Hints of physics beyond the Standard Model in the Flavor Sector

Gino Isidori

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- Introduction [*Flavor Physics within and beyond the SM*]
- 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*, *dark-matter*, U(1) *charges*,…)

↓

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"Common lore" (I) :

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

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

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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
$[\psi = Q_L, u_R, d_R, L_L, e_R]$ ⇒ huge flavor-degeneracy [$U(3)^5$ *symmetry*]

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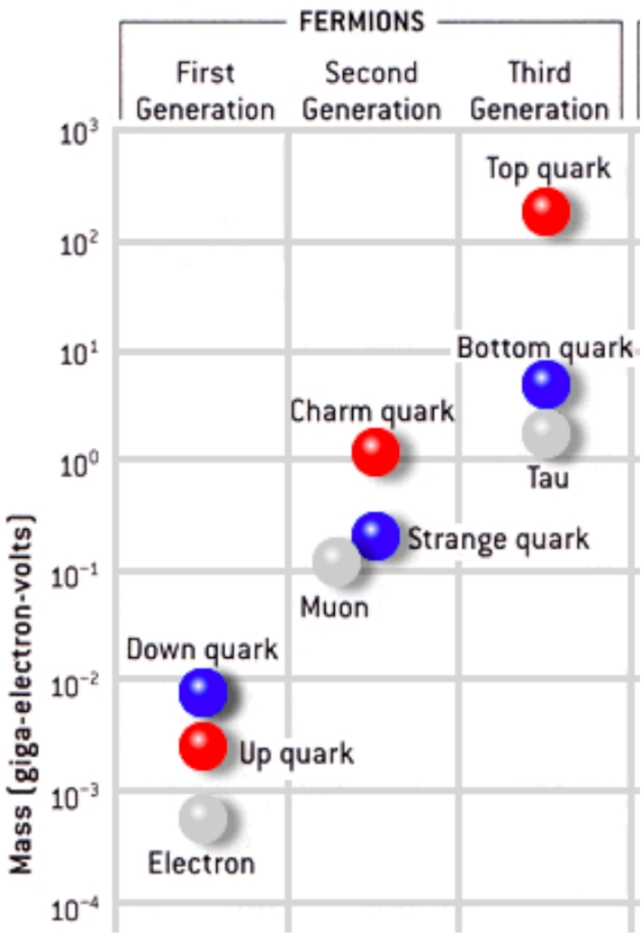
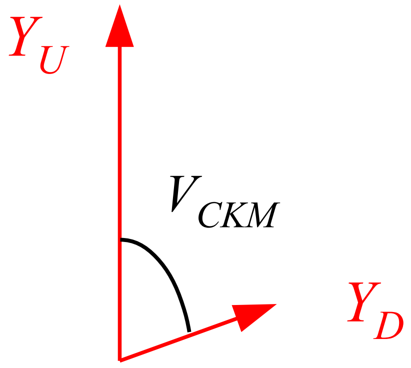
Within the SM the flavor-degeneracy is broken only by the Yukawa interaction:

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

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

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





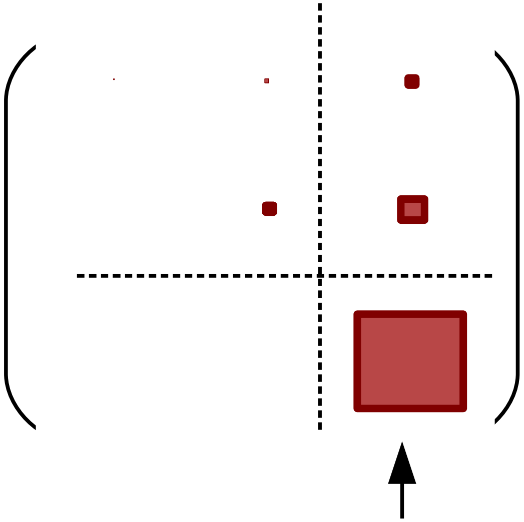
The Flavor structure of the SM

Altogether, the SM flavor (Yukawa) sector is characterized by 13 parameters:

[3 lepton masses + 6 quark masses + 3+1 CKM parameters]

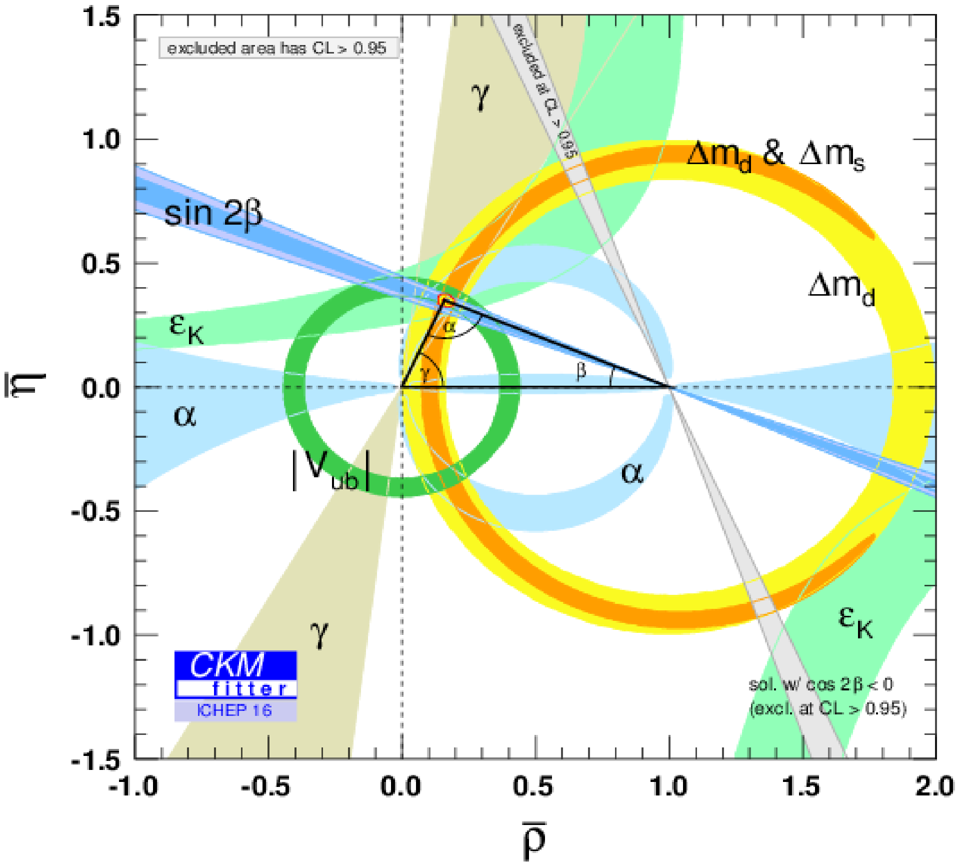
Which do not look at all accidental...

$Y_U \sim$



$$y_t = \frac{\sqrt{2}\, m_t}{\langle \phi \rangle} \approx 1$$

....and which are determined with high accuracy



The Flavor structure of the SM and beyond...

The key question we try to address by continuing doing high-precision measurements of flavor-changing processes of quarks & charged-leptons is:

Are there other sources of flavor symmetry breaking [beside the SM Yukawas] ?

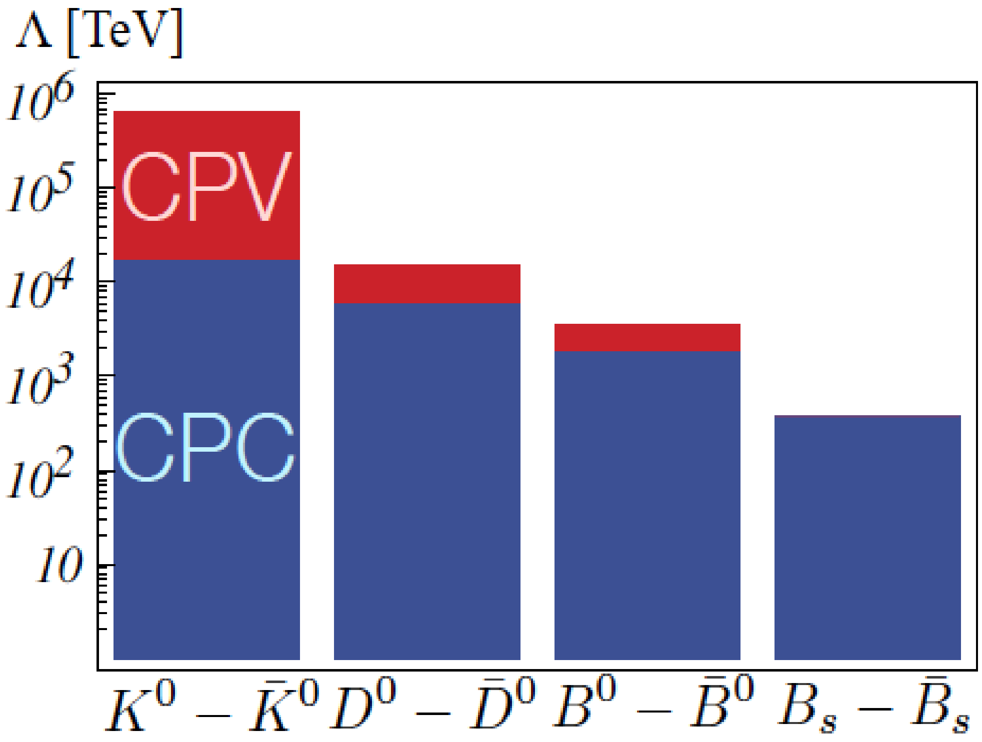
So far everything seems to fit well with the SM→ Strong limits on NP

$$\mathscr{L}_{\text{eff}} = \mathscr{L}_{\text{SM}} + \Sigma \frac{1}{\Lambda^2} \mathrm{O}_{\text{eff}}$$

"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...

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:

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

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

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...*)

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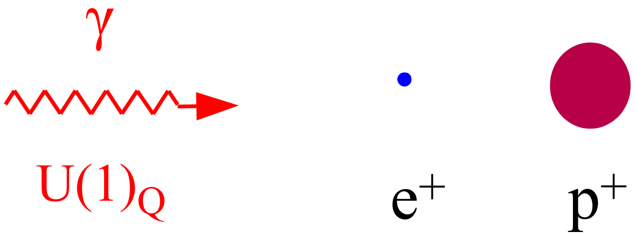
Interesting shift of paradigm
(*in flavor physics, but possibly also beyond*)

A digression on LFU

Let's go back ~ 100 years, and suppose we can test matter only with long wave-length photons...



These two particles seems to be "identical copies" but for their mass ...

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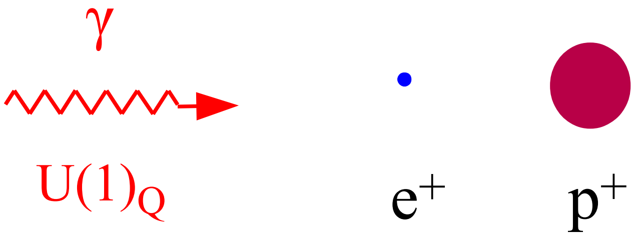

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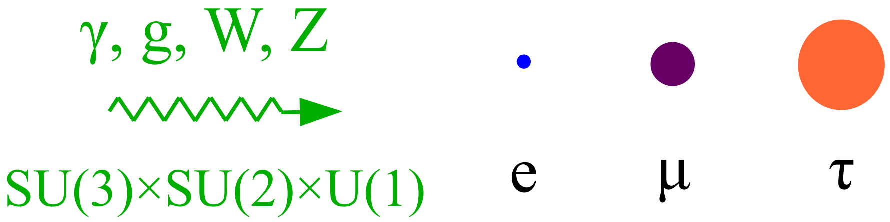
That's exactly the same (misleading) argument we use to infer LFU...



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

"Common lore" (I)

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

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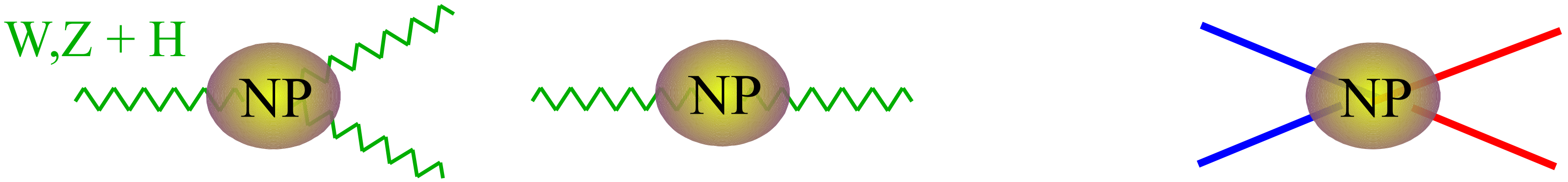

large (*more interesting…*)

small (*less interesting…*)

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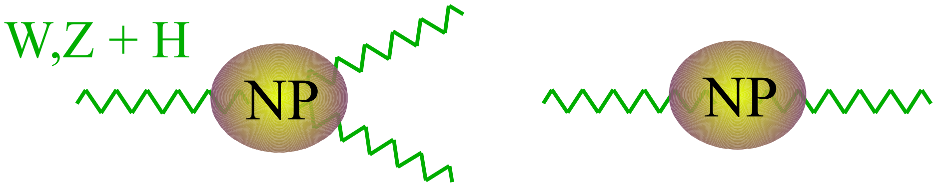
The recent flavor anomalies seem to suggest a shift of paradigm:

- 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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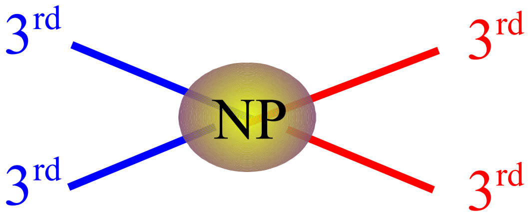

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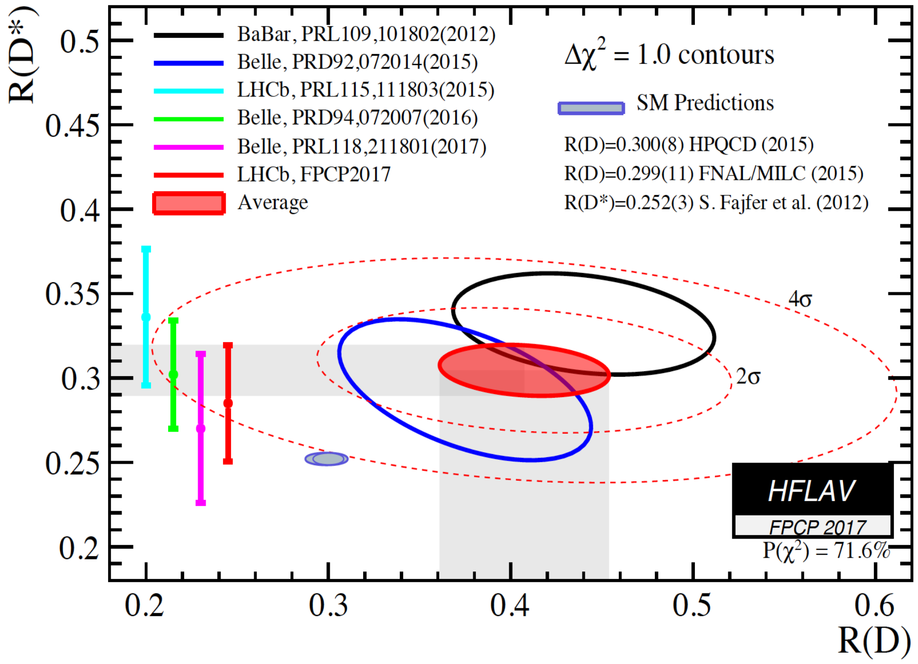
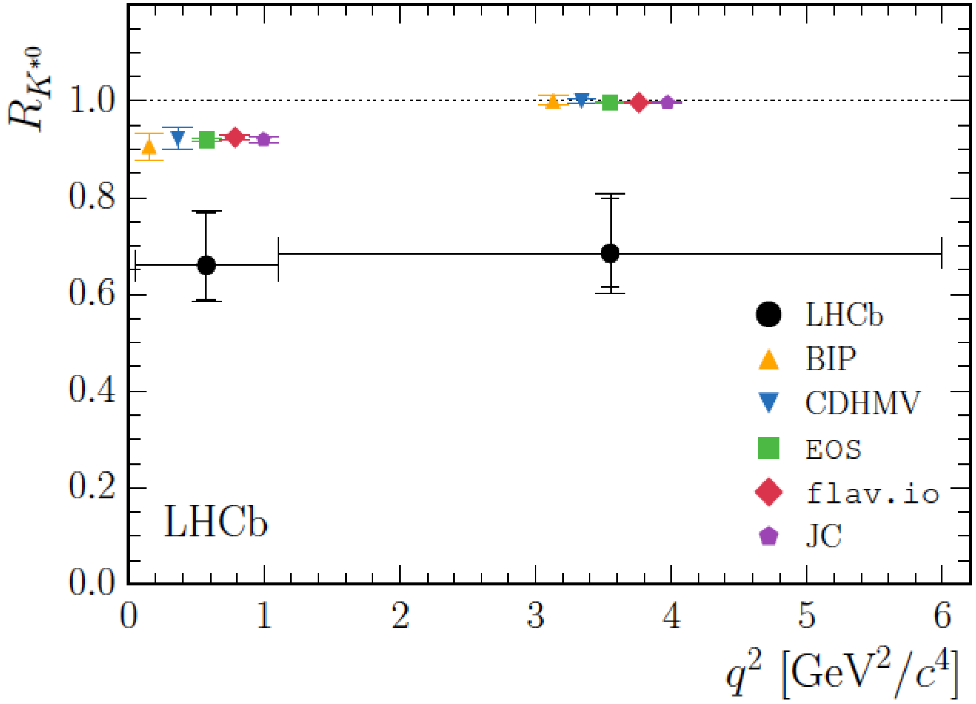
And if we are lucky... these anomalies may help us to shed light on another key problem of the SM that we have postponed (*somehow forgotten...*) for a long time:

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

On the recent B-physics anomalies



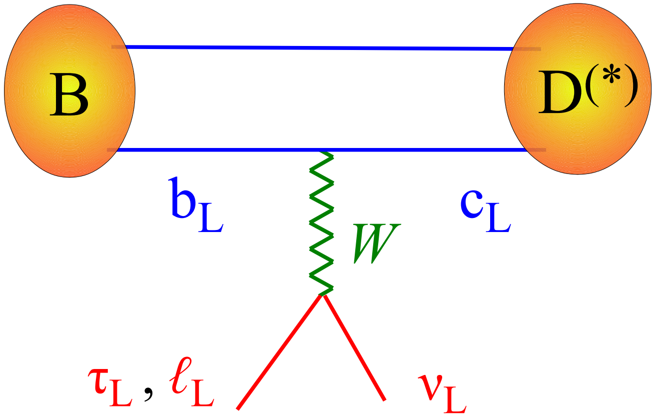


$B \to D^{(*)} \tau\nu$ [Babar, Belle, LHCb]

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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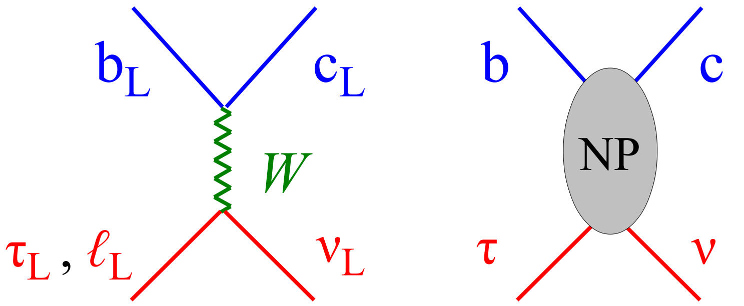

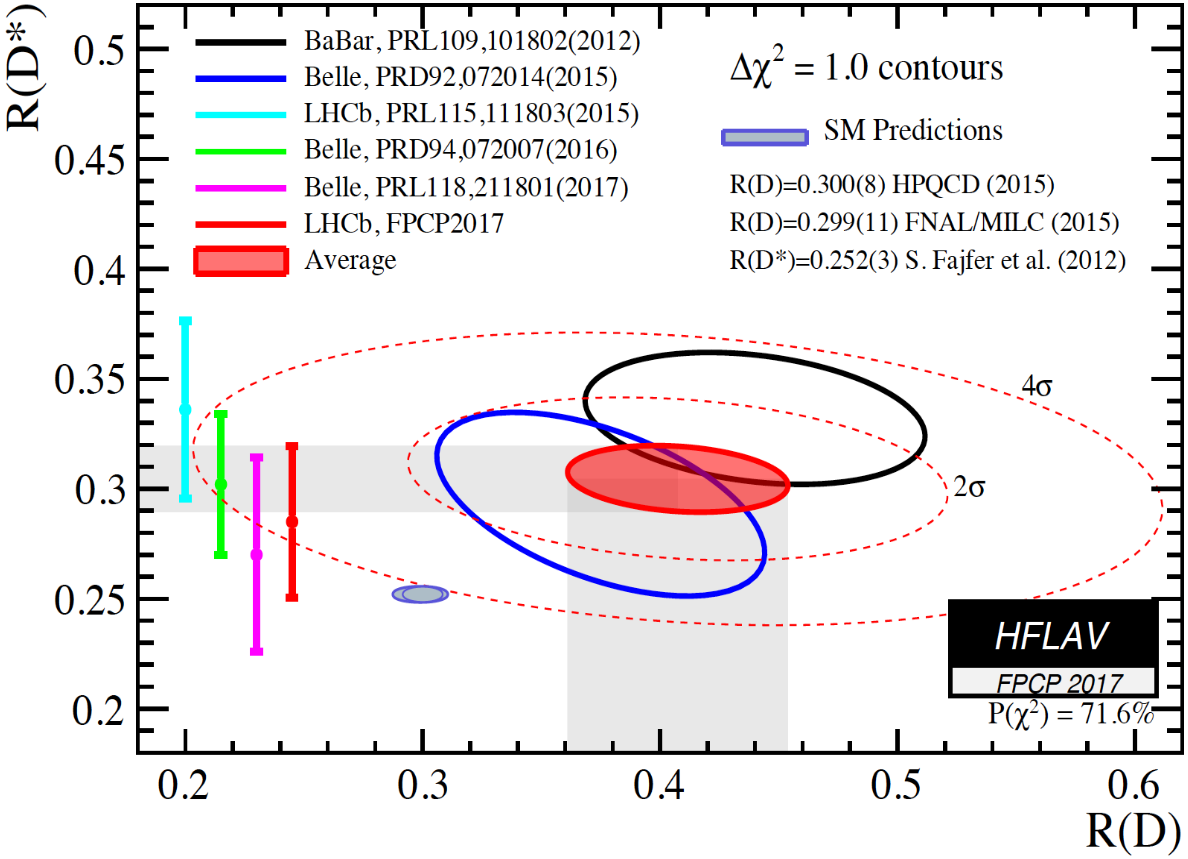

- **SM** prediction quite solid: hadronic uncertainties cancel (*to large extent*) in the ratio and deviations from 1 in *R*(X) expected only from phase-space differences
- Consistent results by 3 different exps. → 3.6–3.9σ excess over SM (*D* + *D**)

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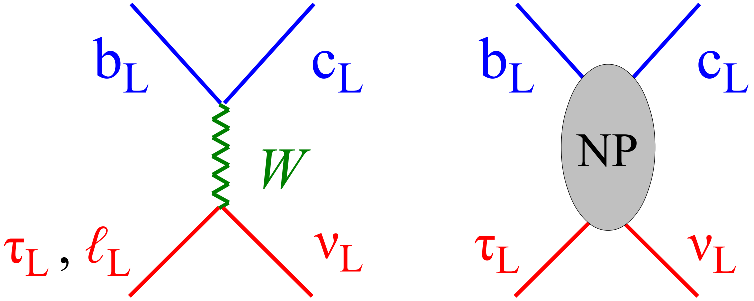
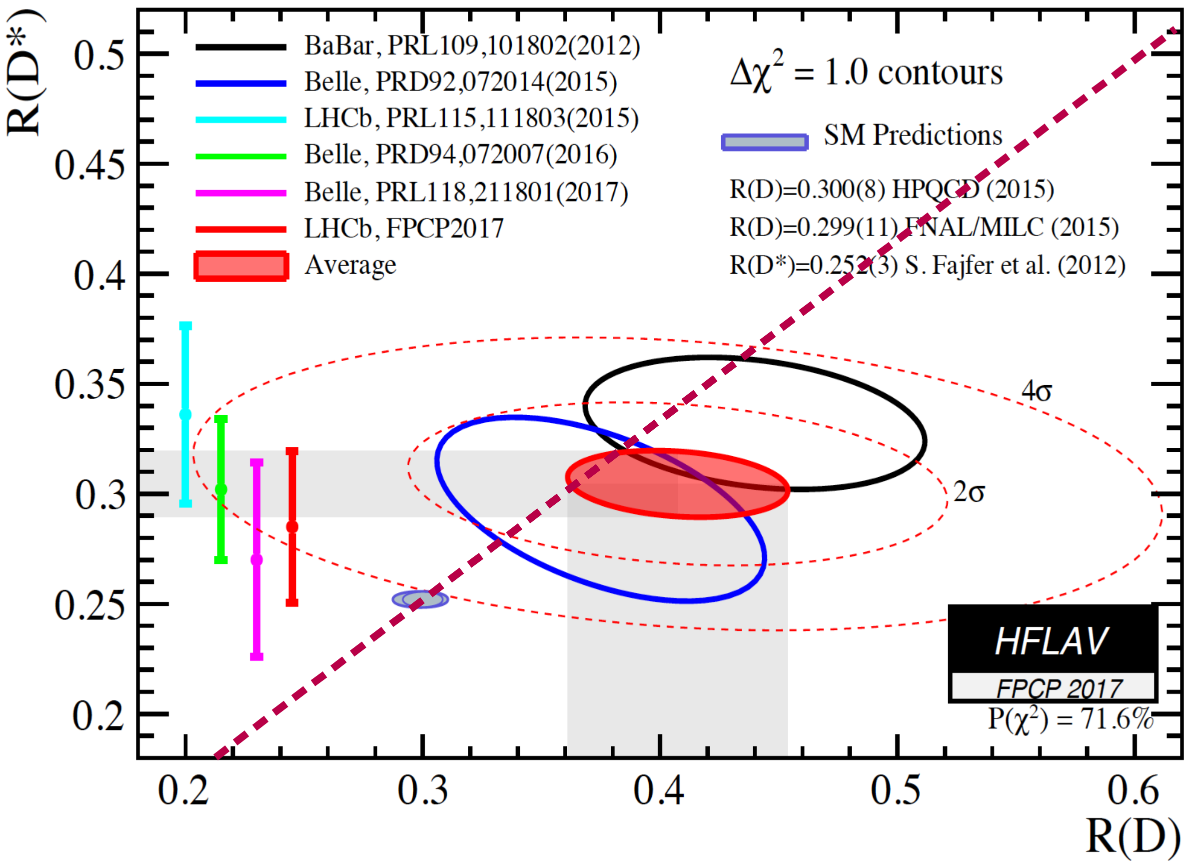




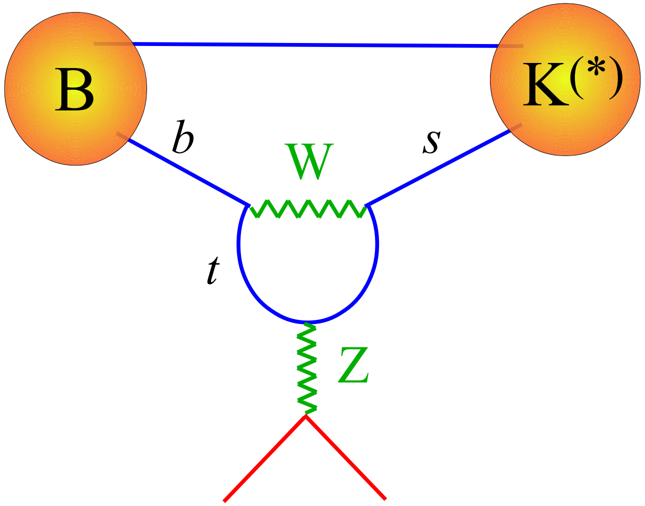
- SM prediction quite solid: hadronic uncertainties cancel (*to large extent*) in the ratio and deviations from 1 in *R*(X) expected only from phase-space differences
- Consistent results by 3 different exps. → 3.6–3.9σ excess over SM (*D* + *D**)
- The two channels are well consistent with a universal 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 → $K^{(*)}$ μμ / ee [LHCb]

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

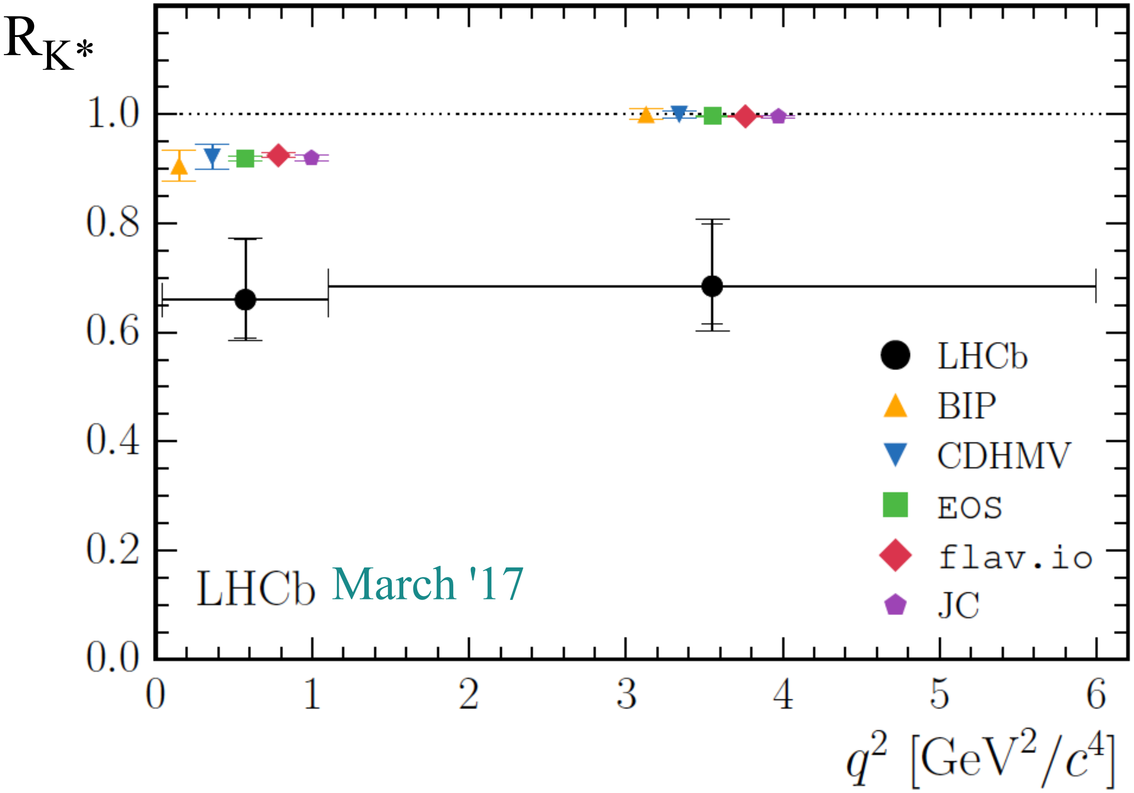
$$R_H = \frac{\int d\Gamma(B \to H\, \mu\mu)}{\int d\Gamma(B \to H\, ee)}$$

R_K [1-6 GeV^2] = 0.75 ± 0.09

LHCb, '14

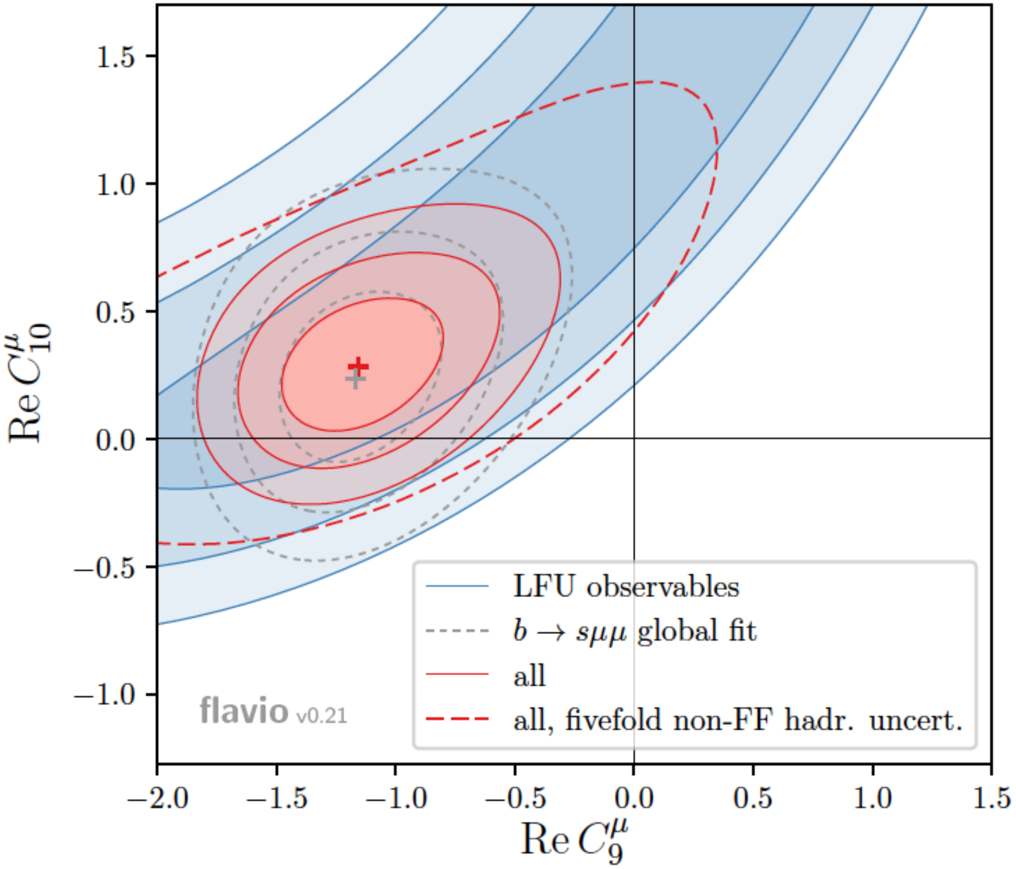
(vs. 1.00±0.01 SM)

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

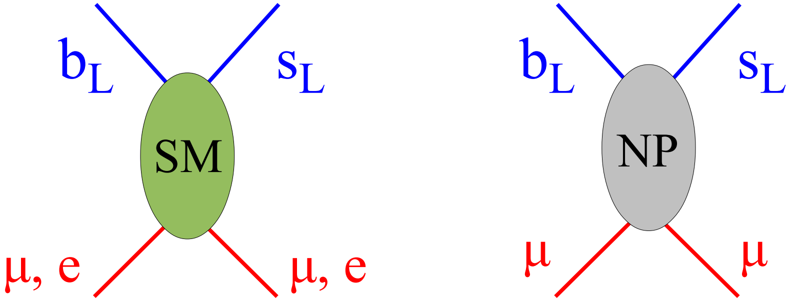


Anomalies in $B \to K^{(*)}$ μμ / ee [LHCb]

- 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.
- Most interesting deviations from the SM in the μ/e "clean" LFU ratios.



Altmannshofer, Stangl, Straub '17



- All effects well described by NP of short-distance origin only in $b \to s\mu\mu$ and (& not in ee)
- LH structure on the quark side largely favored
- Helicity structure on the lepton side less clear

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:

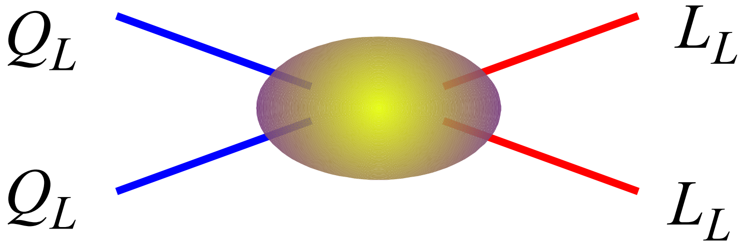
Generic EFT approach
↓
Simplified Dynamical Models
↓
High-energy behavior and UV completion

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* 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
(+many others...)

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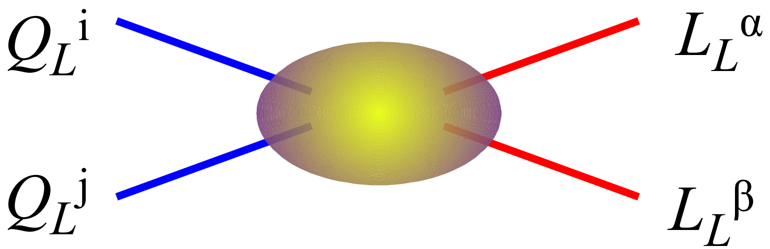

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- Large coupling (competing with SM tree-level) in bc → $l_3\,\nu_3$
- Small non-vanishing coupling (competing with SM FCNC) in bs → $l_2\,l_2$

↓

$$\Lambda_{ij\alpha\beta} = (\delta_{i3}\times\delta_{3j})\times(\delta_{\alpha3}\times\delta_{3\beta}) \; + $$ small terms for 2nd (& 1st) generations →

Link to pattern of the Yukawa couplings !

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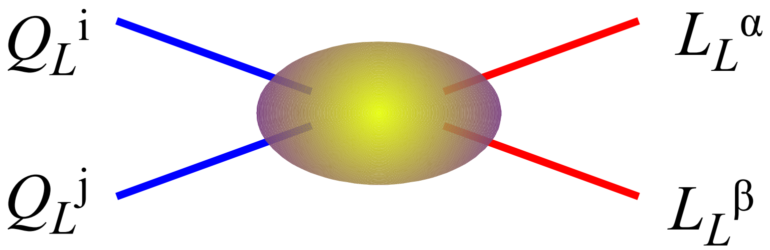
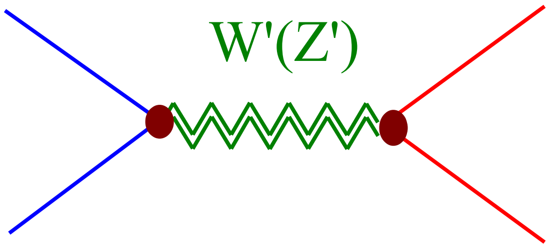
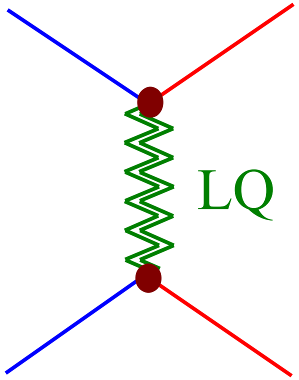




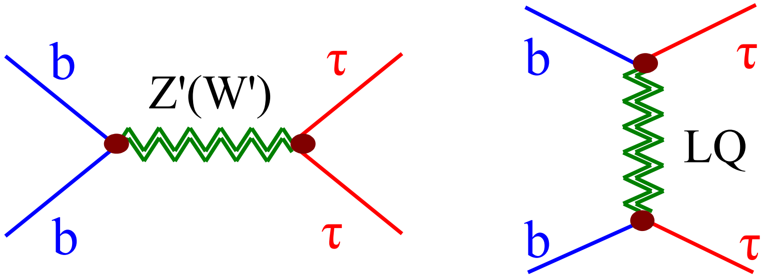


Two classes of (tree-level) mediators, giving rise to different correlations among the anomalies, other low-energy observables, and high-p_T physics

EFT-type considerations

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

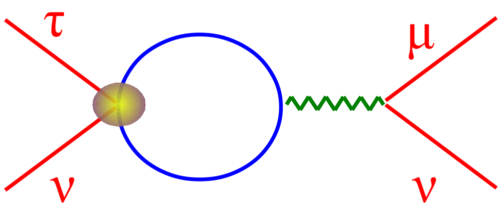
I. *high-p_T constraints*



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

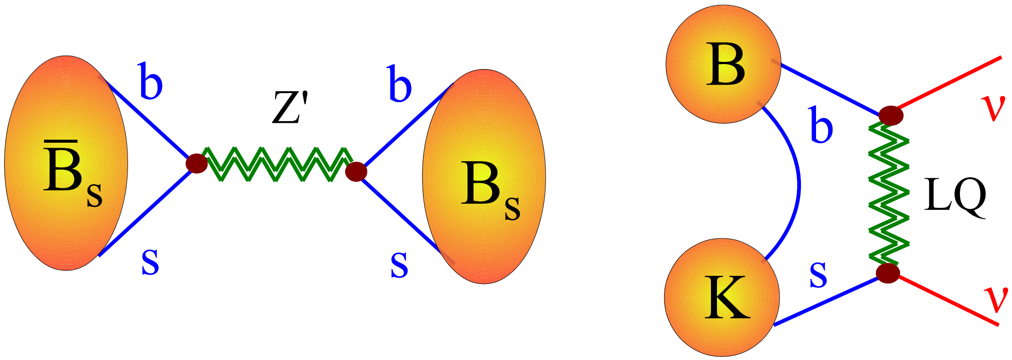
Faroughy, Greljo, Kamenik '16

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)

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

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

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

$\uparrow$

$U(2)_u$

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

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

- NP in left-handed operators only
- Leading NP effects in 3rd generation only
- Light generation couplings controlled by $U(2)_q \times U(2)_l$ flavor symmetry minimally broken (→ link to SM Yuk. coupl.)

Buttazzo, Greljo, GI, Marzocca, '17

“The Zürich's Guide”

⬇

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

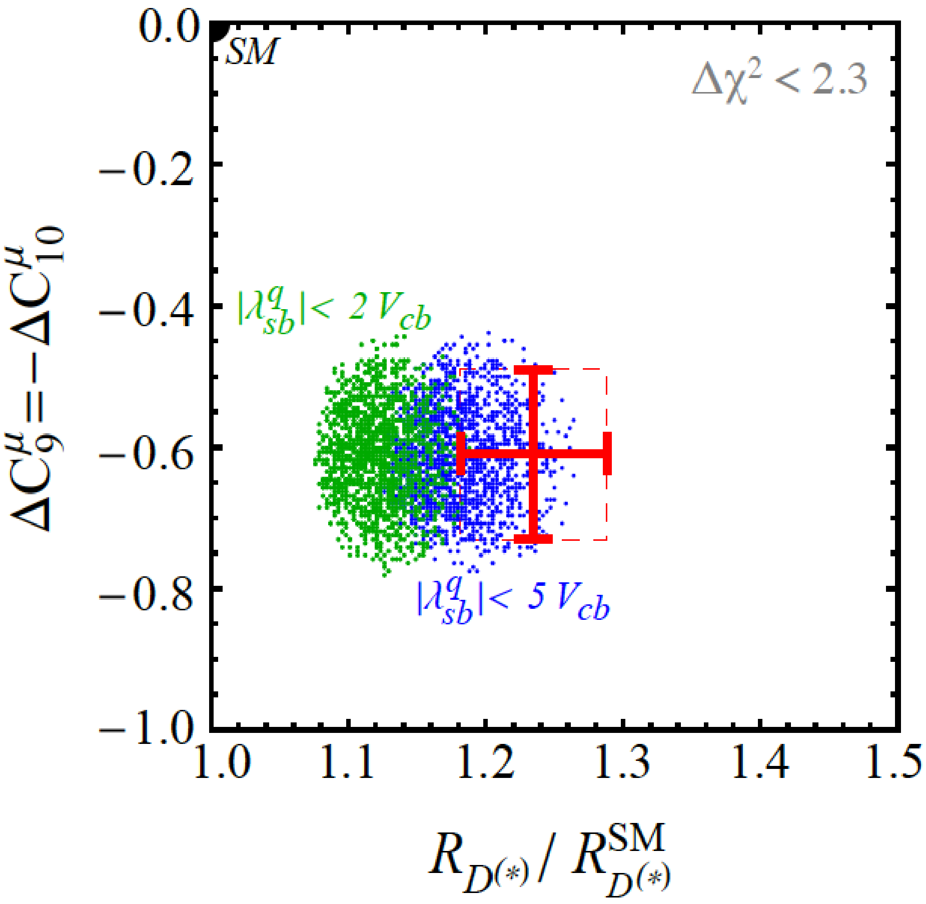
four free parameters...

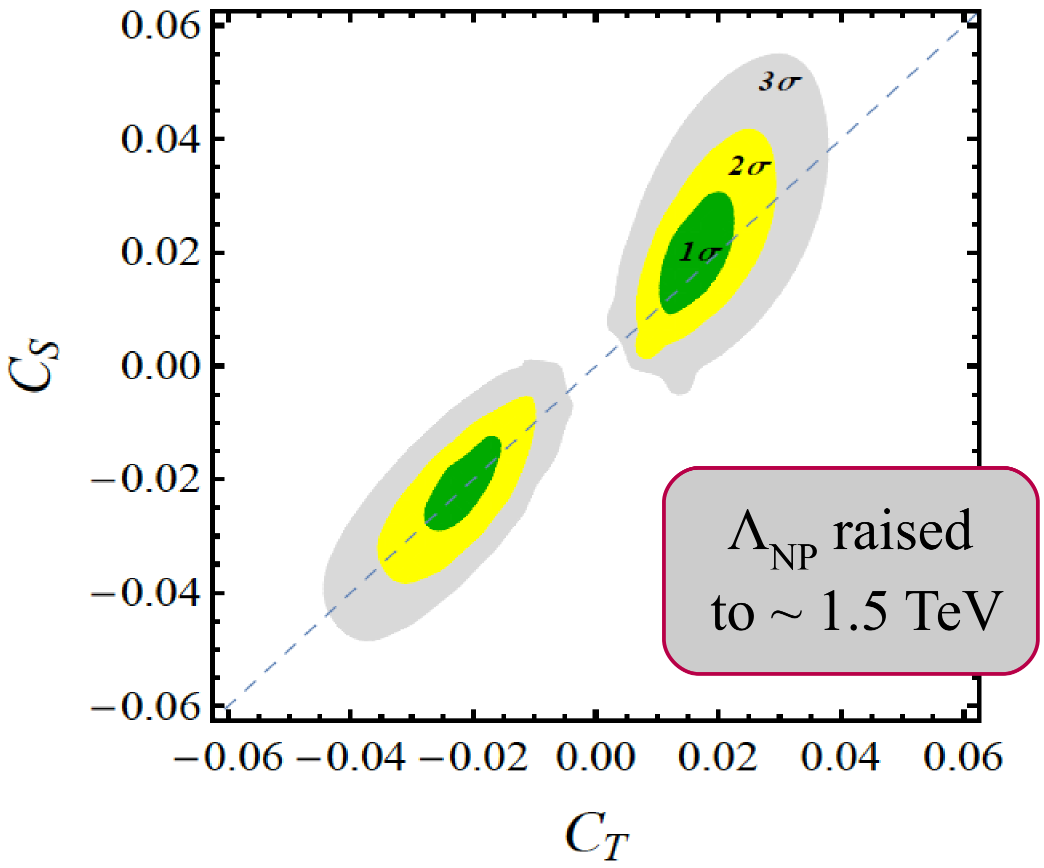
C_T, C_S
$\lambda_{bs} = O(V_{cb})$
$\lambda_{\mu\mu} = O(|V_{\tau\mu}|^2)$

...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





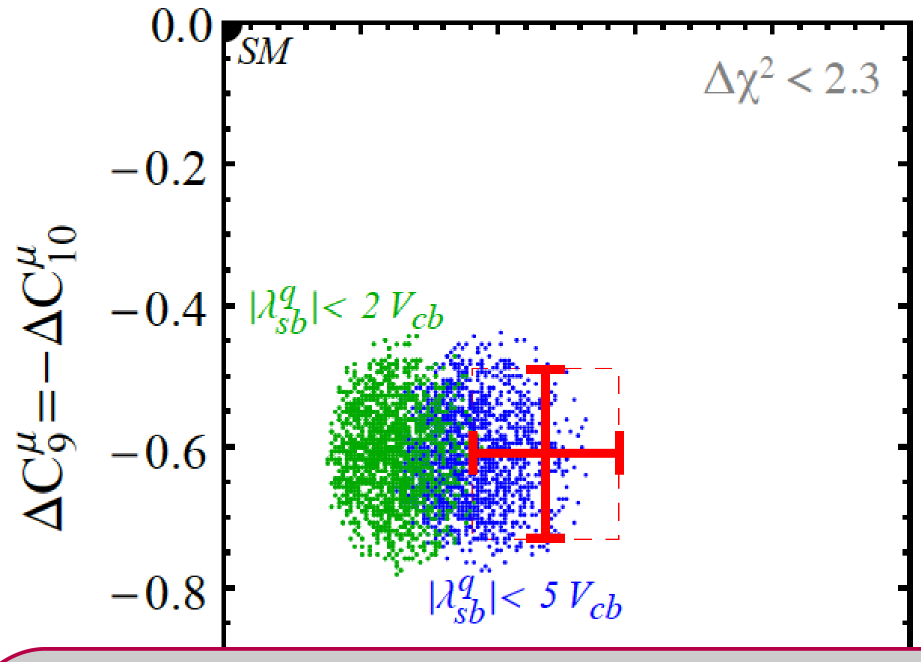
Λ_{NP} raised to ~ 1.5 TeV

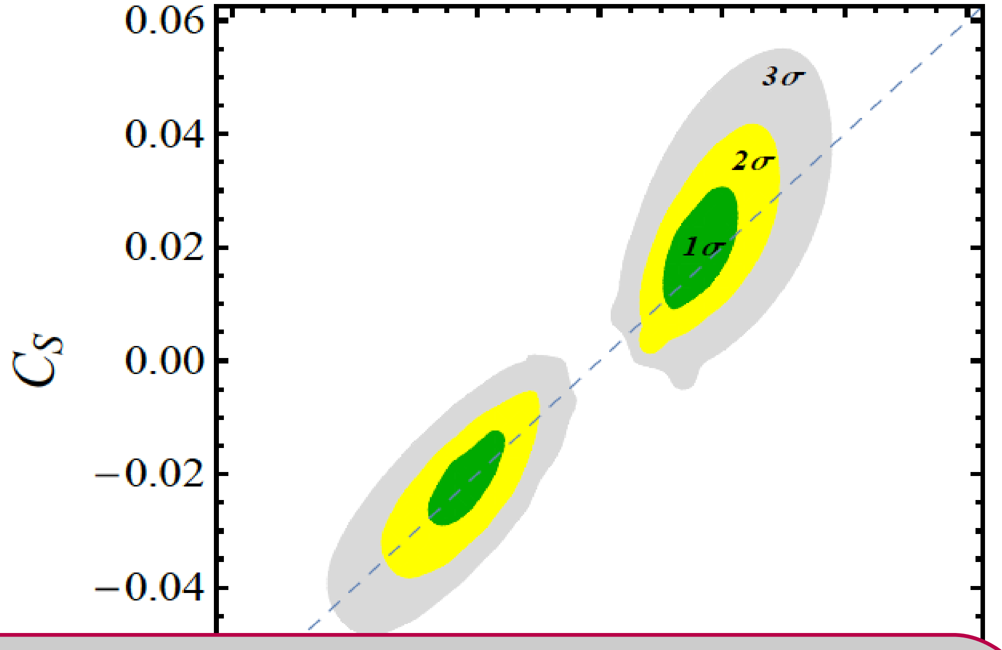
Key features compared to previous analyses:

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

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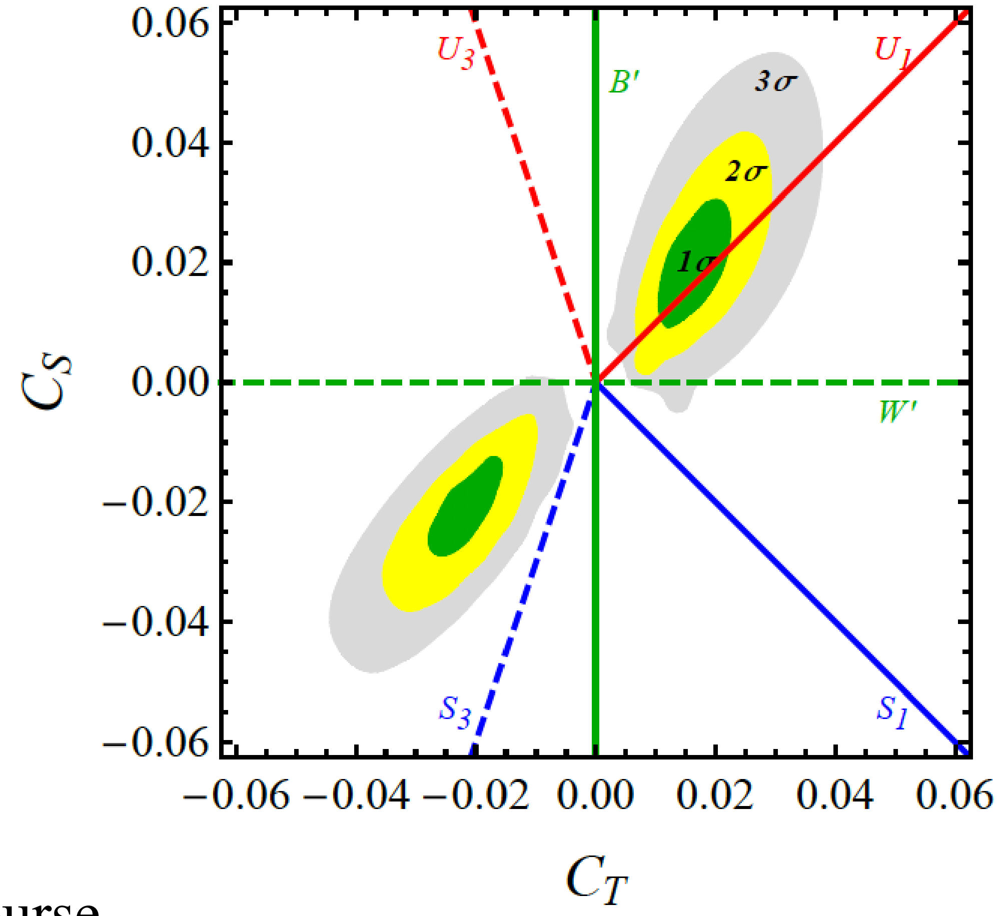

The U_1 option fits quite nicely... but of course models with more than one mediators are possible

Simplified dynamical models [*“The Return of the LeptoQuark”...*]

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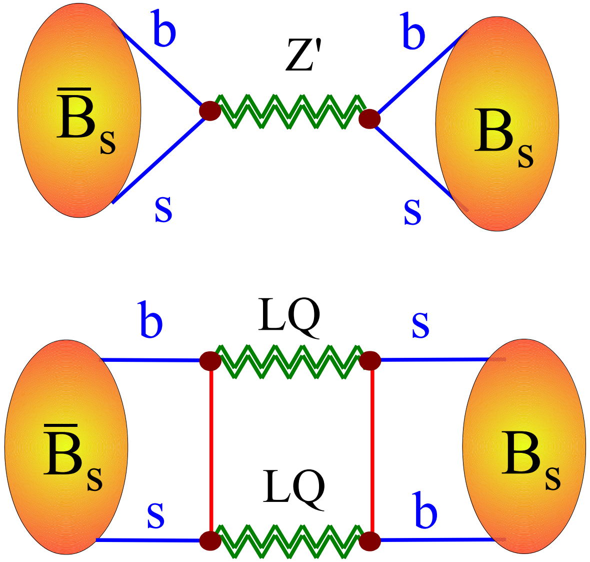
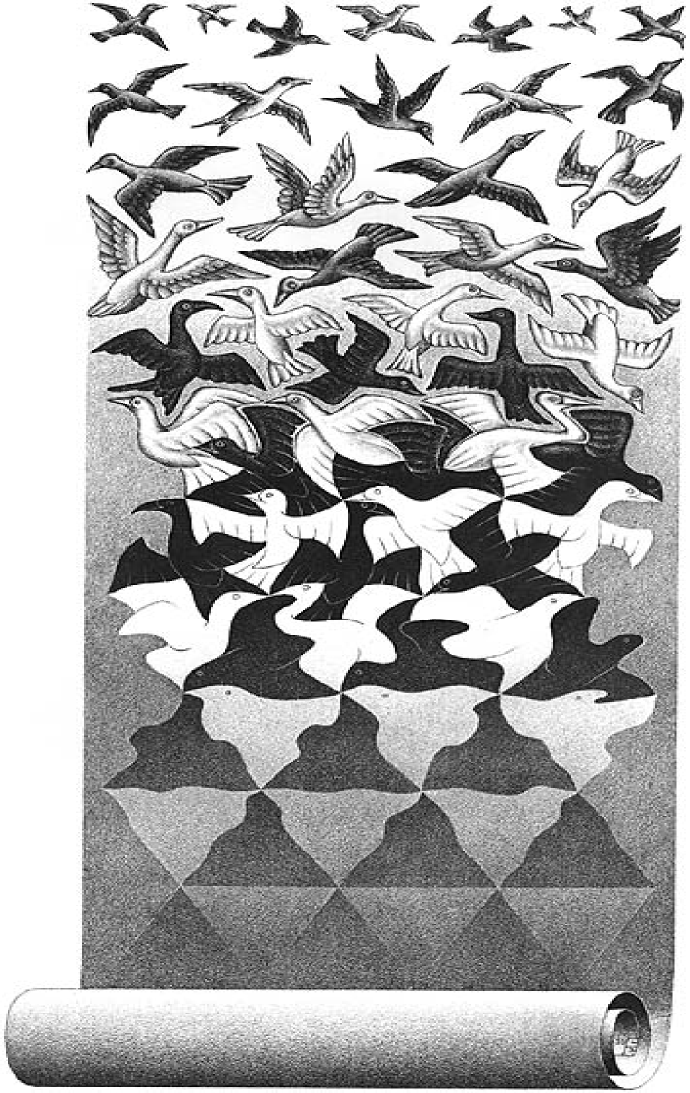
Colorless vector:	B'	W'

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 concentrate on one (class of) option(s), among the gauge models, that I find particularly interesting.

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

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  + ...

Speculations on UV completions

In the following I will concentrate on one (class of) option(s), among the gauge models, that I find particularly interesting.

The starting observation is that the Pati-Salam model [*proposed in 1974 to unify quark and lepton quantum numbers*], predicts a massive vector LQ with the correct quantum numbers

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

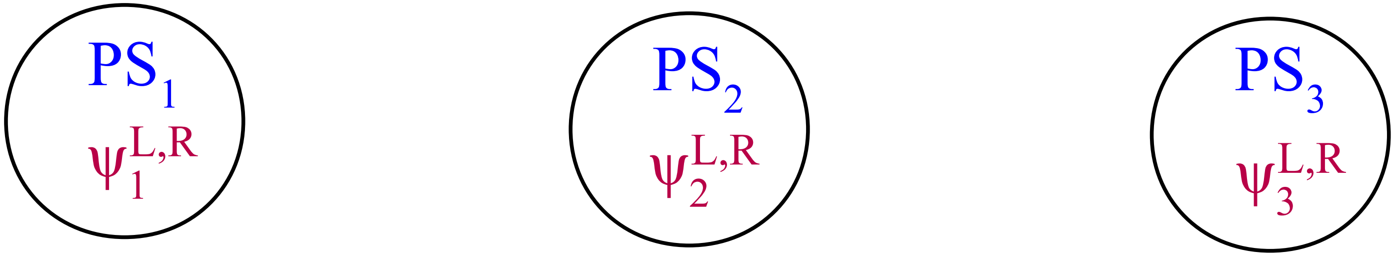
Fermions in SU(4): $\begin{bmatrix} Q_L^{\alpha} \\ Q_L^{\beta} \\ Q_L^{\gamma} \\ L_L \end{bmatrix} \quad \begin{bmatrix} Q_R^{\alpha} \\ Q_R^{\beta} \\ Q_R^{\gamma} \\ L_R \end{bmatrix}$

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]

A more ambitious attempt...



PS_1 $\psi_1^{L,R}$

PS_2 $\psi_2^{L,R}$

PS_3 $\psi_3^{L,R}$

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

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

A three site gauge model for
flavor hierarchies and flavor anomalies

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

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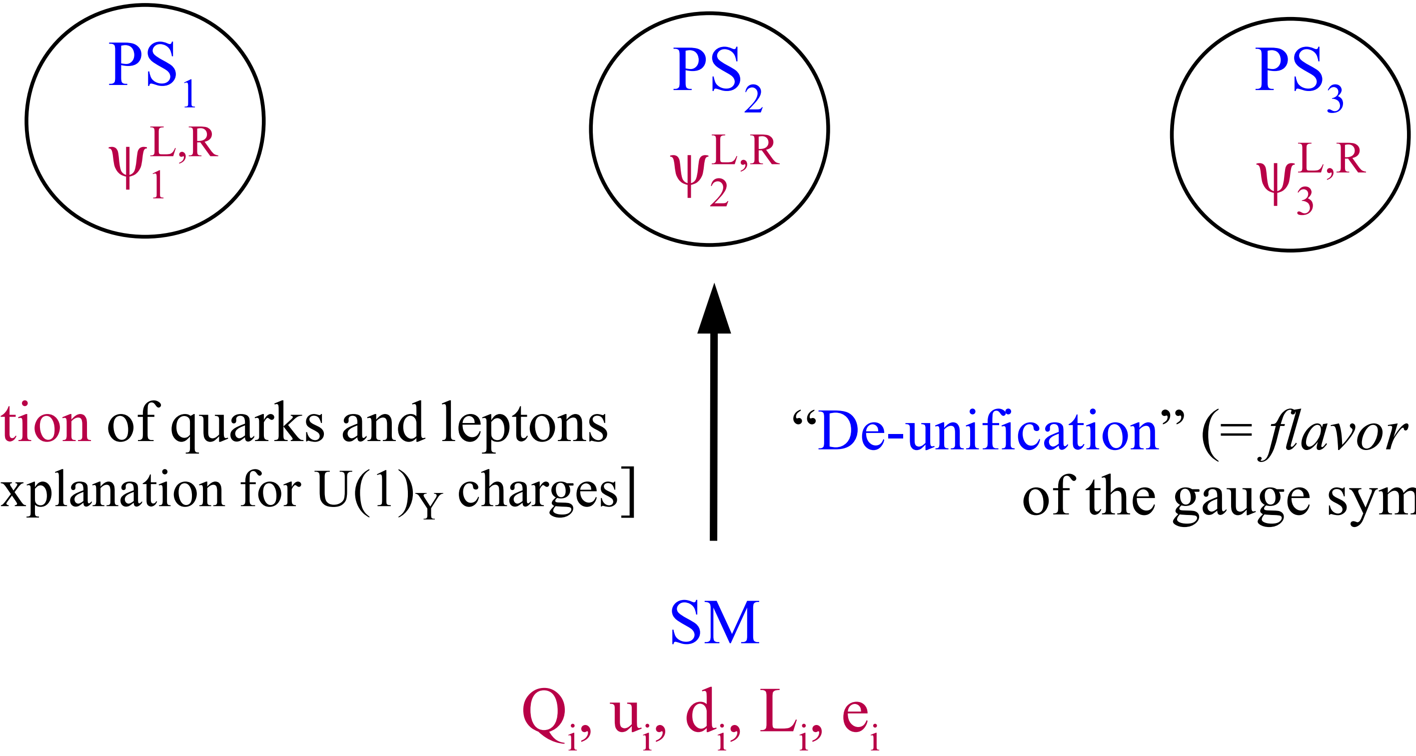

PS_1 $\psi_1^{L,R}$

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
Q_i, u_i, d_i, L_i, e_i

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

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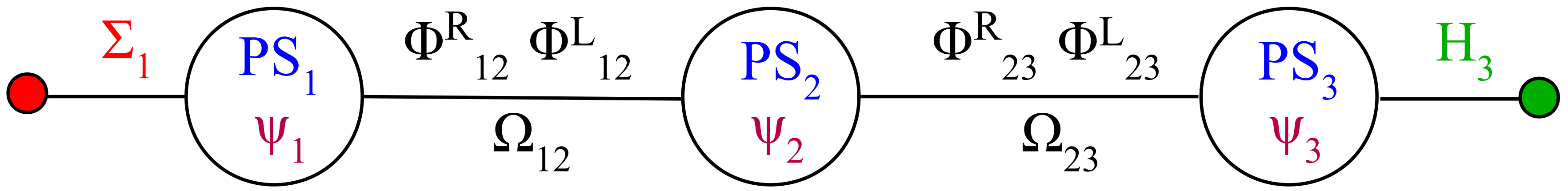
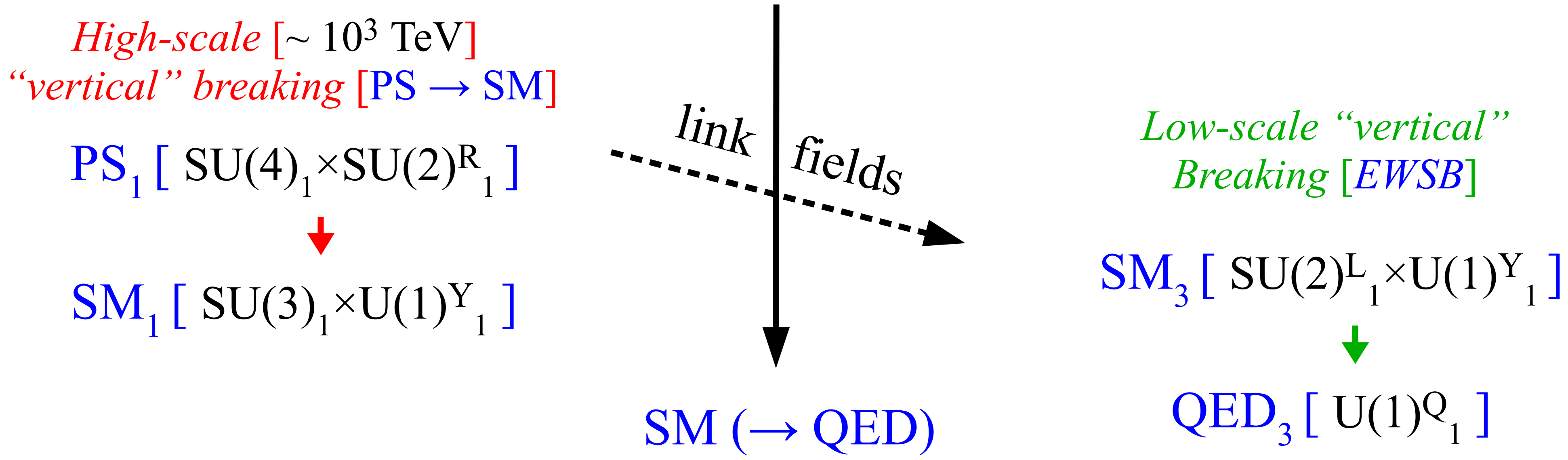



High-scale [~ 10^3 TeV]
"vertical" breaking [PS → SM]

PS_1 [$SU(4)_1 \times SU(2)^R{}_1$]

SM_1 [$SU(3)_1 \times U(1)^Y{}_1$]

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

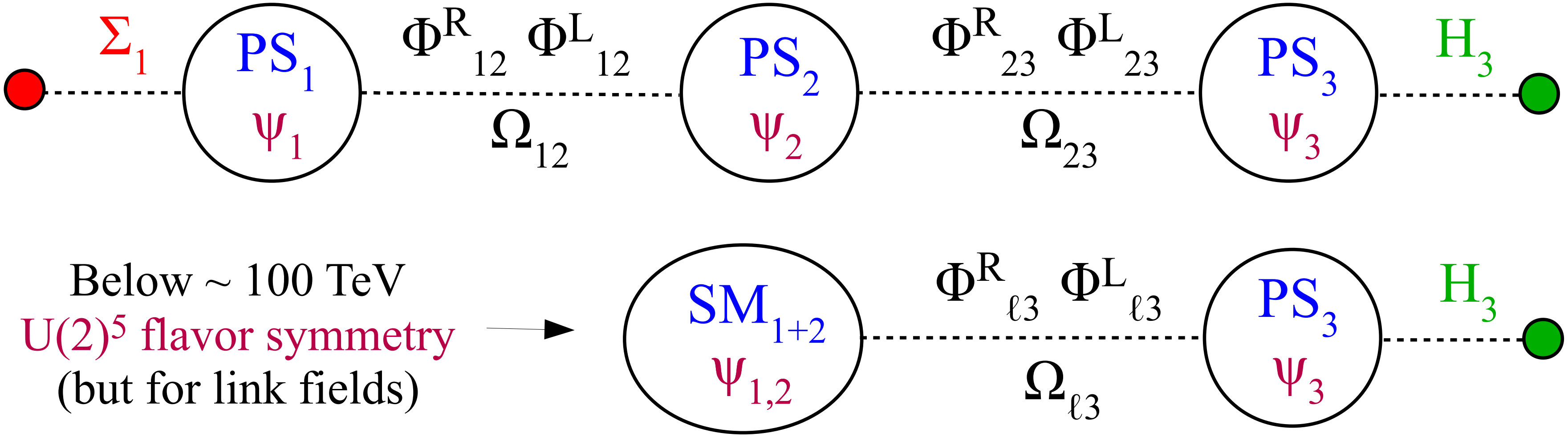
SM_3 [$SU(2)^L{}_1 \times U(1)^Y{}_1$]

QED_3 [$U(1)^Q{}_1$]

SM (→ 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.
[similar to "4321" but "natural" flavor structure: no ad-hoc mixing with vector-like quarks]

A more ambitious attempt...

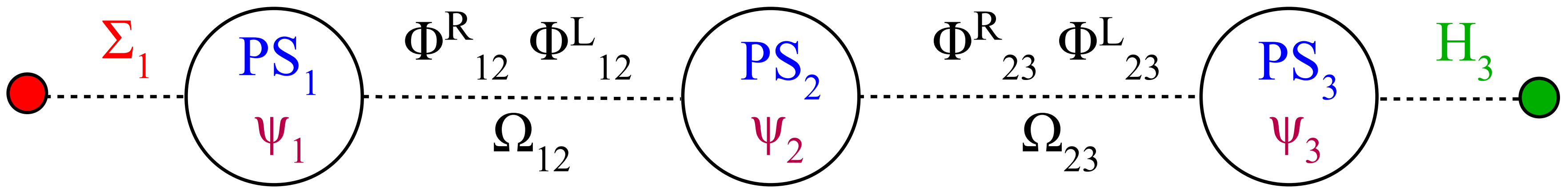


Below ~ 100 TeV
$U(2)^5$ flavor symmetry
(but for link fields)

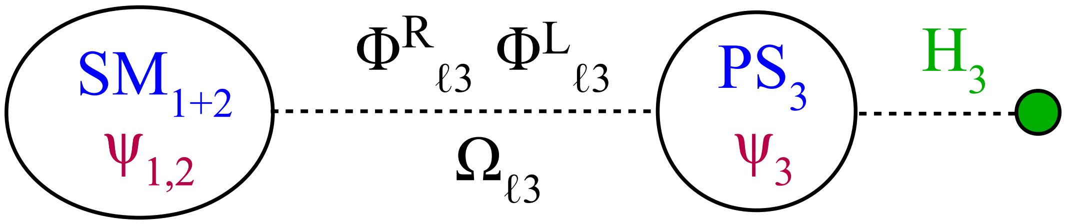
Leading flavor structure:

- 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.

A more ambitious attempt...



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

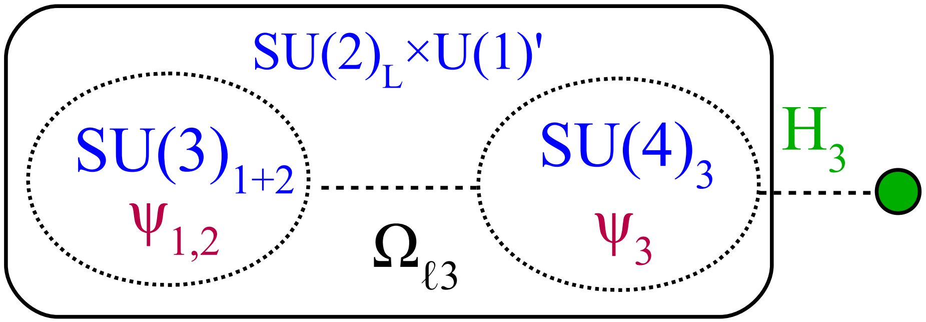


→ $W_L' + W_R'$ [~ 5-10 TeV]

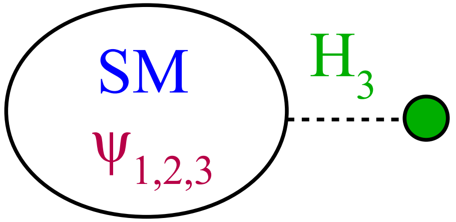
Sub-leading Yukawa terms from higher dim ops:

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

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



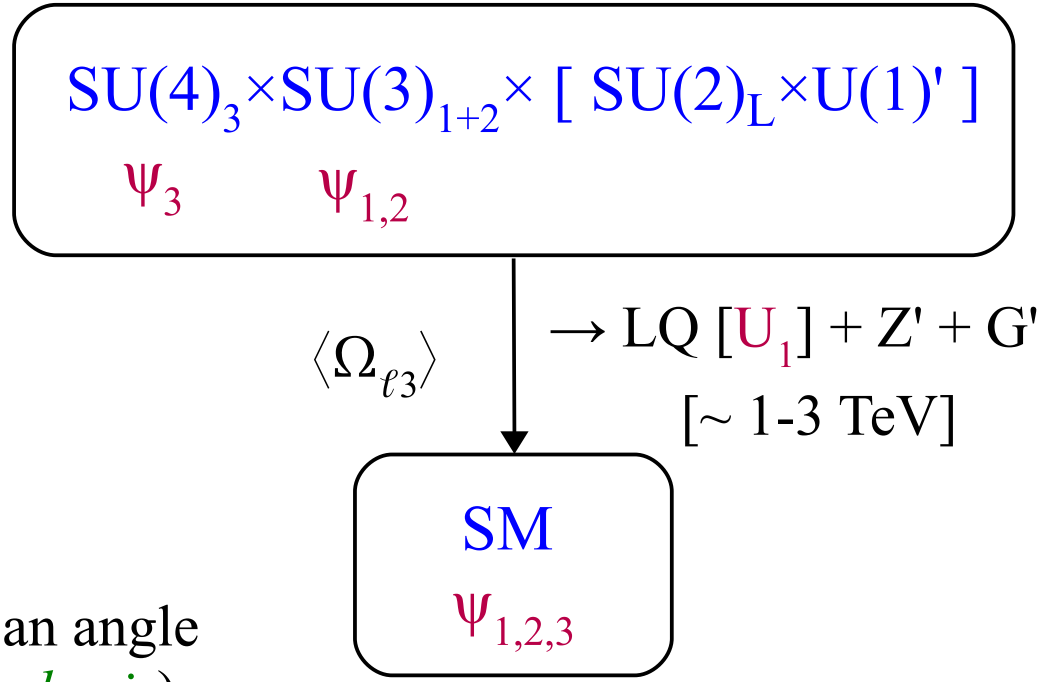
→ LQ [U_1] + Z' + G' [~ 1-2 TeV]



▶ *A more ambitious attempt…*

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 $\psi_{1,2}$

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

$\rightarrow$ 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

A more ambitious attempt...

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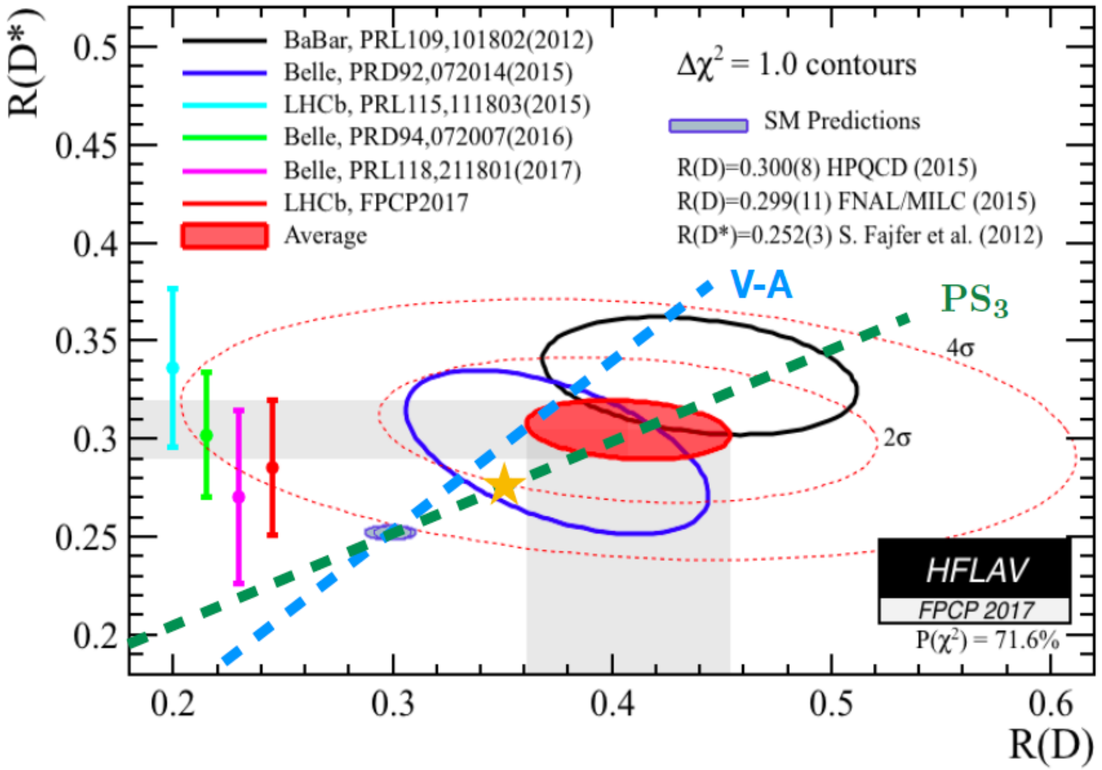
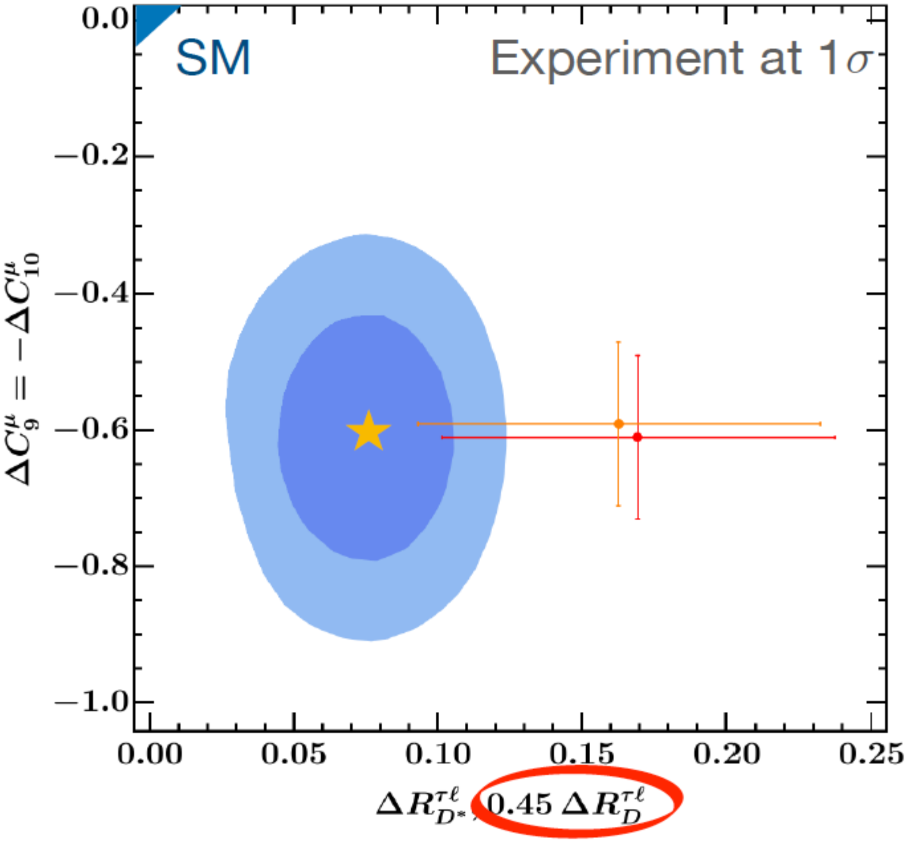
Despite the apparent complexity, the construction is highly constrained



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 measurements

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 measurements

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*]:

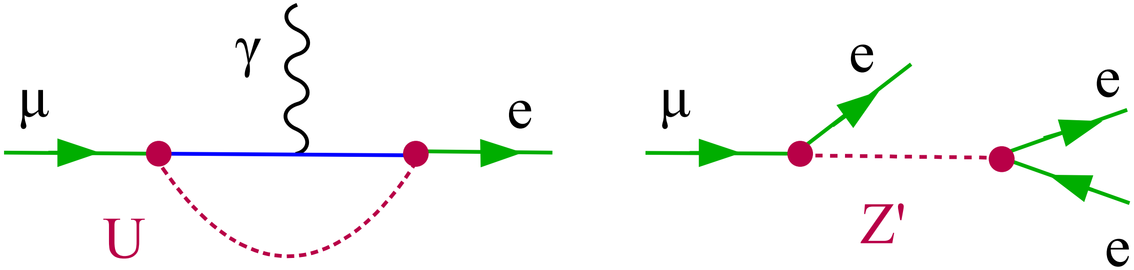
	$\mu\mu$ (ee)	$\tau\tau$	$\nu\nu$	$\tau\mu$	μe
$b \to s$	R_K, R_{K*} O(20%)	$B \to K^{(*)} \tau\tau$ → 100×SM	$B \to K^{(*)} \nu\nu$ O(1)	$B \to K \tau\mu$ $\to \sim 10^{-6}$	$B \to K \mu e$???
$b \to d$	$B_d \to \mu\mu$ $B \to \pi \mu\mu$ $B_s \to K^{(*)} \mu\mu$ O(20%) [R_K=R_π]	$B \to \pi \tau\tau$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

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
- τ decays
  - $\tau \to 3\mu$ can be close to exp. bound ($BR \sim 10^{-10}$)
- $\mu \to e$
  - No firm prediction (*1st family mixing → work in prog...*), but potentially very interesting, with non-trivial interplay between $\mu \to 3e$ [*tree-level Z'*] & $\mu \to e\gamma$ [LQ *loop*]



▶ *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*):

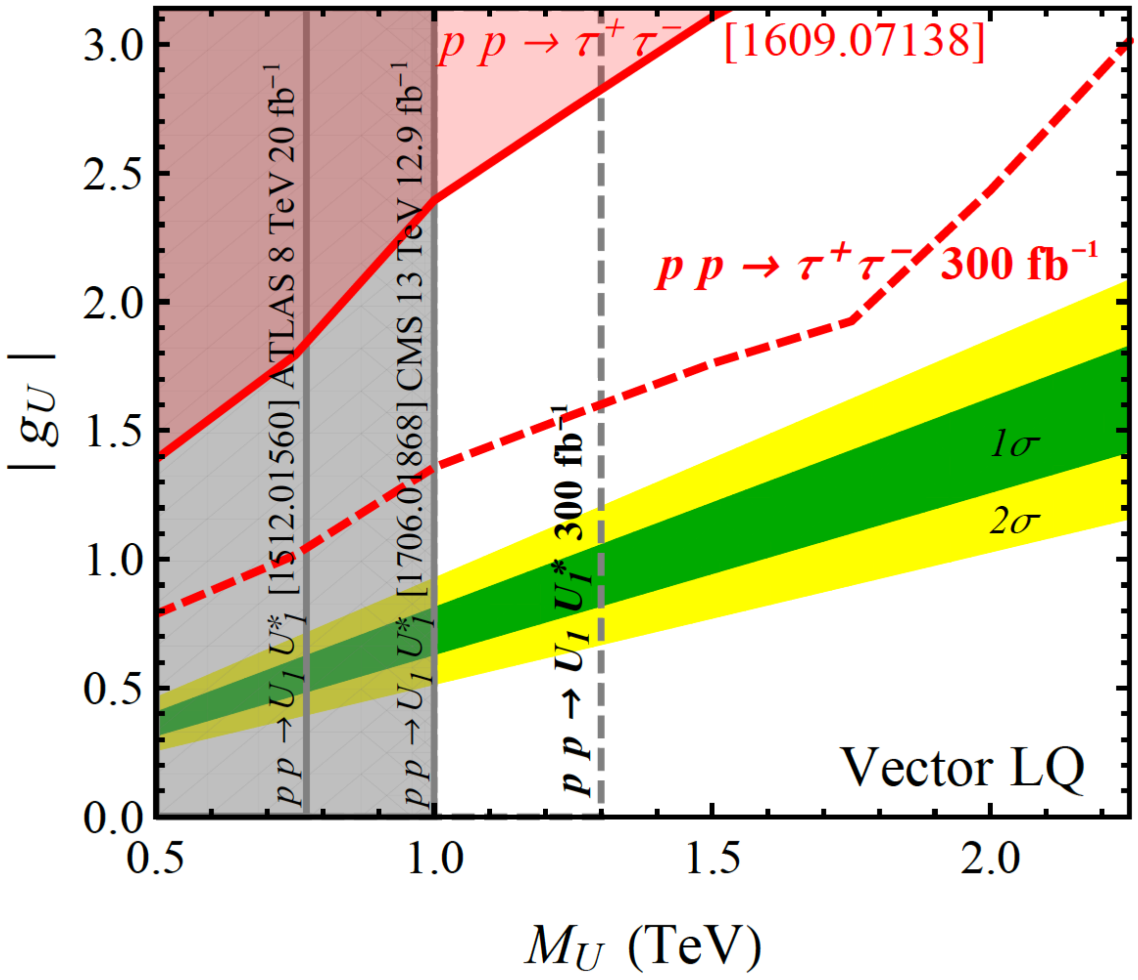
- Coupled mainly to 3rd generation (→ *no large coupl. to proton valence quarks*)
- No narrow peaks in dilepton pairs (*including tau pairs*)

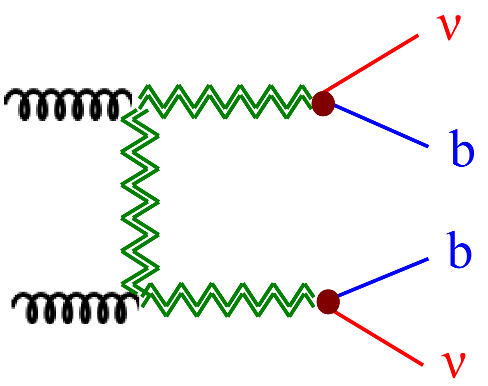
⬇

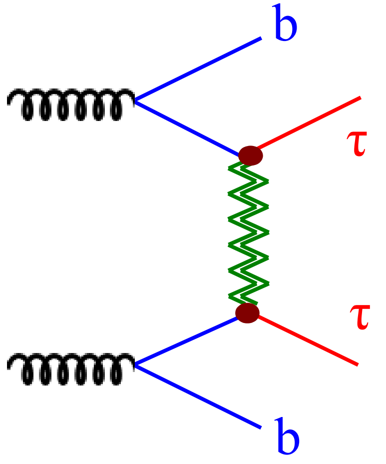
Significant room for improvement for the corresponding searches @ HL-LHC
But only HE-LHC would be able to rule out all reasonable models

Implications for high-p_T physics

In particular, 3rd gen. LQ are (*still*...) in rather good shape also as far as direct searches are concerned:

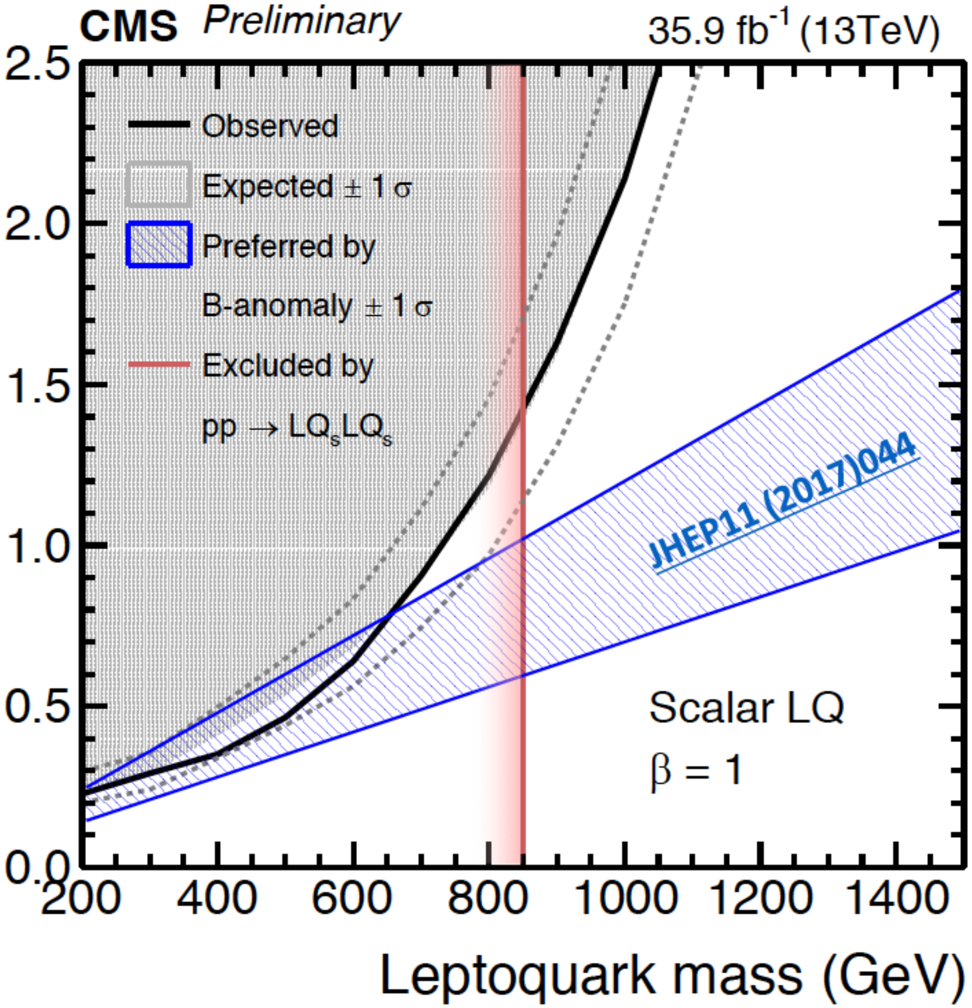

Buttazzo, Greljo, GI, Marzocca, '17



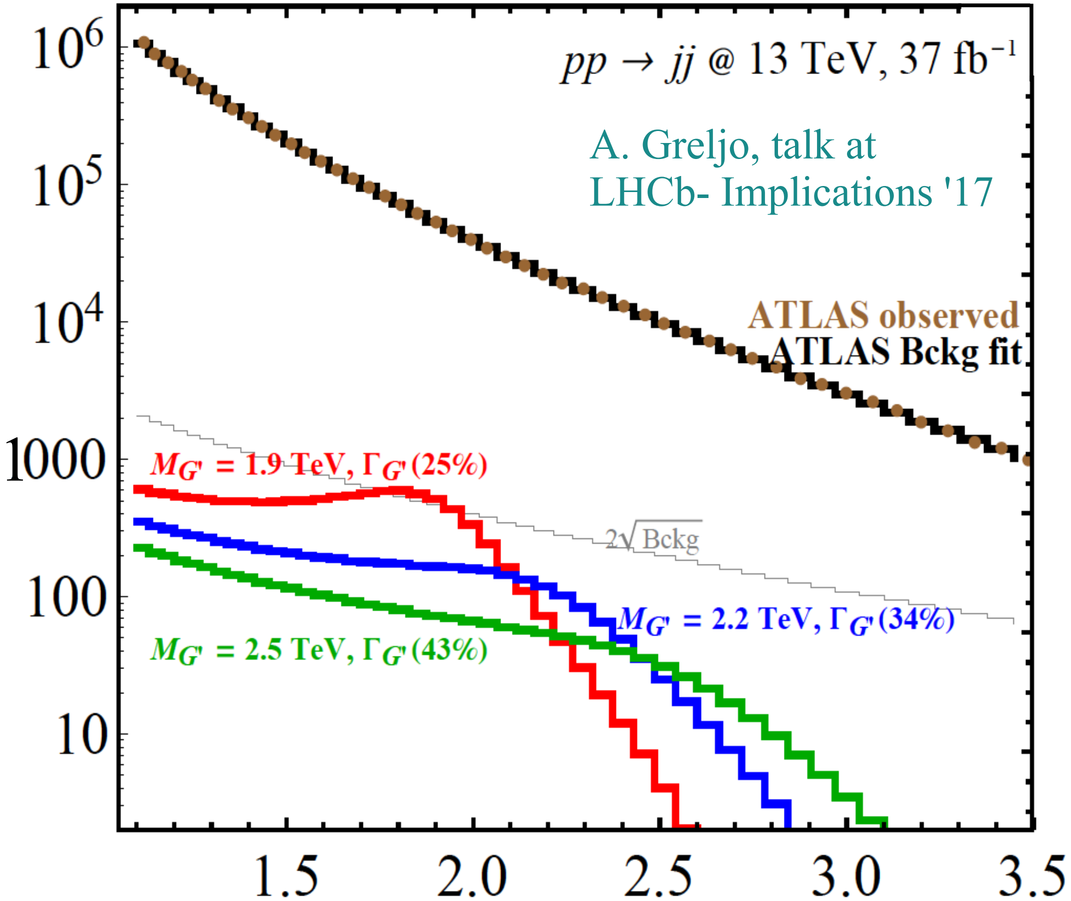


▸ *Implications for high-p_T physics*

Pair vs. Single scalar LQ production @CMS:



The difficult “Coloron” signal:



A. Greljo, talk at
LHCb- Implications '17

Conclusions

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

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- 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 shift of paradigm that these anomalies could imply. But of many points (and possible variations) remains to be clarified/explored...

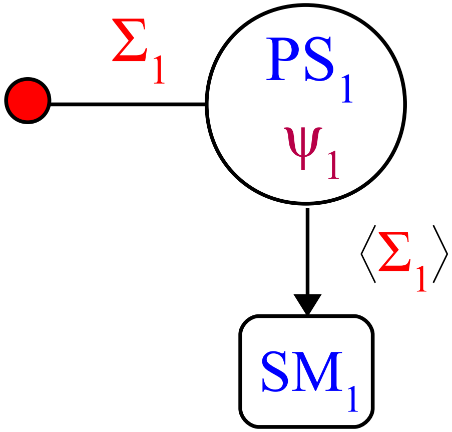
↓

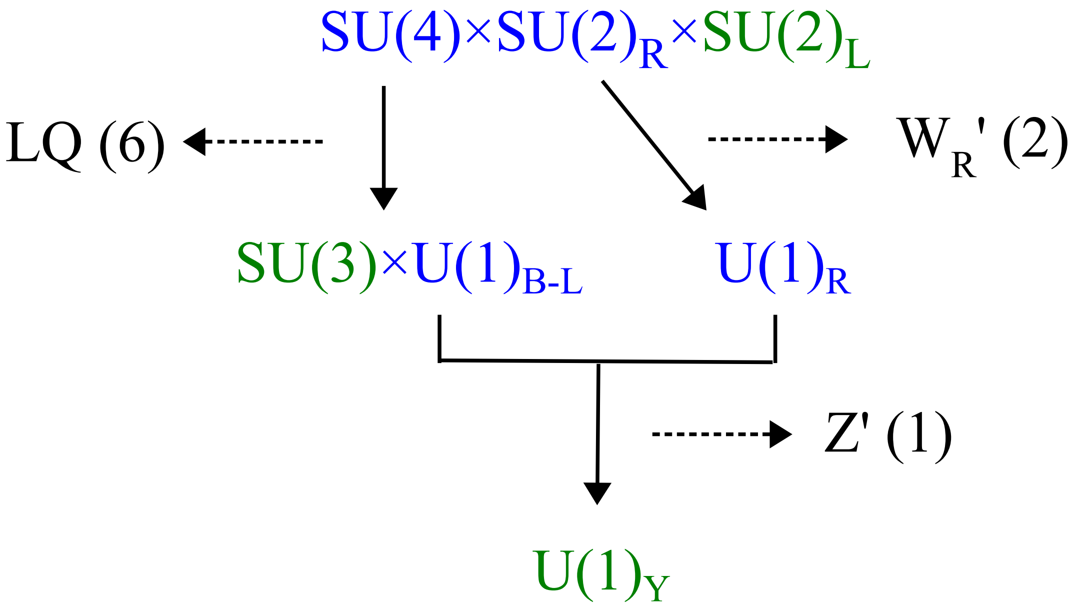
A lot of fun ahead of us...

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


Backup

Symmetry breaking pattern in PS^3





$SU(4)\times SU(2)_R\times SU(2)_L$

LQ (6)

W_R' (2)

$SU(3)\times U(1)_{B-L}$

$U(1)_R$

Z' (1)

$U(1)_Y$

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

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↓

SM_1 [$SU(3)_1\times U(1)^Y{}_1$]

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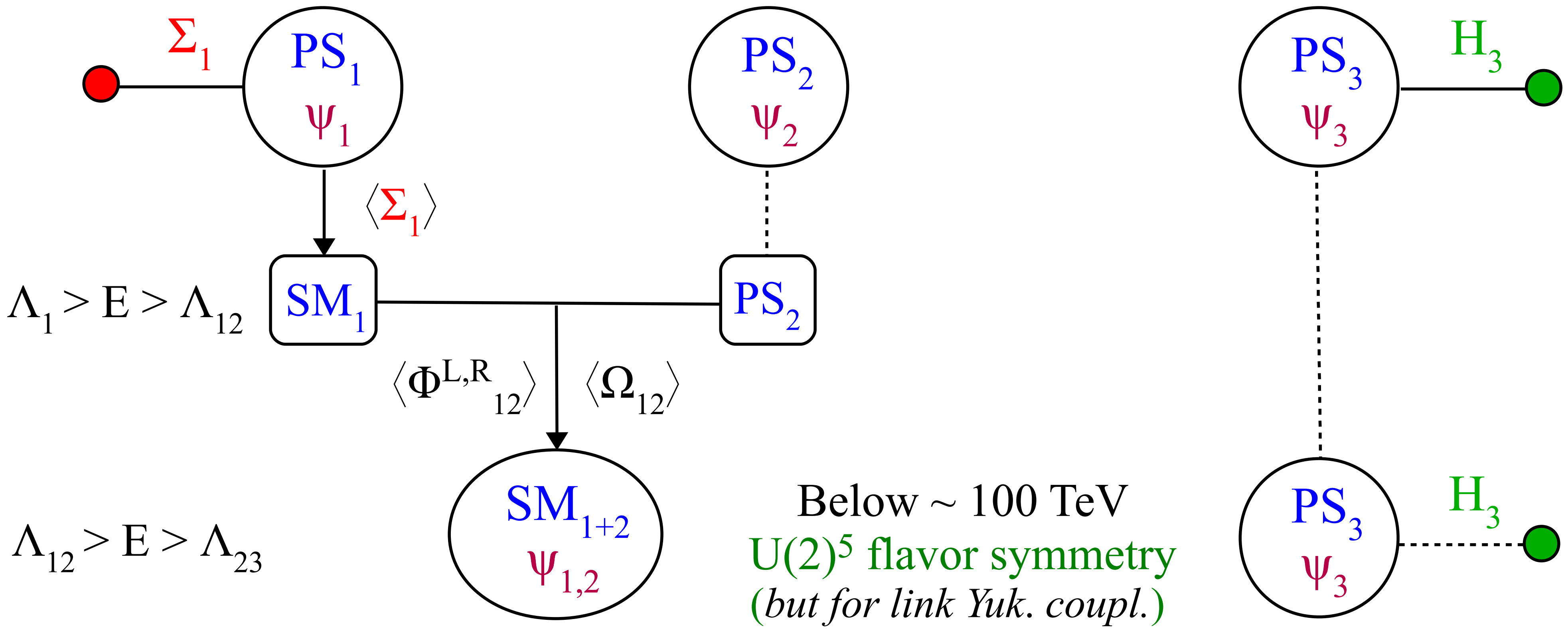


Below ~ 100 TeV
U(2)^5 flavor symmetry
(*but for link Yuk. coupl.*)

$\Phi^L{}_{12} \sim (1,2,1)_1 \times (1,2,1)_2$ 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 $B \to K^{(*)} \mu\mu$ / ee [LHCb]

- The largest anomaly is the one [*obs. in 2013 and confirmed with higher stat. in 2015*] in the P_5' [$B \to K^* \mu\mu$] angular distribution.
- Less significant correlated anomalies present also in other $B \to K^* \mu\mu$ observables and also in other $b \to s\mu\mu$ channels [overall smallness of all BR($B \to$ Hadron + $\mu\mu$)]

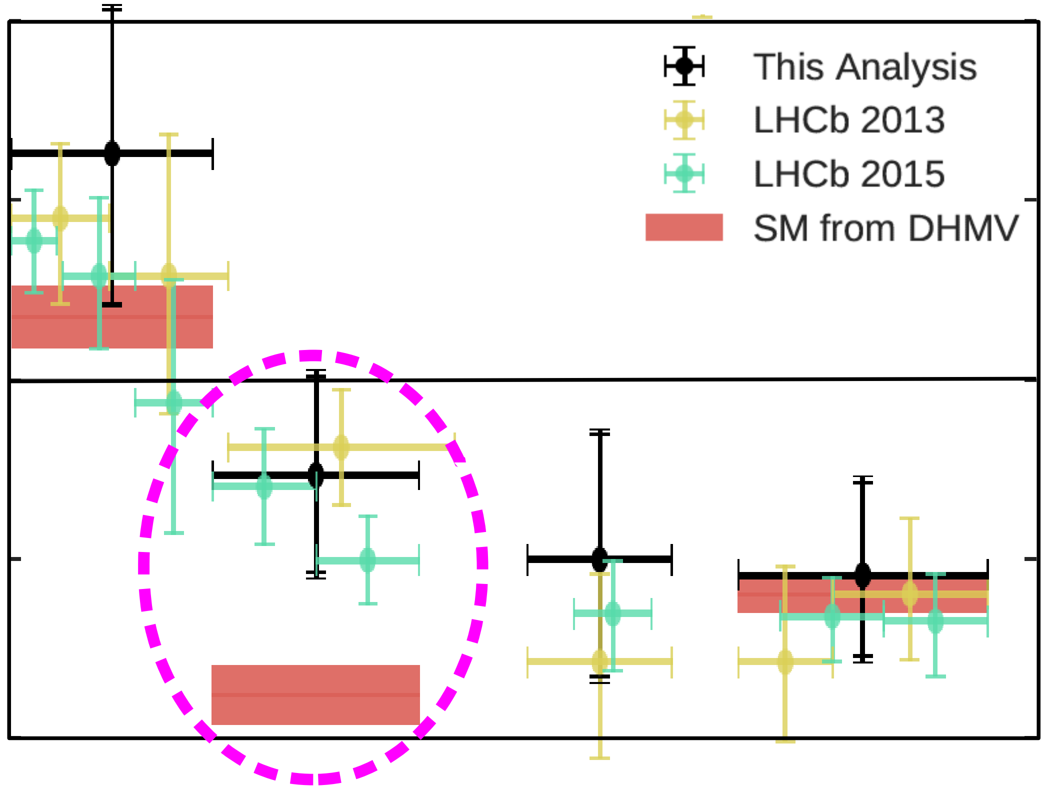
Pro NP:

- Reduced tension in <u>all the observables</u> with a unique fit of non-standard $C_i(M_W)$

Against NP:

- ~~Main effect in P_5' not far from cc threshold~~
- "NP" mainly in C_9 (↔ *charm*)
- Significance reduced with conservative estimates of non-factorizable corrections

Belle '16



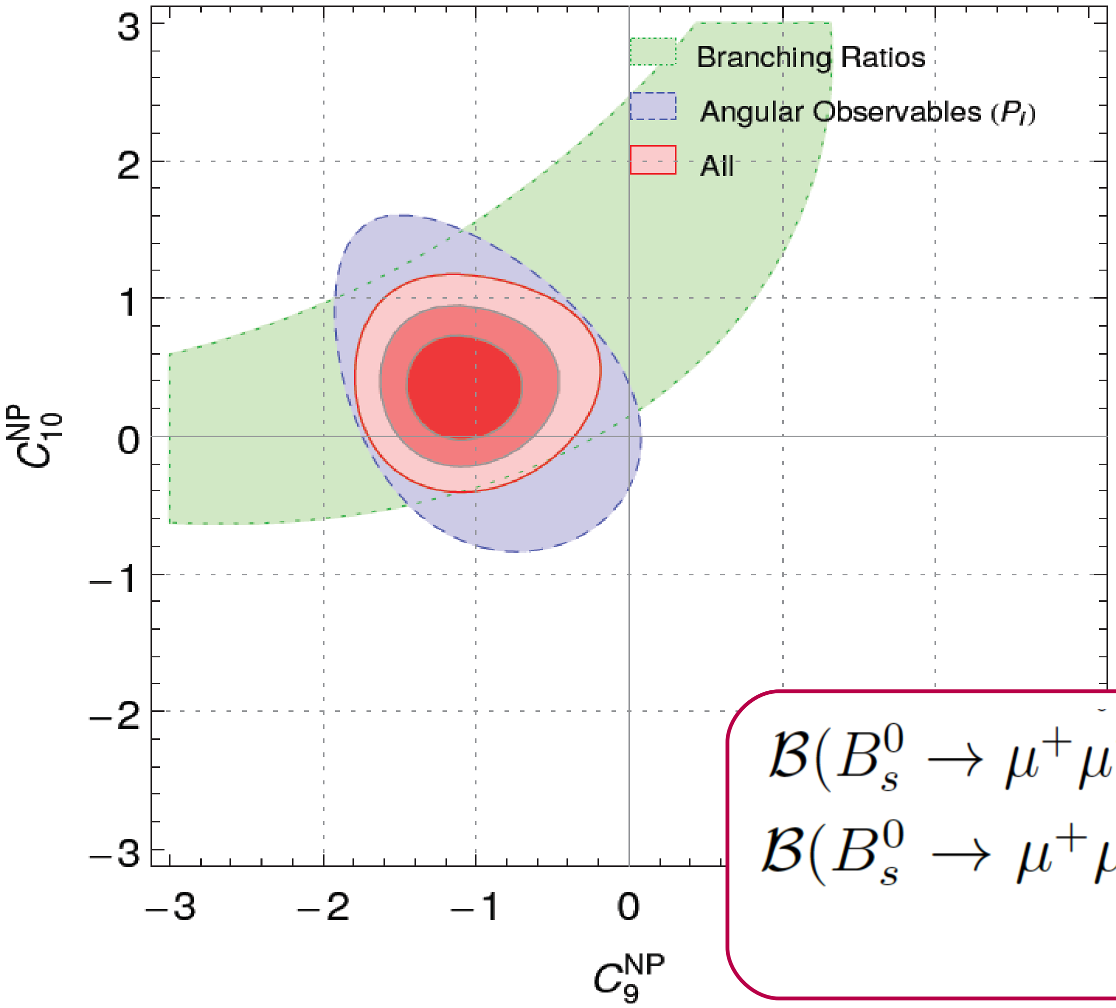
Jaeger *et al.* '12, Hambrock *et al.* '13, Hiller & Zwicky '13, Ciuchini *at al.* '15, ...

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}

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

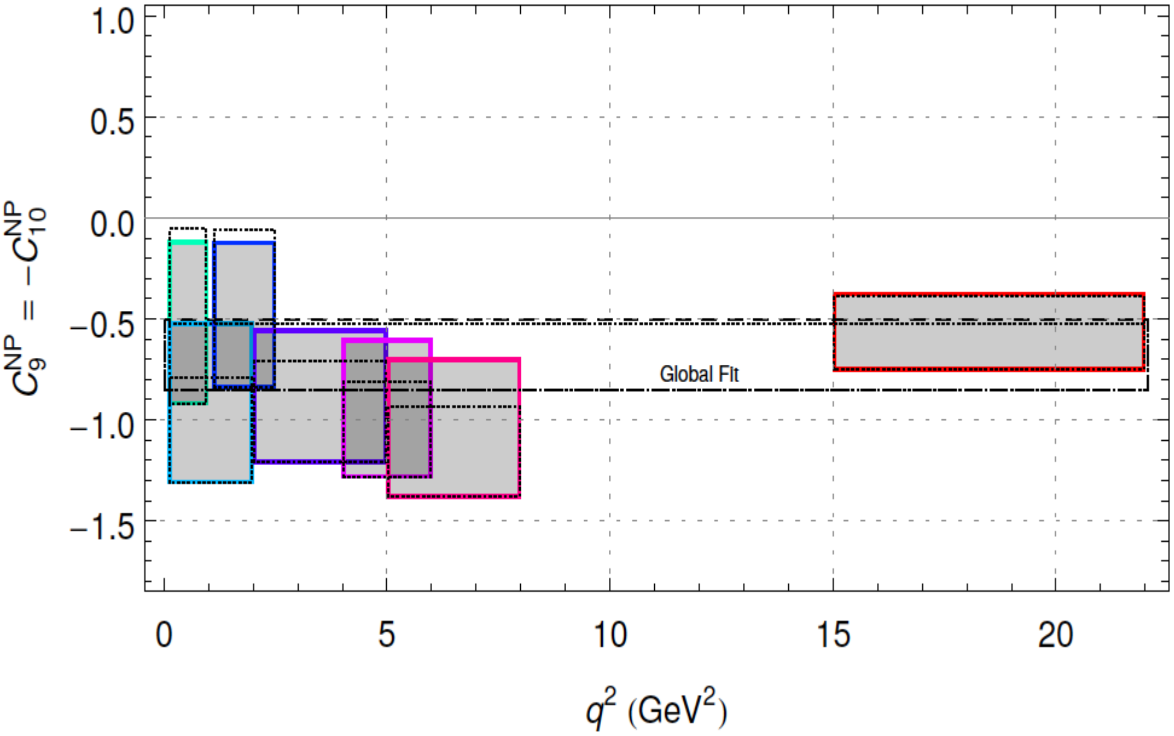
$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) = (2.8\,^{+0.7}_{-0.6}) \times 10^{-9}$$

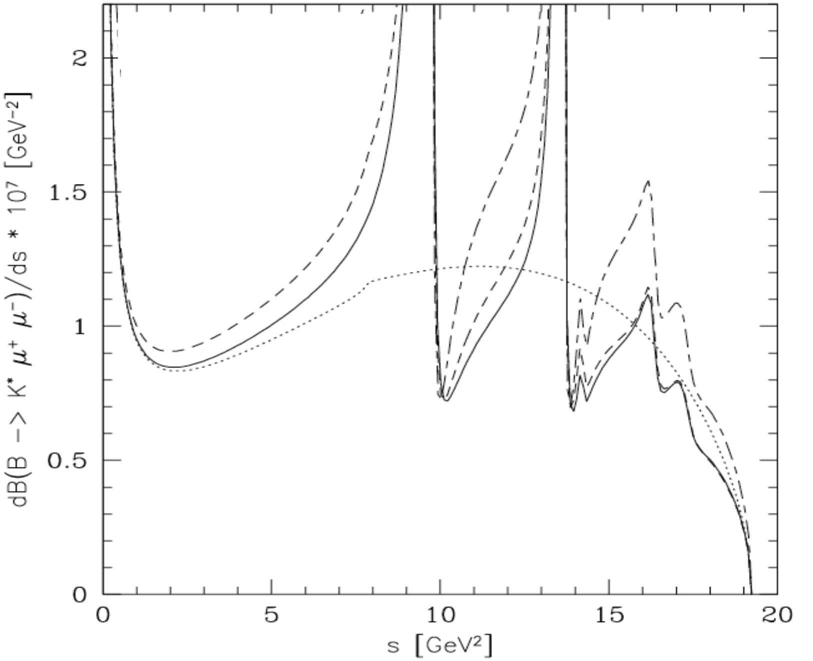
LHCb + CMS

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





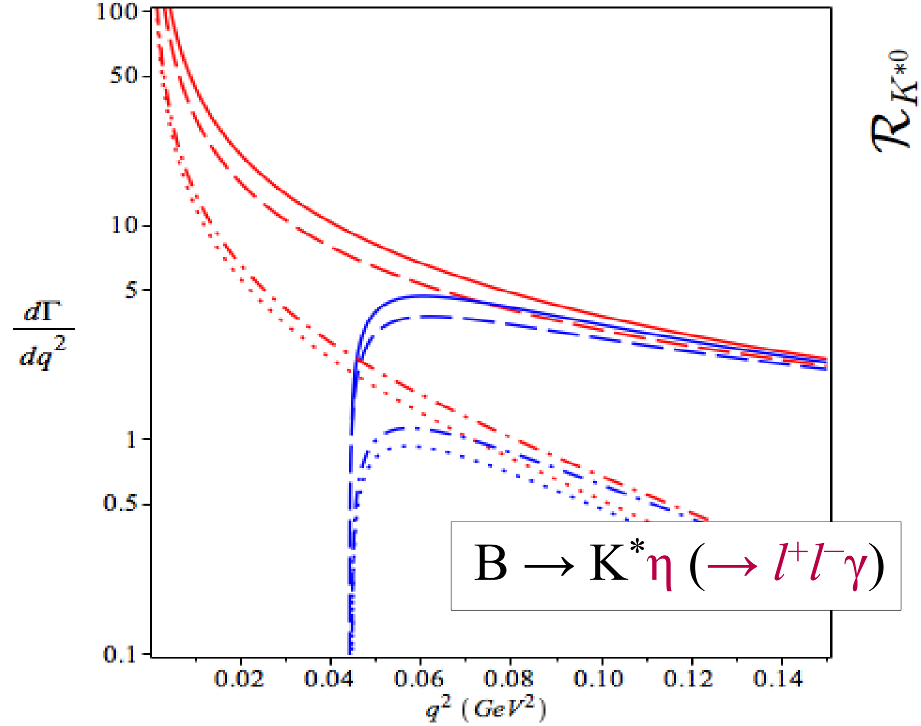
More precise data on the q^2=$m_{\mu\mu}$ distribution can help to distinguish NP vs. SM

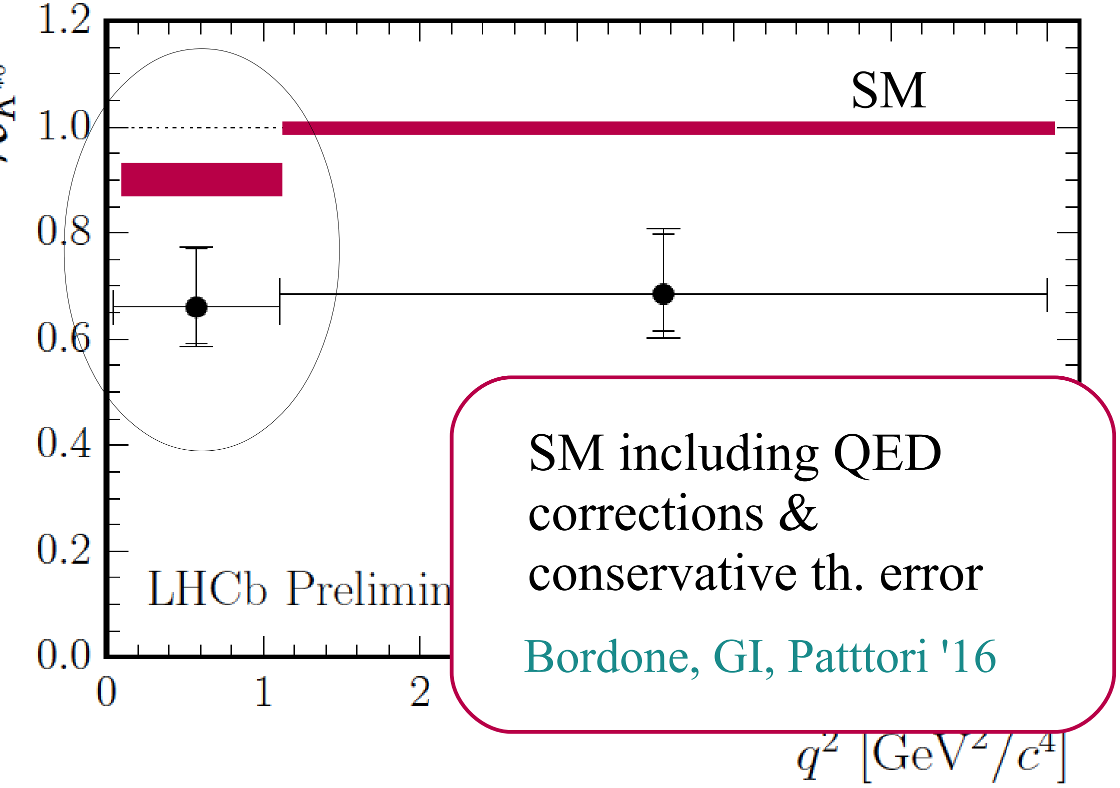
Descotes-Genon, Matias, Virto '15

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

- But also in this case the most interesting effects are the deviations from the SM in appropriate μ/e “clean” LFU ratios:

$$R_{K^*} = \frac{\int d\Gamma(B^0 \to K^*\mu\mu)}{\int d\Gamma(B^0 \to K^*ee)}$$





SM including QED corrections & conservative th. error

Bordone, GI, Pattori '16