B-physics anomalies: model building & future implications

Gino Isidori
[*University of Zürich*]

- Introduction
- Part (I): *Model-building*
  - EFT-type considerations
  - Simplified models
  - UV completions
- Part (II): *Implications*
  - Low-energy measurements
  - High-pT physics
- Conclusions

Disclaimer:
This is not a review talk...
→ *no attempts to cite/discuss all models* (sorry !)

Introduction

Recent data show some convincing evidences of Lepton Flavor Universality violations

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

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

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

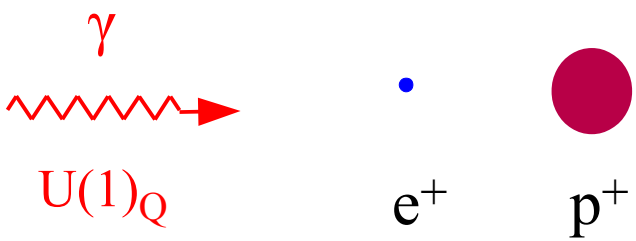
What is particularly interesting, is that these anomalies are challenging an assumption (LFU), that we gave for granted for many years (*without many good theoretical reasons...*)

⬇

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

Introduction [*a digression on LFU*]

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



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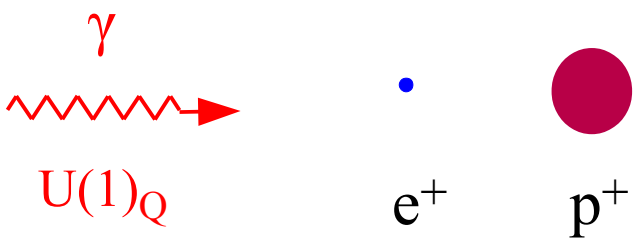
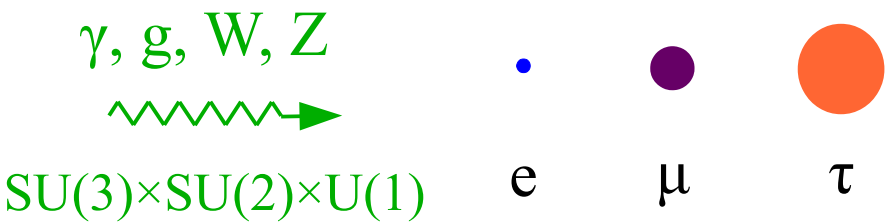


These two particles seems to be "identical copies" but for their mass ...

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



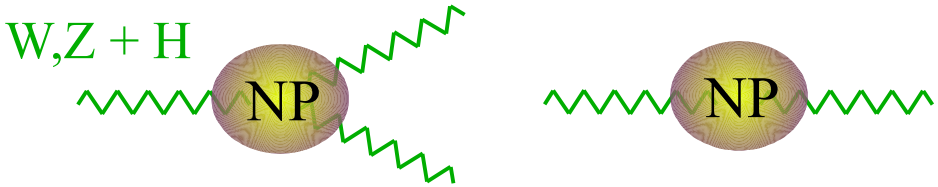
These three (families) of particles seems to be "identical copies" but for their mass ...

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

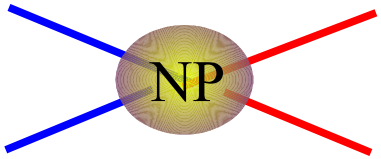
Introduction [*a possible shift of parading in model-building*]

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

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



large (*more interesting...*)



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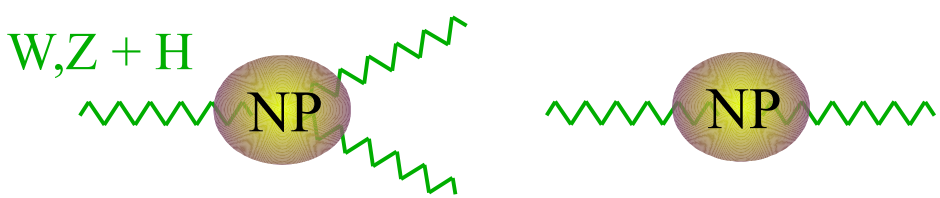
The recent flavor anomalies seem to suggest a shift of paradigm:

- 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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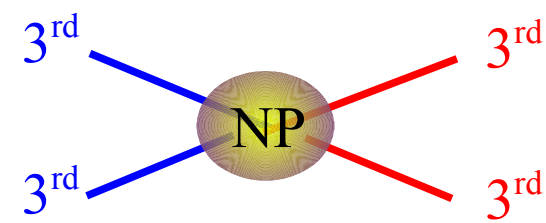

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Part (I): *Model-building*

- EFT-type considerations
- Simplified models
- UV completions

EFT-type considerations

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- $b \to c$ charged currents: τ vs. light leptons (μ, e) [R_D, R_{D*}]
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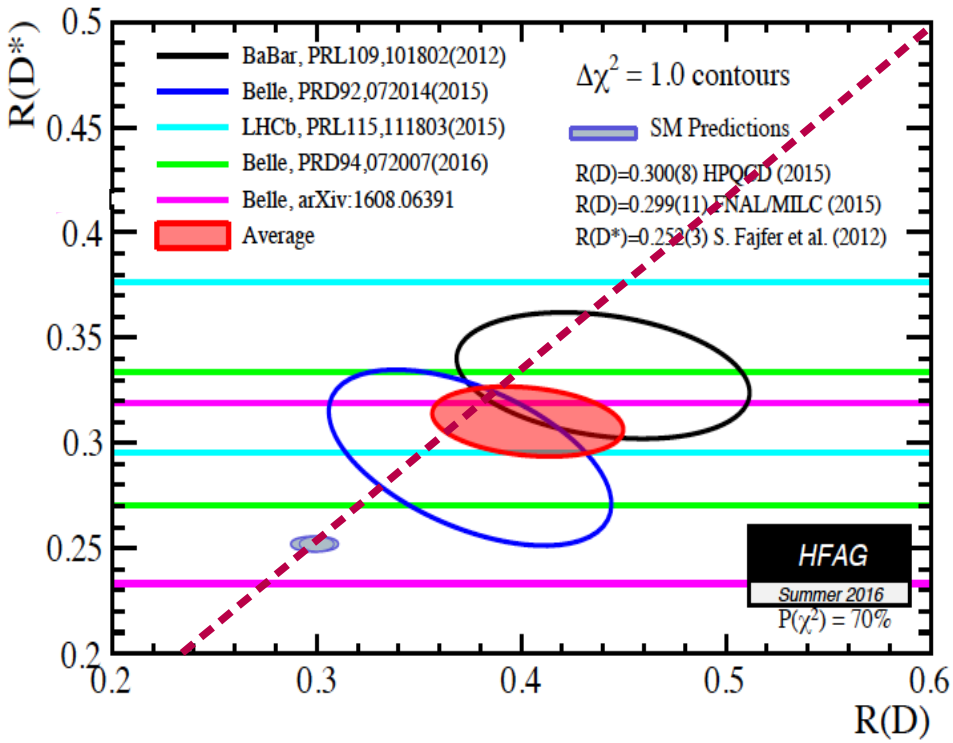
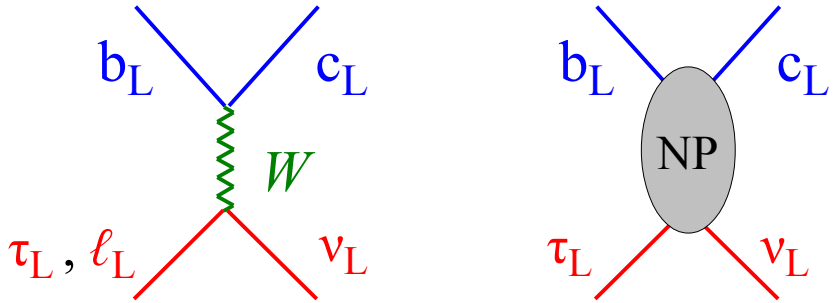
→ *talks Thursday morning*





- R(D) and R(D*) consistent with a universal enhancement (~30%) of the SM $b_L \to c_L\, \tau_L\, \nu_L$ amplitude

(*RH or scalar amplitudes disfavored*)

EFT-type considerations

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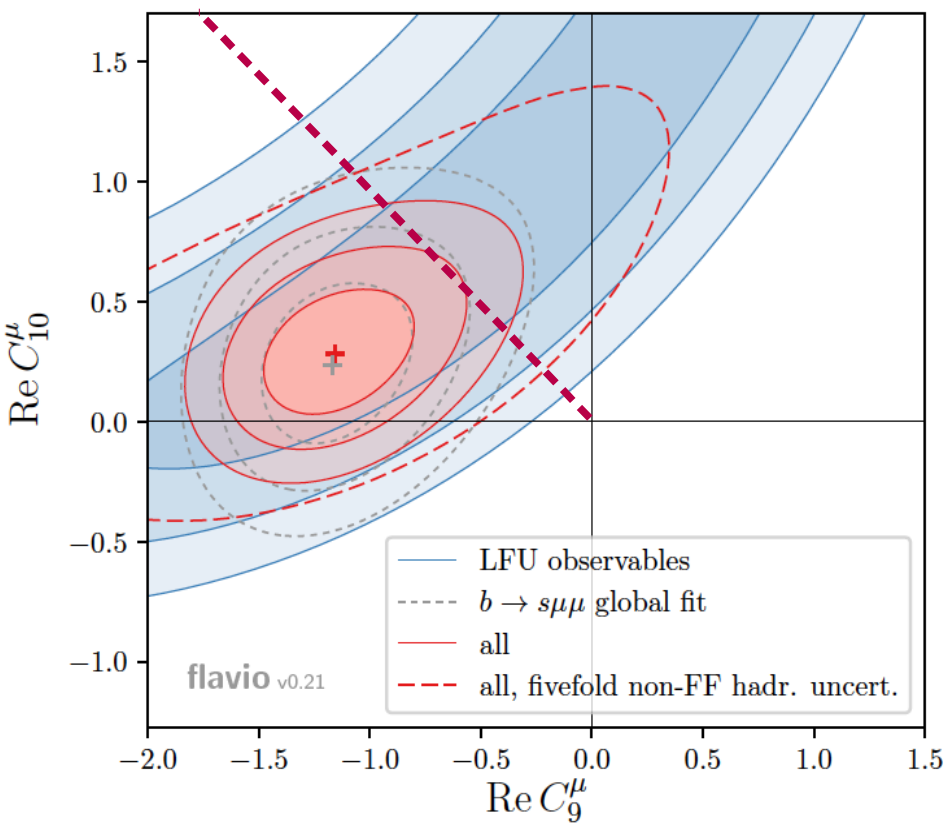
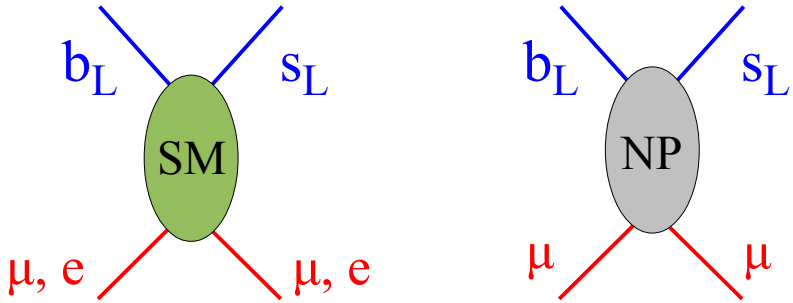
→ *talks Wednesday morning*

Altmannshofer, Stangl, Straub '17





- All effects well described by NP 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

EFT-type considerations

- Anomalies are seen only in semi-leptonic (quark×lepton) operators
- RR and scalar currents disfavored → LL current-current operators
- Necessity of at least one $SU(2)_L$-triplet effective operator is we aim to a combined explanation (*as in the Fermi theory*):

$$\frac{g_q g_\ell}{\Lambda^2}\lambda^q_{ij}\lambda^\ell_{kl}(\bar{Q}^i_L T^a\gamma_\mu Q^j_L)(\bar{L}^k_L T^a\gamma^\mu L^l_L)$$

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

- Large coupling (competing with SM tree-level) in bc → $l_3\,\nu_3$
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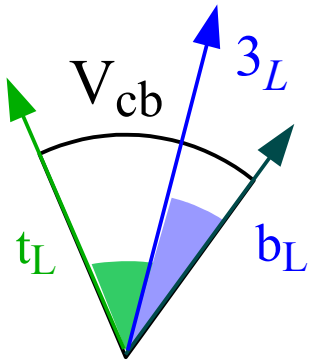
up to CKM rotations of $O(V_{cb})$



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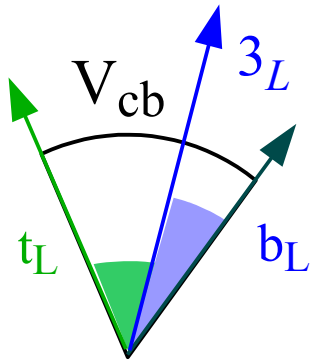

$$\lambda^{q,\ell}_{ij} = \delta_{i3}\delta_{3j} \; + \; \text{small corrections for } 2^{nd} \text{ (\& } 1^{st}\text{) generations}$$

→ *link to patterns in the Yukawa couplings*

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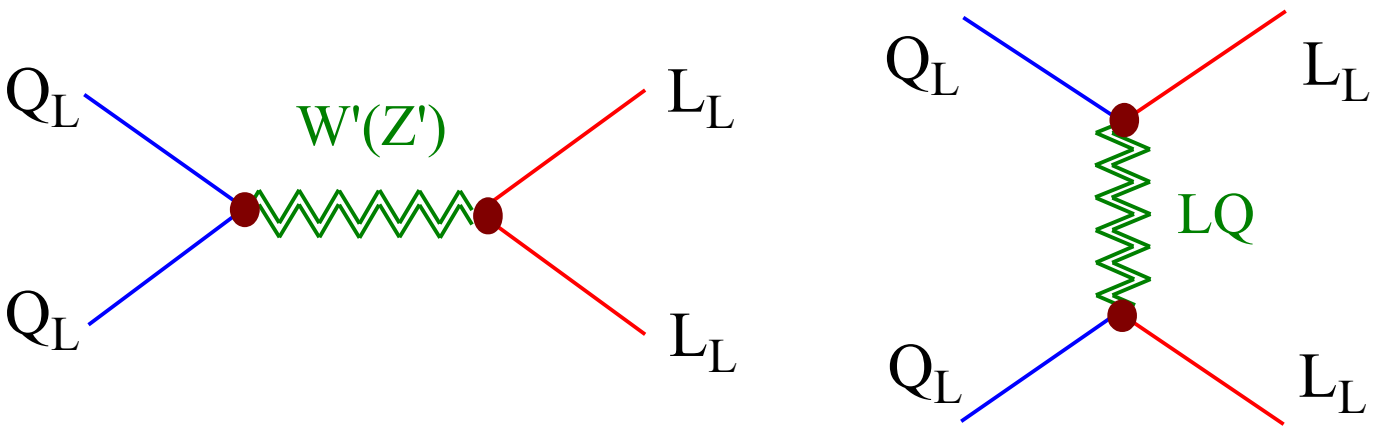
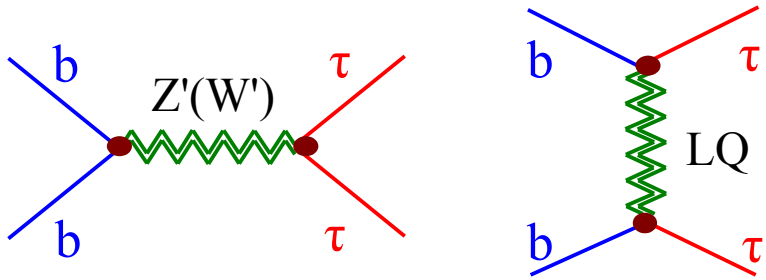


- Two classes of (tree-level) mediators, giving rise to different correlations among the anomalies, other low-energy observables, and high-p_T physics

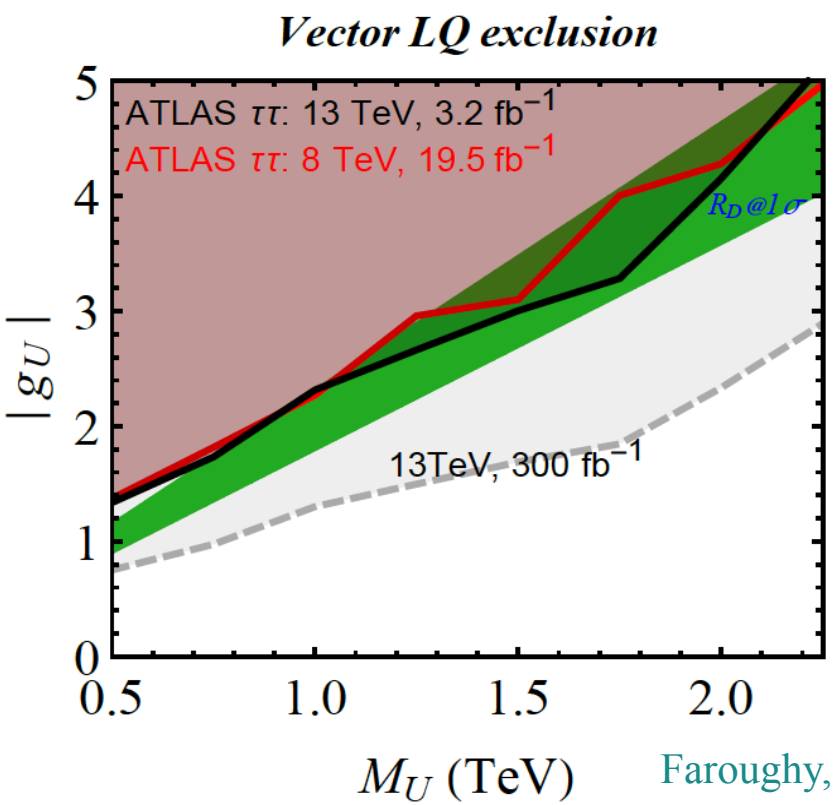
EFT-type considerations [The main problems]

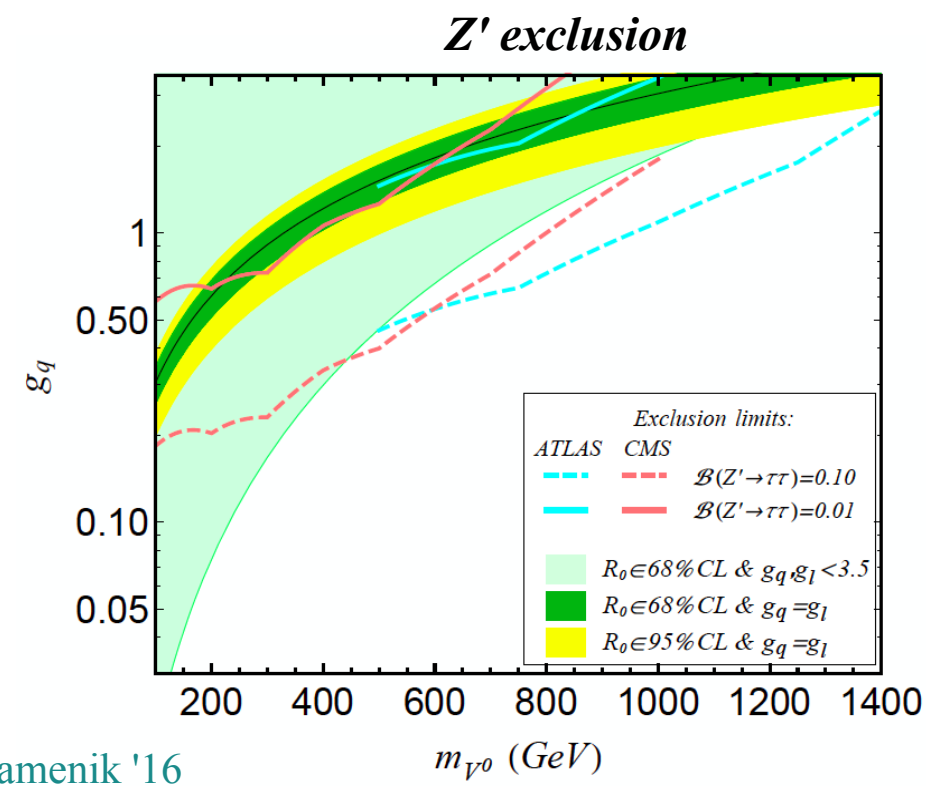
Three main problems identified in the recent literature (*driven mainly by R_D*...):

I. *high-p_T constraints*



Naïve EFT scale
[*from R_D - setting g, $\lambda \to 1$*]: $\Lambda \sim 700$ GeV





Faroughy, Greljo, Kamenik '16

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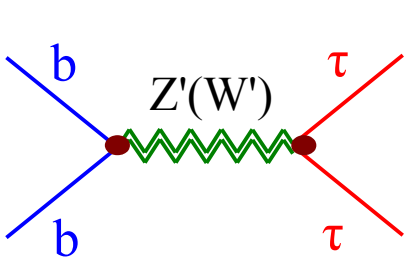
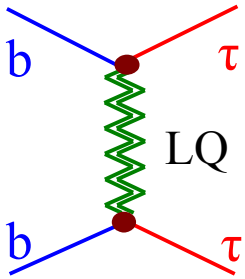
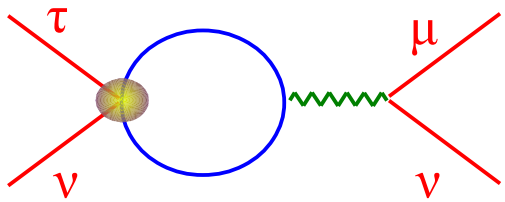
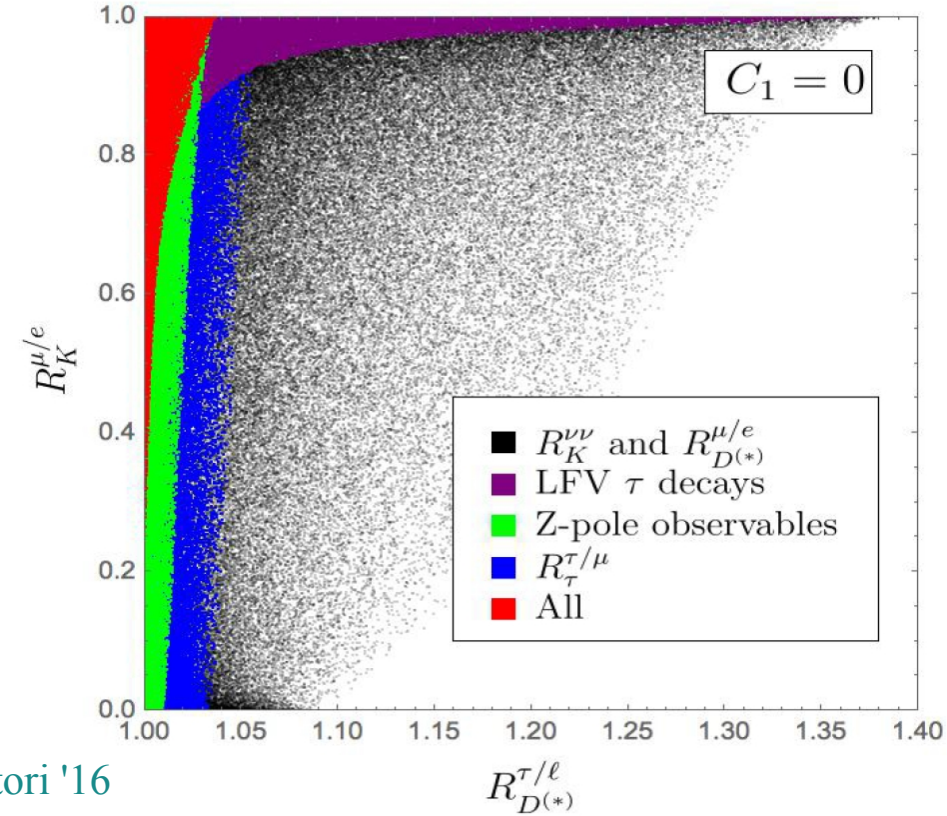




II. *radiative constraints*





Feruglio, Paradisi, Pattori '16

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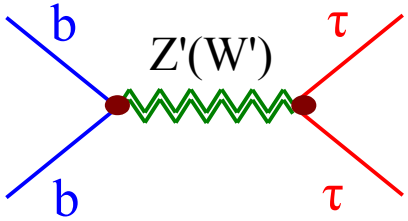

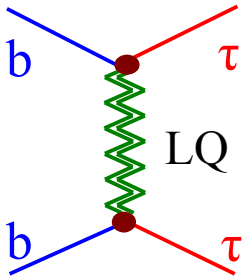

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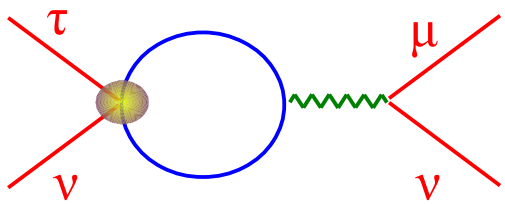
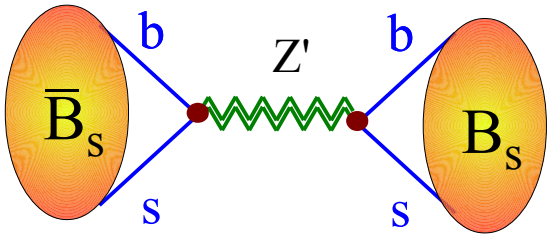
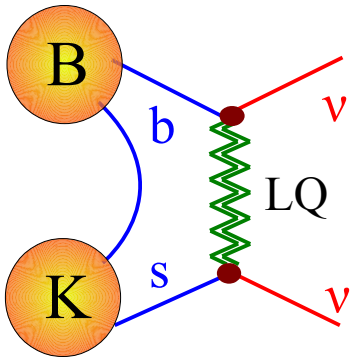


III. *flavor bounds*





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 is provided by a suitable EFT based on a few simple assumptions:

- 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"

⬇

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

→ *talk by Admir Greljo*

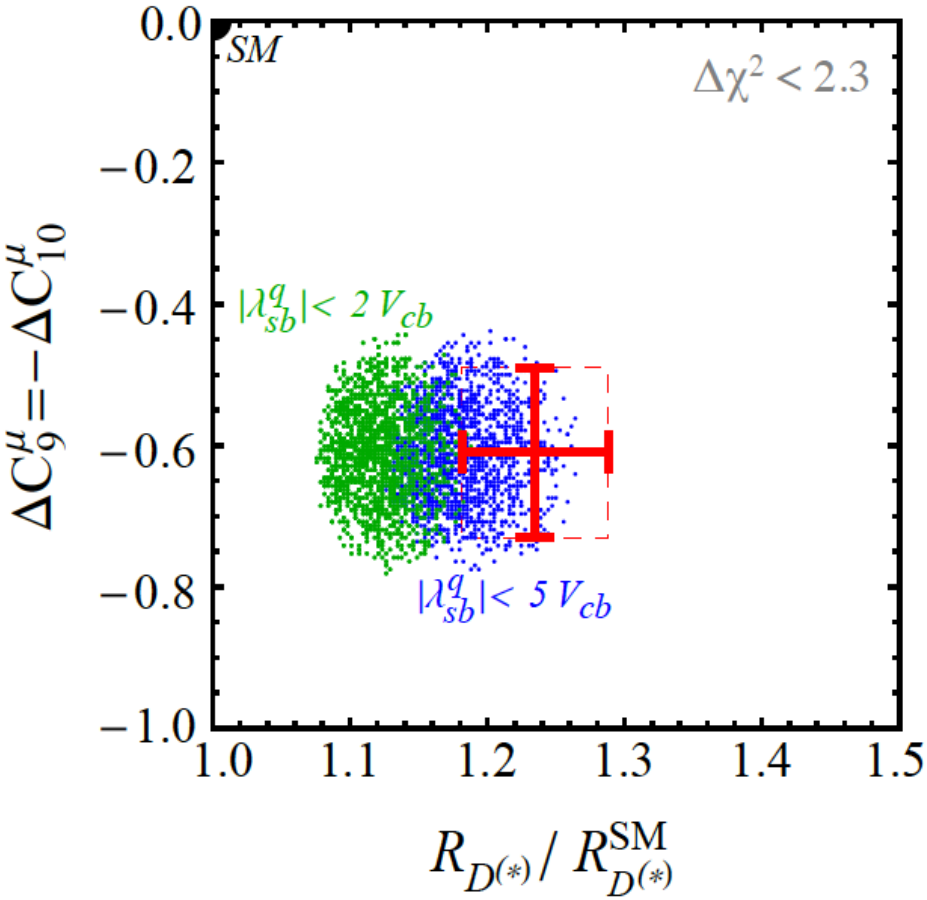
four free parameters...

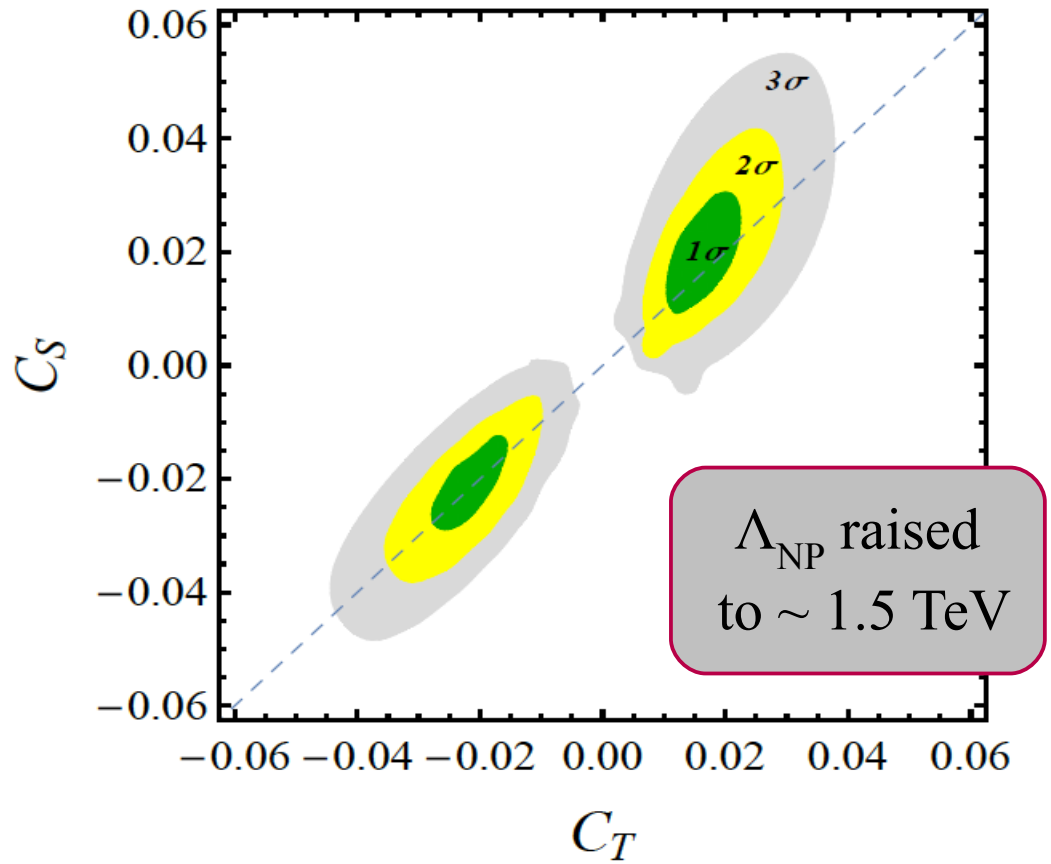
C_T, C_S
$\lambda_{bs} = O(V_{cb})$
$\lambda_{\mu\mu} = O(|V_{\tau\mu}|^2)$

...and a long list of constraints

EFT-type considerations [The global fit]

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 global fit]

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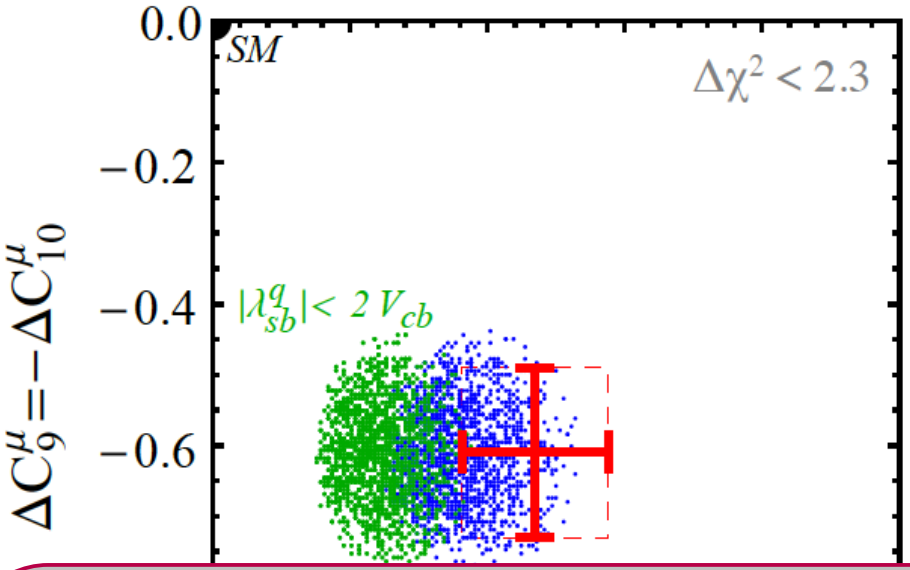

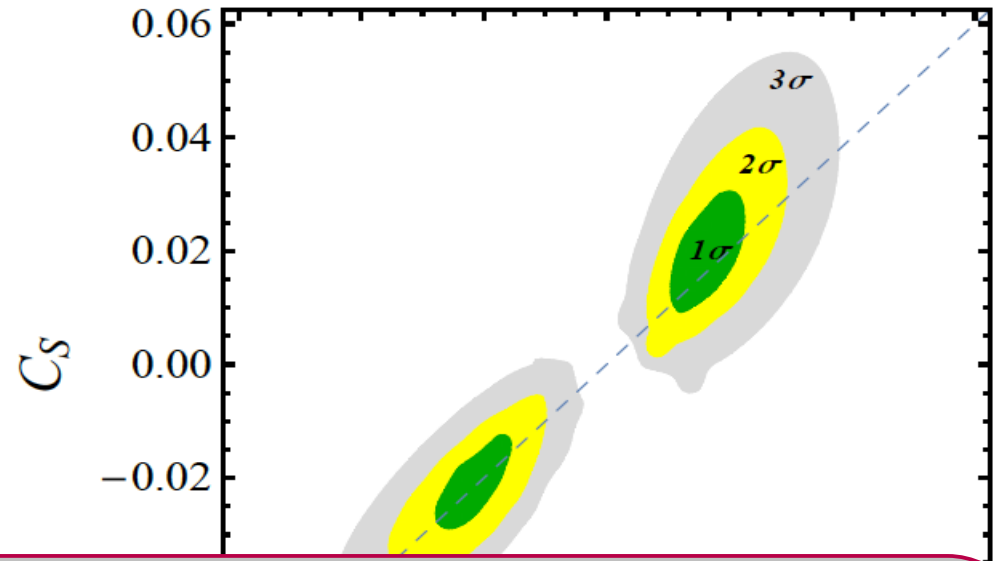

- This EFT approach shows that is possible to find a "combined" (*motivated*) explanation of the two set of anomalies. Very useful in identifying implications in other low-energy measurements [→ *more later...*]
- The EFT solution is not unique [e.g. sub-leading RH currents can be added], but large variations are possible only <u>if the R_D anom. goes away completely</u> [→ *higher effective NP scale, no need of charged curr.* → *an heavy Z' can do the job...*]

Simplified dynamical models

Simplified dynamical models

While the EFT is useful to derive relation among low-energy observables, *simplified dynamical models* with explicit mediators are particularly useful to

- reduce the number of free parameters (*not always...*)
- check the consistency with high-energy data (*that is quite relevant...*)
- identify possible UV completions

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'

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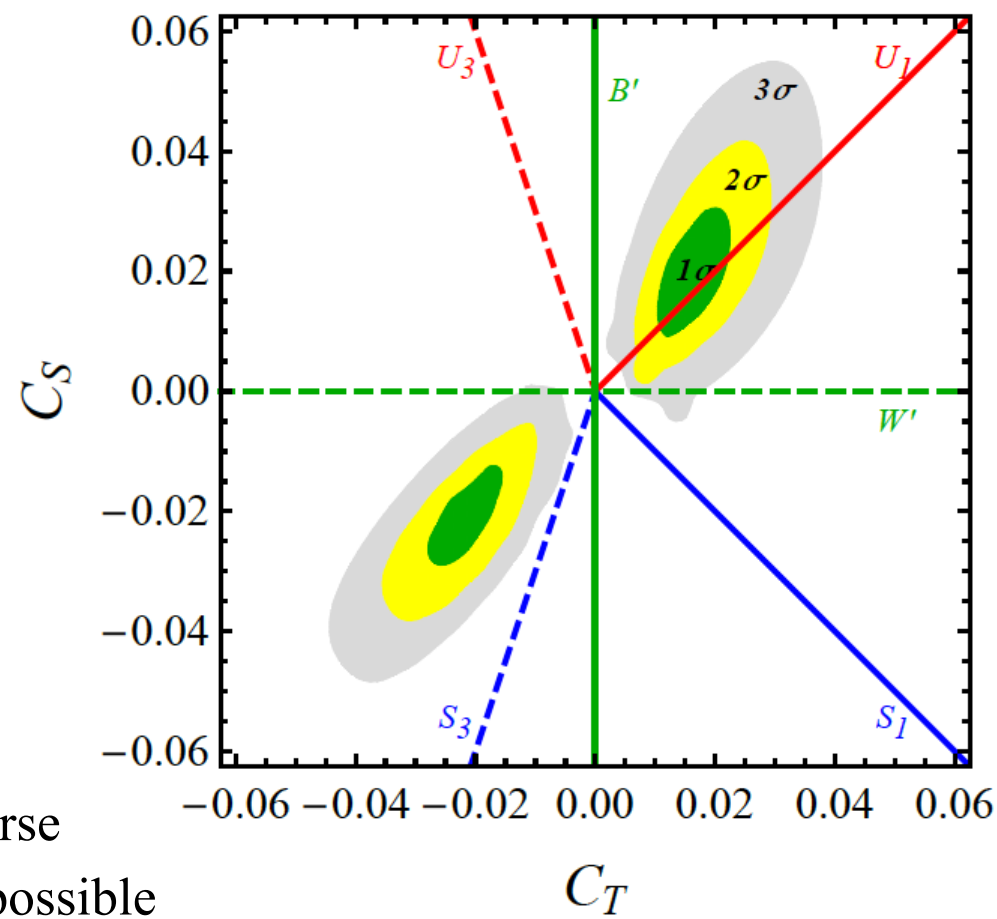

The U_1 option fits quite nicely... but of course models with more than one mediators are possible

- *Simplified dynamical models* [main features of the 3 options]

I. Vector LQ [U_1]

- Minimal number of free parameters (3) → very good fit of both R_{K^*} and R_D + all radiative constraints, without any tuning
- Not renormalizable at the level of simplified model (→ *quadratically divergent contribution to Bs mixing not fully under control*)
- UV completion not in main stream BSM...

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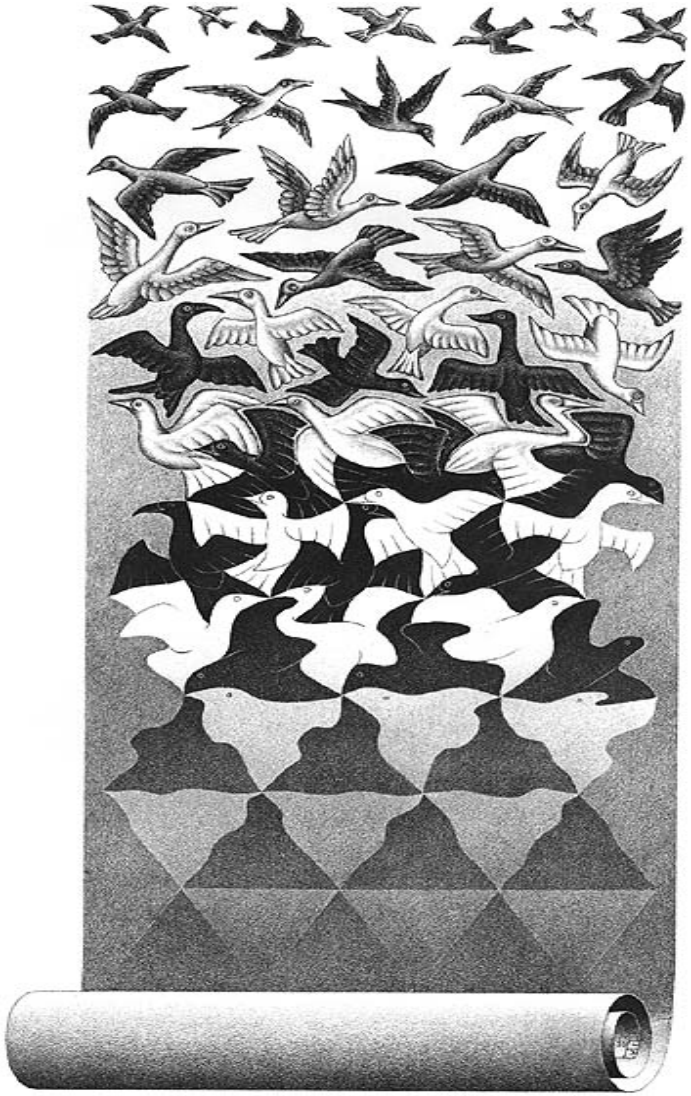
II. Scalar LQ model [S_1, S_3]

- Renormalizable (small contrib. to Bs mixing), easy to explain why these are the lightest NP states (possible NG bosons)
- Good fit of both R_{K*} and R_D + all radiative constraints require some adjustment among the coupling of the two mediators

III. Colorless vectors [W', Z']

- Very natural NP states in many NP models (↔ hierarchy problem)
- Significant (but not unnatural) tuning of the various couplings to evade bounds + light masses → tension with direct searches & Bs mixing

Speculations on UV completions



Speculations on UV completions

Two main approaches

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

- Possible connections to EW hierarchy prob.
- Light mediators as PNGB

- Rather ugly cosets...
- Limited calculability

Perturbative TeV-scale dynamics
[*renormalizable models*]

- Good predictive powers beyond lowest-order

- No simple connections to EW hierarchy prob. (*at least so far..*)

- Flavor structure put by hand (*at least so far..*)

Speculations on UV completions

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

- Scalar LQ as PNG
  Gripaios, '10
  Gripaios, Nardecchia, Renner, '14
- Vector LQ (or W',Z') as techni-fermion resonances
  Barbieri *et al.* '15, Buttazzo *et al.* '16
  Barbieri, Murphy, Senia, '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
  + ...

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

$SU(4)\times SU(3)\times SU(2)_L\times U(1) \to SM$

$SU(3)_C$

TeV-scale LQ [U_1] + Z' + G'

Ad-hoc flavor mixing with vector-like fermions

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
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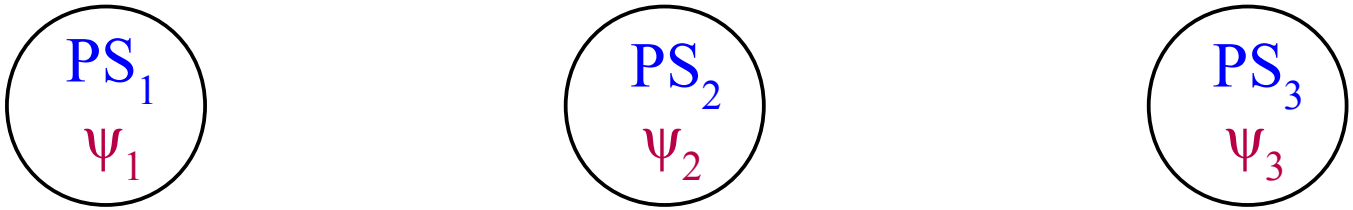
A more ambitious attempt...



A three-site gauge model for flavor hierarchies & flavor anomalies

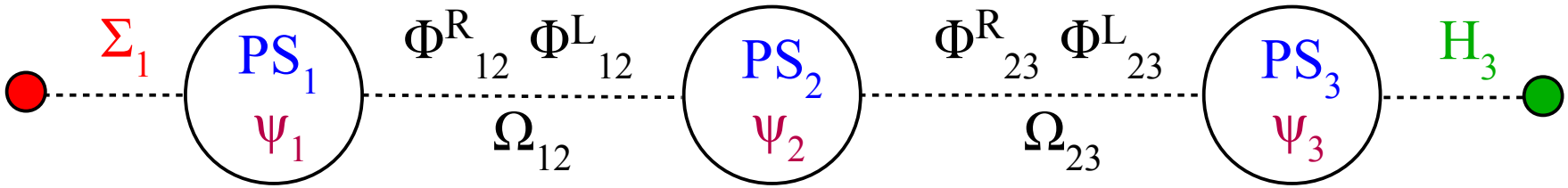
Bordone, Cornella, Fuentes-Martin, GI

to appear soon...

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

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

A more ambitious attempt...



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

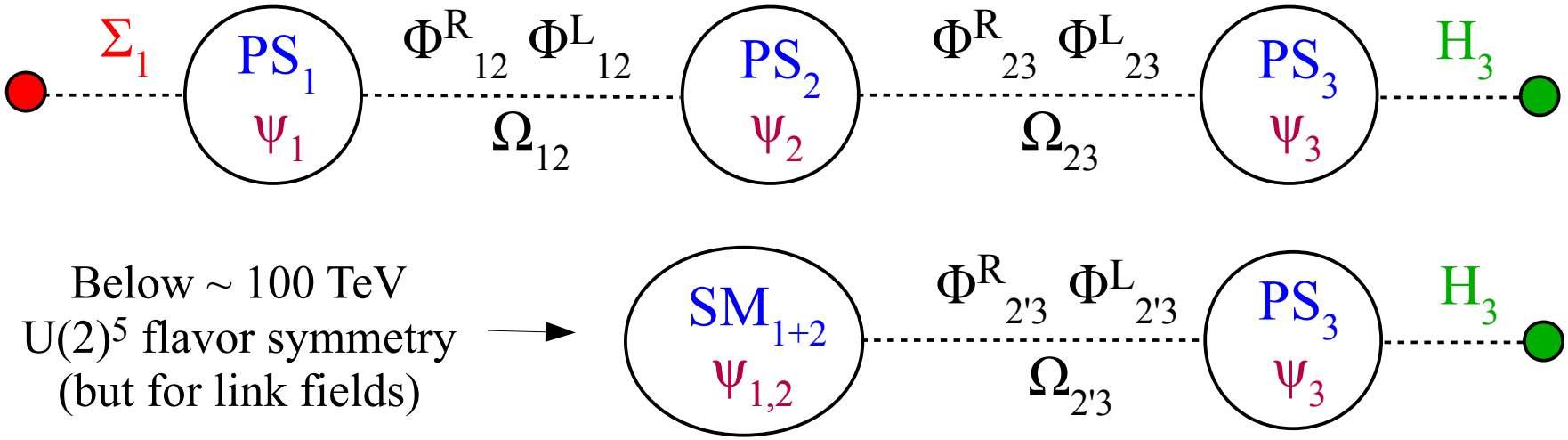
↓

QED_3 [$U(1)^Q_1$]

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

- 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. [very similar to "DGN-4321" but "natural" flavor structure & no vector-like quarks]

A more ambitious attempt...



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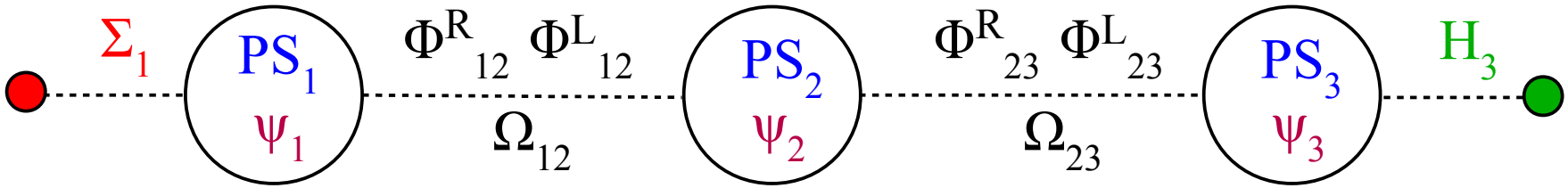
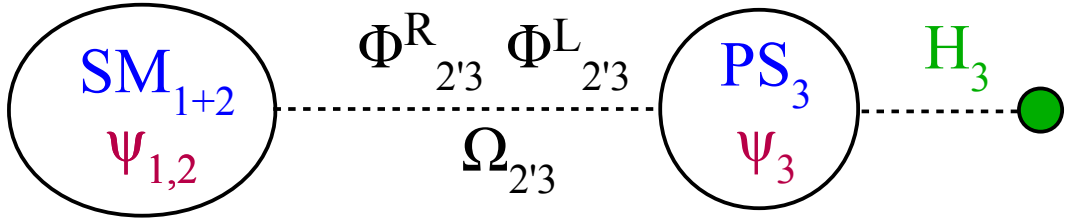


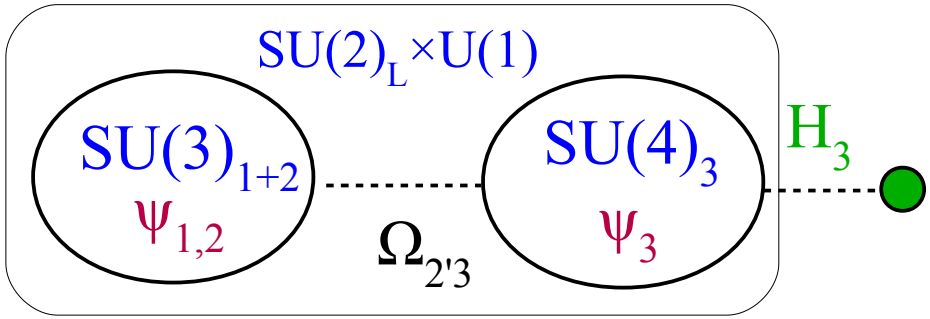
Below ~ 100 TeV
$U(2)^5$ flavor symmetry
(but for link fields)



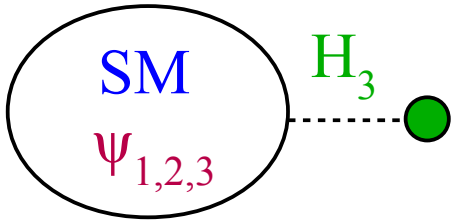
$\rightarrow W_L' + W_R'$ [~ 5-10 TeV]

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

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

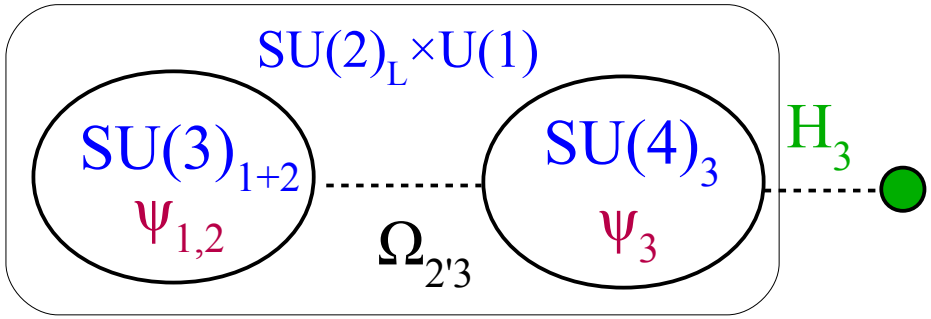


$\rightarrow$ LQ [U_1] + Z' + G' [~ 1-2 TeV]



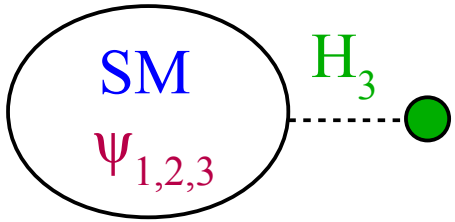
A more ambitious attempt...

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



→ LQ [U_1] + Z' + G' [~ 1-2 TeV]

In its minimal version, the model works better for R_D than for R_K (*LQ fully aligned to 3rd generation*)



But a good fit to R_K can be achieved with a (slightly) more involved structure of the link fields.

Part (II): *Implications*

- Low-energy measurements
- High-pT physics

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 upgrades (*I, II and beyond...*) and also other flavor physics facilities (Belle-II, Kaons, CLFV)

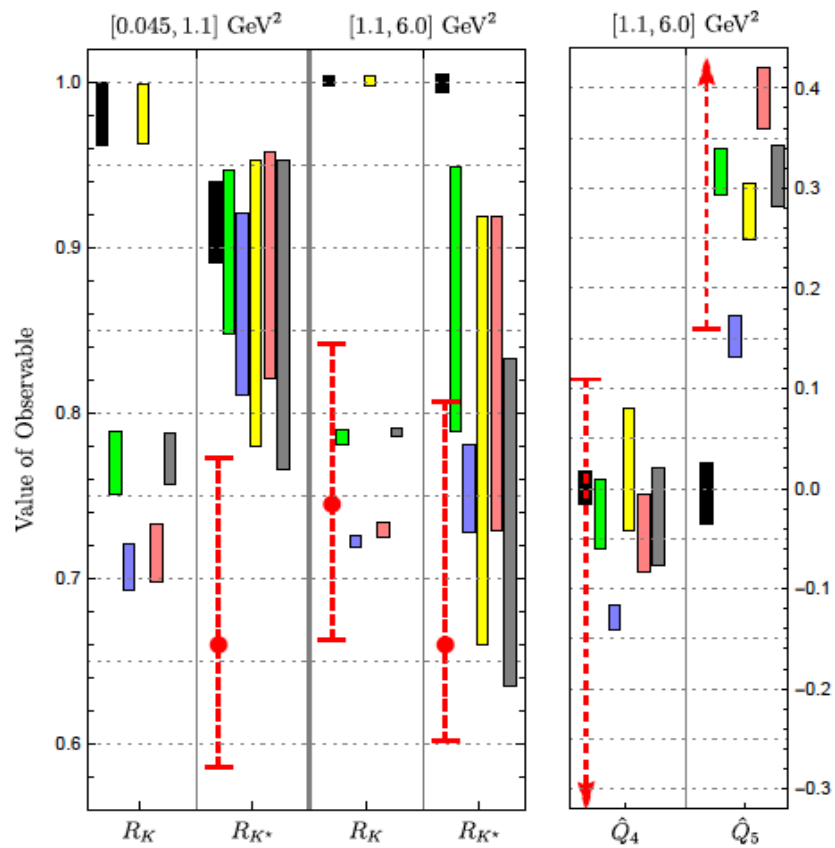
- This program is essential to determine the flavor structure of the new sector
- Correlations among low-energy obs. can be studied by means of EFT

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*]:

	μμ (ee)
$b \to s$	R_K, R_{K^*} *present anomalies*



Capdevila, Crivellin, Descotes-Genon, Matias, Virto 1704.05340

More statistics on the various $B \to K^{(*)}ll$ modes would allow to better determine the helicity structure of the amplitudes...

→ *talks on Wednesday morning*

Implications for low-energy measurements

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E.g.: 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^*} *present anomalies*	$B \to K^{(*)} \tau\tau$ ⋮	$B \to K^{(*)} \nu\nu$ ⋮
$b \to d$	$B_d \to \mu\mu$ $B \to \pi \mu\mu$ $B_s \to K^{(*)} \mu\mu$ ⋮	$B \to \pi \tau\tau$ ⋮	$B \to \pi \nu\nu$ ⋮
$s \to d$	*long-distance pollution*	*NA*	$K \to \pi \nu\nu$

Implications for low-energy measurements

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E.g.: 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%)	$B \to K^{(*)} \tau\tau$ $\to$ 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_π]	$B \to \pi \tau\tau$ $\to$ 100×SM	$B \to \pi \nu\nu$ O(1)
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R_D

R_K

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$b \to d$	$B_d \to \mu\mu$ $B \to \pi\, \mu\mu$ $B_s \to K^{(*)} \mu\mu$ O(20%) [$R_K = R_\pi$]	$B \to \pi\, \tau\tau$ $\to$ 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

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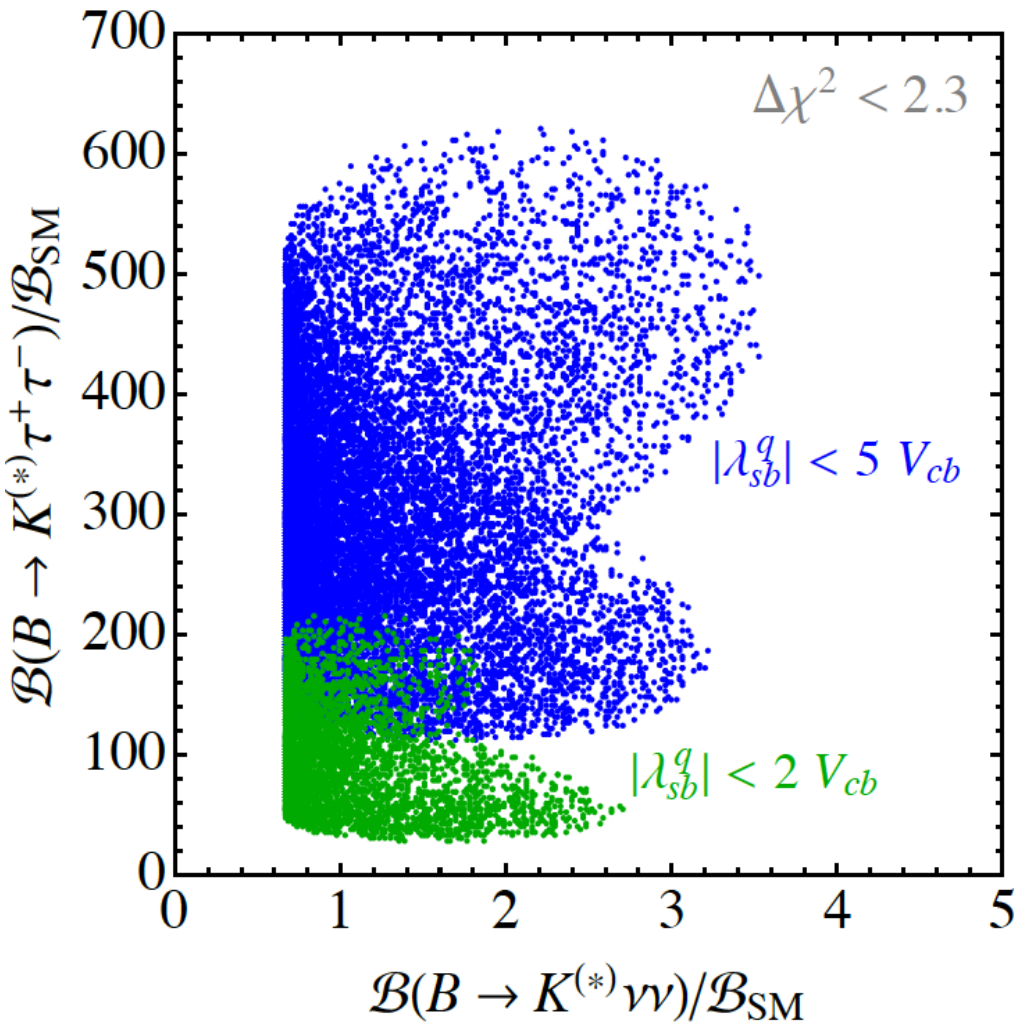

Crivellin, Muller, Ota '17
Buttazzo *et al.* '17

Implications for low-energy measurements

A similar table can be made also for charged currents, and in this case the predictions of the EFT are more simple/robust:

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

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

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

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Any mode for which we can predict well the LFU ratio is good for such tests...

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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 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

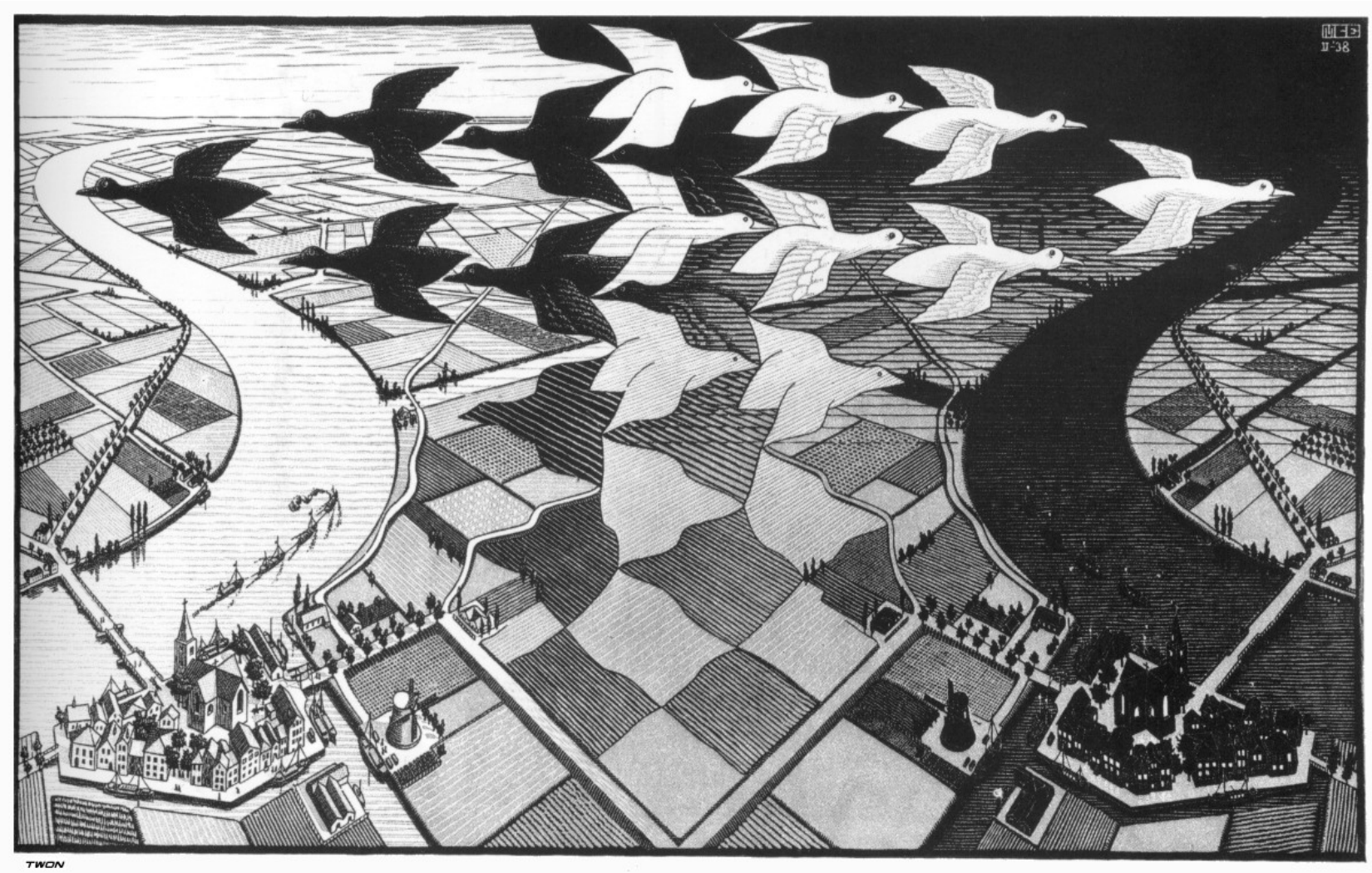
Implications for low-energy measurements

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 $\sim 10^{-9}$)
  - O(0.1%) deviations in BR($\tau\to\mu\nu\nu$)/BR($\tau\to e\nu\nu$) and $G_F^{(\tau)}$ vs. $G_F^{(\mu)}$

Implications for high-pT physics



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: $M \sim g \times (1.0 \div 1.5)$ TeV
- $R_{K(*)}$ also points to a low NP scale, but for (unnaturally) large flavor-violating coupl.: $M \sim g \times (8.0 \text{ TeV}) \left[\frac{\lambda_{bs}\,\lambda_{\mu\mu}}{V_{ts}}\right]^{1/2}$

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

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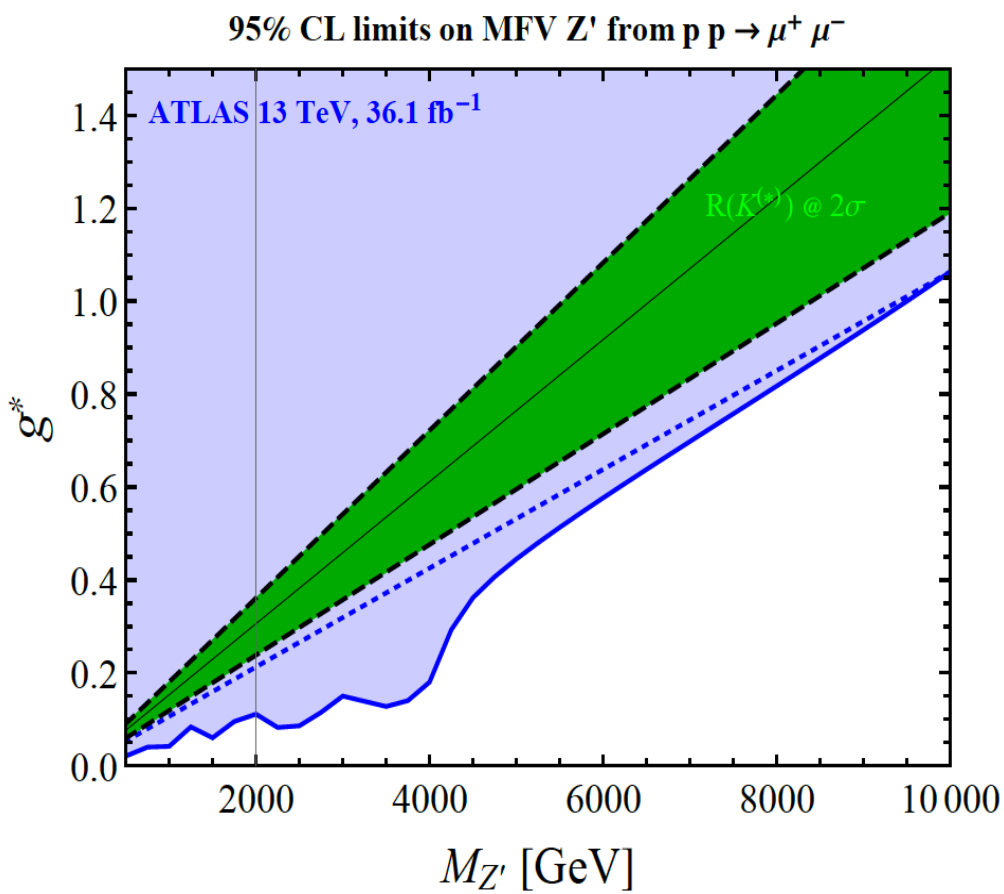
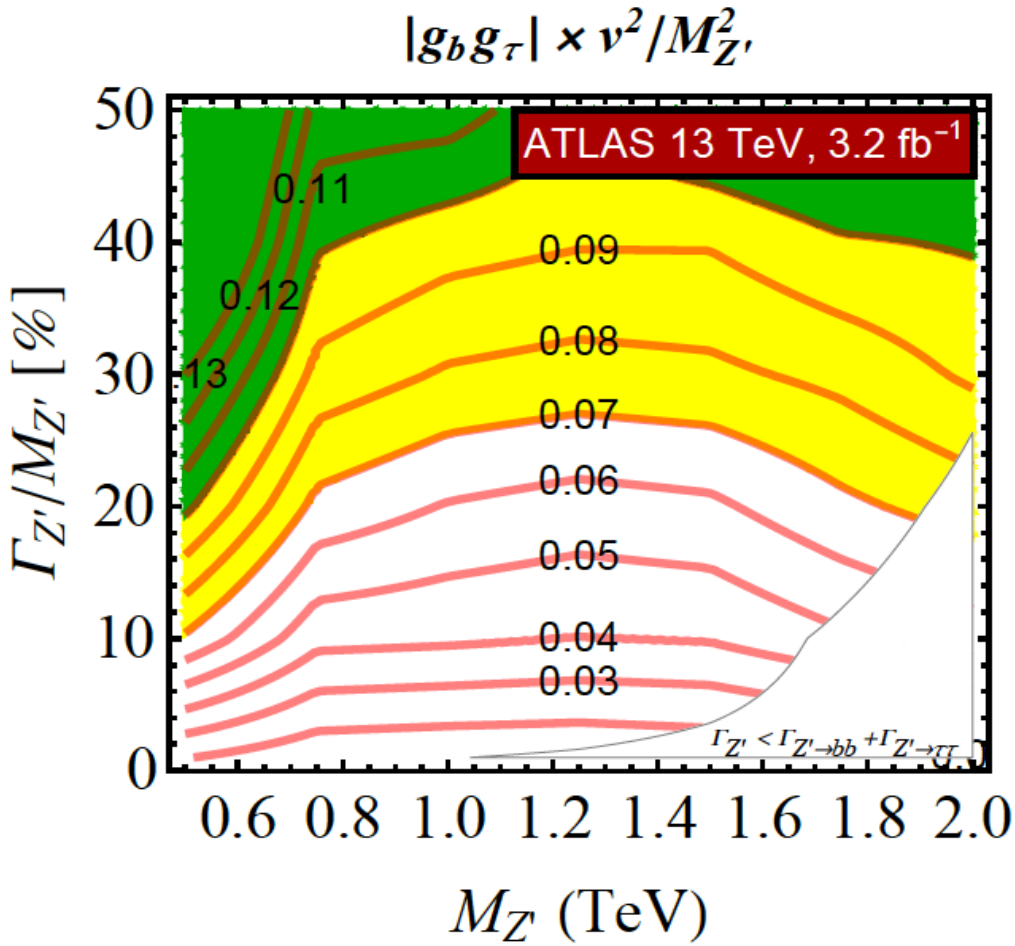


Greljo, Marzocca '17

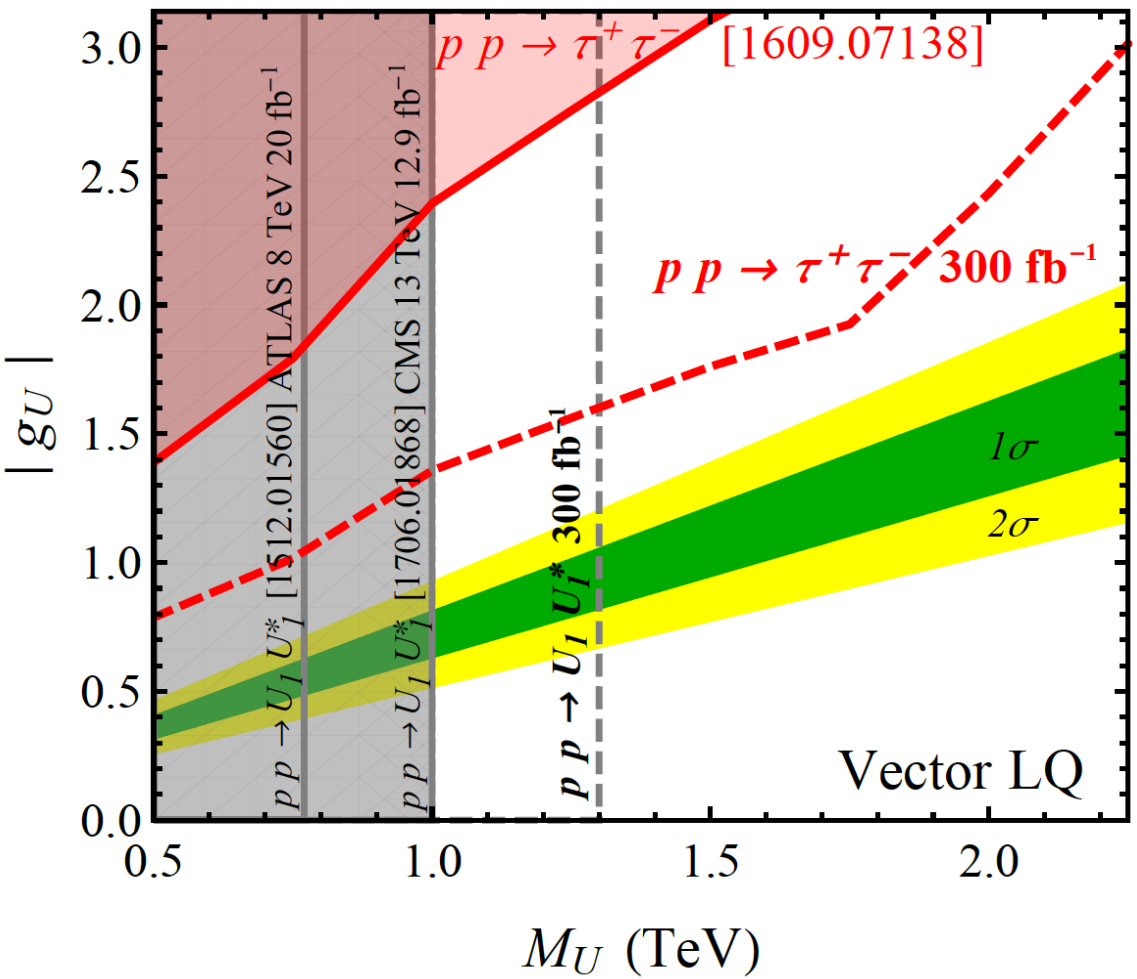


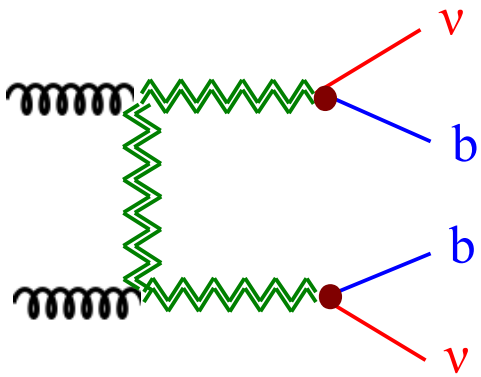
Faroughy, Greljo, Kamenik '16

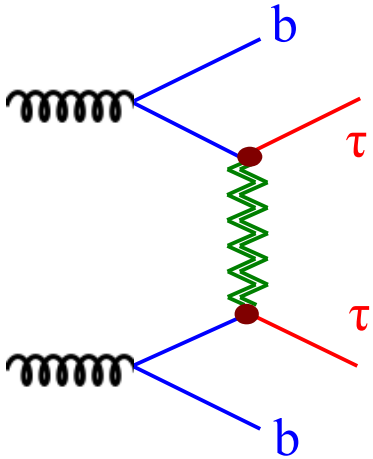
Implications for high-p_T physics

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

Buttazzo, Greljo, GI, Marzocca, '17





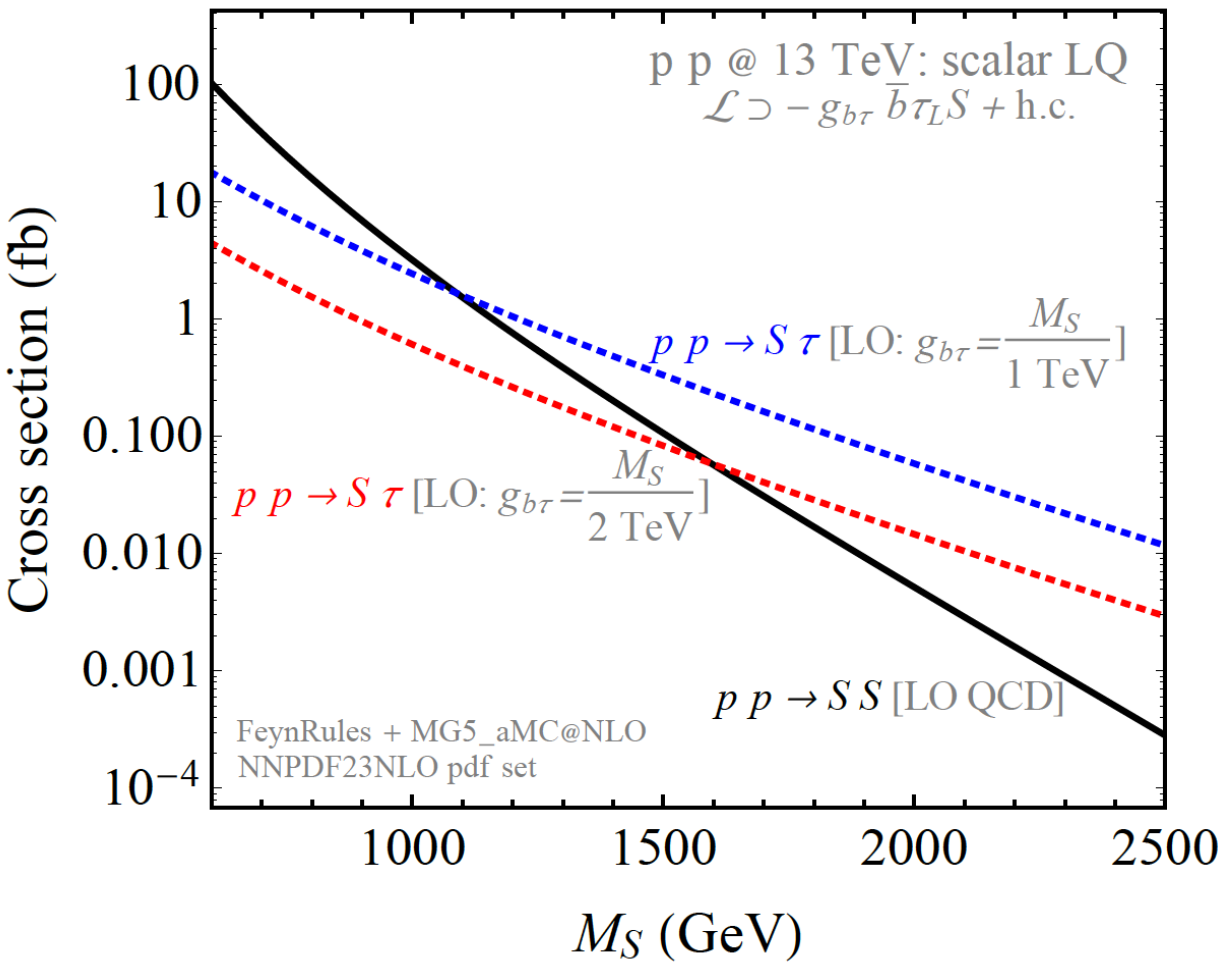


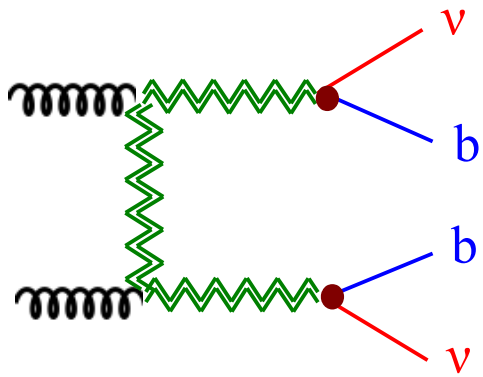
Implications for high-p_T physics

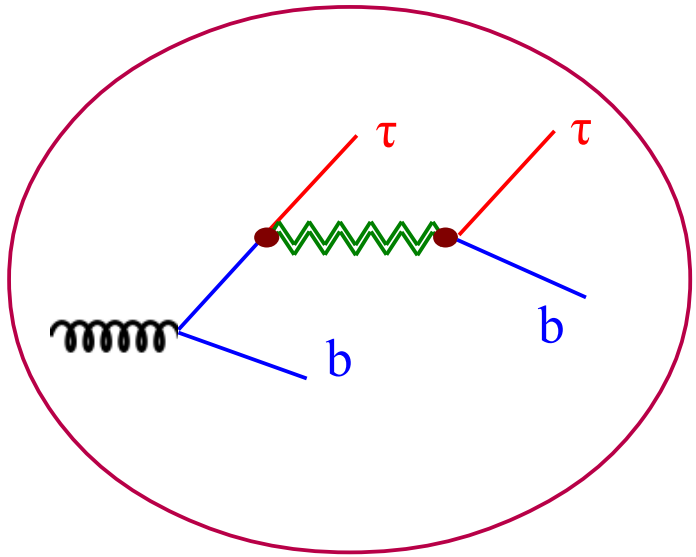
Also as far as direct searches are concerned, 3rd gen. LQ are in good shape:

N.B.: The single production (*for which so far there are no dedicated searches*) might be the dominant prod. channel

Buttazzo, Greljo, GI, Marzocca, '17







Implications for high-p_T physics

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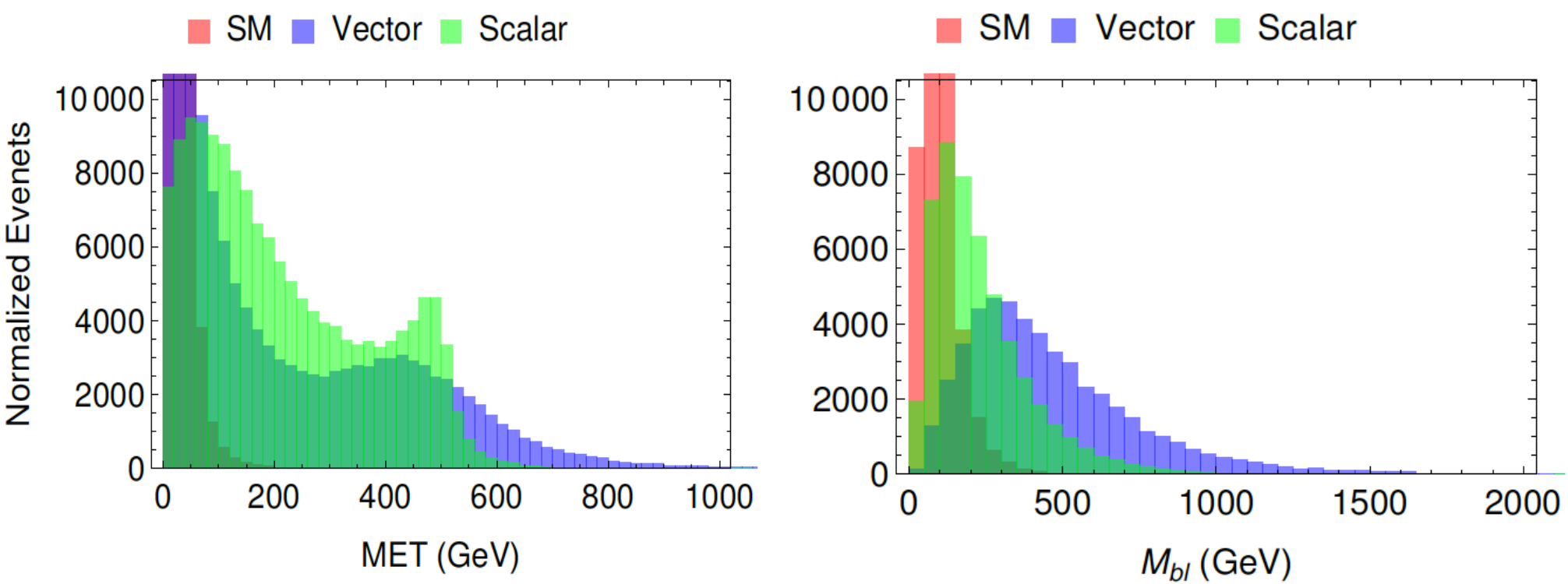
N.B.: More generally, $pp \to b\,\tau \to b\,l + \not{E}_T$ is a key (model-independent) search relevant to any model addressing the RD anomaly

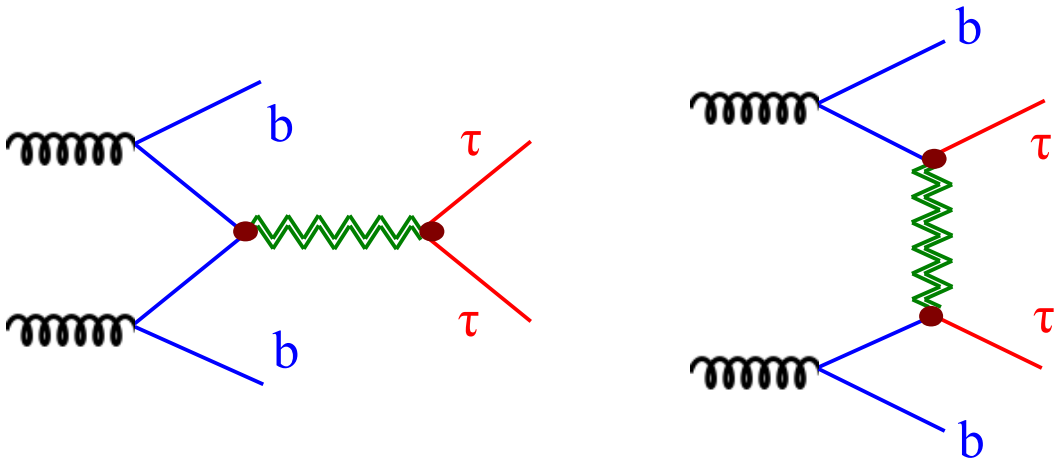


Altmannshofer, Dev, Soni, '17

Implications for high-p_T physics

More specific 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 BRs into τ pairs in the final state [*but narrow peaks in ττ disfavored*]

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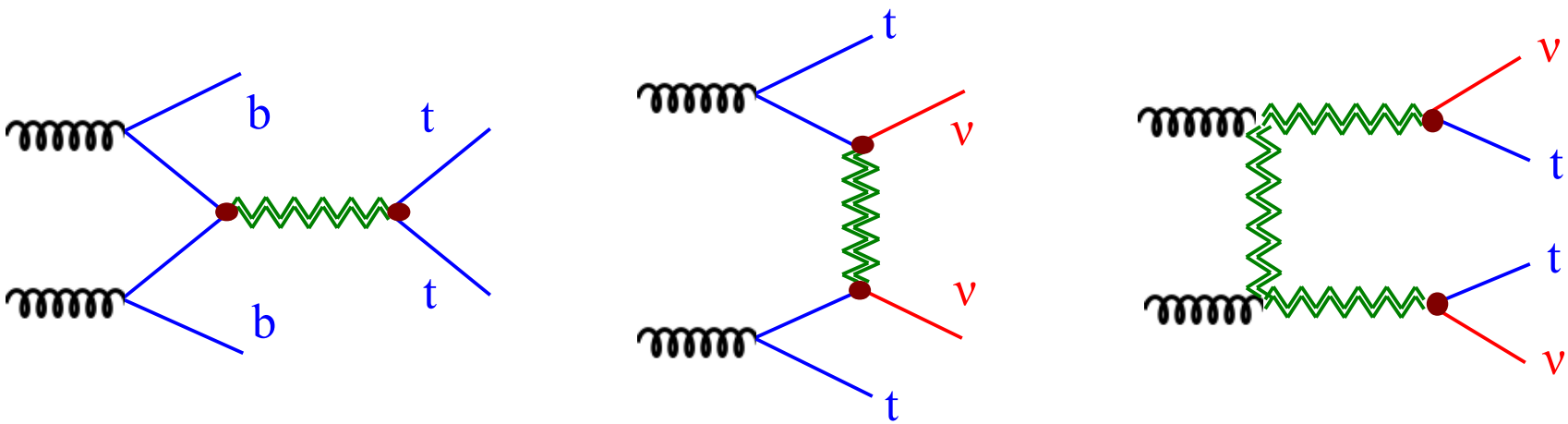

II. The R_D anomaly unambiguously points out to large BRs into τ pairs in the final state [*but narrow peaks in ττ disfavored*]

III. Large BRs into top pairs naturally expected in most models [*but S/B worse due to SM top production*]

Implications for high-p_T physics

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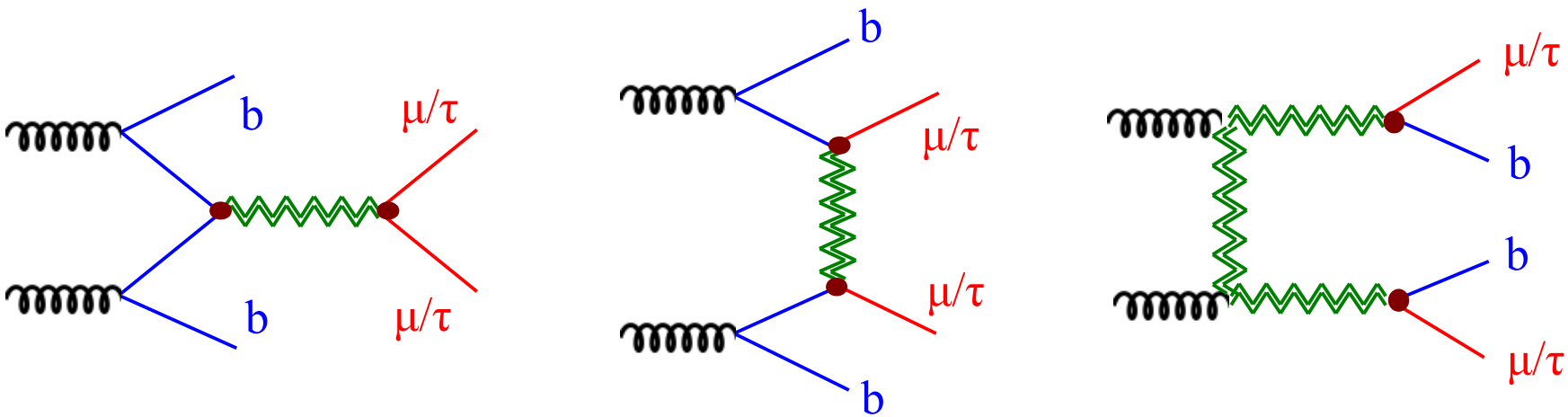

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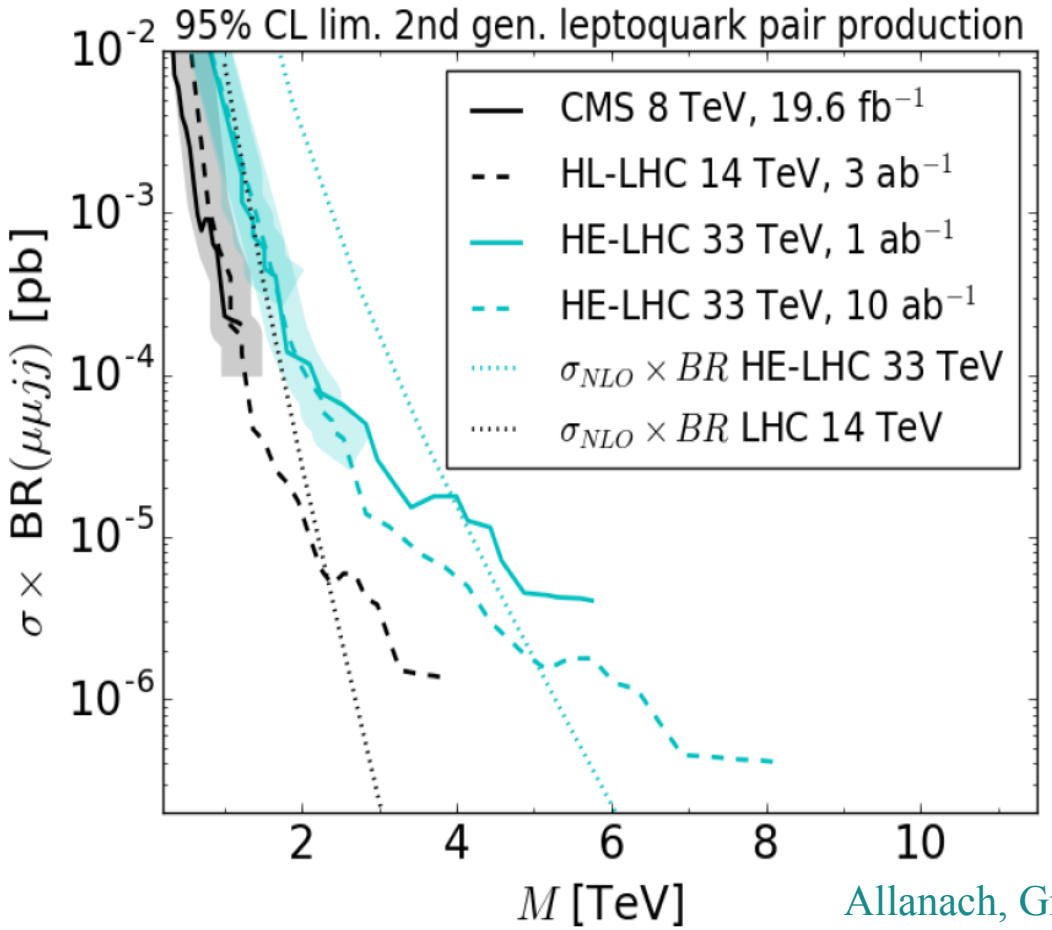
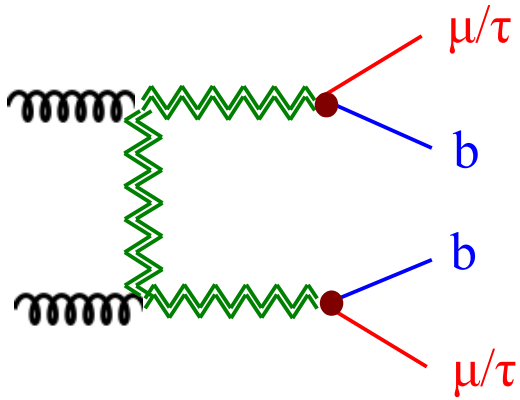
IV. BR into μ pairs (or μτ) always expected but naturally suppressed vs. taus
[O(0.1) @ amplitude level for each muon – larger model dependence]
except in models addressing only R_K

Implications for high-p_T physics



Allanach, Gripaios, You '17



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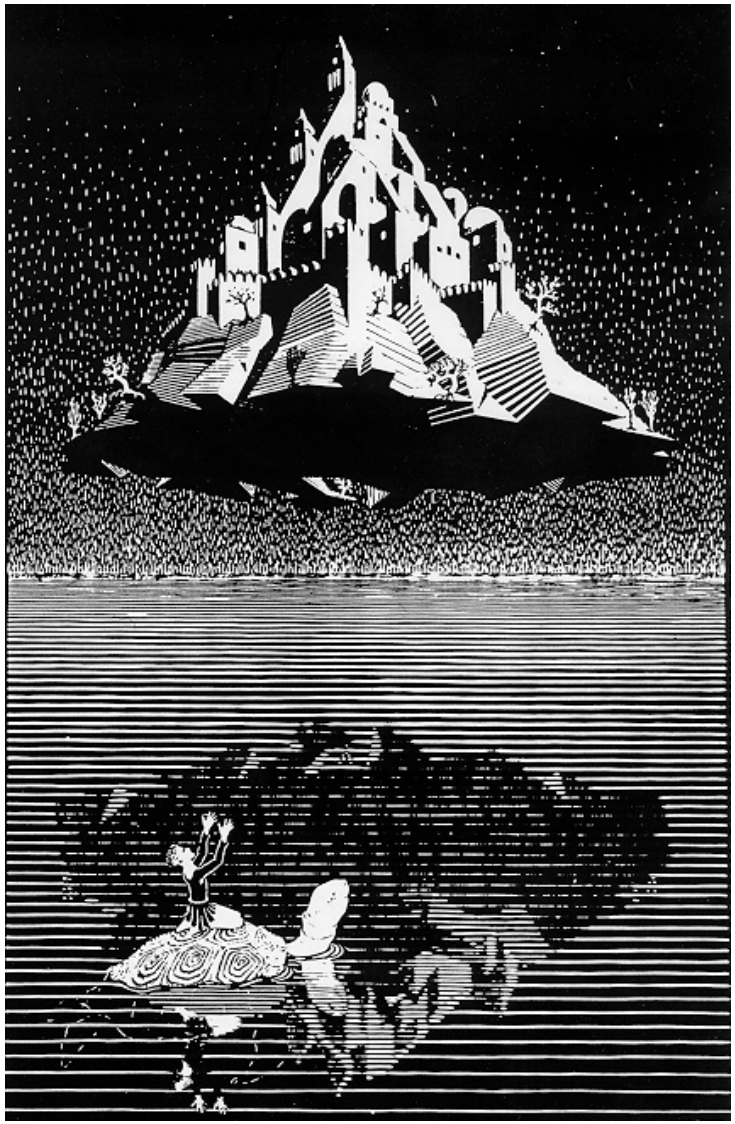
Conclusions



Maybe it's all a castle in the air...

Or maybe it is not...

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  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

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↓

- These anomalies cannot "remain isolated"... Many additional signals expected both at low- and at high-energy (*although many are not easy...*)

- Clear model-independent implication of RD → large deviations from SM in $\tau\tau$ final states both at high-energy ($pp \to \tau\tau$) and in rare decays ($B \to X\tau\tau$)

↓

A lot of fun ahead of us...

If you wish to discuss more about flavor anomalies (*and more generally about flavor physics BSM*), you are all cordially invited to:

ZPW2018

Flavours: light, heavy and dark

15-17 January Venue Accommodation Program and registration Speakers Workshop Dinner

https://www.zpw.ethz.ch/2018/

Zürich, Jan. 15-17 2018