University of Zurich^{UZH}

Old and recent puzzles in Flavor Physics

Gino Isidori
[*University of Zürich*]

- Introduction [*Old & recent problems, common lore, recent hopes*]
- On the recent B-physics anomalies
- 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:

EW hierarchy problem

Flavor puzzle
Neutrino masses
U(1) charges
Strong CP problem

Dark-matter
Dark-energy
Inflation
Matter-antim. Asym.

Quantum gravity

→ The Standard Model (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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	problem due to...	*...indicating*
EW hierarchy problem	→ *Instability of the Higgs mass term*	→ *New dynamics close to the Fermi scale* (~ 1 TeV)
Flavor puzzle Neutrino masses U(1) charges Strong CP problem	→ *Ad hoc tuning in the model parameters*	*No well-defined energy scale*
Dark-matter Dark-energy Inflation Matter-antim. Asym.	→ *Cosmological implementation of the SM*	
Quantum gravity	→ *General problem of any QFTs*	

Introduction

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"Common lore" (I) :

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Quantum gravity

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

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

Introduction

This "main avenue" has led to very appealing BMS constructions...

...however, so far these do not find experimental confirmation (*making these theories less and less appealing...*) → worth to explore new directions.

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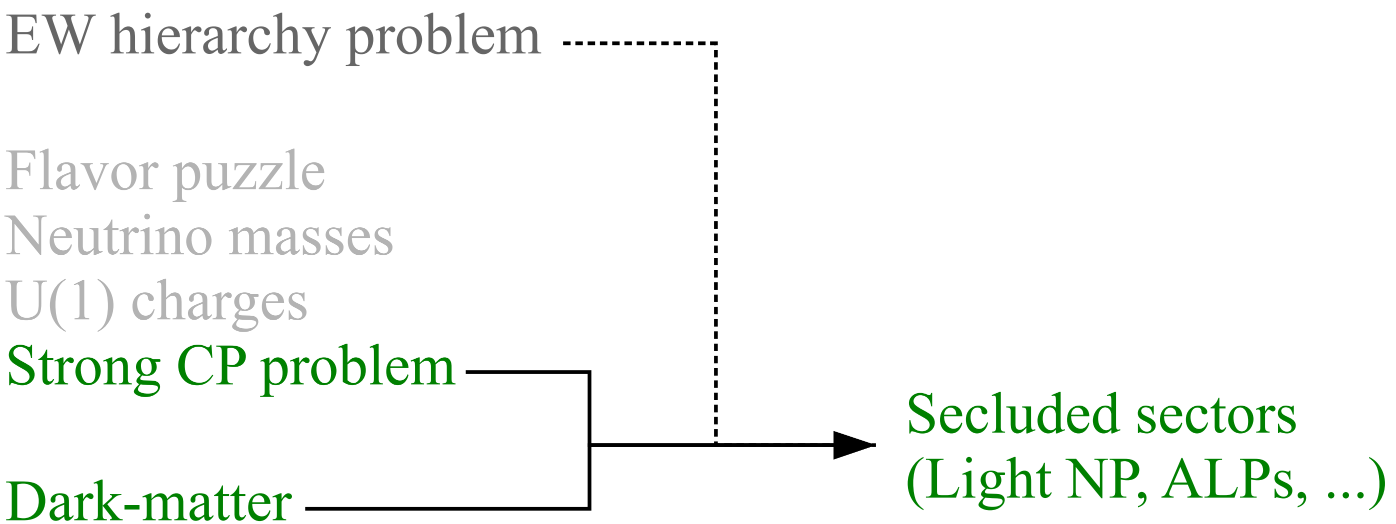

EW hierarchy problem

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Secluded sectors
(Light NP, ALPs, ...)

A direction that is definitely worth to explore, keeping in mind that the possible interesting parameter range is huge (*a large fraction os beyond the reach of particle-physics exp.*)

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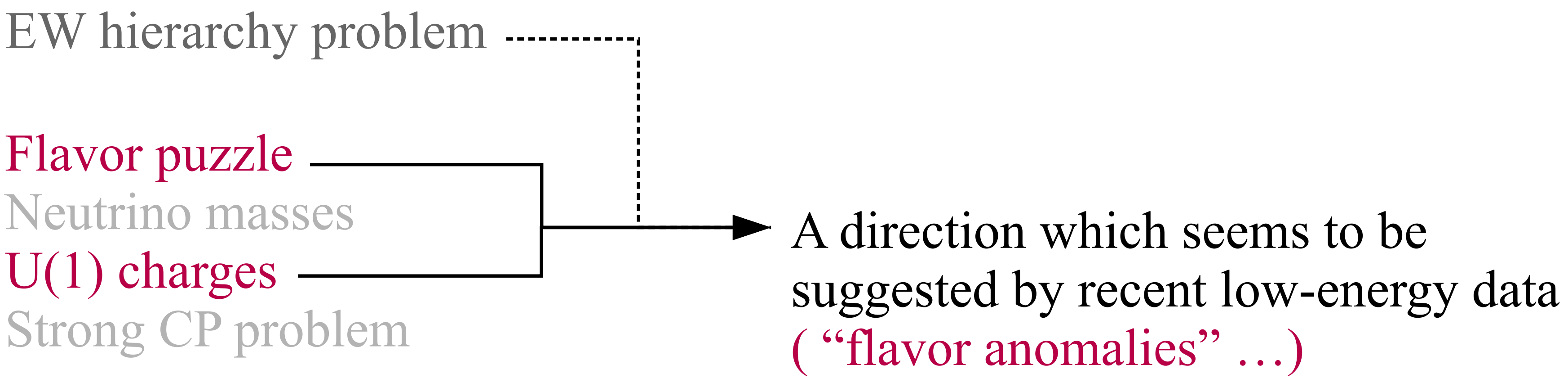

EW hierarchy problem

Flavor puzzle

Neutrino masses

U(1) charges

Strong CP problem

A direction which seems to be suggested by recent low-energy data ("flavor anomalies" …)

Dark-matter

Dark-energy

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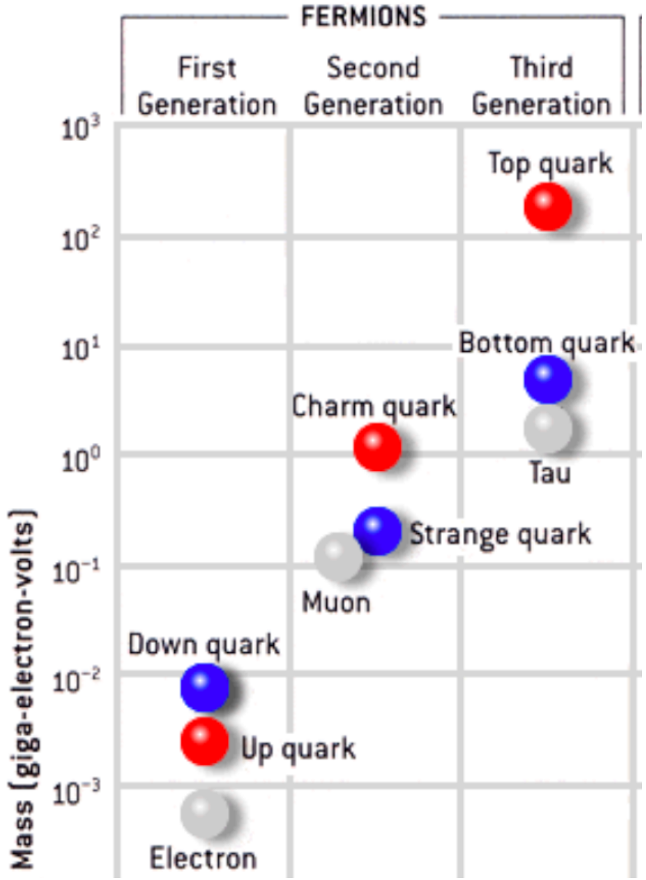
If correct... → very important implications for addressing also the other problems

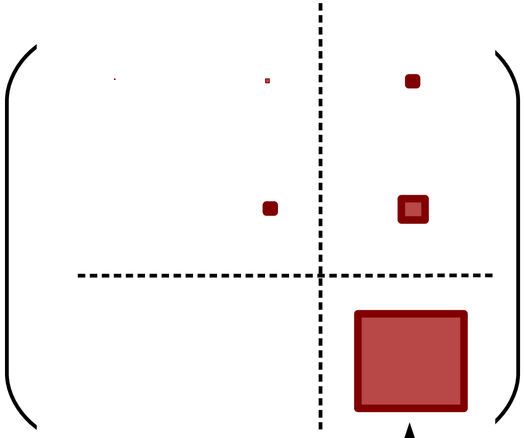
▶ Introduction [*the flavor structure of the SM*]

The SM flavor sector (= *the Yukawa sector*) contains a large number of free parameters (fermion masses & mixing angles), which *do not look at all accidental...*

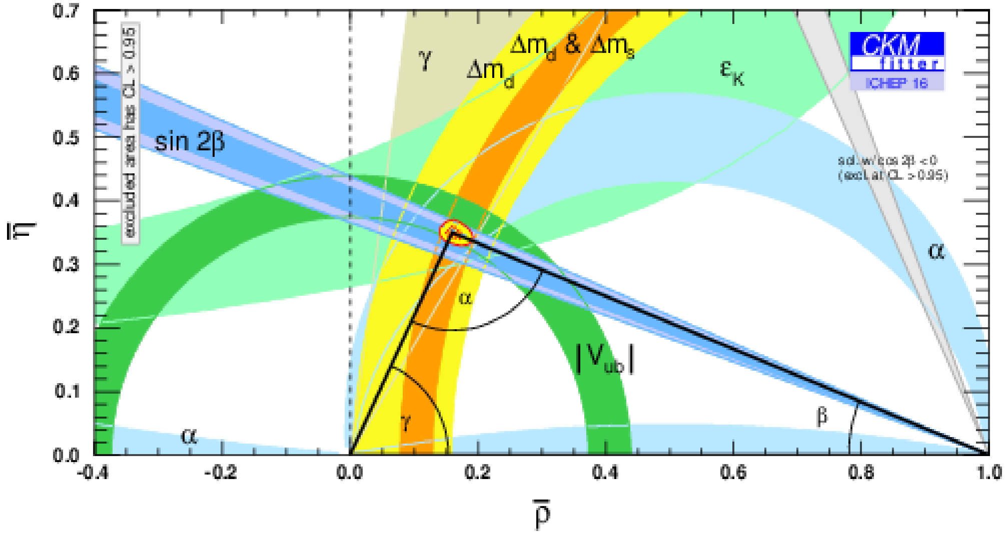


E.g.:

$Y_U \sim$



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



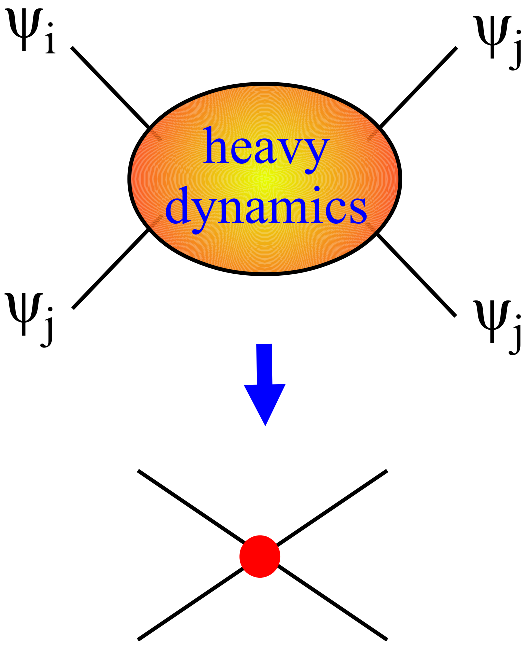
The "old" flavor puzzle...

Introduction [*the flavor structure of the SM & beyond*]

“Common lore” (II) :

The flavor structures are generated at some very heavy energy scale → *No chance to probe their dynamical origin*

This idea is supported by a series of precision measurement of rare flavor-violating processes which show no deviations from the SM:



$$\frac{1}{\Lambda^2}(\bar{\psi}_i \psi_j)^2$$

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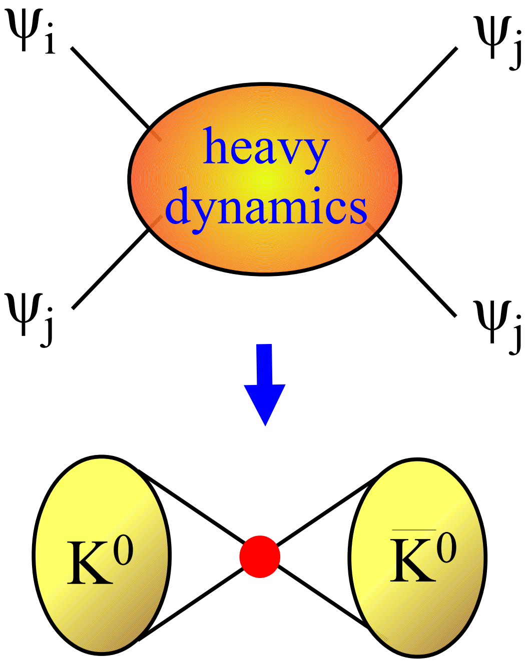

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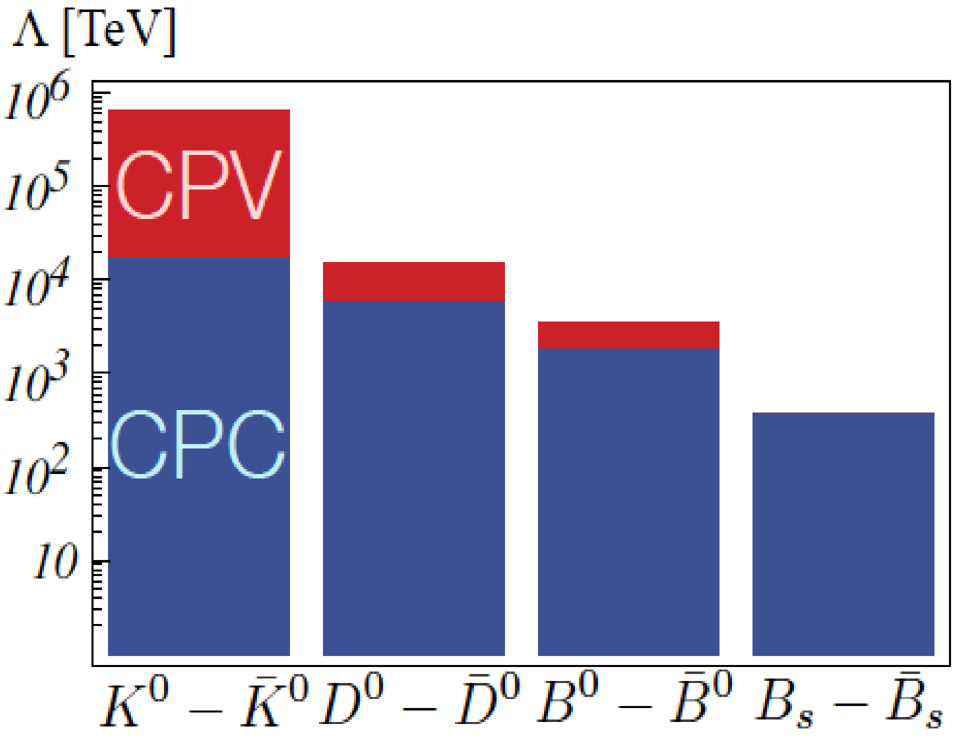


Since so far (*almost*) everything fits well with the SM→ Strong limits on NP

▶ Introduction [*the new flavor puzzle*]

This point of view is challenged by the recent "anomalies" in B physics, i.e. the observation of a *non-universal* behavior of different lepton species in specific in b (3rd gen.) → c,s (2nd) semi-leptonic processes:

- b → c charged currents: τ vs. light leptons (μ, e)
- b → 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...

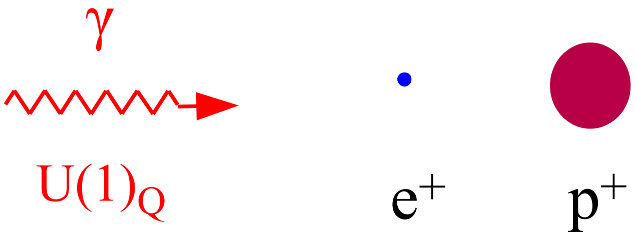
What is particularly interesting, is that these anomalies are challenging an assumption (Lepton Flavor Universality), that we gave for granted for many years (*without many good theoretical reasons...*)

⬇

Interesting new avenue in BSM constructions
(with implications beyond flavor physics)

Introduction [*more about LFU violations*]

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 ...

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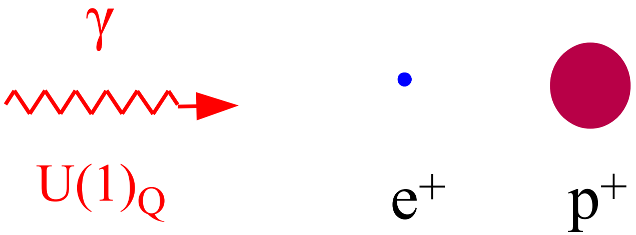

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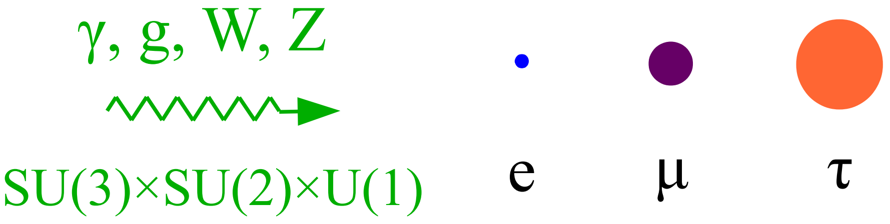
That's exactly the same (misleading) argument we use to infer LFU...



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

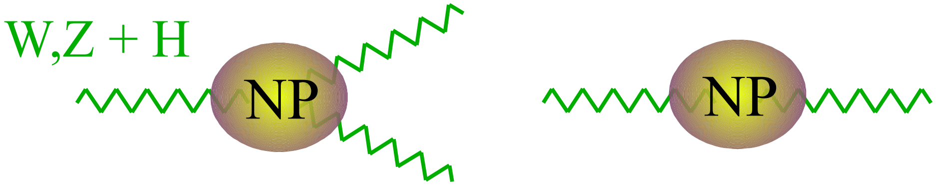
Introduction [*more about LFU violations*]

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

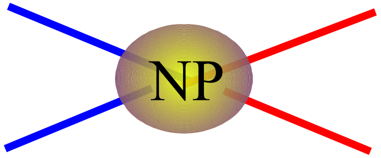
- Concentrate only on the Higgs hierarchy problem
- Postpone (ignore) the flavor problem, implicitly assuming the 3 families are "identical" copies (but for Yukawa-type interactions)

"Common lore" (I)

"Common lore" (II)



large (*more interesting...*)



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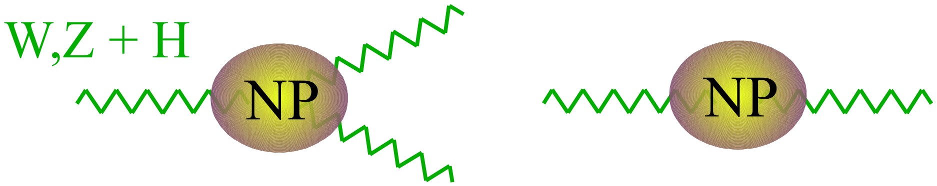
The recent flavor anomalies seem to suggest a new avenue in BSM approaches:

- 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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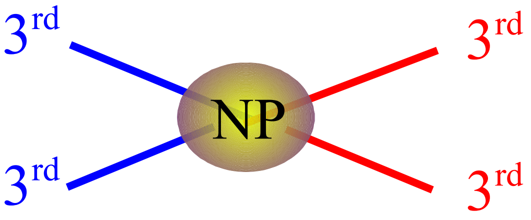

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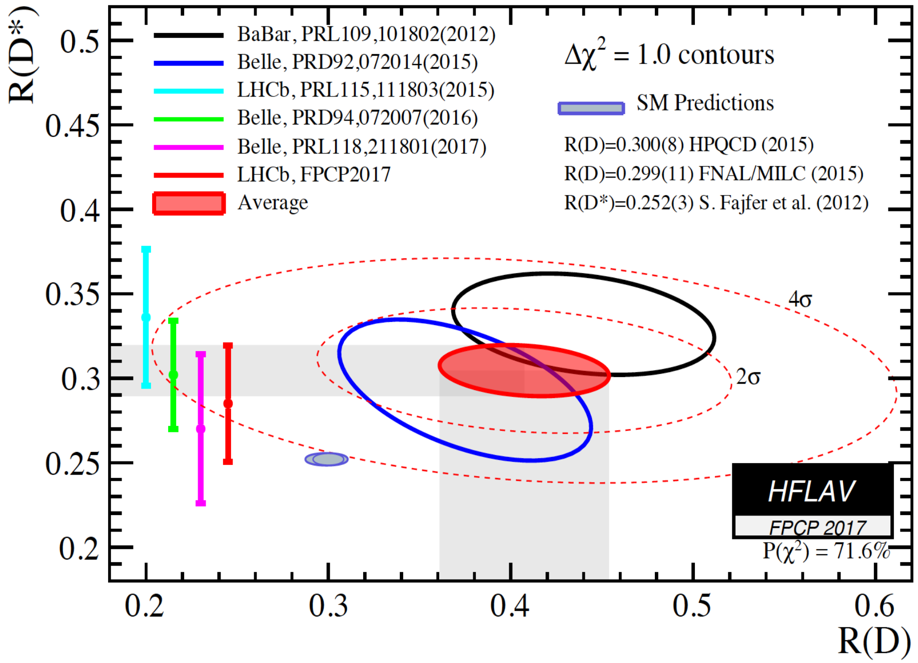
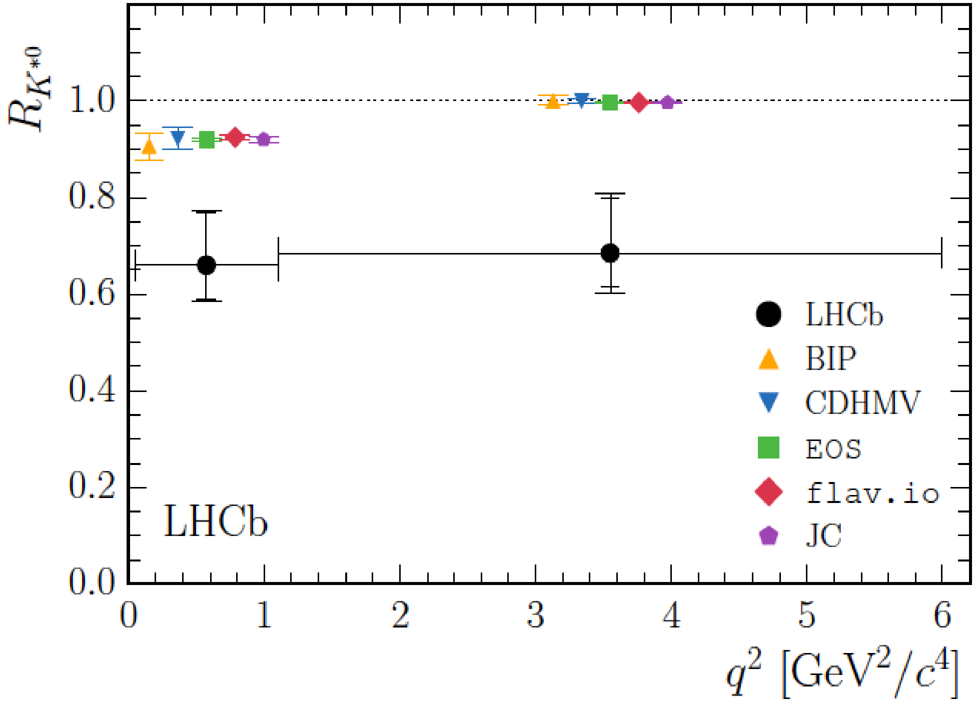
From first model-building attempts, it seems these anomalies may help us to shed light on another key problem of the SM that we have postponed (*somehow forgotten...*) for a long time:

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

On the recent B-physics anomalies



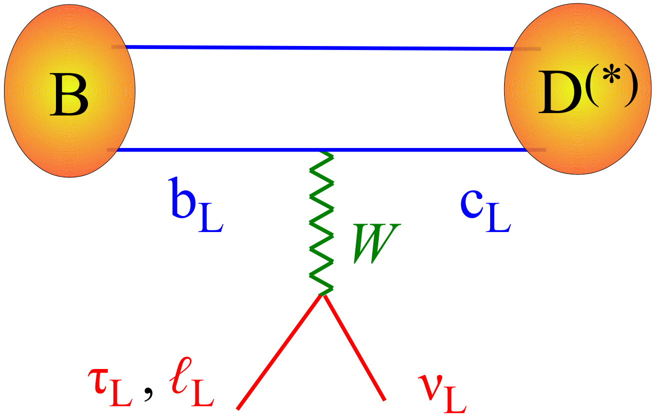


$B \to D^{(*)} \tau\nu$ [Babar, Belle, LHCb]

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

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

$X = \mathrm{D}$ 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 and radiative corr. [de Boer, Kitahara, Nisandzic '18]

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

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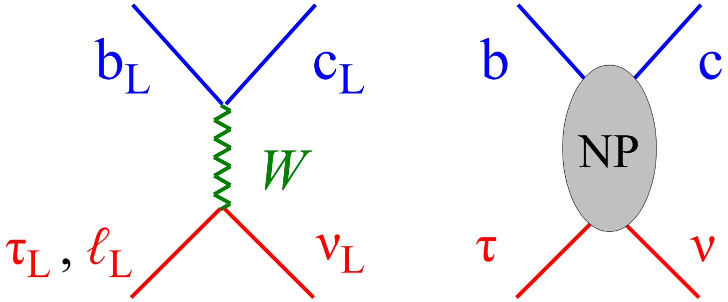

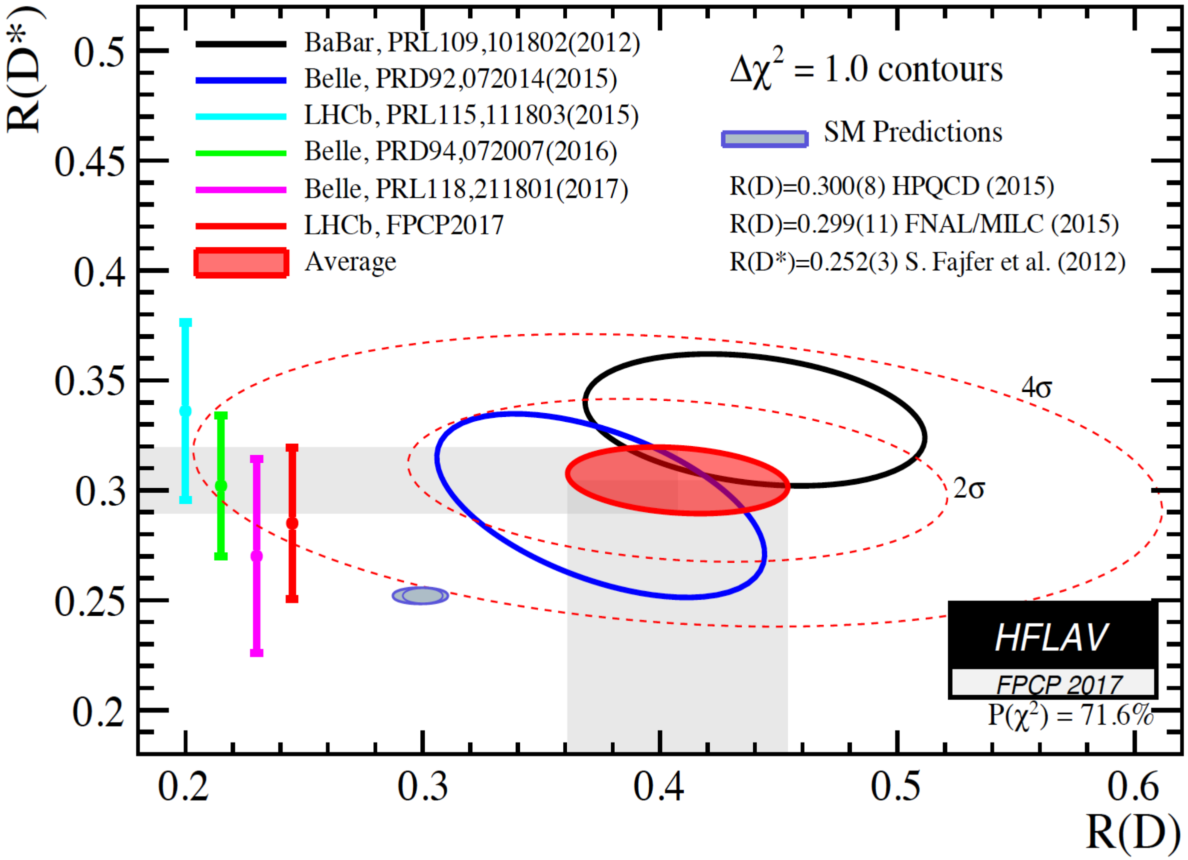

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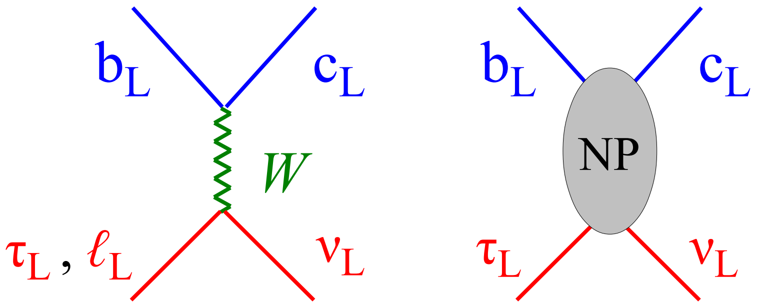
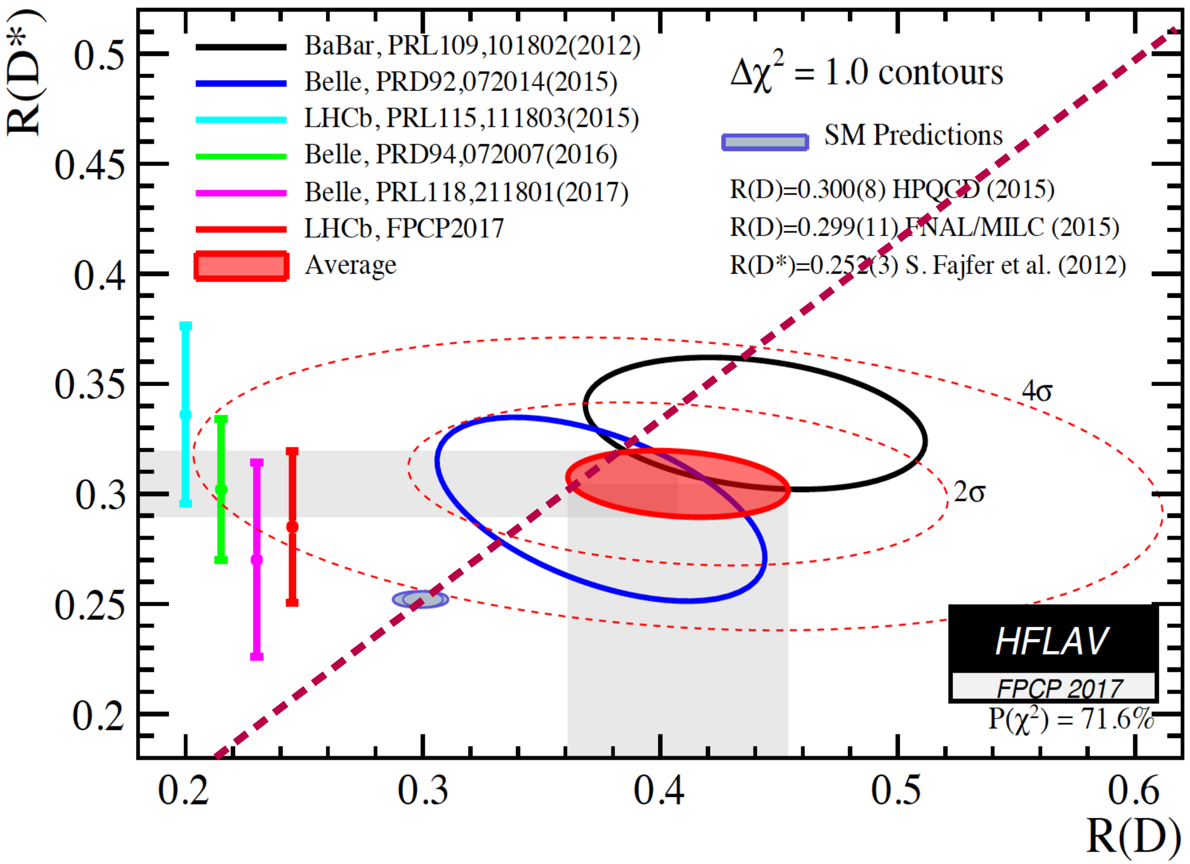




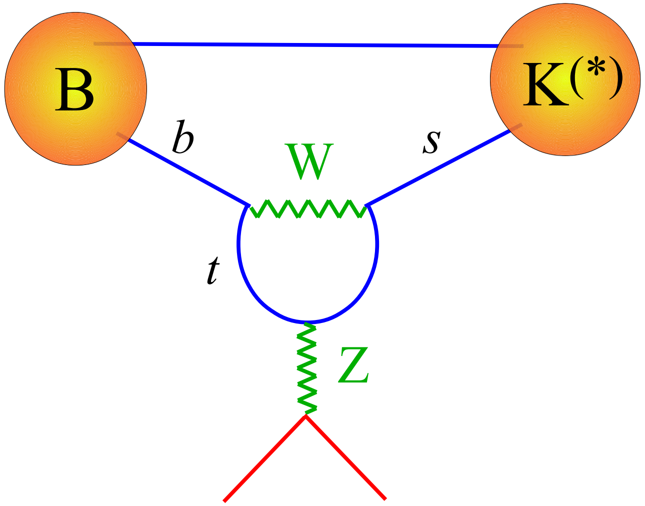
- SM prediction quite solid: hadronic uncertainties cancel (*to large extent*) in the ratio and deviations from 1 in *R*(X) expected only from phase-space differences
- Consistent results by 3 different exps. → 3.6–3.9σ excess over SM (*D* + *D**)
- The two channels are well consistent with a universal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

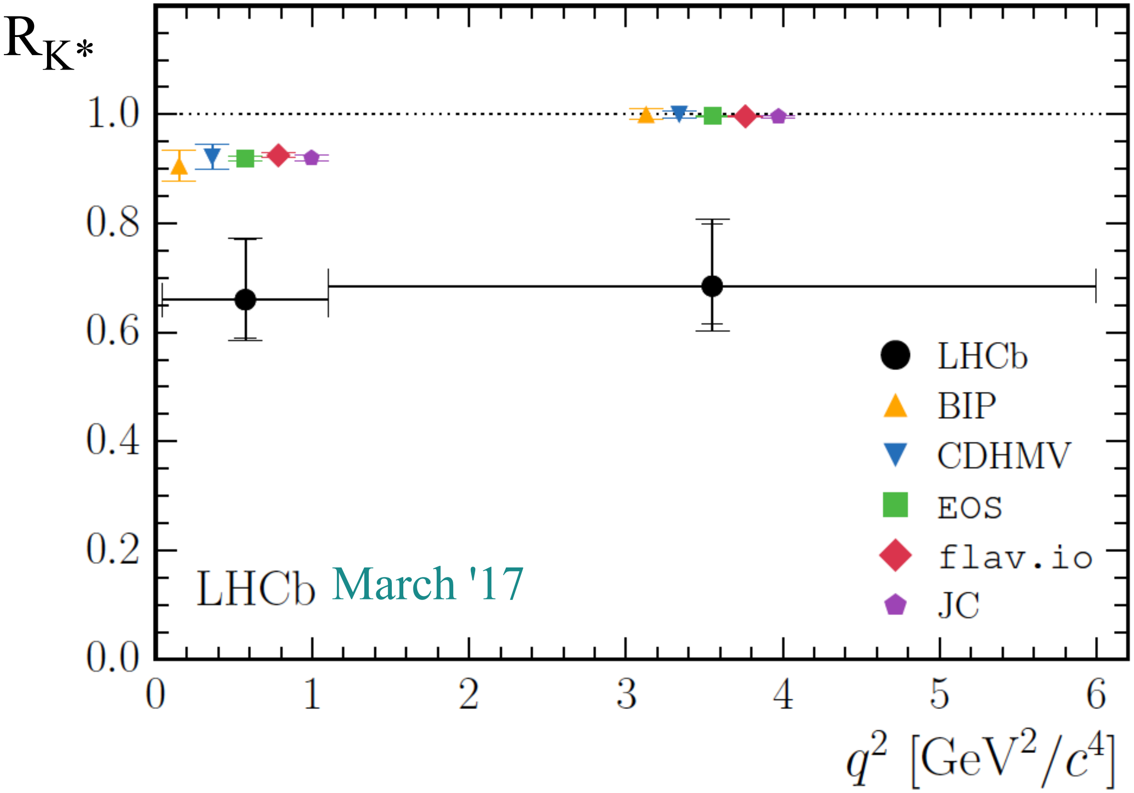
$$R_H = \frac{\int d\Gamma(B \to H\,\mu\mu)}{\int d\Gamma(B \to H\,ee)}$$

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*)

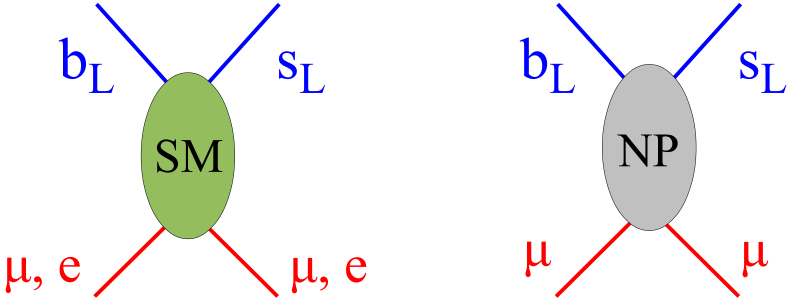


Anomalies in B → $K^{(*)}$ μμ / ee [LHCb]

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...

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

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

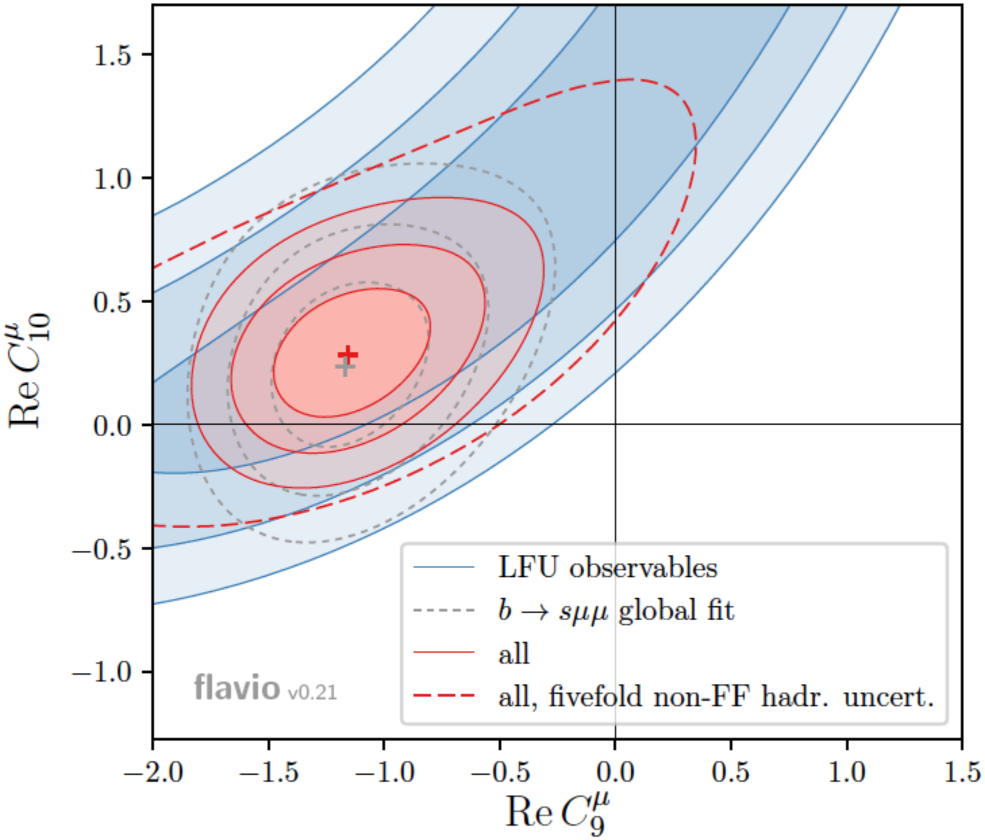


- All effects well described by NP of short-distance origin only in b→sμμ and (& not in ee)
- LH structure on the quark side:

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

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

Altmannshofer, Stangl, Straub '17



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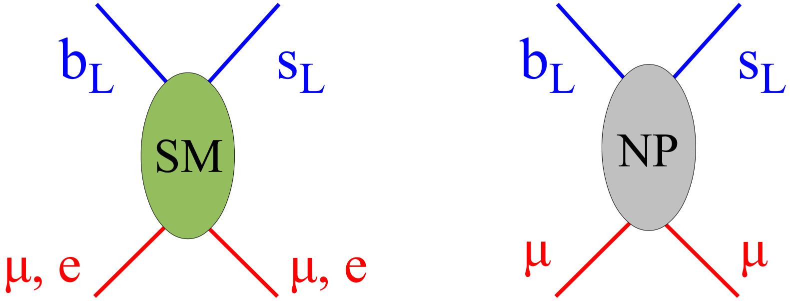

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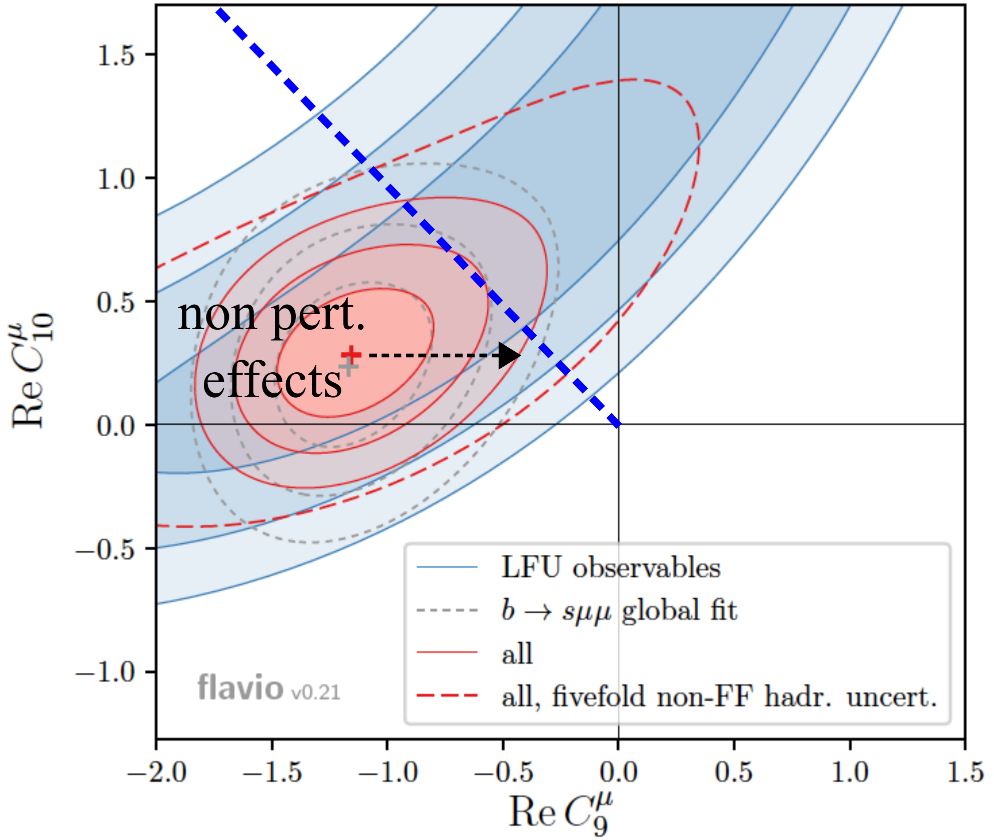
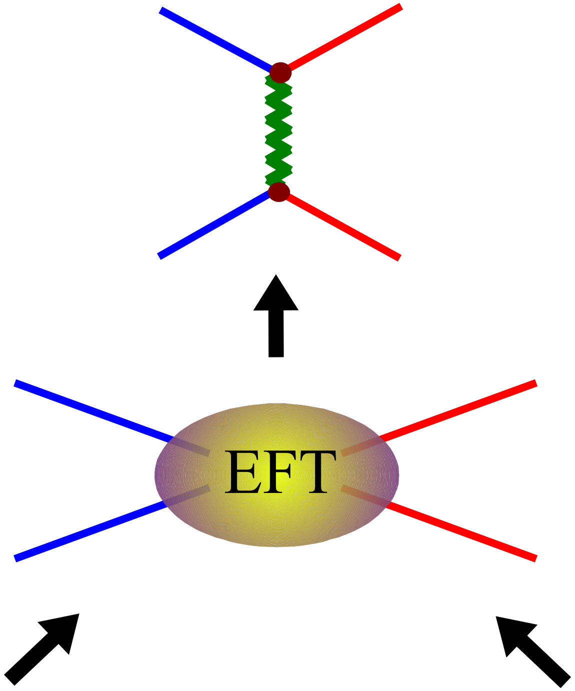
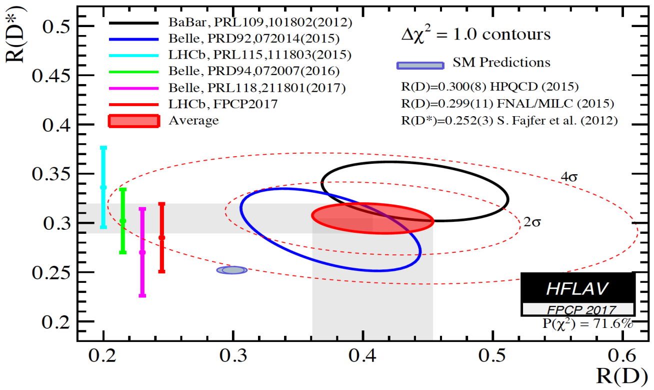
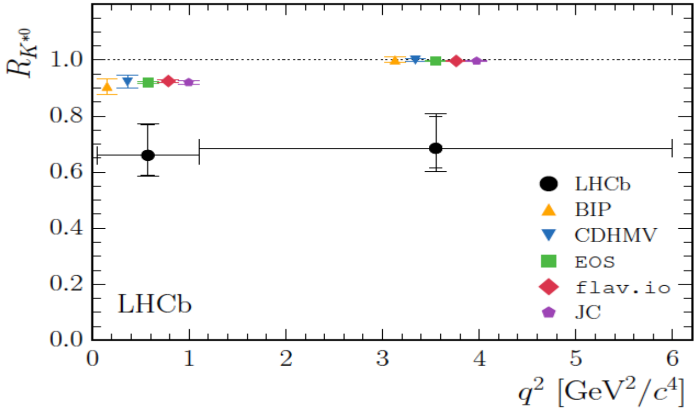


Bottom-up approaches to describe the anomalies

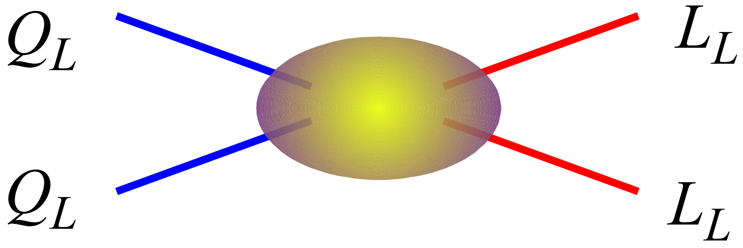






EFT-type considerations

- 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
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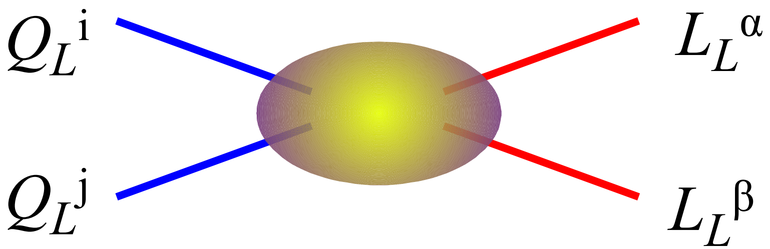

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- Large coupling (competing with SM tree-level) in bc → $l_3\,\nu_3$
- Small non-vanishing coupling (competing with SM FCNC) in bs → $l_2\,l_2$

↓

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

→

Link to pattern of the Yukawa couplings !

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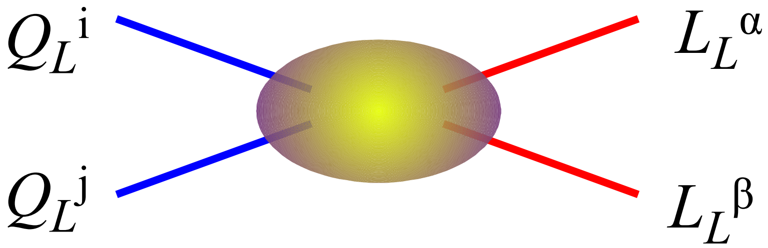
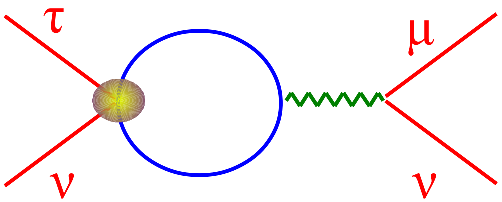
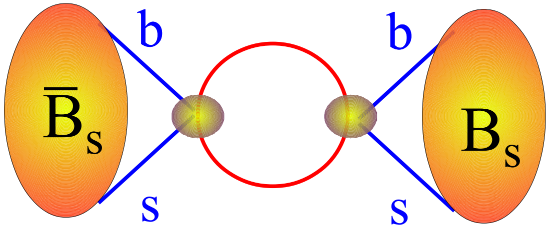


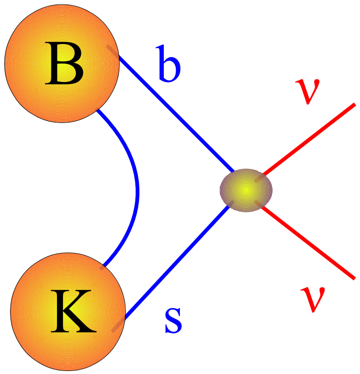
Long list of constraints [FCNCs + semi-leptonic b decays + π, K, τ decays + EWPO]

E.g:



Feruglio, Paradisi, Pattori '16





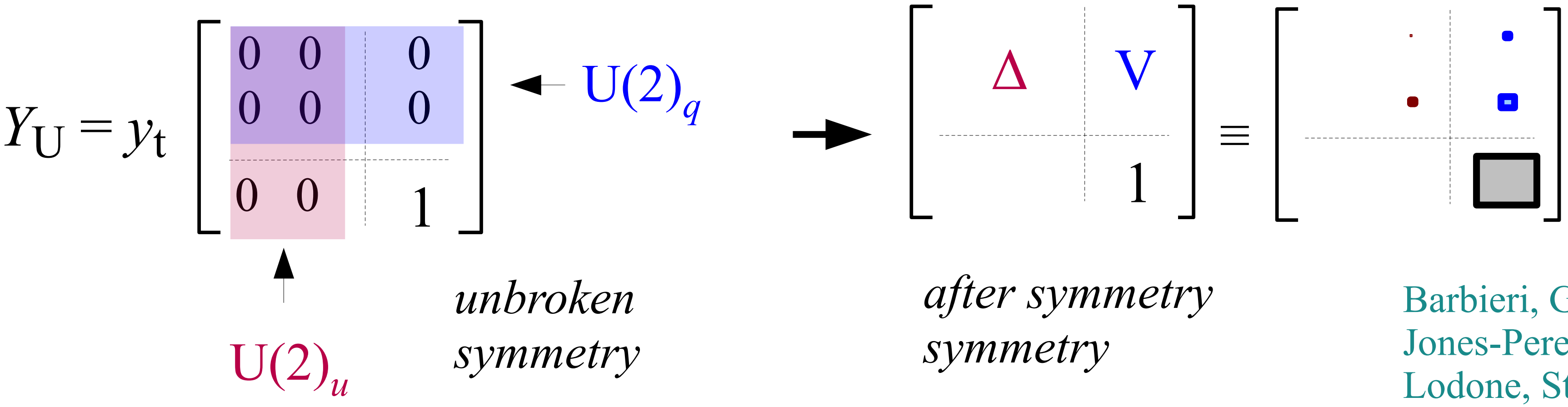
Calibbi, Crivellin, Ota, '15
(+many others...)

\+ *many more...*

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

A good fit to all data + natural link with the origin of the Yukawa couplings, is obtained building the EFT on the hypothesis of an approximate U(2)-type chiral flavor symmetry

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



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

$\leftarrow U(2)_q$

$\uparrow U(2)_u$

unbroken symmetry

after symmetry symmetry

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...!*]

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

A good fit to all data + natural link with the origin of the Yukawa couplings, is obtained building the EFT on the hypothesis of an approximate U(2)-type chiral flavor symmetry

+

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

Buttazzo, Greljo, GI, Marzocca, '17

"The Zürich's Guide"

↓

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

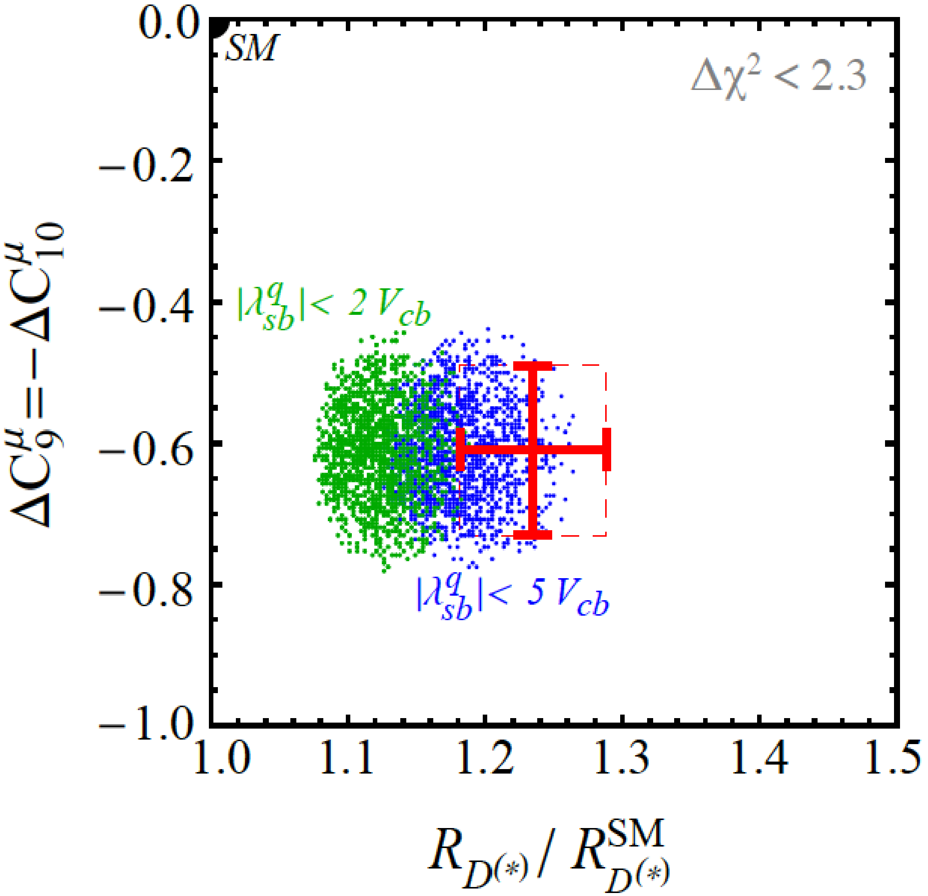
four free parameters...

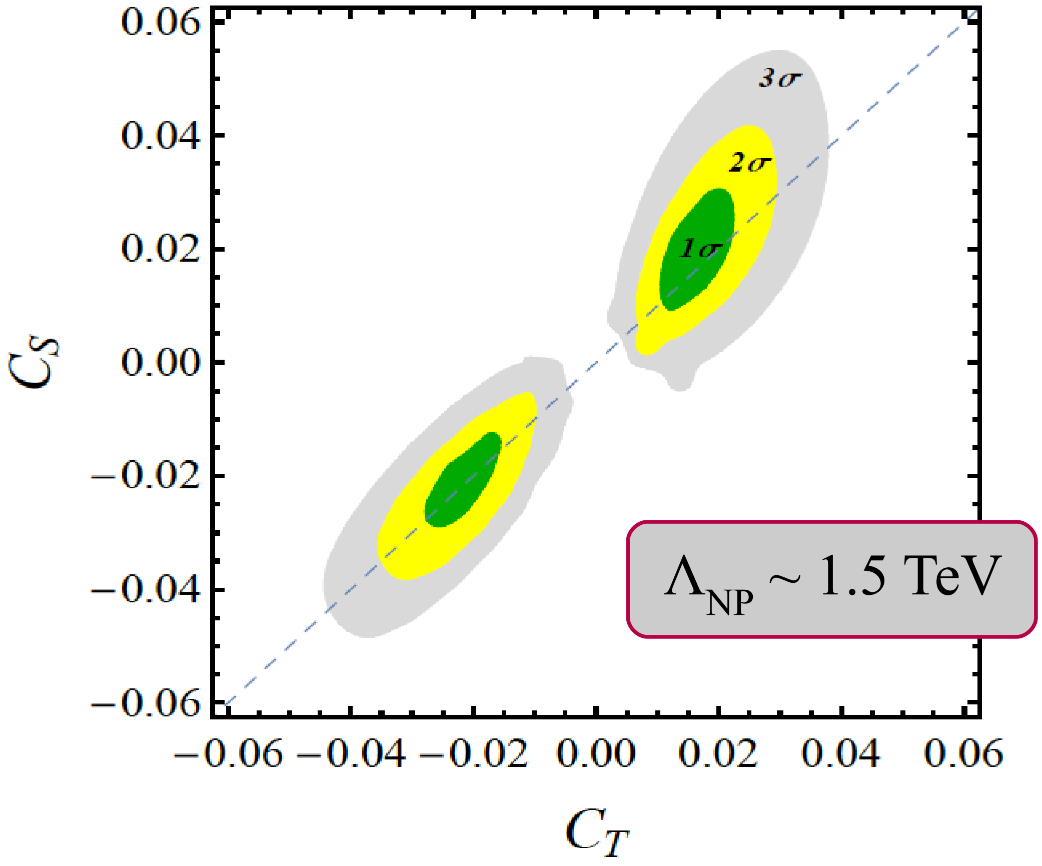
C_T, C_S
$\lambda_{bs} = O(V_{cb})$
$\lambda_{\mu\mu} = O(|V_{\tau\mu}|^2)$

...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





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

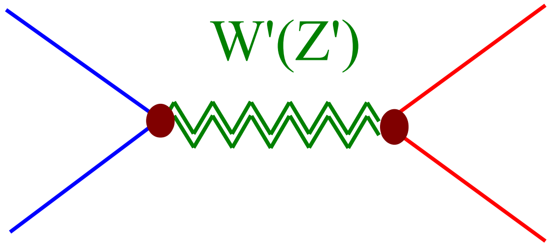
- The virtue of this EFT approach is the demonstration that is possible to find a “combined” (*motivated*) explanation of the two set of anomalies.
- The EFT solution is not unique [e.g. sub-leading RH currents can be added], but large variations are possible only if the R_D anom. goes away completely

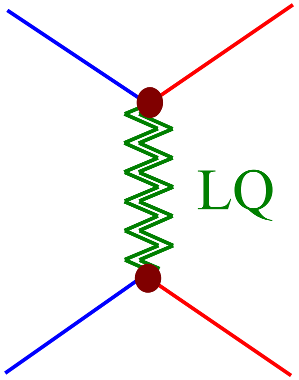
Simplified dynamical models [*"The Return of the LeptoQuark"*...]

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'





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

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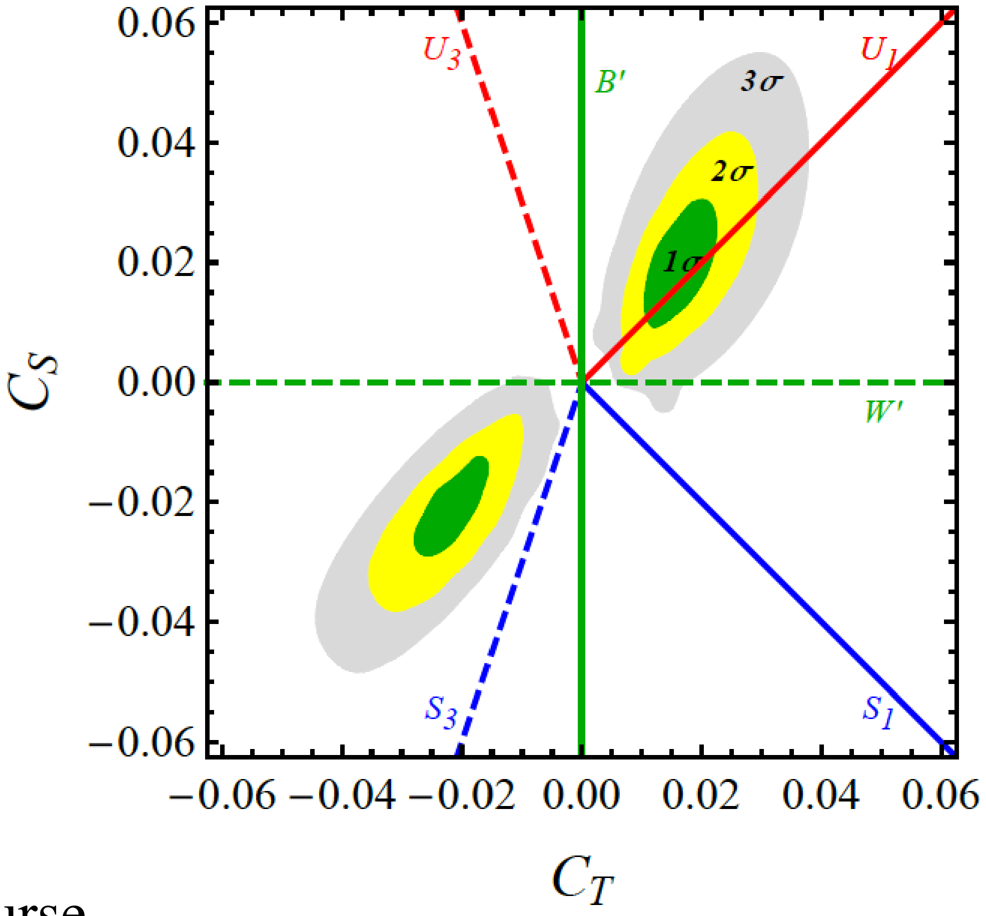

The U_1 option fits quite nicely... but of course models with more than one mediators are possible

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

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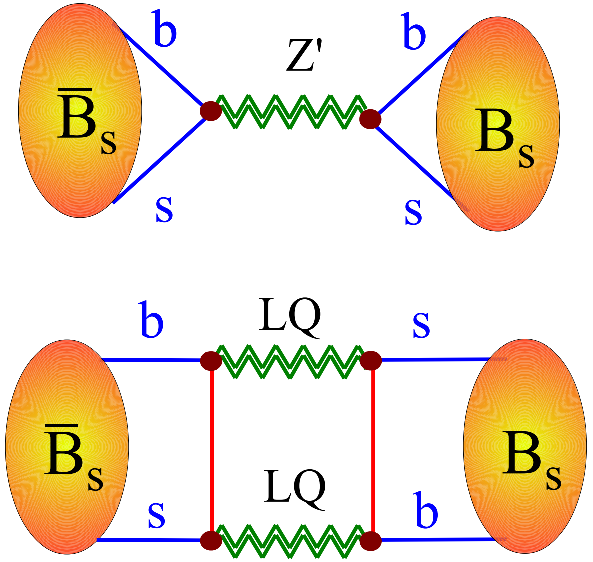
(*for the combined explanation*):

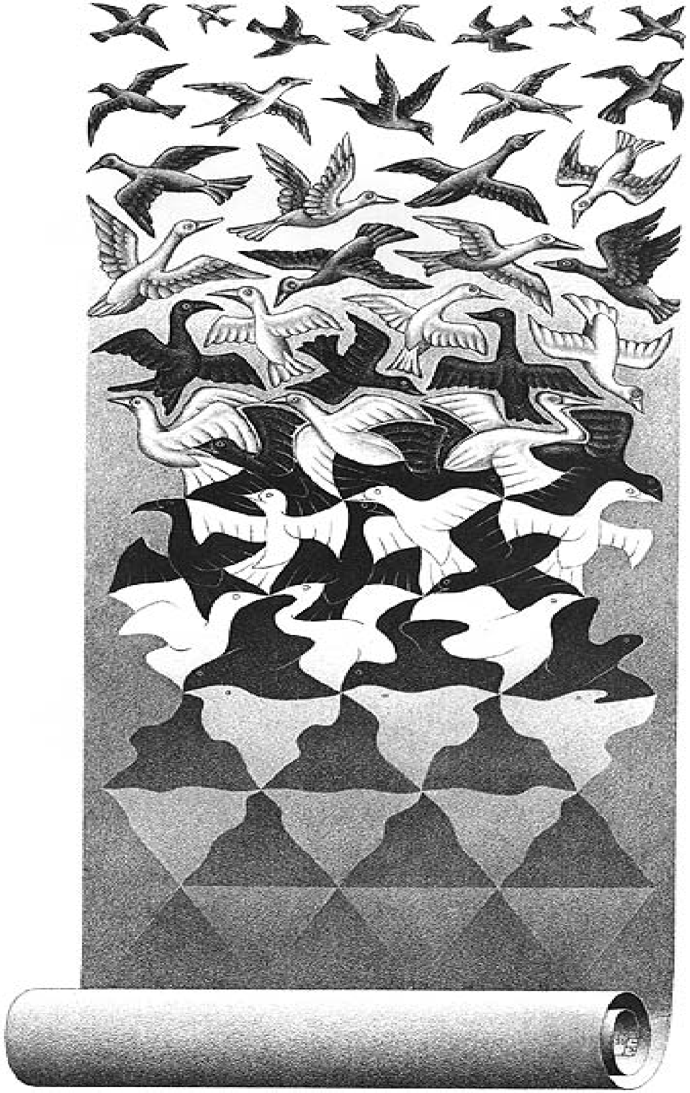
	$SU(2)_L$	
	singlet	triplet
Vector LQ:	U_1	U_3
Scalar LQ:	S_1	S_3
Colorless vector:	B'	W'

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

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



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):

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

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

The massive LQ [U_1] arise from the breaking $SU(4) \rightarrow SU(3)_c$

▶ Speculations on UV completions

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

The massive LQ [U_1] arise from the breaking $SU(4) \to SU(3)_c$

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 $K_L \to \mu e$].

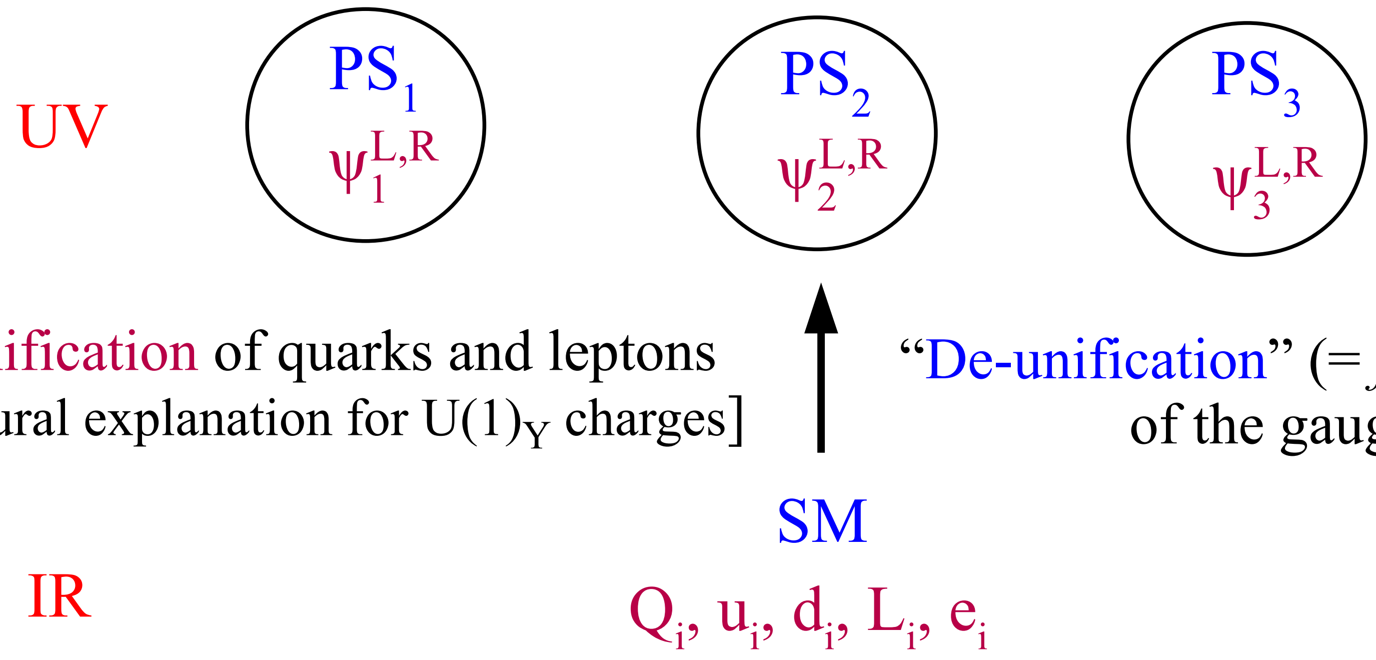
Interesting recent attempts to solve this problem adding extra fermions and/or modifying the gauge group [Calibbi, Crivellin, Li, '17; Di Luzio, Greljo, Nardecchia, '17]

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 !*)



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

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

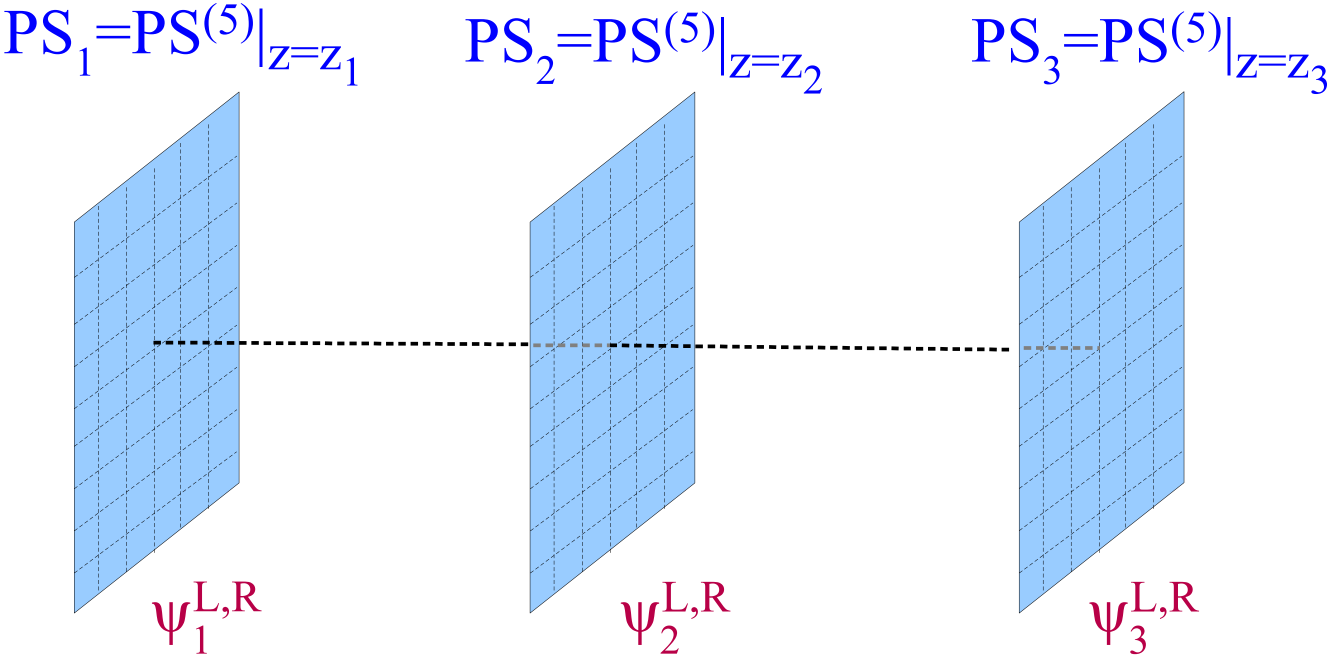
Key advantages:

- 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



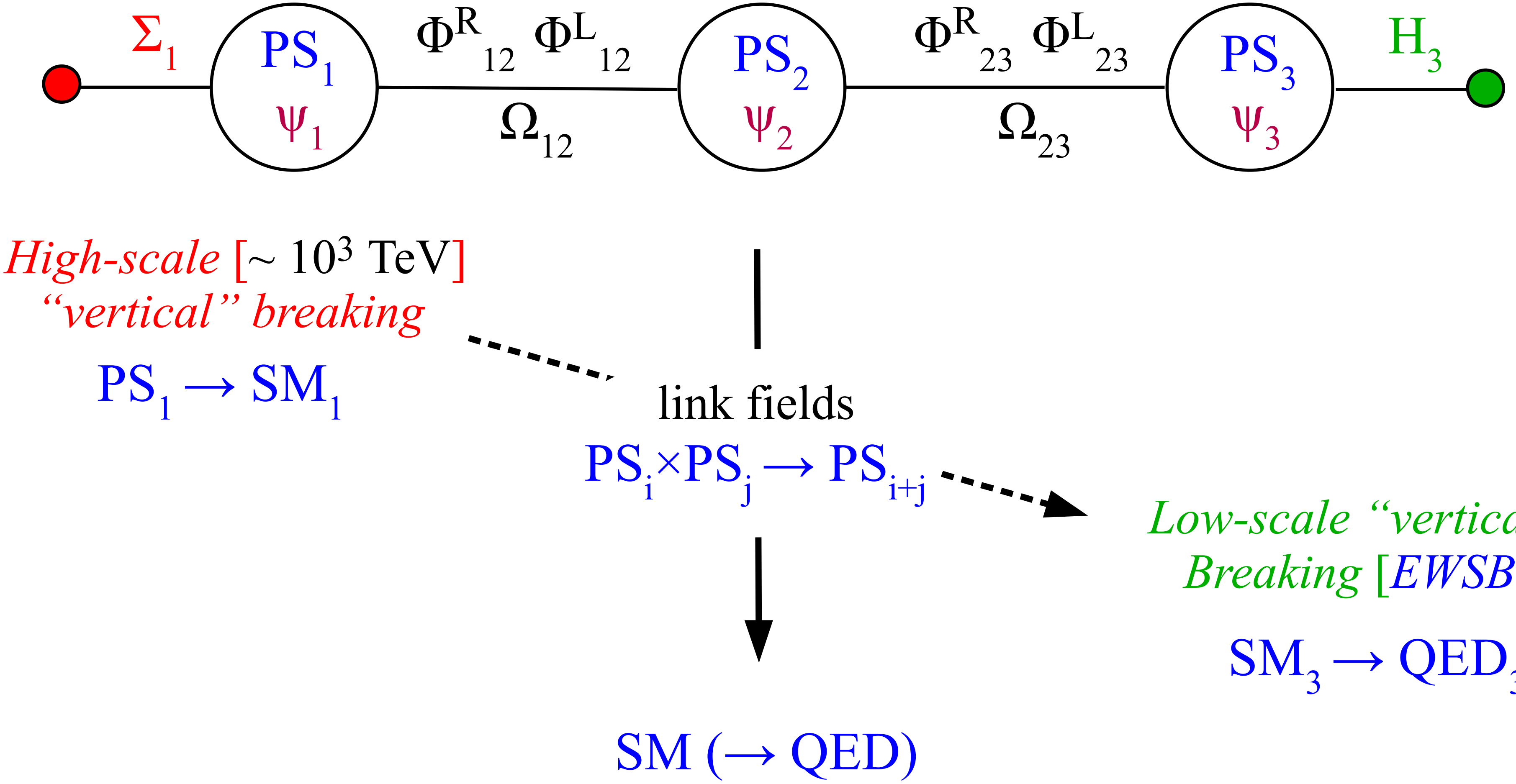
Unification
of quarks and leptons

"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



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

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

$PS_1 \to SM_1$

link fields

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

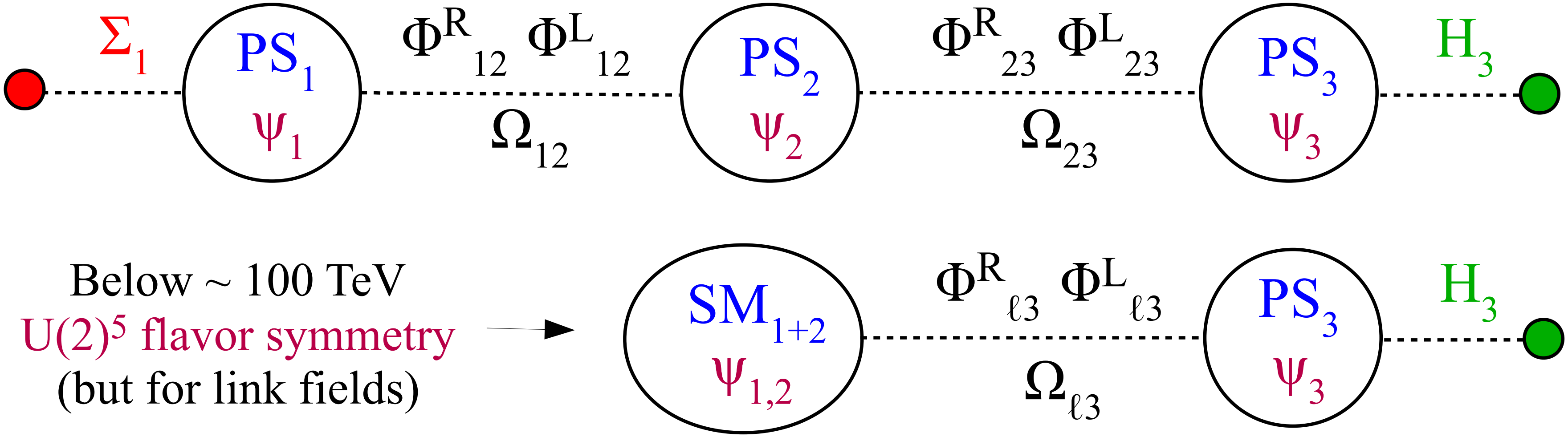
Low-scale "vertical"
Breaking [*EWSB*]

$SM_3 \to QED_3$

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.

The PS^3 model

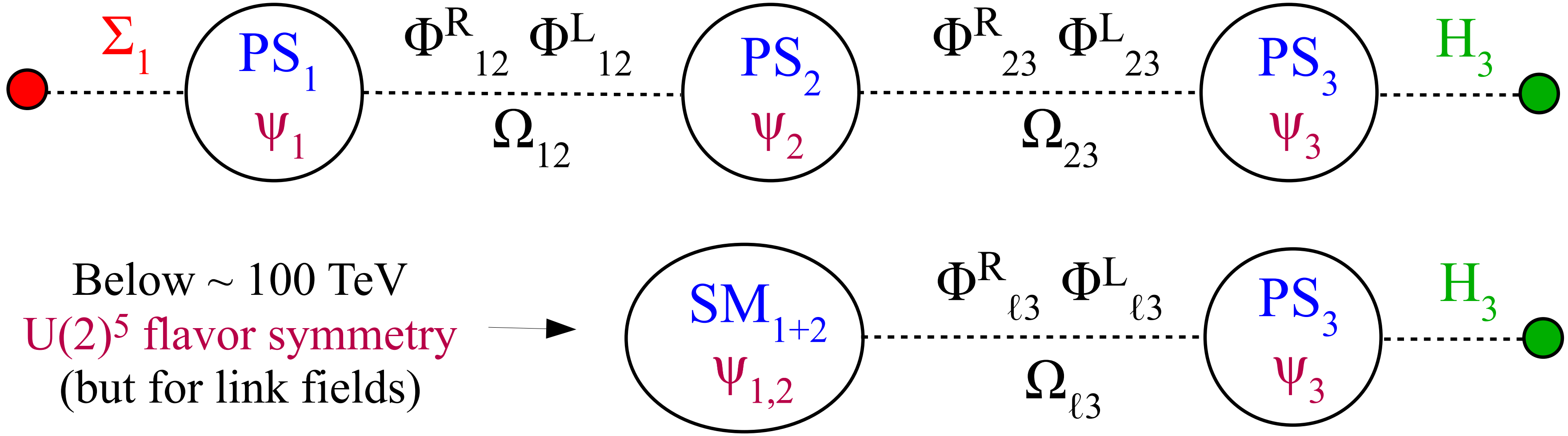


Below ~ 100 TeV
U(2)^5 flavor symmetry
(but for link fields)

Leading flavor structure:

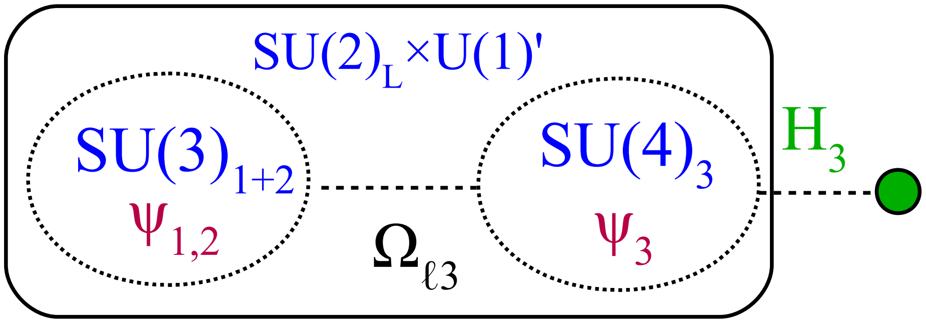
- Yukawa coupling for 3rd gen. only
- “Light” LQ field (from PS$_3$) coupled only to 3rd gen.
- U(2)^5 symmetry protects flavor-violating effects on light gen.

The PS^3 model

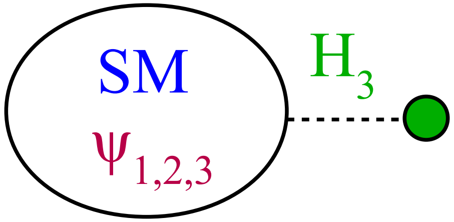


Below ~ 100 TeV
U(2)^5 flavor symmetry
(but for link fields) →

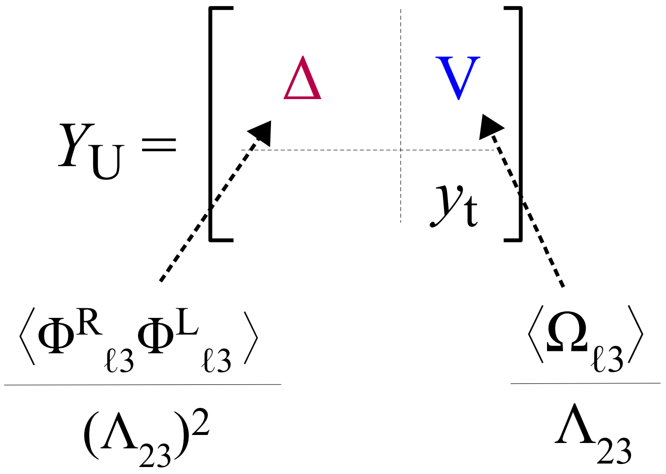
→ $W_L' + W_R'$ [~ 5-10 TeV]



→ LQ [U_1] + Z' + G' [~ 2-3 TeV]



Sub-leading Yukawa terms from higher dim ops:



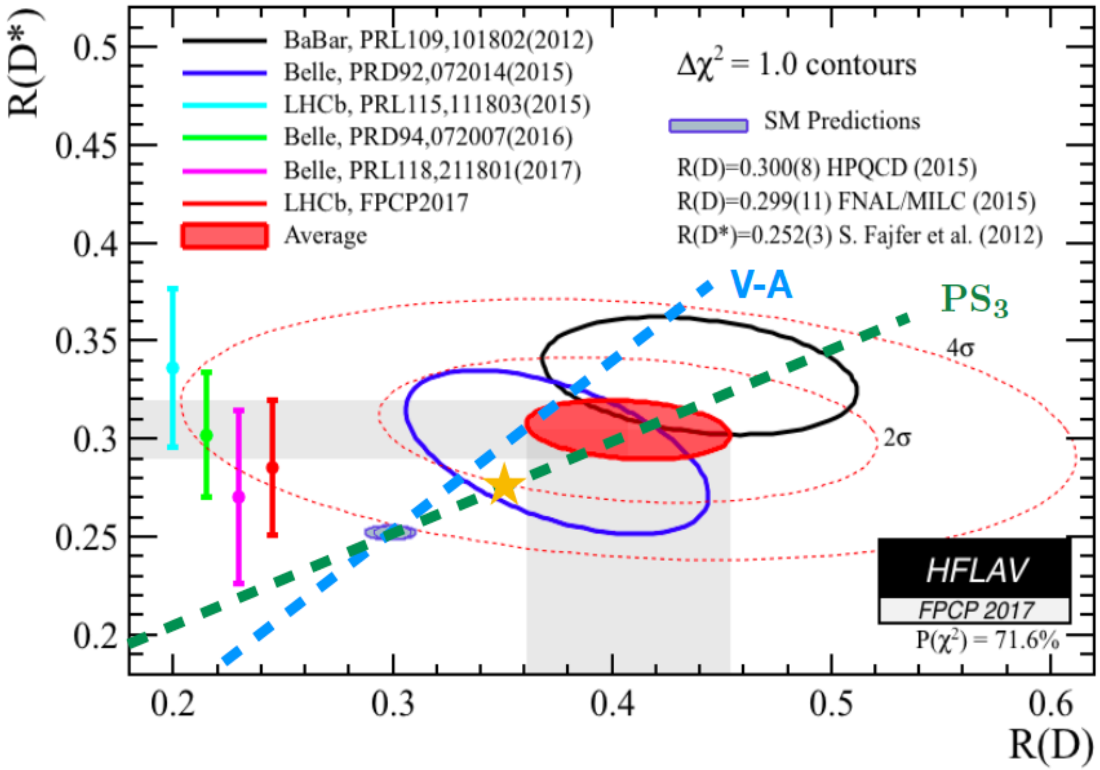
$$Y_U = \begin{bmatrix} \Delta & V \\ & y_t \end{bmatrix}$$

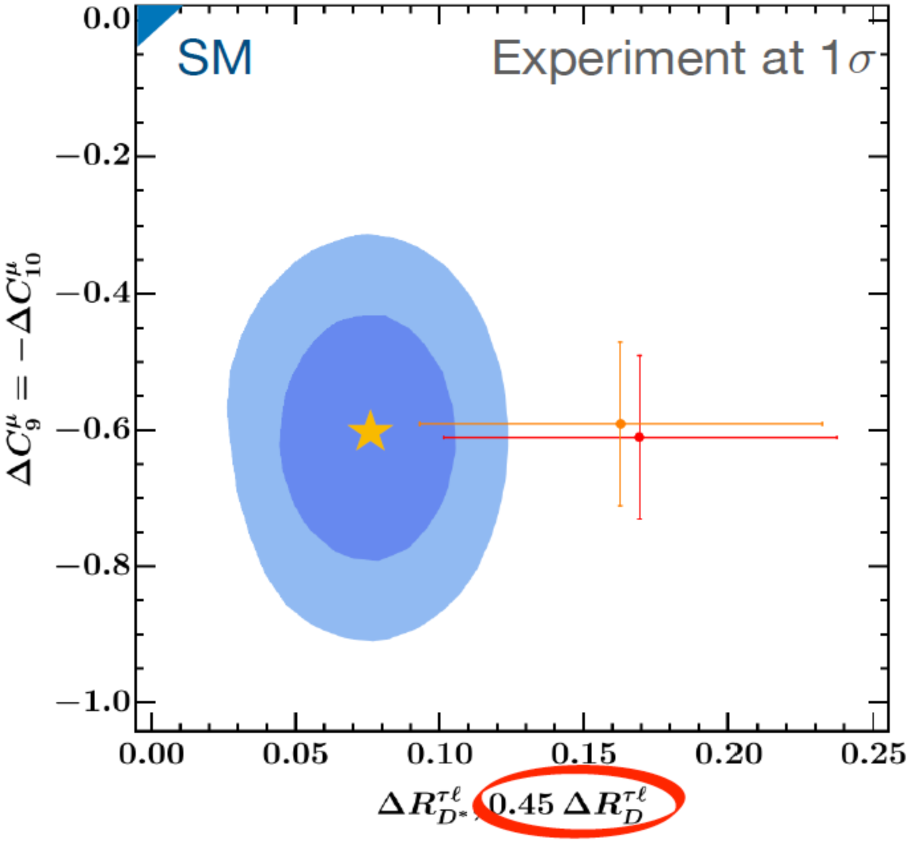
$$\frac{\langle \Phi^R{}_{\ell 3} \Phi^L{}_{\ell 3} \rangle}{(\Lambda_{23})^2} \qquad \frac{\langle \Omega_{\ell 3} \rangle}{\Lambda_{23}}$$

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 rather good

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

Important difference with respect to all other models:
RH couplings of the LQ

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)

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

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

Implications for low-energy flavor physics

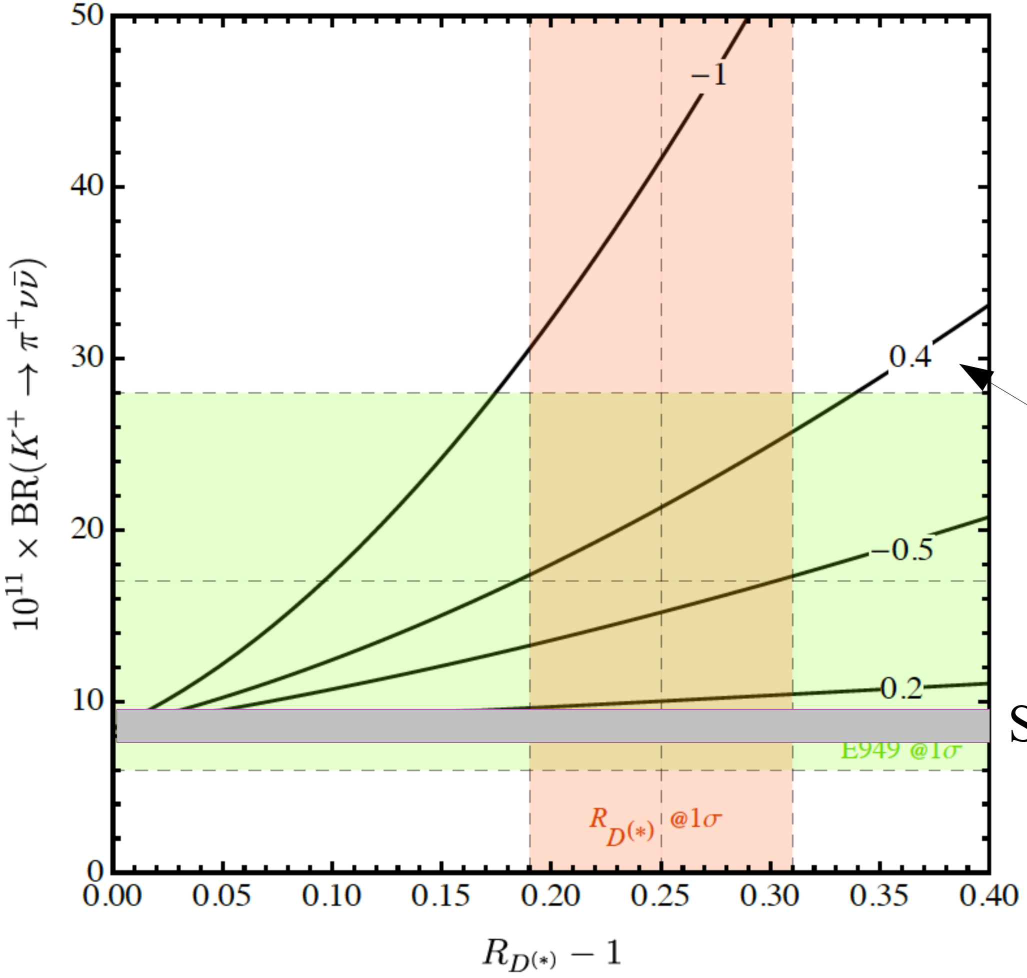
A closer look to K → πνν:

$$\Gamma(K \to \pi\nu\nu) = \Gamma(K \to \pi\nu_e\bar{\nu}_e) + \Gamma(K \to \pi\nu_\mu\bar{\nu}_\mu) + \Gamma(K \to \pi\nu_\tau\bar{\nu}_\tau)$$

SM like

few % deviation
as in b→sμμ

possible large deviation
from SM as in b→sττ



SM

O(1) parameter
of the EFT

Very interesting in view of NA62 !

Barbieri *et al.* '16
Bordone, Buttazzo, GI, Monard '17

Implications for low-energy flavor physics

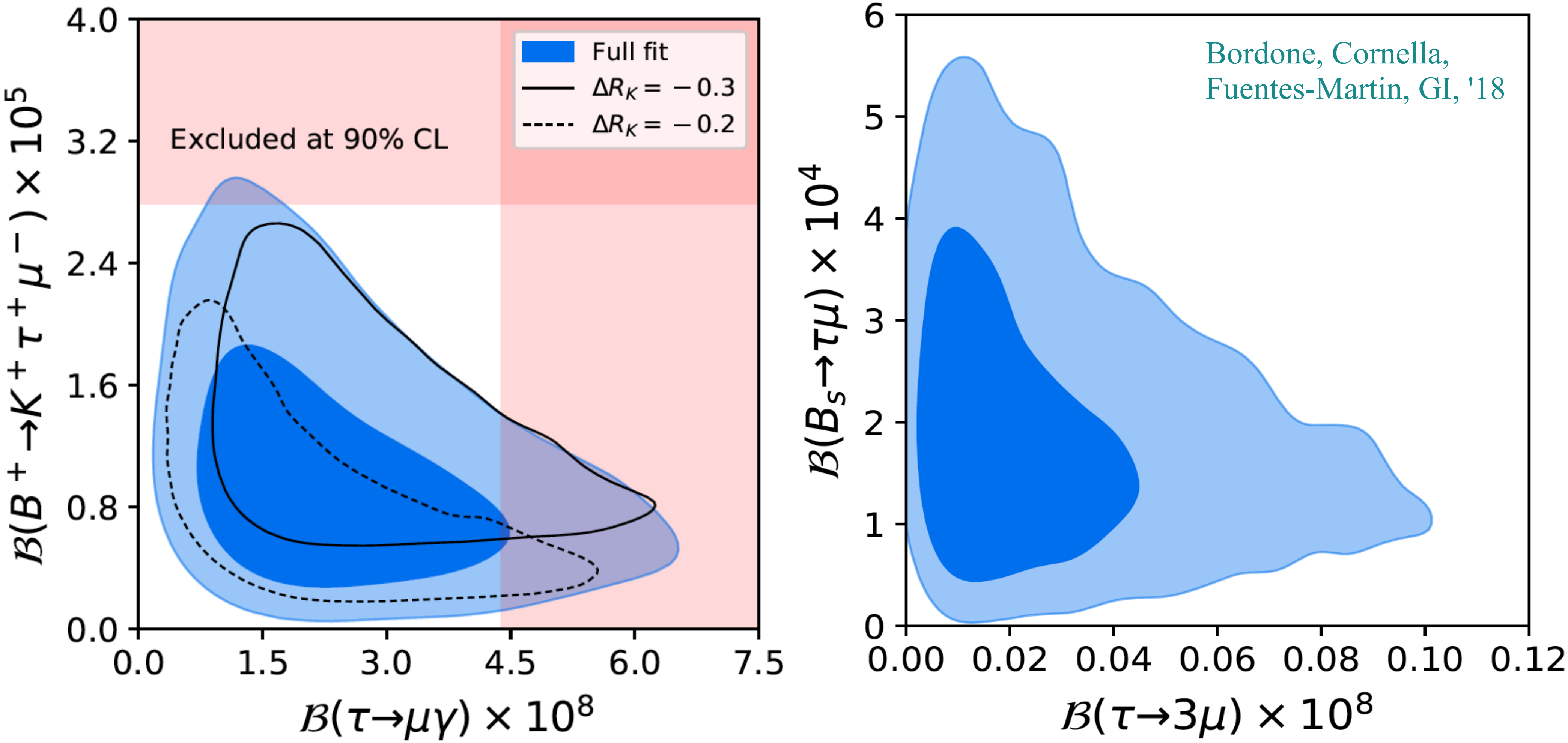
If the anomalies are due to NP, we should expect to see several other BSM effects in low-energy observables

E.g. (II): correlations among down-type FCNCs including LFV rates:

	$\mu\mu$ (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)	$B \to K \tau\mu$ $\to \sim 10^{-5}$	$B \to K \mu e$???
$b \to d$	$B_d \to \mu\mu$ $B \to \pi \mu\mu$ $B_s \to K^{(*)} \mu\mu$ 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*	$K \to \mu e$ $\to \sim 10^{-12}$

Implications for low-energy flavor physics

A closer look to 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 low-energy flavor physics*

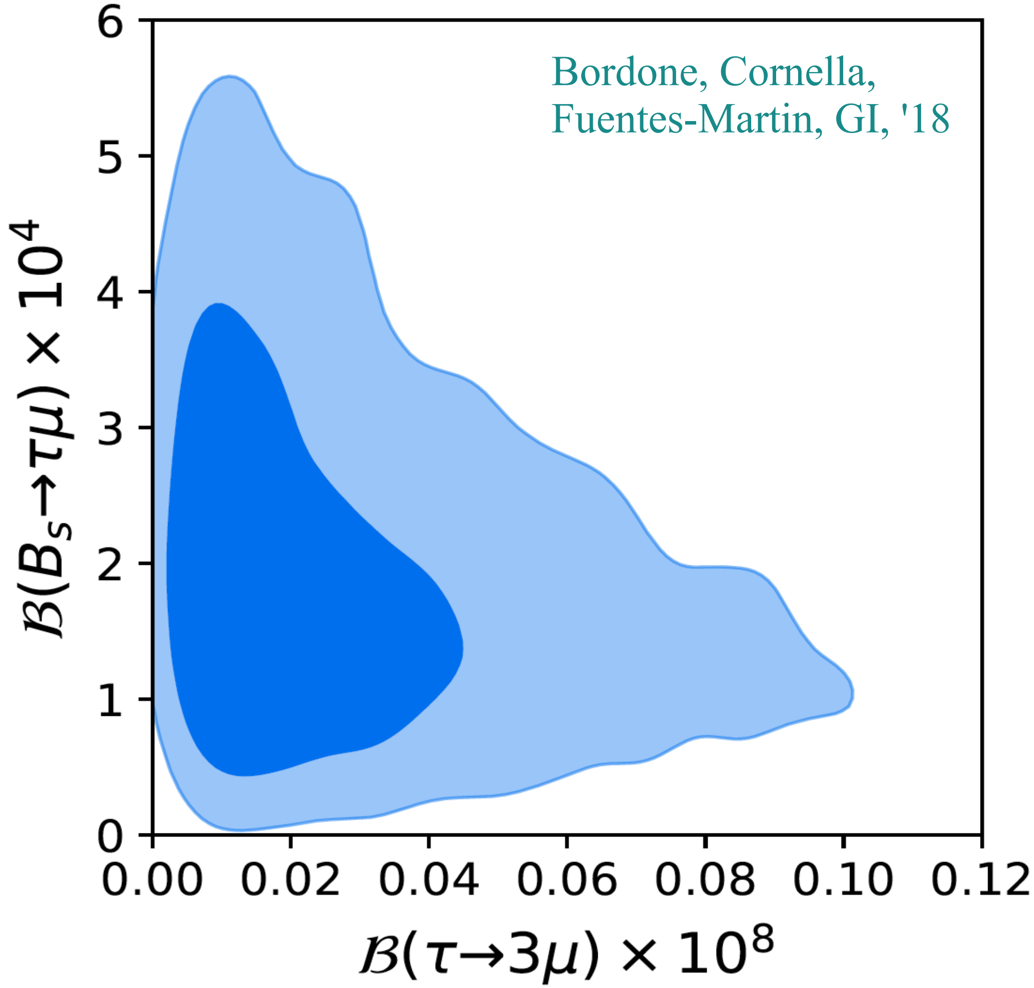
A closer look to LFV processes in the PS^3 model:

More difficult to make precise predictions for μ → e transitions.

But the main message is that both $\mu \to 3e$ and $K_L \to \mu e$ could close to their present exp. bounds:

$BR(\mu \to 3e)$ → few 10^{-14}

$BR(K_L \to \mu e)$ → few 10^{-12}



Implications for low-energy flavor physics

E.g. (III): correlations of LFU violations in charged currents [U(2)-*based EFT*]

- LH operators [universality of all $R^{\tau/\mu}(b \to c)$ ratios]:

$$\frac{R_D}{(R_D)_{SM}} = \frac{\Gamma(B \to D^* \tau\nu)/\Gamma_{SM}}{\Gamma(B \to D^* \mu\nu)/\Gamma_{SM}} = \frac{\Gamma(B_c \to \psi\tau\nu)/\Gamma_{SM}}{\Gamma(B_c \to \psi\mu\nu)/\Gamma_{SM}} = \frac{\Gamma(\Lambda_b \to \Lambda_c\tau\nu)/\Gamma_{SM}}{\Gamma(\Lambda_b \to \Lambda_c\mu\nu)/\Gamma_{SM}} = \ldots$$

N.B.: these relations are violated if there are RH currents...

Implications for low-energy flavor physics

E.g. (III): correlations of LFU violations in charged currents [U(2)-*based EFT*]

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N.B.: these relations are violated if there are RH currents...

- U(2) symmetry [$R^{\tau/\mu}(b\to c)=R^{\tau/\mu}(b\to u)$ universality]:

$$\frac{\Gamma(B\to\pi\ \tau\nu)/\Gamma_{SM}}{\Gamma(B\to\pi\ \mu\nu)/\Gamma_{SM}} = \frac{\Gamma(\Lambda_b\to p\ \tau\nu)/\Gamma_{SM}}{\Gamma(\Lambda_b\to p\ \mu\nu)/\Gamma_{SM}} = \frac{\Gamma(B_s\to K^*\tau\nu)/\Gamma_{SM}}{\Gamma(B_s\to K^*\mu\nu)/\Gamma_{SM}} = \ldots = \frac{R_D}{(R_D)_{SM}}$$

N.B.: The only info on $b\to u\tau\nu$ we have is $BR(B_u\to\tau\nu)^{exp}/BR_{SM} = 1.31 \pm 0.27$
→ perfectly consistent with I+II (*but also with SM and PS³...*) UTfit. '16

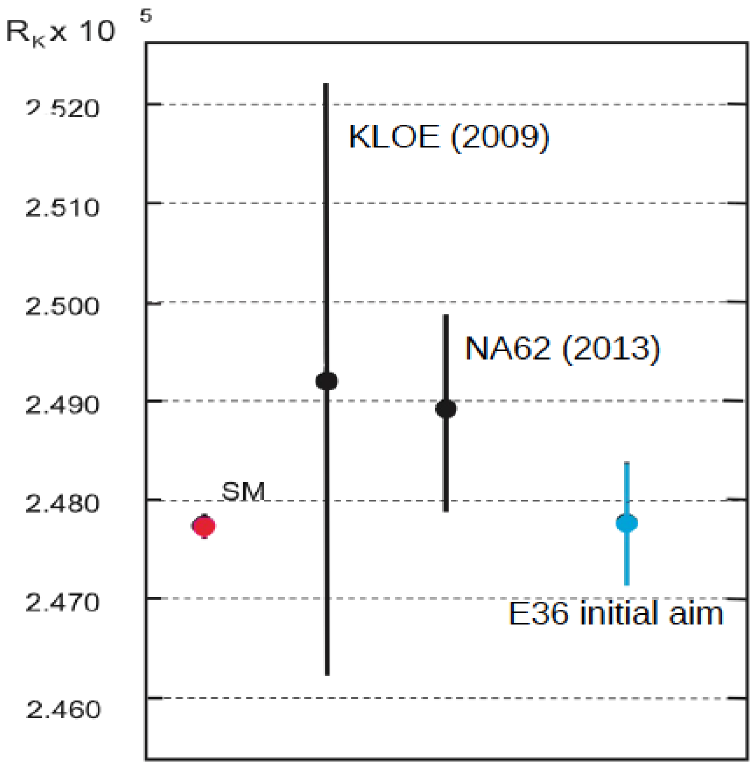
N.B.: The predictions for $R^{\mu/e}(b\to c)$ are more uncertain, but up to O(2%) possible
→ worth to improve

▶ *Implications for low-energy flavor physics*

What about LFU tests with charged-current in kaons ? [*work in prog.*]

The best tests at the moment comes from $R_K = \Gamma(K^+ \to e\nu)/\Gamma(K^+ \to \mu\nu)$

From $R(D^*)$ & $R(D)$:
$[\Gamma(b \to c\tau\nu)/\Gamma(b \to c\mu\nu)] \sim 20\%$ $\xrightarrow[U(2)_l]{U(2)_q}$ $\left.\frac{\Delta R_K}{R_K}\right|_{NP} \gtrsim 10^{-4}$



With similar relative effects expected also in K_{l3}

Maybe beyond reach given the SM error...

SM prediction
[Cirigliano, Rossel '07]: $\left.\frac{\Delta R_K}{R_K}\right|_{th} = 4\times10^{-4}$

… but this is only a preliminary estimate (*with some th. prejudice...*) → definitely worth trying to improve the measurment

▸ *Implications for high-p_T physics*

Some general considerations:

Independently of the details of the UV models, the anomalies point to NP in the ball-park of direct searches @ LHC

- $R_{D(*)}$ necessarily points to a low NP scale: $M \sim g \times (1.0\ \text{TeV})$
- $R_{K(*)}$ also points to a low NP scale, but for (unnaturally) large flavor-violating couplings

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*)

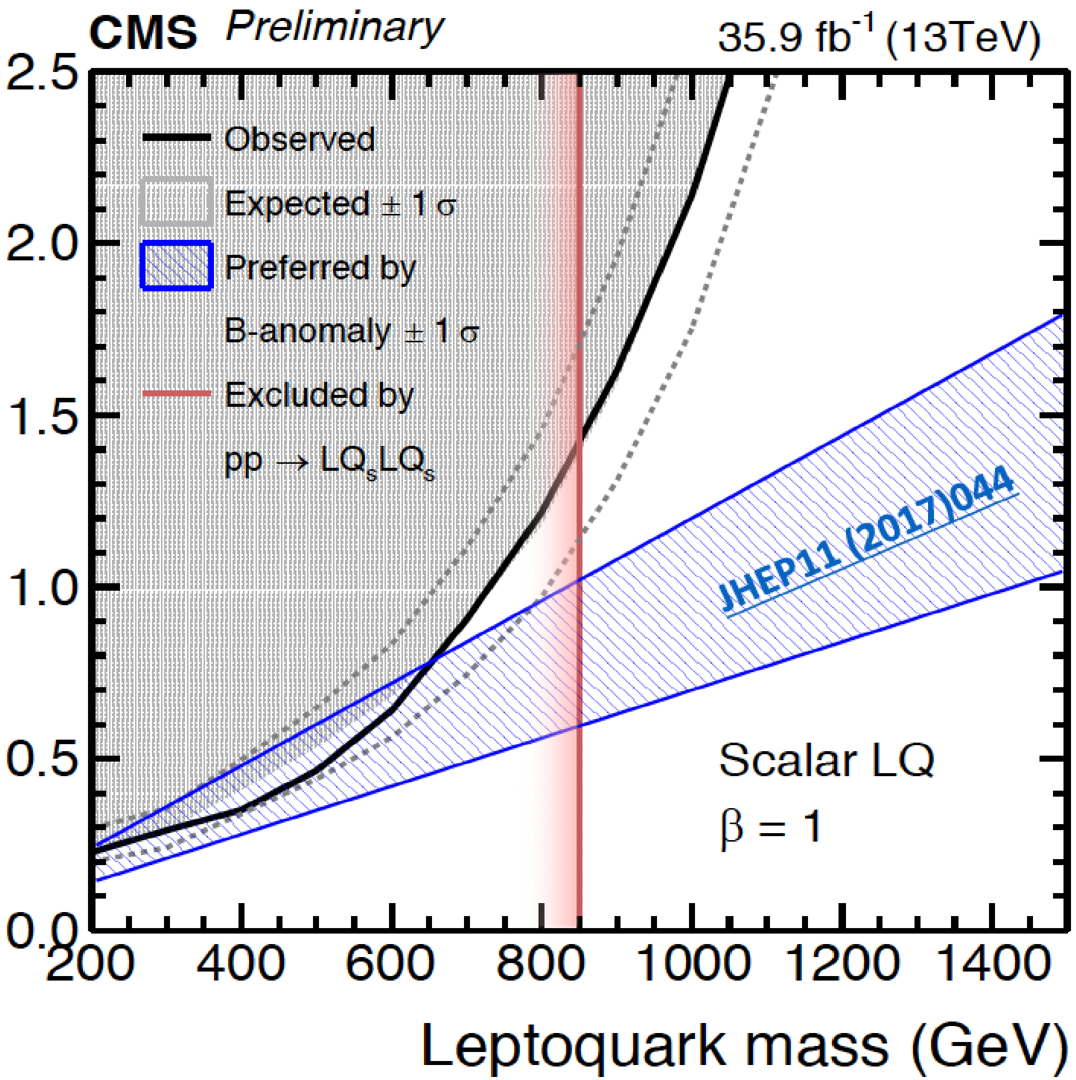
⬇

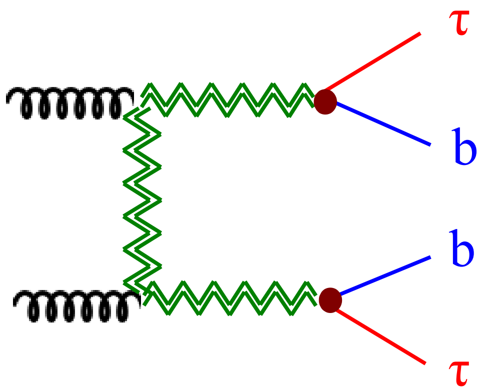
Significant room for improvement for the corresponding searches @ HL-LHC
But only HE-LHC would be able to rule out all reasonable models

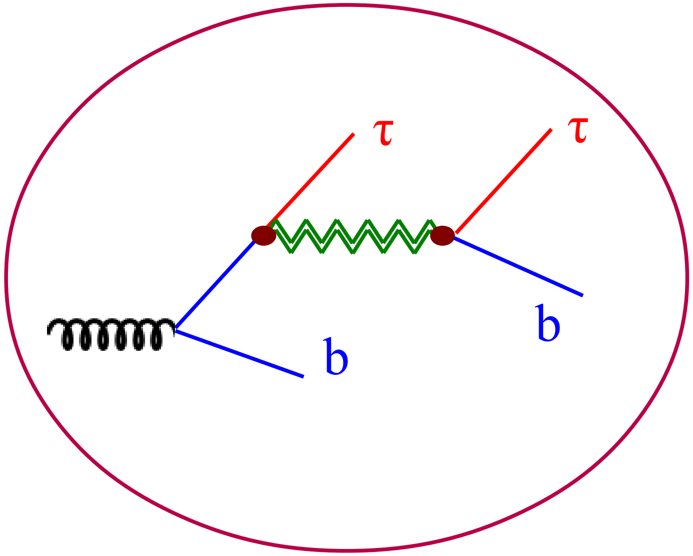
▸ *Implications for high-p_T physics*

Also as far as direct searches are concerned, 3rd gen. LQ are in good shape:

N.B.: The single production might be quite relevant



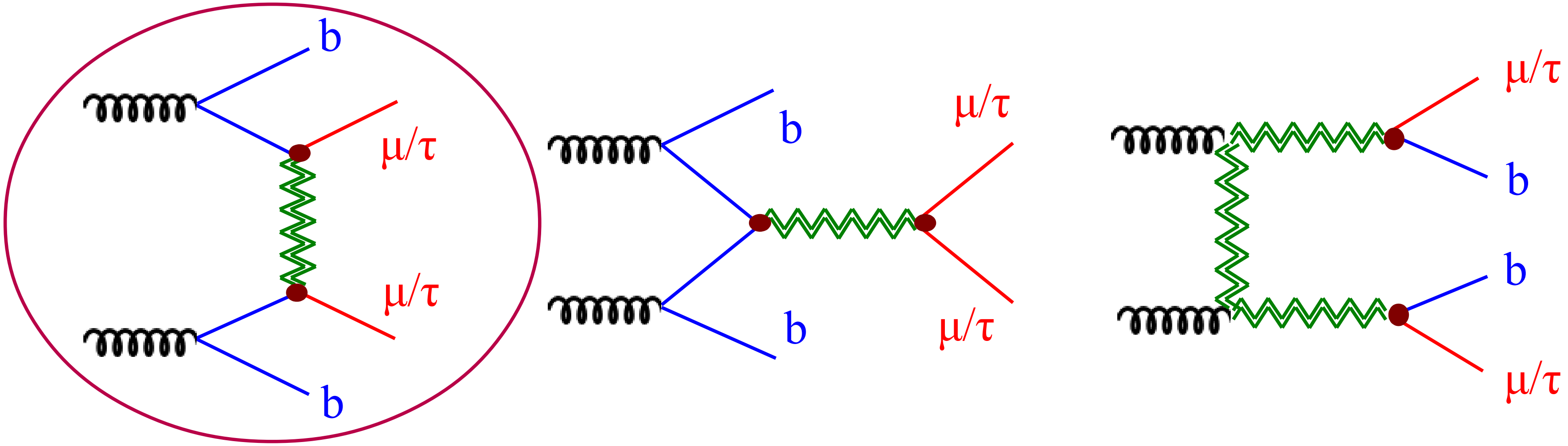




▸ *Implications for high-p_T physics*

Additional considerations for direct searches:

I. The production of all type of mediators occurs predominantly in conjunction with b quarks → b-tag helps



II. The R_D anomaly unambiguously points out to large pp → ττ (independently of the mediator), but narrow peaks in ττ disfavored

III. BR into μ pairs (or μτ) always expected but naturally suppressed vs. taus [O(0.1) @ amplitude level for each muon – larger model dependence] except in models addressing only R_K

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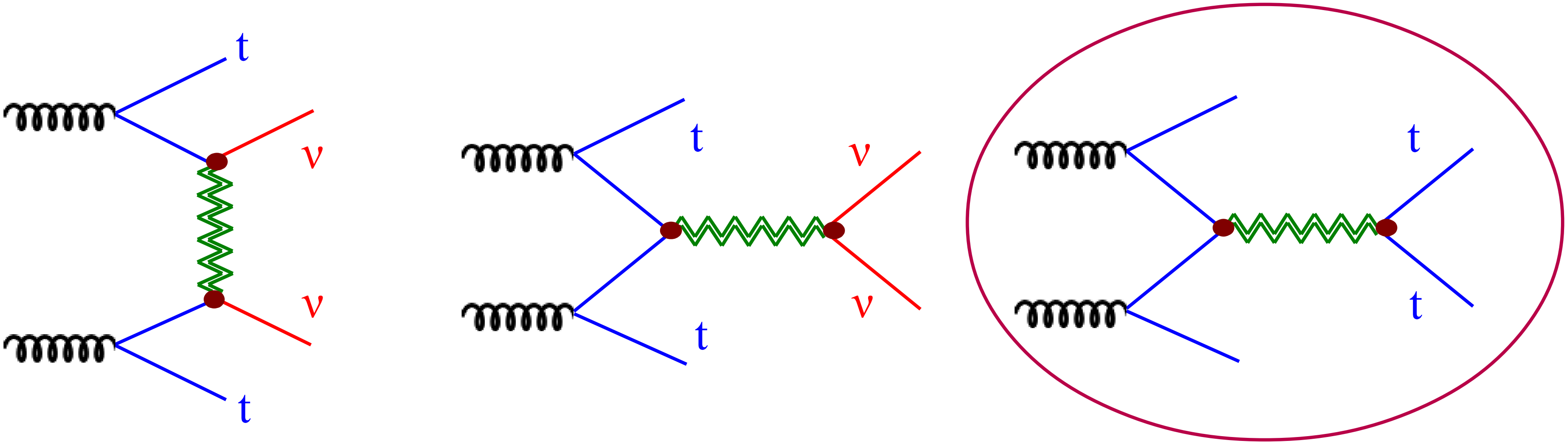

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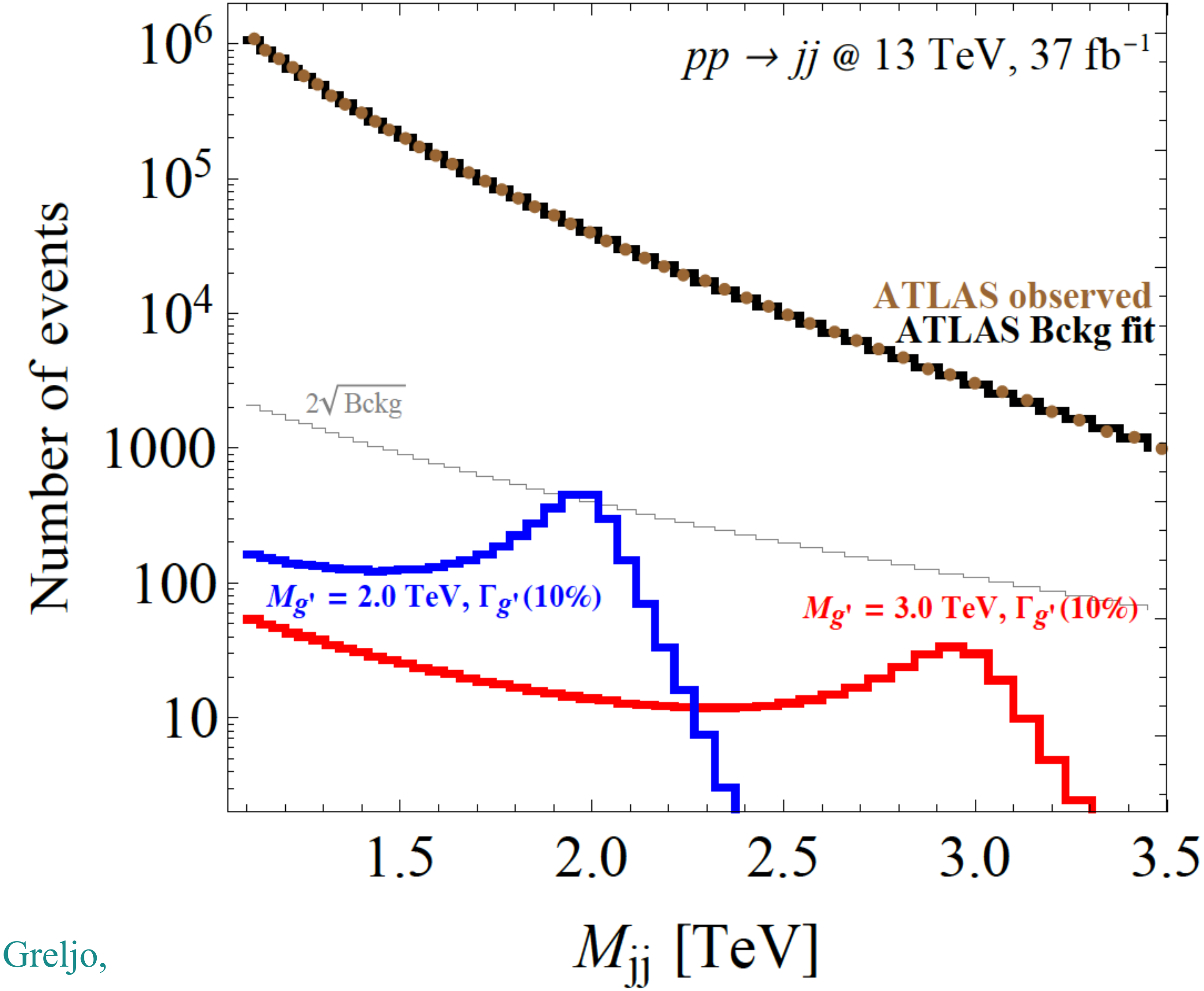
VI. Large BRs into top pairs naturally expected in most models, especially when considering also "additional" heavy states

▸ *Implications for high-p_T physics*

E.g.: The “Coloron”

In models such as PS^3 or the 4321, the LQ is accompanied by a (non-universal) heavy gluon, coupled mainly to 3rd gen.



Di Luzio, Fuentes-Martin, Greljo, Nardecchia, Renner '18

- *Implications for high-p_T physics*

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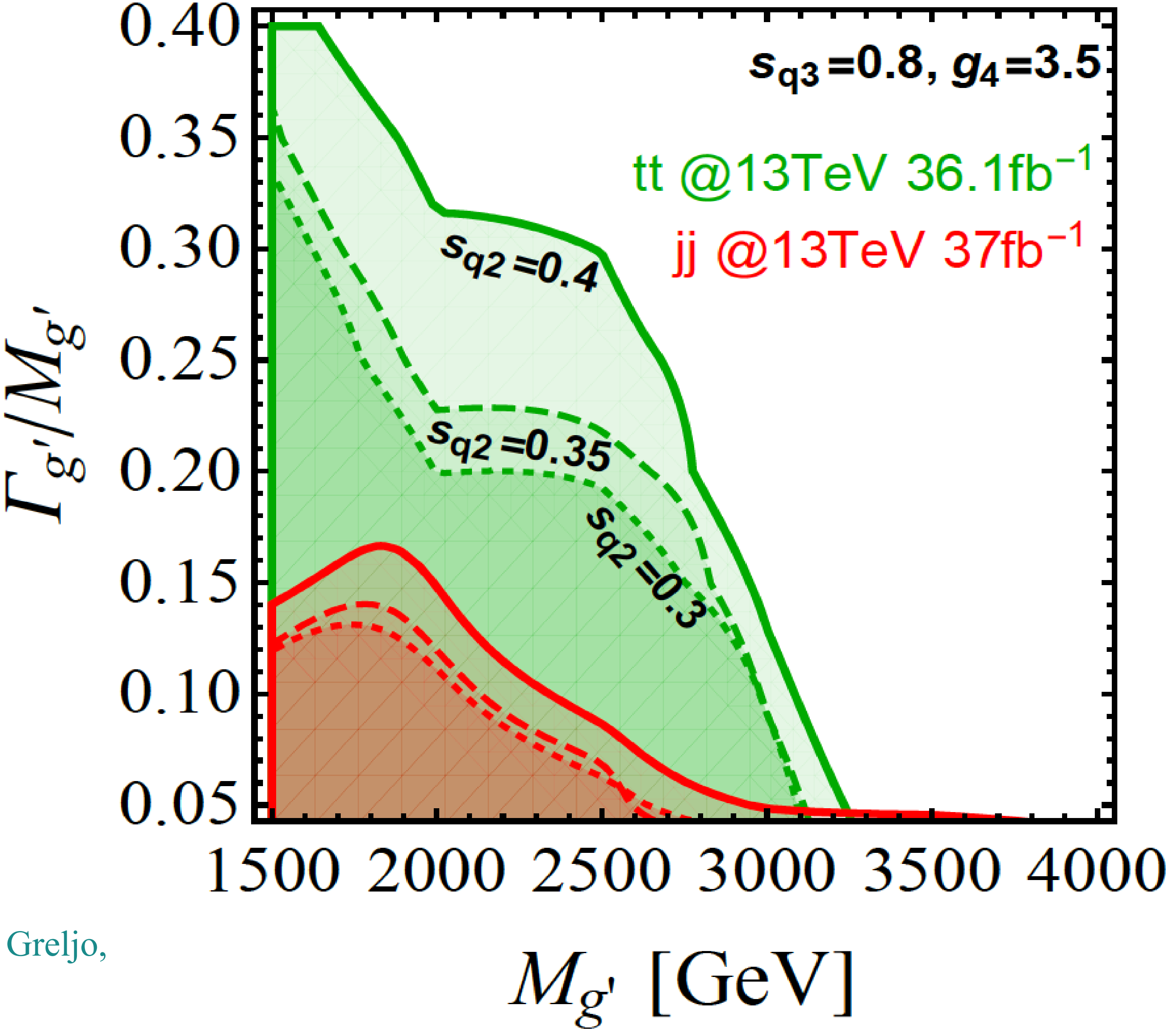


Di Luzio, Fuentes-Martin, Greljo, Nardecchia, Renner '18

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 approach in model building that these anomalies could imply.
But many points/possible-variations remains to be clarified/explored...

↓

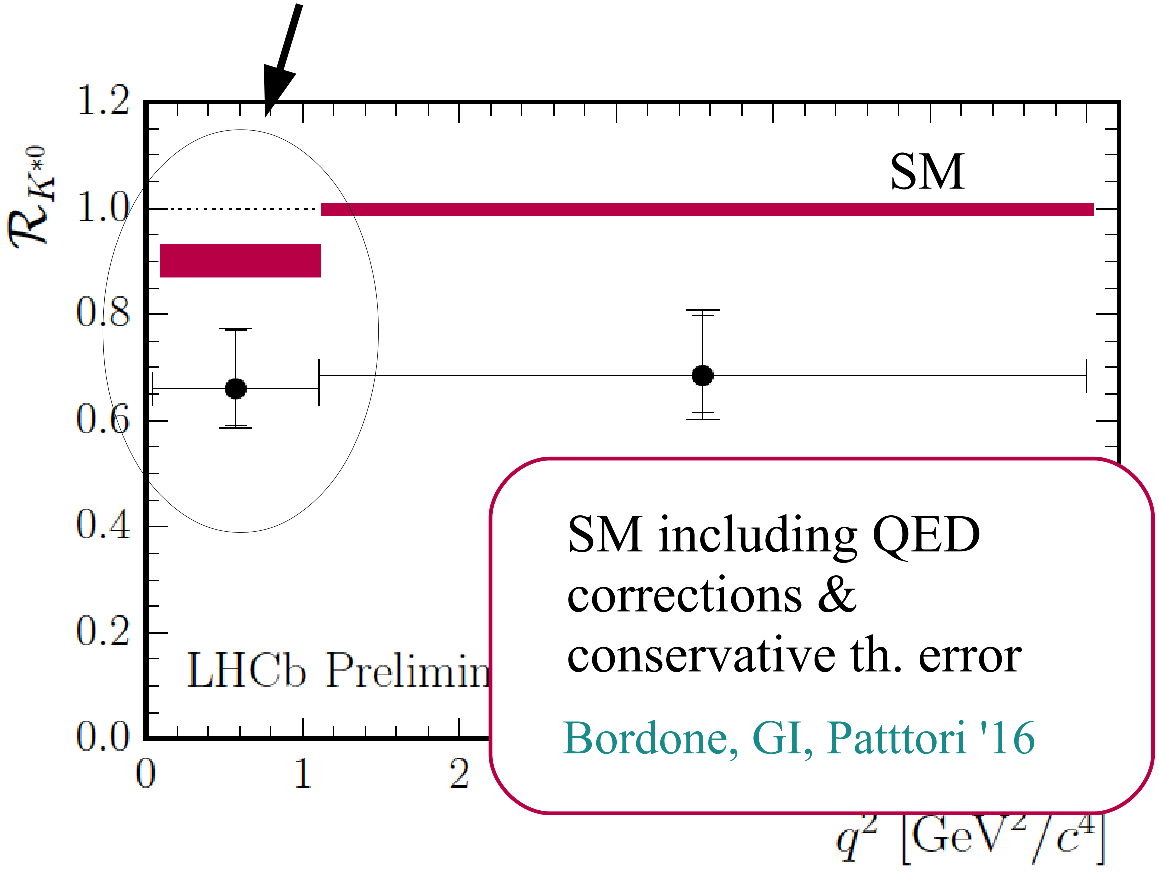
A lot of fun ahead of us...
(both on the exp., the pheno, and model-building point of view)


Backup

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

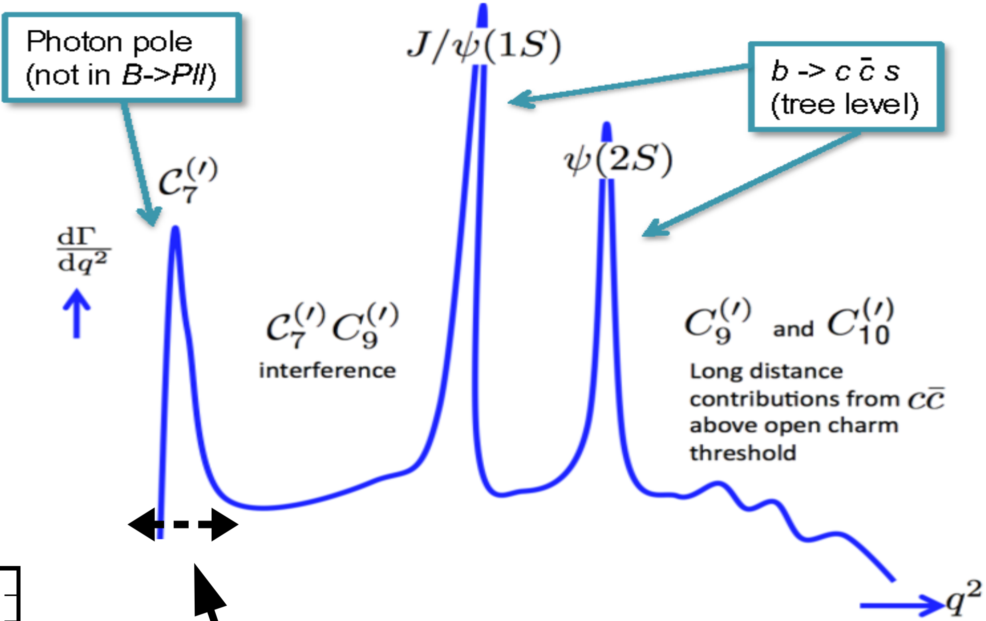
Technical note: I don't think we should be too worried about the low-q^2 bin...

“dangerous” choice of the bin starting from the di-muon threshold



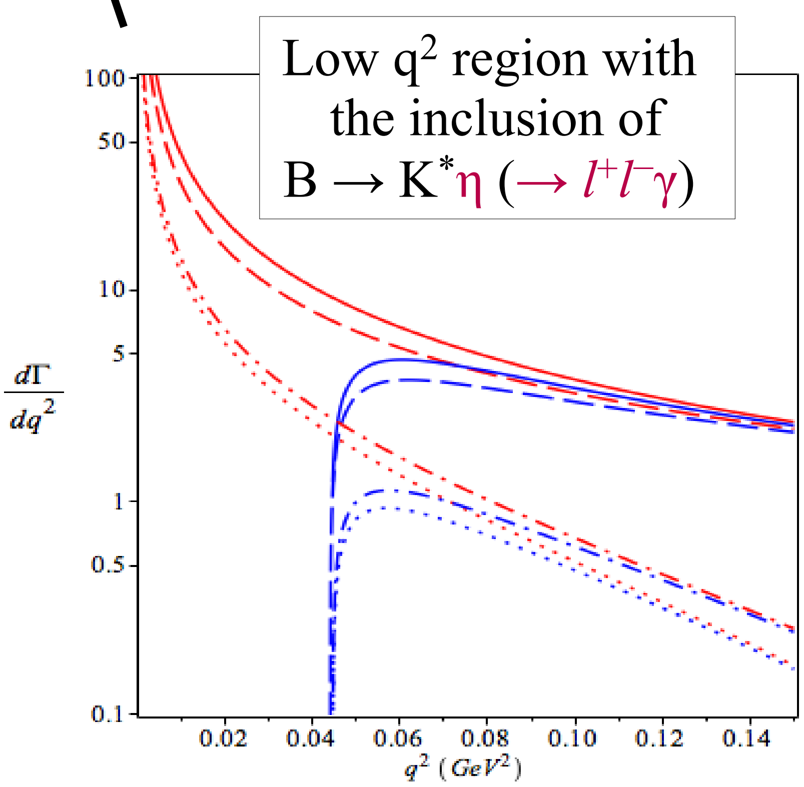
SM including QED corrections & conservative th. error

Bordone, GI, Patttori '16



Photon pole (not in B->Pll)

b -> c $\bar{c}$ s (tree level)

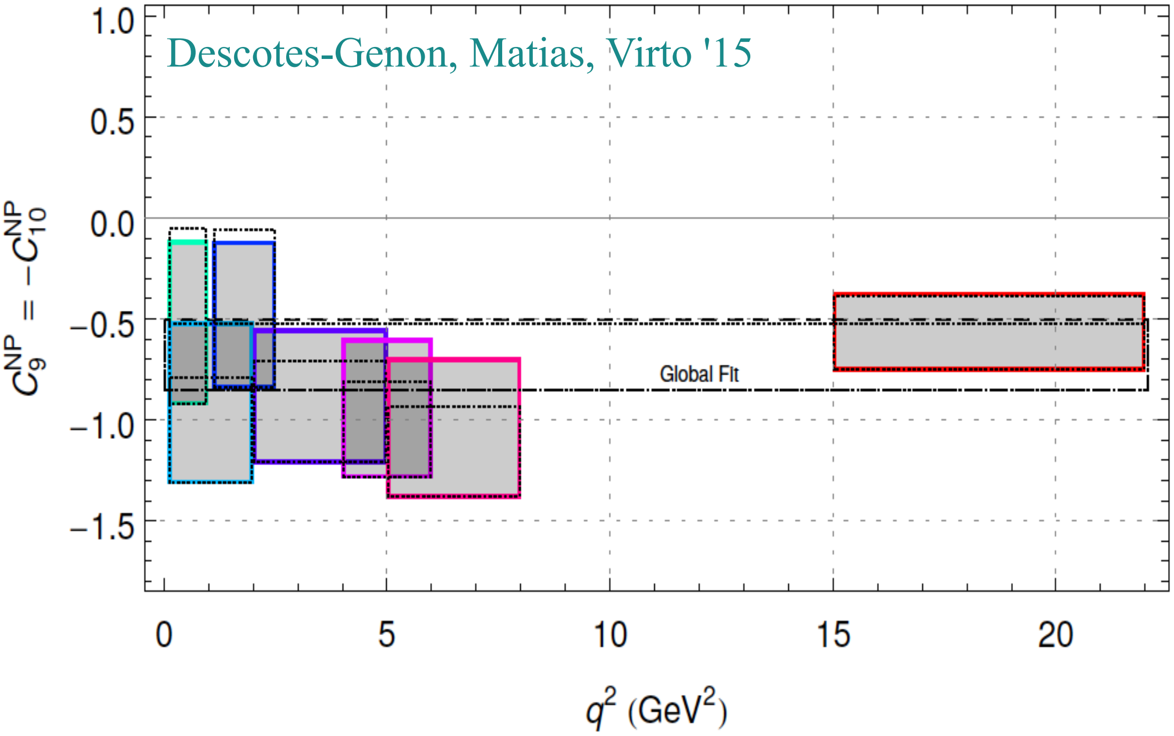


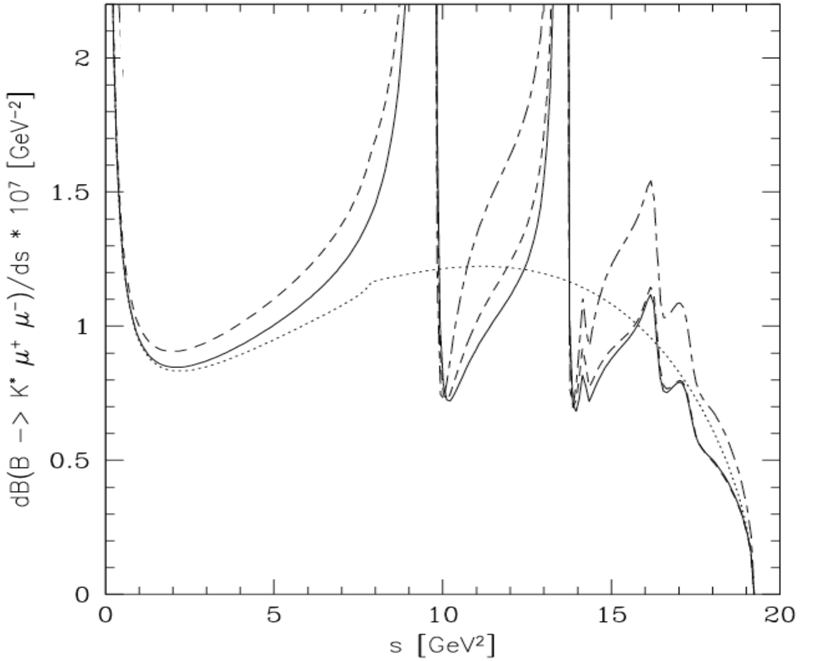
Low q^2 region with the inclusion of $B \to K^*\eta$ ($\to l^+l^-\gamma$)

Anomalies in $B \to K^{(*)} \mu\mu$ / 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
Capdevila *et al.* '17; D'Amico *et al.* '17
Altmannshofer & Straub '13, '15
Ciuchini *et al.* '17; Hurth *et al.* '16, '17
Many others...


Descotes-Genon, Matias, Virto '15



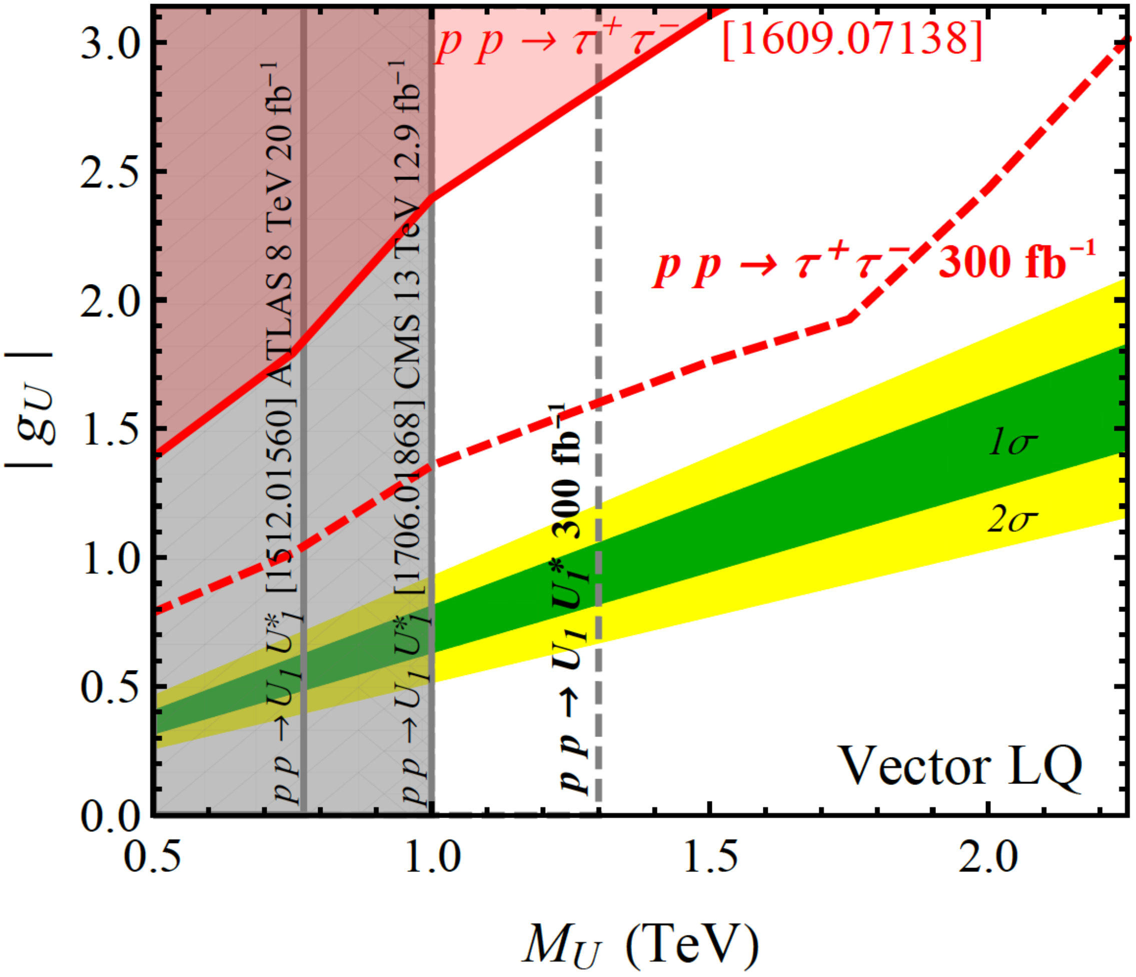
More precise data on the $q^2 = m_{\mu\mu}$ distribution can help to distinguish NP vs. SM

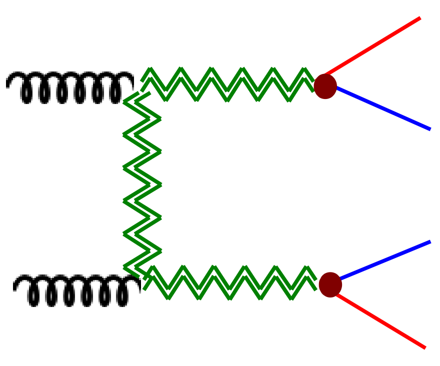
▶ Implications for high-p_T physics

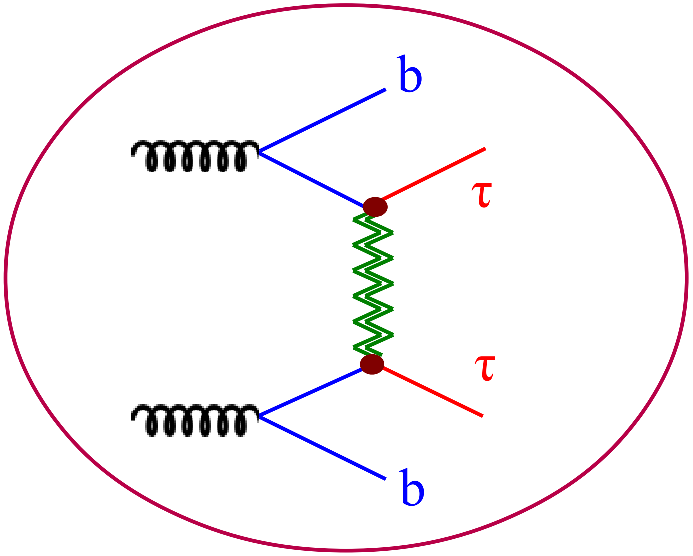
Also as far as direct searches are concerned, 3rd gen. LQ are in good shape:

At high masses pp → ττ is the most effective search mode

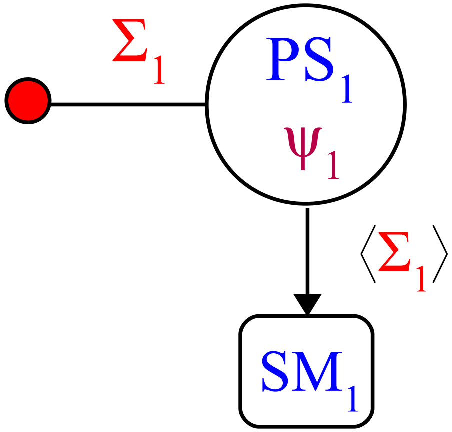
Buttazzo, Greljo, GI, Marzocca, '17

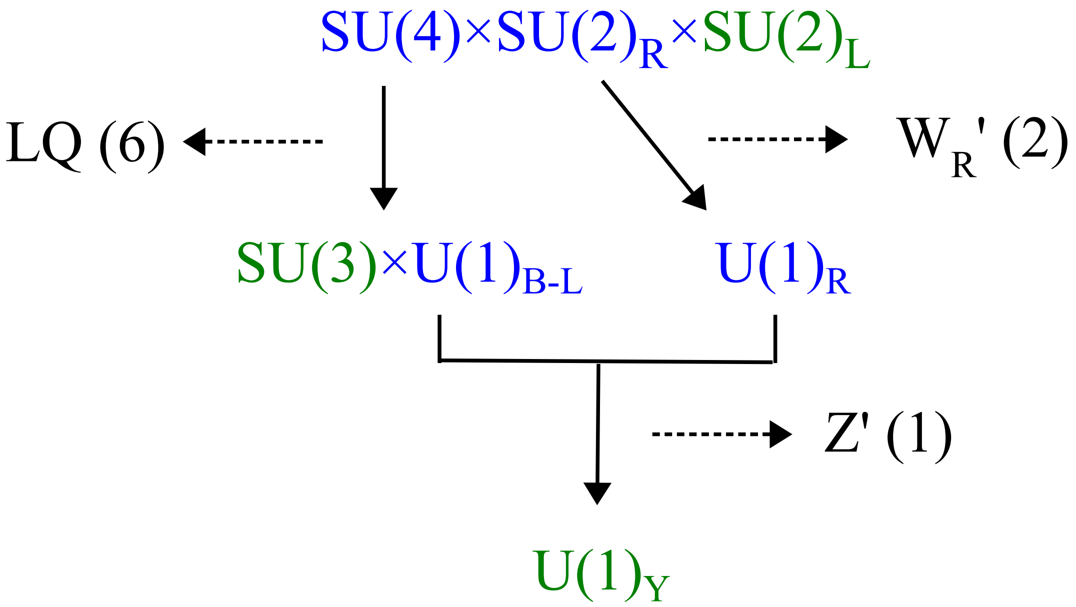






- *Symmetry breaking pattern in* PS^3





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

LQ (6)

W_R' (2)

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

$U(1)_R$

Z' (1)

$U(1)_Y$

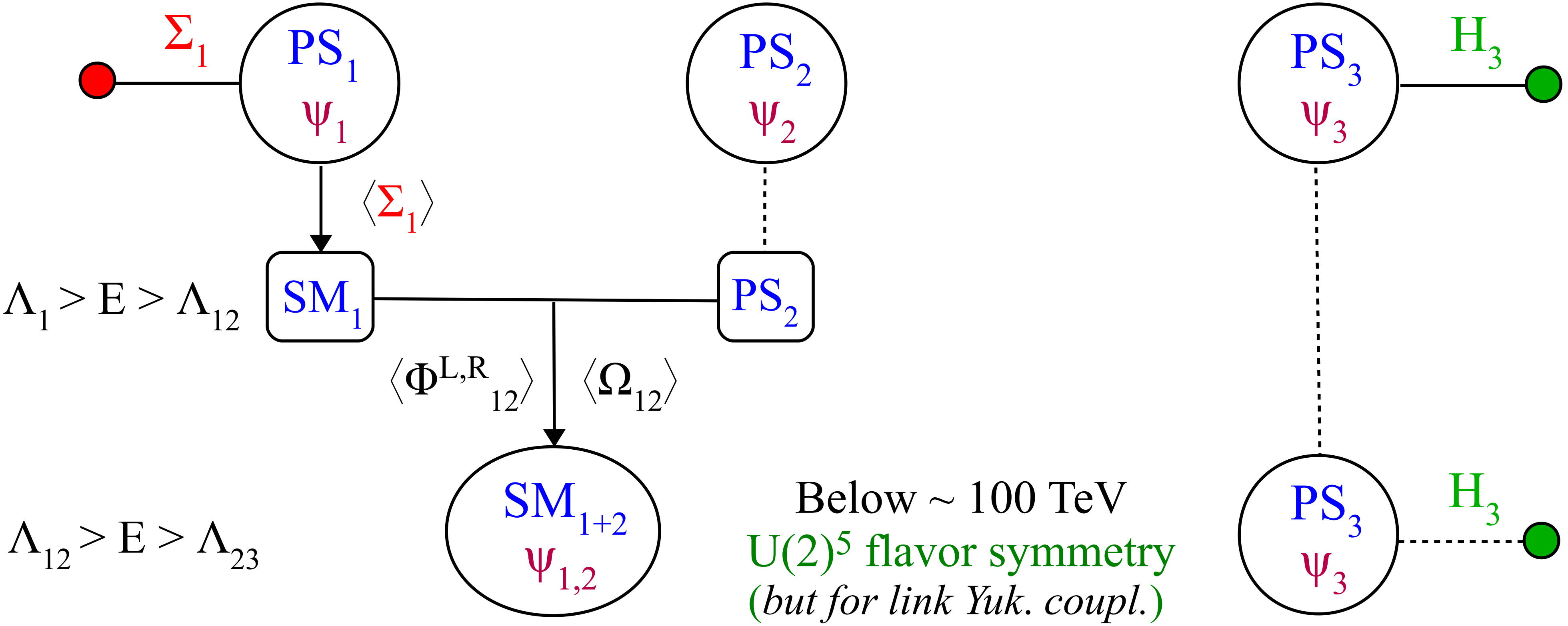
High-scale [~ 10^3 TeV]
"vertical" breaking [PS → SM]

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

↓

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

Symmetry breaking pattern in PS^3



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 $\rightarrow SU(4)_{1+2}$ & $SU(2)^L{}_{1+2}$