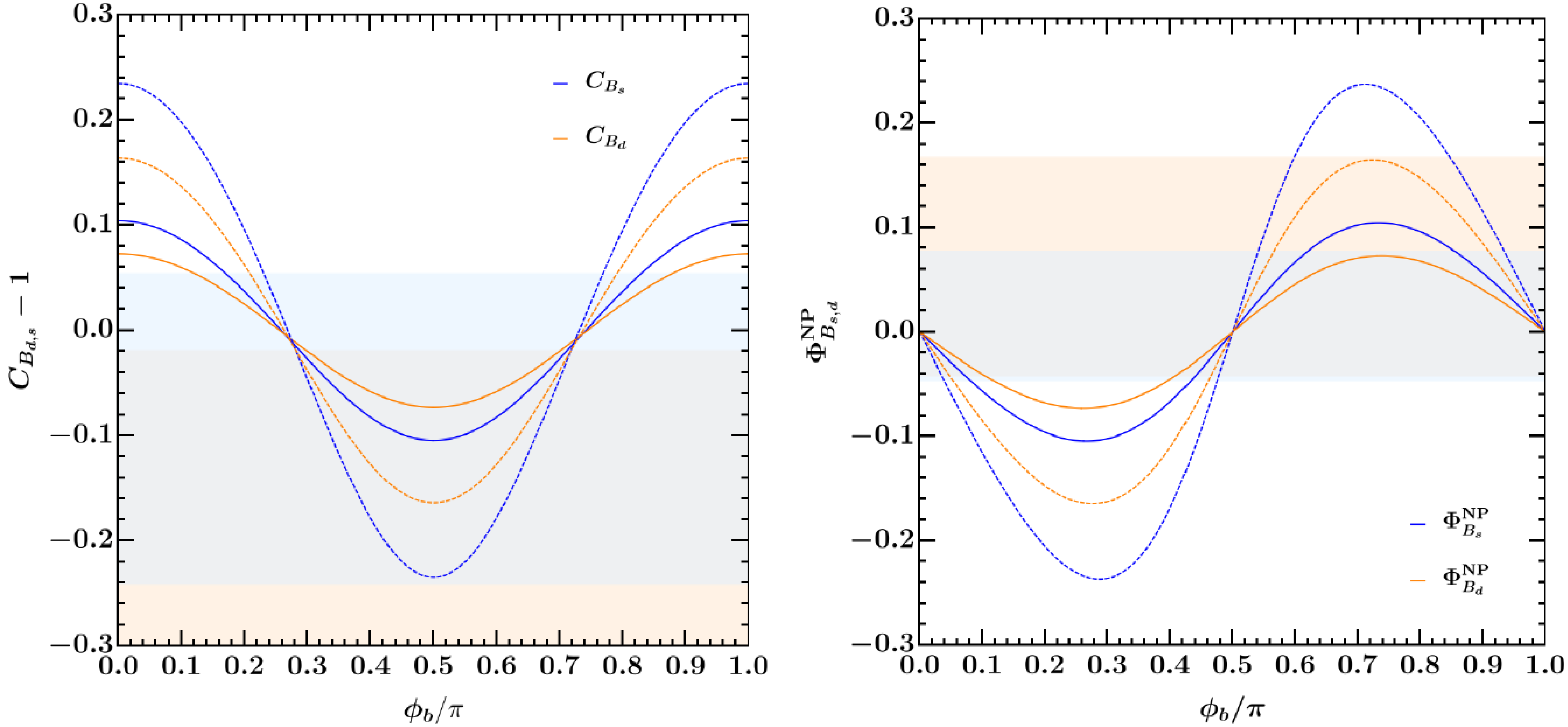




More precise data on the q^2=$m_{\mu\mu}$ distribution can help to distinguish NP vs. SM

Descotes-Genon, Matias, Virto '15


$\Delta\mathcal{B}(B \to \tau\nu)|_{\Delta\alpha_d=0}$
$\Delta\mathcal{B}(B \to \tau\nu)|_{\Delta\alpha_d=\pi}$
ΔR_D
ΔR_{D^*}
Excluded by
LFU$_\tau$ (95% CL)
$\Delta\mathcal{B}(B \to \tau\nu)$, ΔR_D, ΔR_{D^*}
M_U/g_U [TeV]
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
0.5
0.6
0.7
0.8
0.9
1.0


C_{B_s}
C_{B_d}
$C_{B_{d,s}} - 1$
0.3
0.2
0.1
0.0
−0.1
−0.2
−0.3
0.0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1.0
ϕ_b/π
$\Phi^{\rm NP}_{B_{s,d}}$
$\Phi^{\rm NP}_{B_s}$
$\Phi^{\rm NP}_{B_d}$
0.3
0.2
0.1
0.0
−0.1
−0.2
−0.3
0.0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1.0
ϕ_b/π