The BSM potential of rare kaon decays

Gino Isidori
[*University of Zürich*]

- Introduction
- The two flavor problems
- Flavor non-universal interactions
- The role of $K \to \pi\nu\nu$
  - *Effective-theory approach*
  - *A motivated BSM example*
- Other modes [*very incomplete...*]
- Conclusions

University of Zurich[UZH]

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Introduction

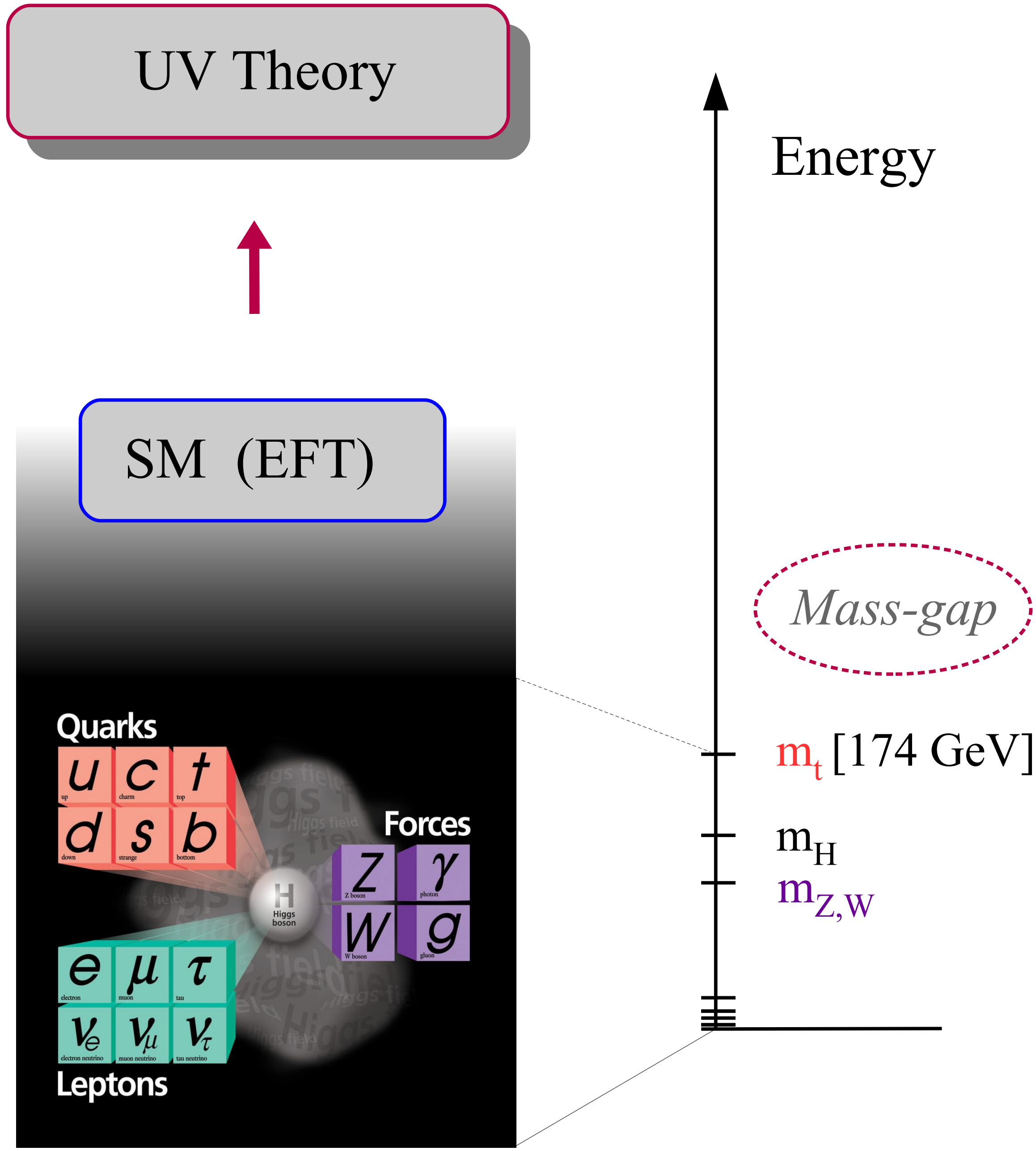
There are several reasons why we think the SM must be extended at high energies:

Electroweak hierarchy problem

Flavor puzzle
U(1) charges
Neutrino masses

Dark-matter
Dark-energy
Inflation

Quantum gravity



Introduction

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	problem due to...	*...indicating*
Electroweak hierarchy problem	→ *Instability of the Higgs mass term*	non-trivial properties of the SM Lagrangian if interpreted as EFT
Flavor puzzle U(1) charges Neutrino masses	→ *Ad hoc tuning in the model parameters*	↓
Dark-matter Dark-energy Inflation	→ *Cosmological implementation of the SM*	Useful hints for its UV completion
Quantum gravity	→ *General problem of any QFT*	

Introduction

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Neutrino masses

non-trivial properties of the SM Lagrangian if interpreted as EFT

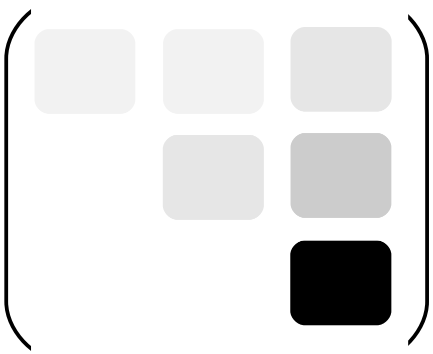
↓

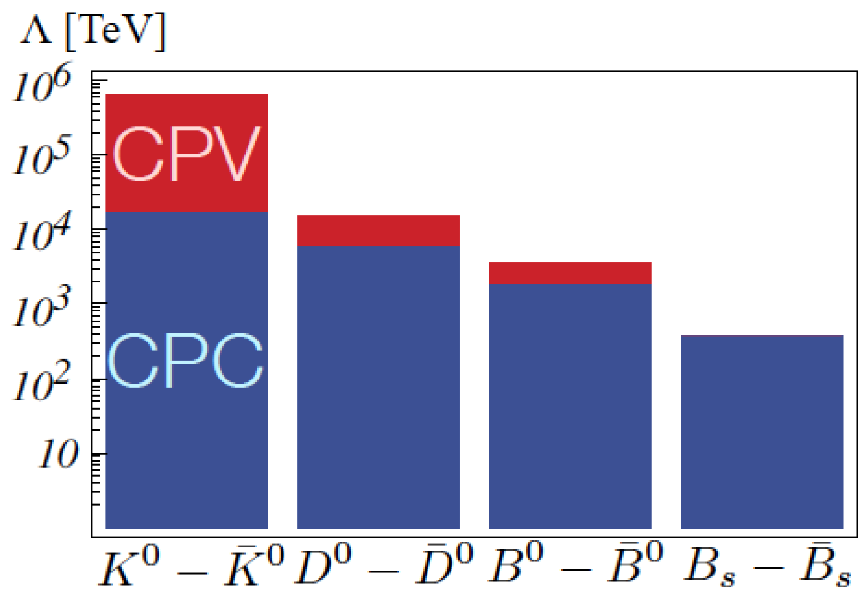
Useful hints for its UV completion

Key role played by future rare-K decay experiments in exploiting further these hints

The two flavor puzzles

$Y_U \sim$





The two flavor puzzles

There are two (long-standing) open issues in flavor physics:

I. The observed pattern of SM Yukawa couplings does not look accidental

→ Is there a deeper explanation for this peculiar structures?

The SM flavor puzzle

II. If the SM is only an effective theory, valid below an ultraviolet cut-off , why we do not see any deviation from the SM predictions in the (suppressed) flavor changing processes?

→ Which is the flavor structure of physics beyond the SM?

The NP flavor puzzle

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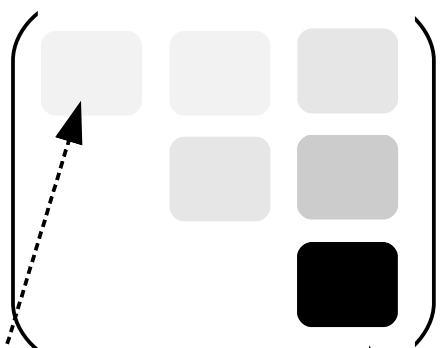
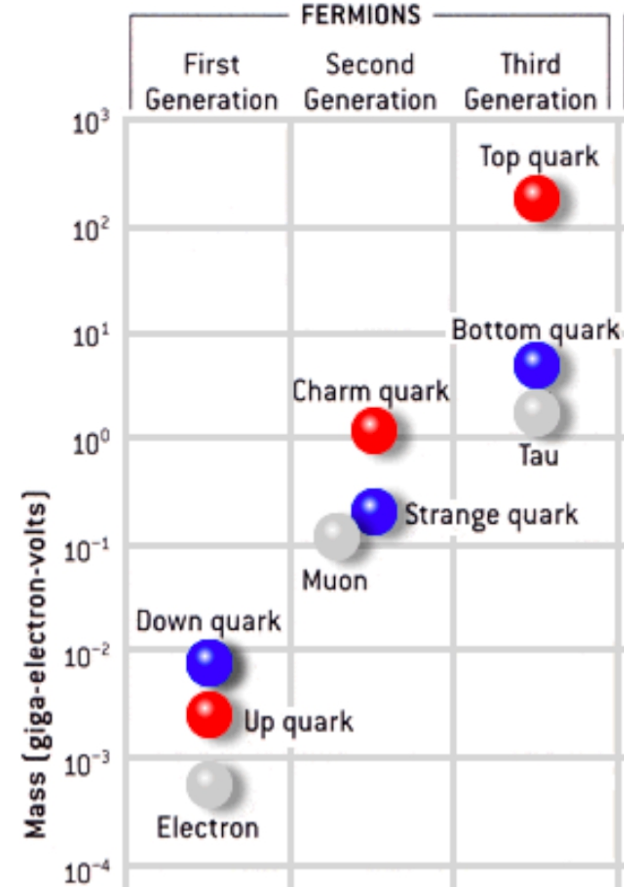
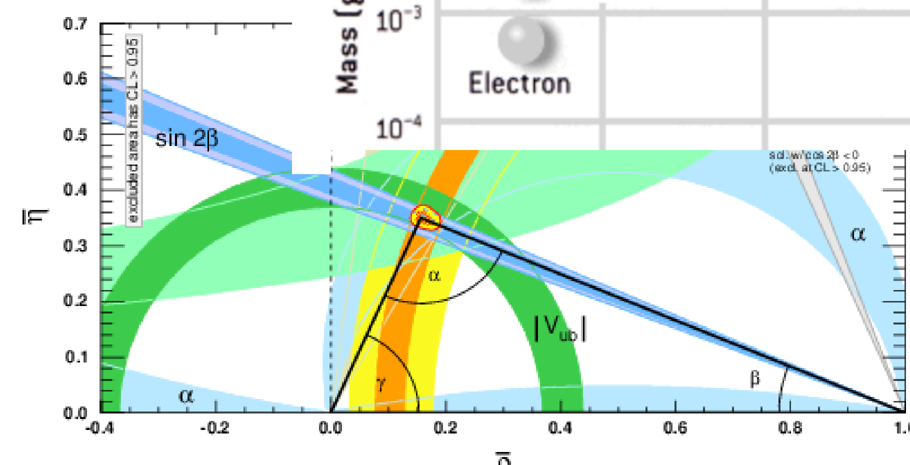
$Y_U \sim$ 





$$y_u = \frac{\sqrt{2}\, m_u}{\langle H \rangle} \approx 10^{-5} \qquad y_t = \frac{\sqrt{2}\, m_t}{\langle H \rangle} \approx 1$$

[Y_U in the basis where Y_D is diagonal]

The two flavor puzzles

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I. The observed pattern of SM Yukawa couplings does not look accidental:

$$\begin{array}{cc} & \overbrace{\qquad\qquad\qquad}^{U(2)_u} \\ Y_U \sim & \left(\begin{array}{cc|c} \multicolumn{2}{c|}{< 0.01} & 0.003 \\ & & 0.04 \\ \hline & & 1 \end{array}\right) \leftarrow U(2)_q \end{array}$$

$$\bar{Q}_L \, Y_U \, U_R \, H$$

What we observe in the Yukawa couplings is an approximate $U(2)^n$ symmetry acting on the light families

The two flavor puzzles

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$$\mathscr{L}_{\text{SM-EFT}} = \mathscr{L}_{\text{gauge}} + \mathscr{L}_{\text{Higgs}} + \sum_{d,i} \frac{c_i^{[d]}}{\Lambda^{d-4}} O_i^{d\geq 5}$$

Large flavor symmetry

Three identical replica of the basic fermion family [$U(3)^5$ symmetry]

Flavor-degeneracy broken by the Yukawa interaction

$$y_{ij}\, \psi_L^{\,i}\, \psi_R^{\,j}\, H \;\to\; m_{ij}\, \psi_L^{\,i}\, \psi_R^{\,j}$$

"Peculiar" breaking structure

Exact & approximate (*accidental* ?) symmetries

Eg:

- $U(1)_{L_e} \times U(1)_{L_\mu} \times U(1)_{L_\mu}$ = (individual) Lepton Flavor [*exact symmetry*]
- $m_u \approx m_d \approx 0 \;\to$ Isospin symmetry [*approximate symmetry*]

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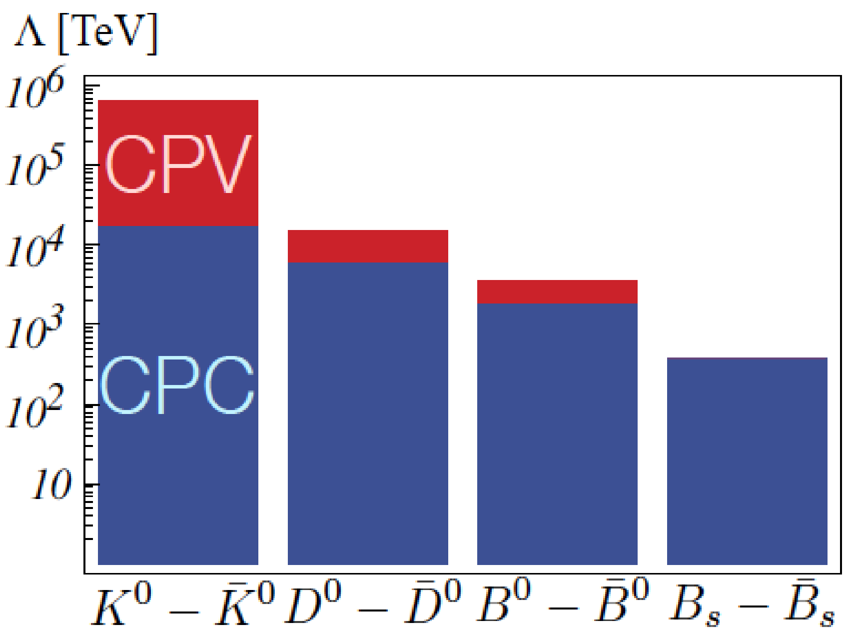
In principle, we could expect many violations of the accidental symmetries from the heavy dynamics (→ *new flavor violating effects*). However, beside some anomalies in B-physics (*still unclear…*), we observe none.

↓

Stringent bounds on the scale of possible new flavor non-universal interactions:

The NP flavor puzzle



N.B: These high scales can be a "mirage" (= *artifact of the accidental symmetry*).

The only unambiguous message of these bounds is:

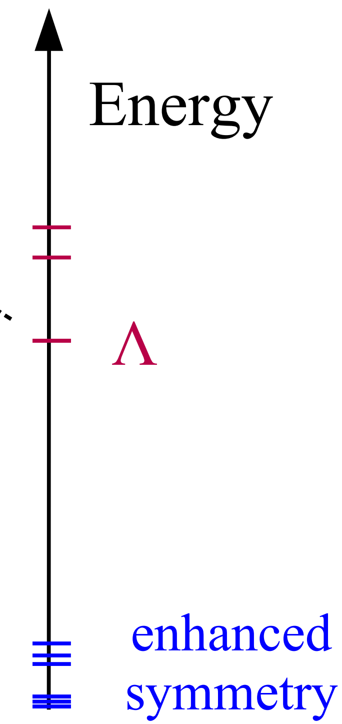
No large breaking of the approximate $U(2)^n$ flavor symmetry at near-by energy scales

Accidental symmetries in QFT [a brief detour]

$$\mathscr{L}_{\cancel{\text{SM-EFT}}} = \mathscr{L}_{\text{gauge}} + \mathscr{L}_{\text{Higgs}} + \sum_{d,i} \frac{c_i^{[d]}}{\Lambda^{d-4}} O_i^{d\geq 5}$$

[SM-2]-EFT

(long-distance interactions) (local contact interact.)



Back in 1973: SM with 2 generations, as "reference model" → CP violation is an accidental symmetry [KM, '73]

But CP violation is observed in K mixing [→ remnant of "heavy NP"]

$$\Lambda_{CP} \sim 10^4 \text{ TeV}$$

$$\frac{e^{i\delta}}{\Lambda_{CP}^2} (\bar{s}\,\Gamma\, d)^2$$

"Super-weak" interaction
[L. Wolfenstein, '64]

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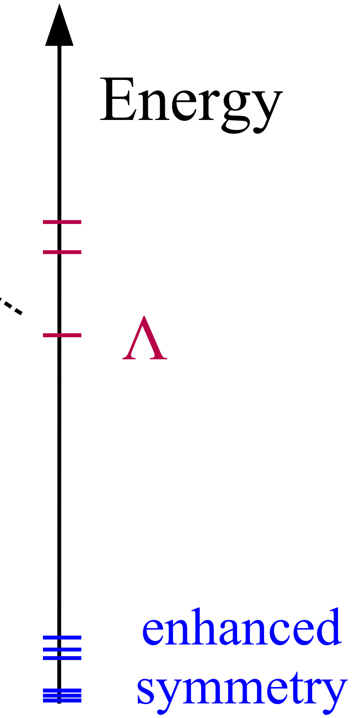

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SM-3
[KM, '73]

$$\frac{1}{\Lambda_{CP}^2} \sim \frac{(G_F m_t V_{ts} V_{td})^2}{4\pi^2}$$

Ellis, Gaillard, Nanopulos, '76

Key message: beware of seemingly high scales in EFT approaches: they can be a "mirage"...

The two flavor puzzles

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Flavor-degeneracy:
$U(3)^5$ symmetry

Yukawa couplings:
$U(3)^5 \to (\sim)\ U(2)^n$
peculiar breaking of the flavor symm.

Stringent bounds on generic flavor-violating ops.
$\updownarrow$
approx. $U(2)^n$ holds also beyond the SM

The big questions in flavor physics:

- Can we find an explanation for the Yukawa hierarchies?
- If the (residual) flavor symmetries are accidental symmetries, at which scale are they broken? Can be there multiple scales behind the origin of flavor?

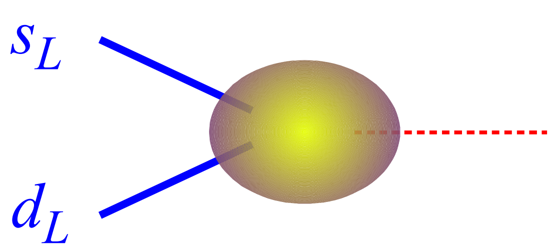
The role or rare K decays

In this context Kaon physics plays a unique role:

$\boxed{\text{Unique probe of flavor-symmetry breaking involving light families}}$

The SM (approximate) accidental symmetries imply an extremely strong suppression for

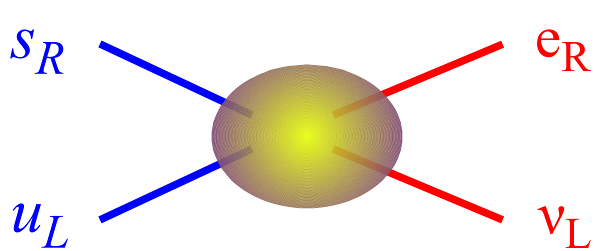
- $A(s_L \to d_L)_{FCNC}$ [probed precisely only by $B(K^+ \to \pi^+ \nu\nu)$]



$$A_{SM} \sim \frac{y_t^2 V_{ts}^* V_{td}}{16\pi^2 V_{us}} A(K \to \pi e \nu)$$

$(\sim 1\ 10^{-5})$

- helicity-suppressed amplitudes, such as $A(s_R \to u_L e_R \nu_L)$ [probed by $R_{e/\mu}(K)$]



$$A_{SM} \sim \frac{y_e}{y_\mu} A(K \to \mu\nu)$$

$(\sim 5\ 10^{-3})$

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$\oplus$

Unique probe of possible light, weakly coupled, new dynamics

Unique probe of some of the fundamental SM parameters

Ideal set-up for the "R&D" of theory tools about non pert. dynamics

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Not covered in this talk, despite very interesting

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The big questions in flavor physics:

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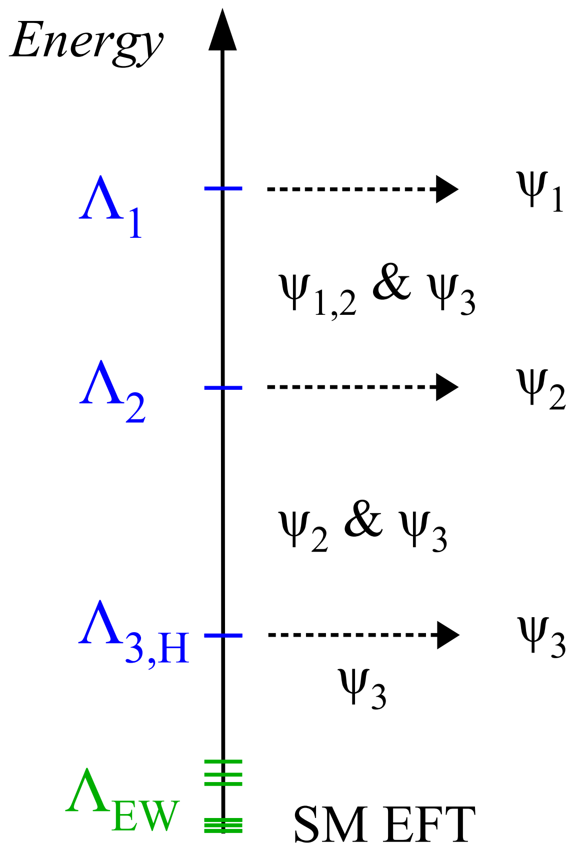
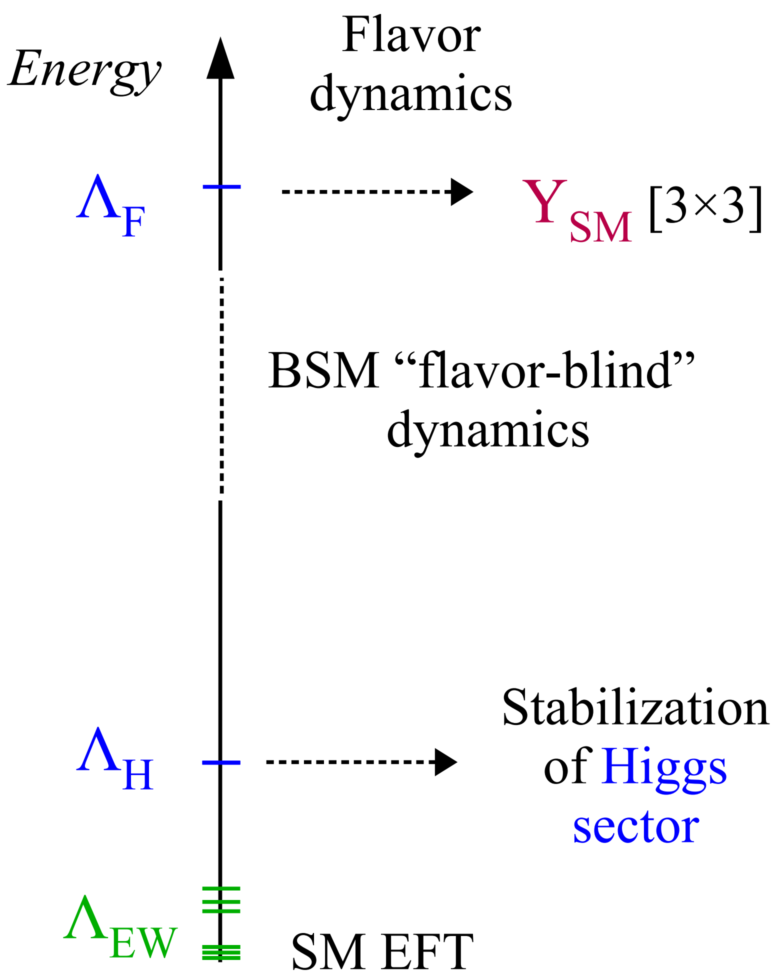
→ **Some (general) hypotheses needed to address these questions**

Flavor non-universal interactions



Flavor non-universal interactions

For a long time, the vast majority of model-building attempts to extend the SM was based on the *implicit* hypotheses of *flavor-universal* New Physics



- Concentrate on the Higgs hierarchy problem
- Postpone the flavor problem to higher scales

↕

The "MFV paradigm"
+
"Horizontal" flavor symm. @ high scales

3 gen. = "identical copies" up to high energies

▶ *Flavor non-universal interactions*

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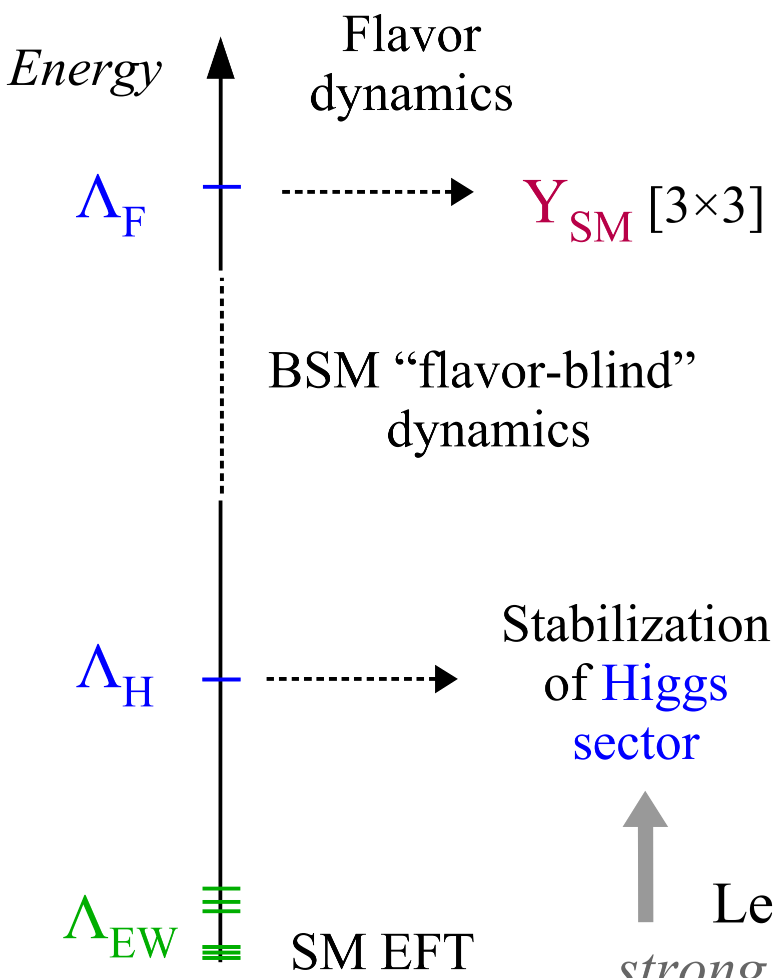

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The "MFV paradigm"

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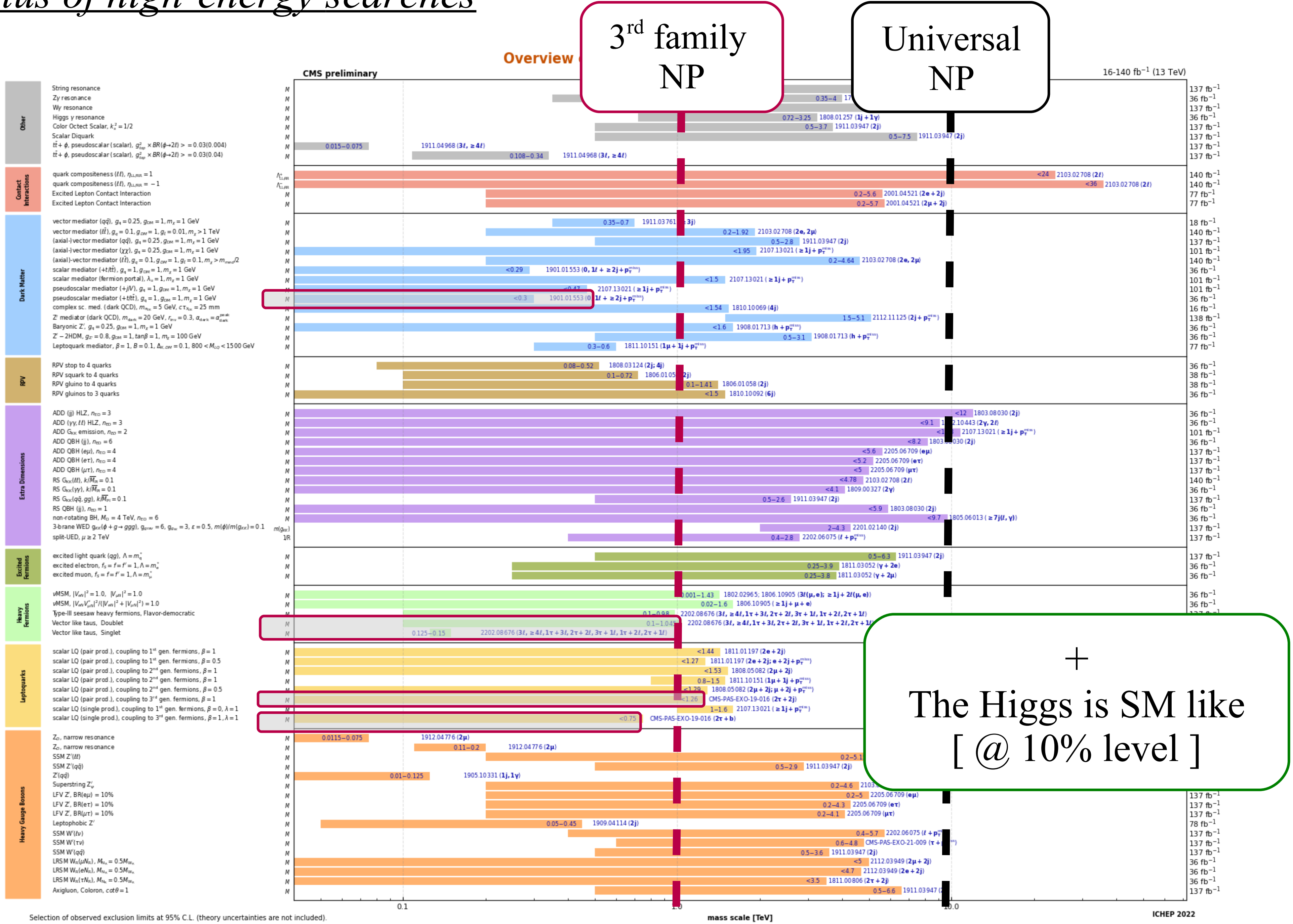
"Horizontal" flavor symm. @ high scales

Less compelling after LHC results (run I+II):

strong bounds on NP coupled universally to all families

worsening of the Higgs hierarchy problem

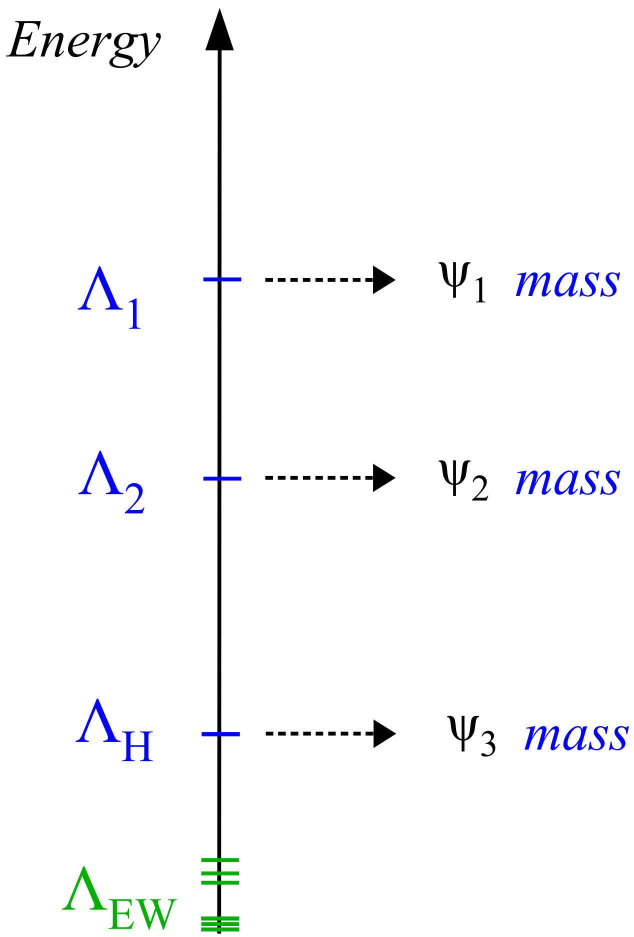
▸ *Status of high-energy searches*



Flavor non-universal interactions

A more efficient paradigm to address both flavor puzzles (I+II), & *possibly* the Higgs hierarchy, is a *multi-scale* UV with *flavor non-universal* interactions

Dvali & Shifman '00
Panico & Pomarol '16
⋮
Bordone *et al.* '17
Allwicher, GI, Thomsen '20
Barbieri '21
Davighi & G.I. '23



Basic idea:

- 1st & 2nd generations have small masses (+ small coupling to NP) because these are generated by new dynamics at heavier scales
- *"flavor deconstruction"* of the SM gauge symmetry → flavor hierarchies emerge as accidental symmetries

⬇

~~3 gen. = "identical copies" up to high energies~~

Flavor non-universal interactions

A more efficient paradigm to address both flavor puzzles (I+II), & *possibly* the Higgs hierarchy, is a *multi-scale* UV with *flavor non-universal* interactions

* *"flavor deconstruction"* of the SM gauge symmetries:

Last step of the symm. breaking chain: [@ few TeV]

$$G^{[3]} \times G^{[12]} \rightarrow G^{[\mathrm{Univ}]}$$

G = subset of SM gauge

Symmetry acting on 3rd gen. + Higgs

Symmetry acting on light gen.

- This symmetry-breaking pattern is very general (*no need to tune couplings or potential*) → flavor universality emerges "naturally" at low energies
- Charging the Higgs under $G_{SM}^{[3]}$ → only Yukawa of the third generation are allowed → "solution" of the SM flavor problem
- $G_{SM}^{[12]}$ symmetry → accidental $U(2)^n$ flavor symmetry → protection of flavor-changing processes as effective as in MFV

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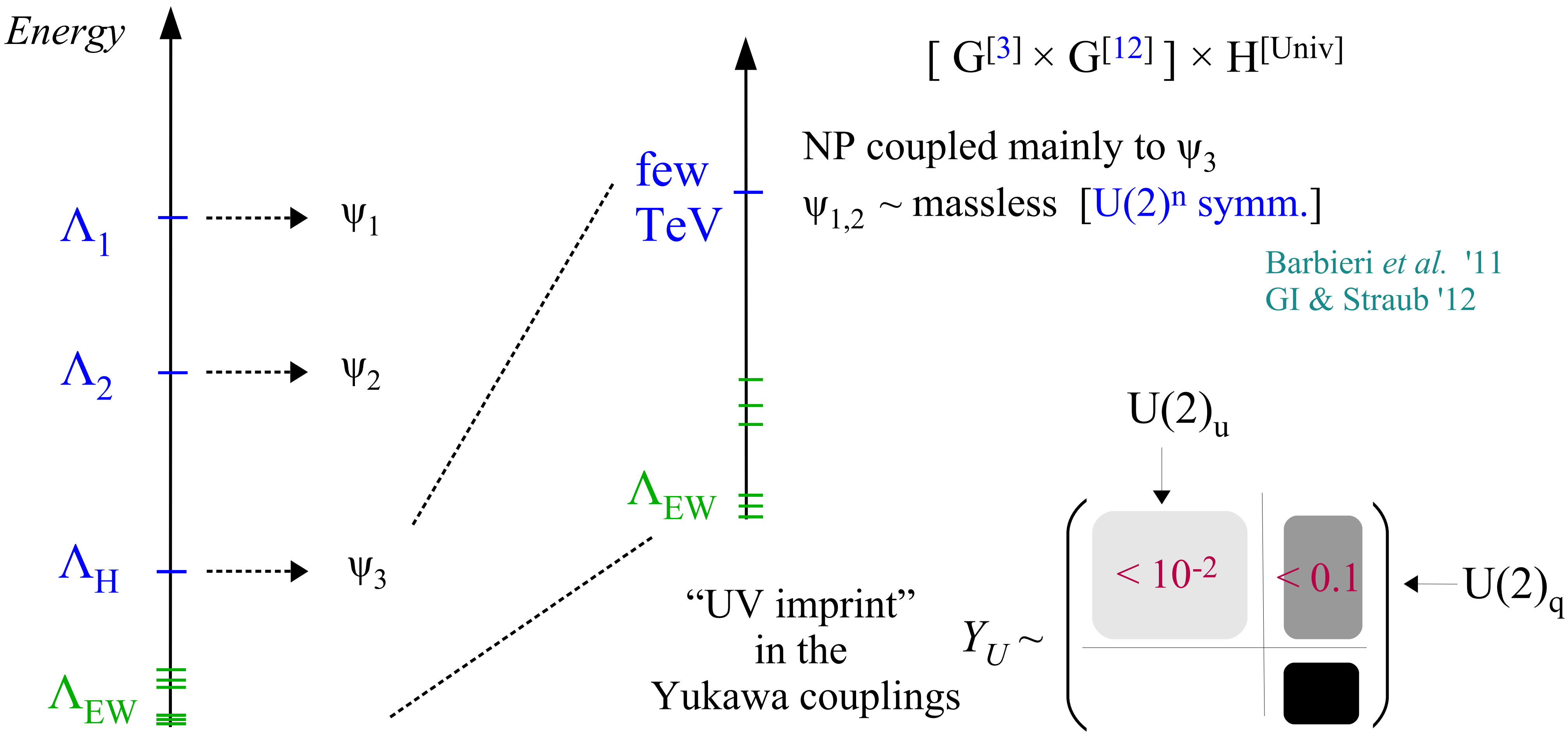
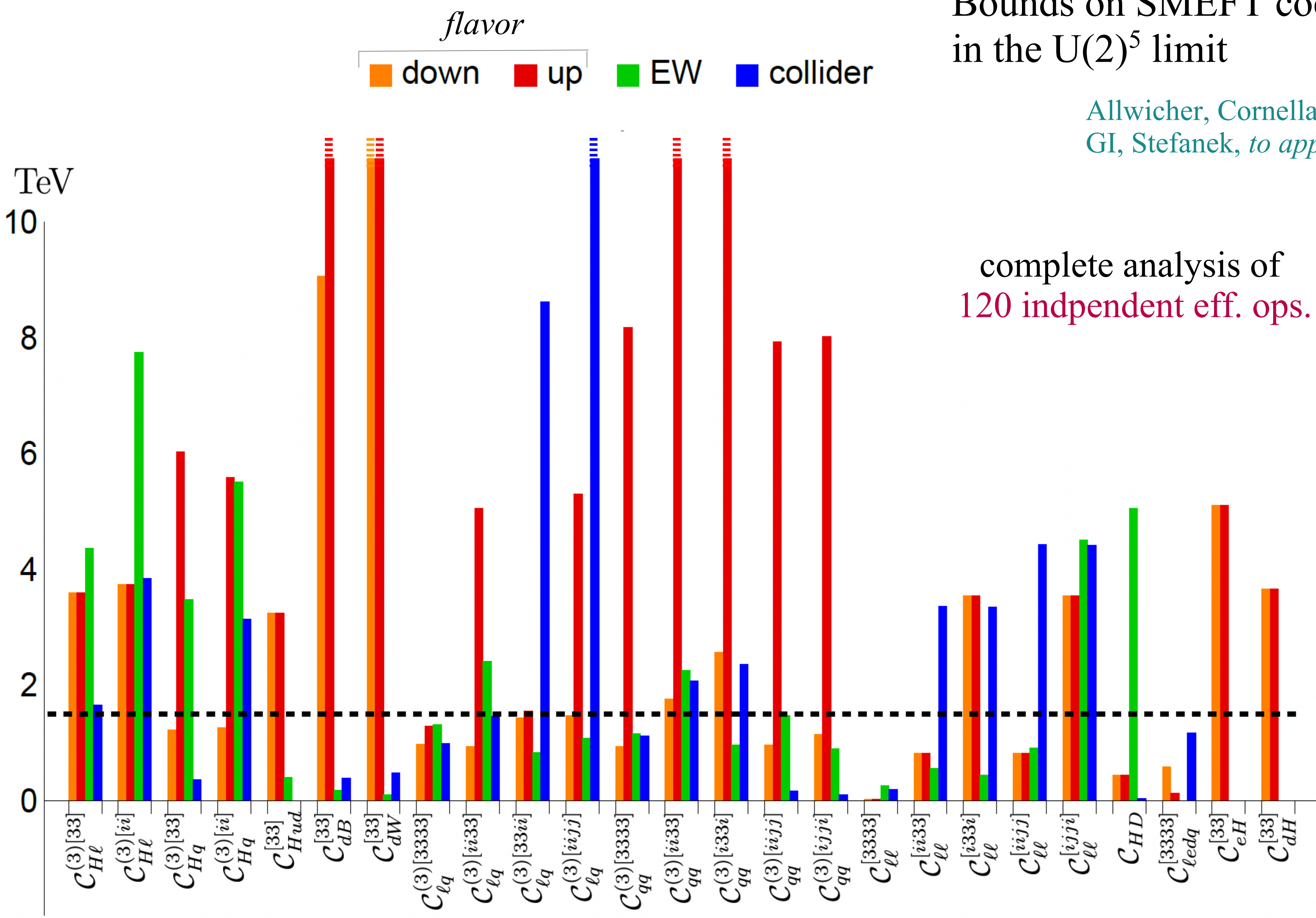


Effective organizing principle for the flavor structure of the SMEFT

▶ *Flavor non-universal interactions*

Bounds on SMEFT coeff. in the $U(2)^5$ limit

Allwicher, Cornella, GI, Stefanek, *to appear.*



complete analysis of 120 indpendent eff. ops.

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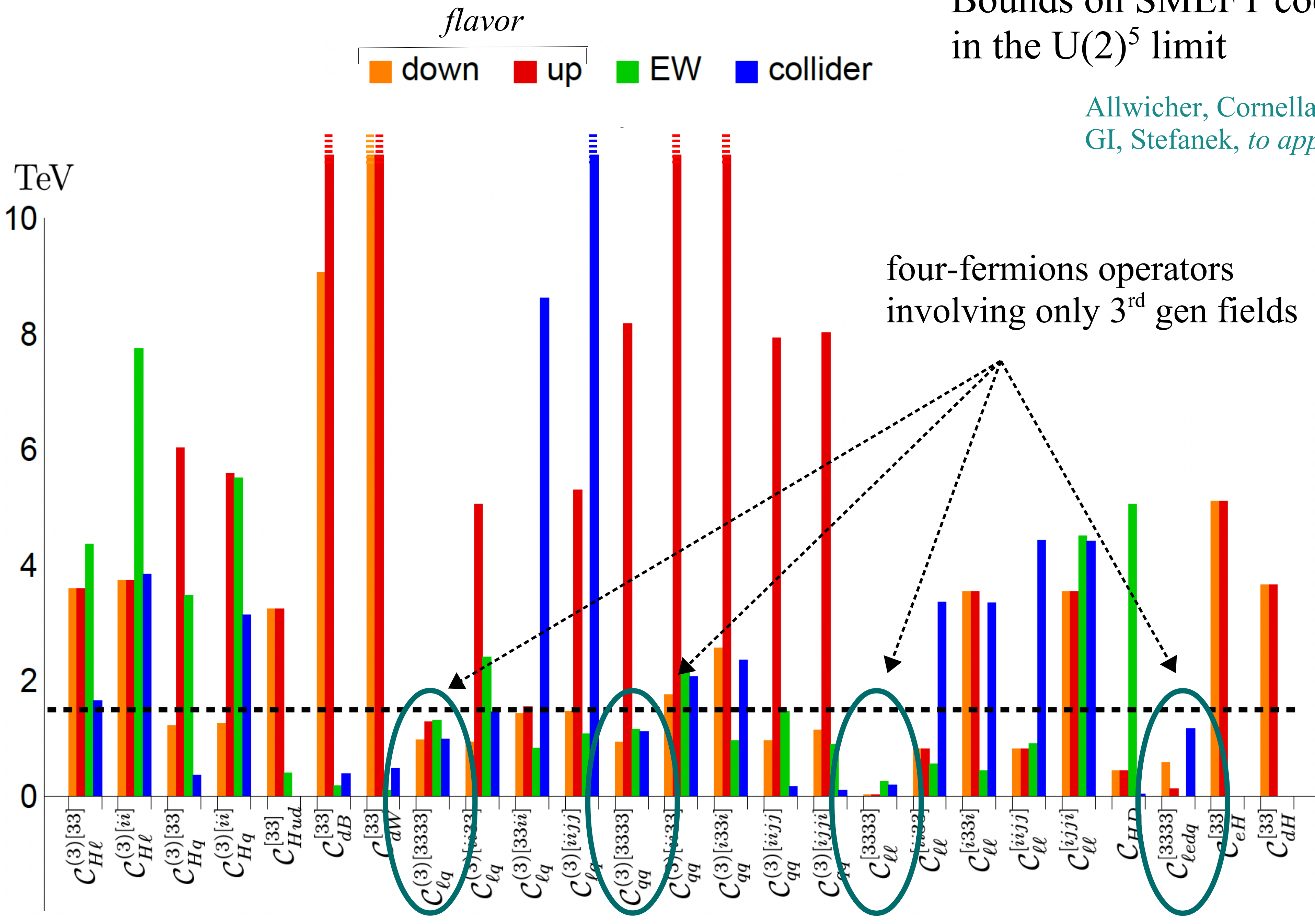

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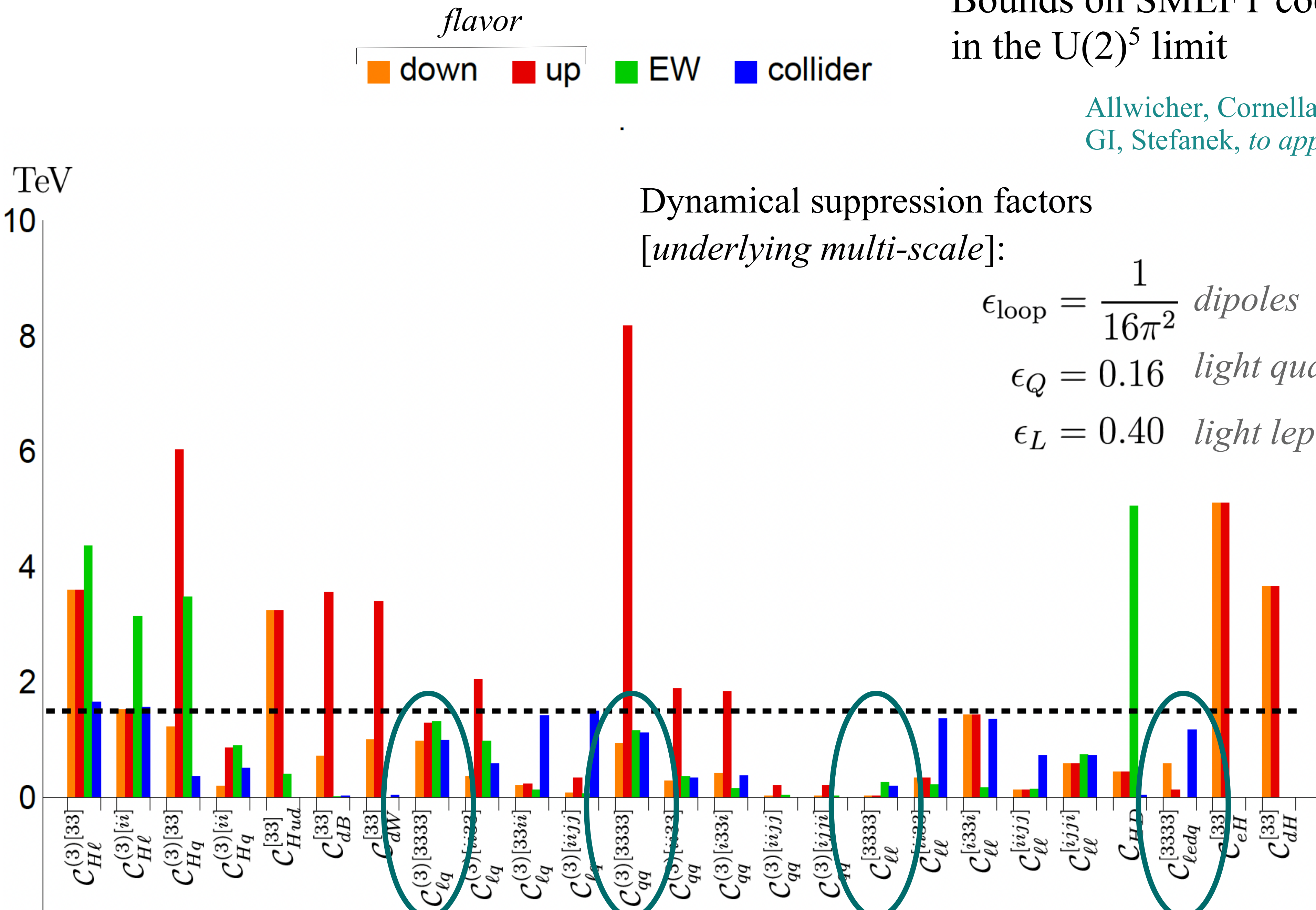

Dynamical suppression factors [*underlying multi-scale*]:

$$\epsilon_{\rm loop} = \frac{1}{16\pi^2} \quad \textit{dipoles}$$

$$\epsilon_Q = 0.16 \quad \textit{light quarks}$$

$$\epsilon_L = 0.40 \quad \textit{light leptons}$$

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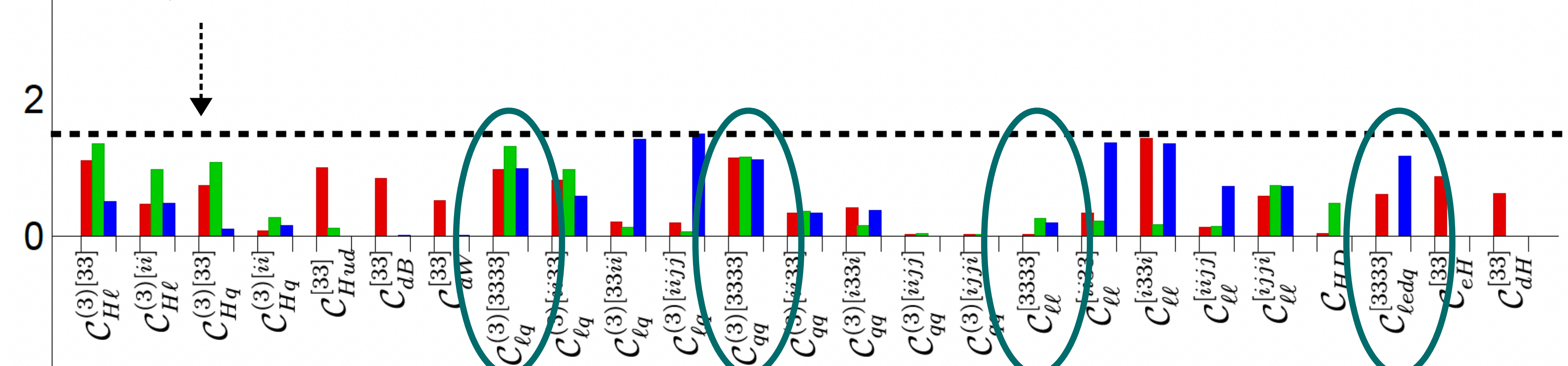
$$\epsilon_H = 0.31 \quad \textit{Higgs fields}$$
$$\epsilon_{\rm mis} = 0.15 \quad \textit{down-align.}$$

Key message:

NP coupled mainly to the third generation as low as 1-2 TeV is perfectly compatible with present data !

Under general conditions related to the underlying multi-scale hypothesis the bounds on all the 120 independent ops. fall below this line



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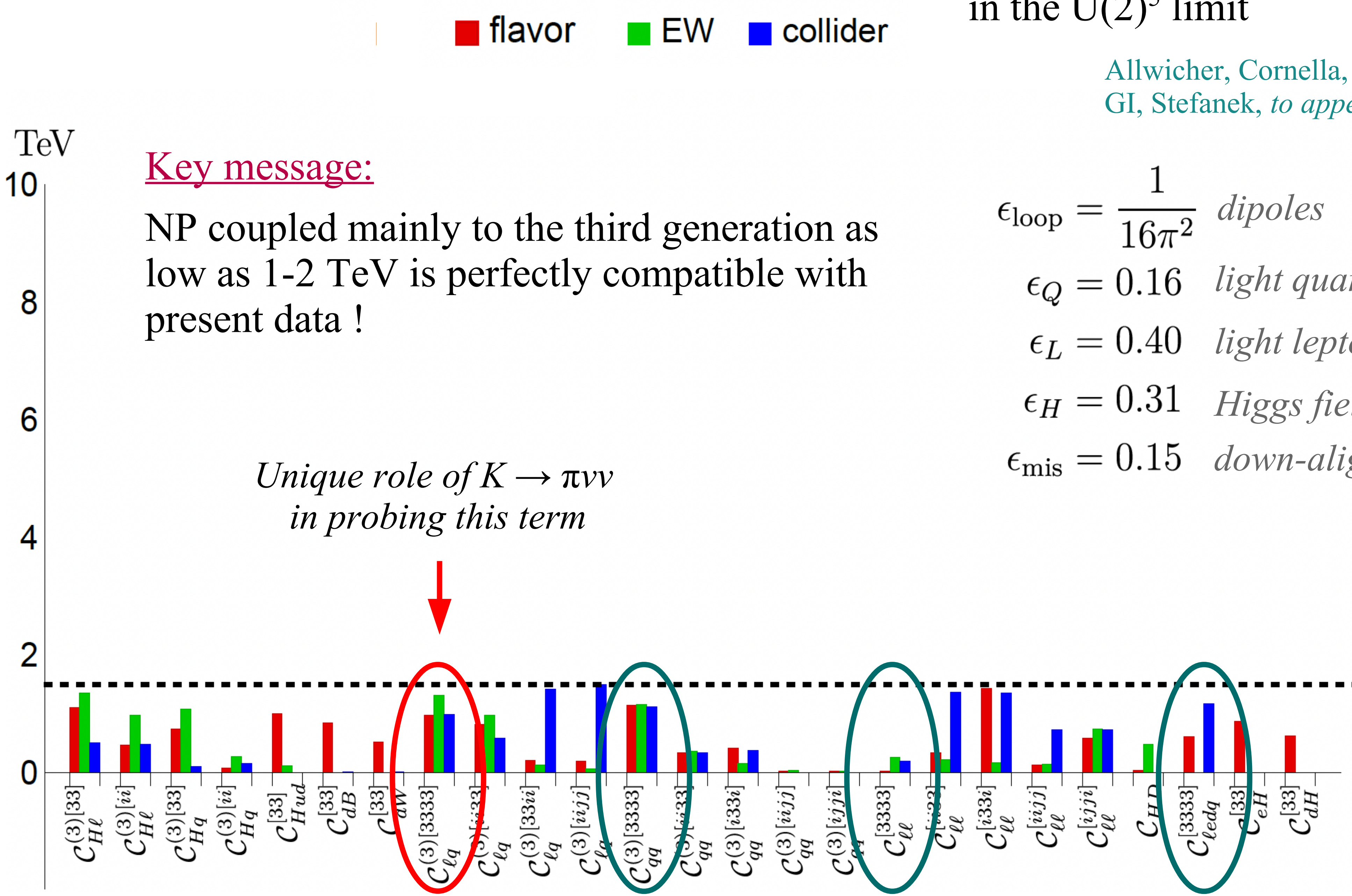
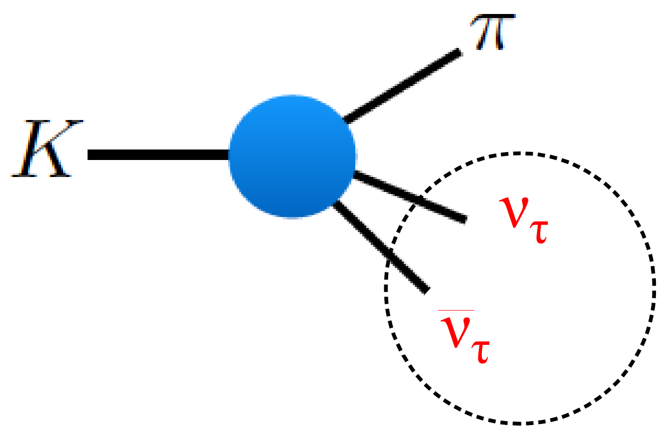


The role of K → $\pi\nu\nu$



The role of $K \to \pi\nu\nu$

$$B(K^+ \to \pi^+\nu\nu)_{SM} = (8.60 \pm 0.42)\times 10^{-11}$$ Buras *et al.* '15, '21

Th. error with sizable parametric component [Lattice, CKM, m_c] → will go down to $\lesssim 3\%$

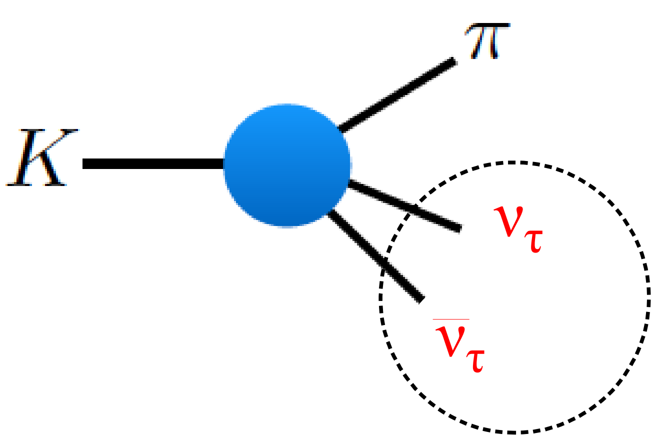
→ Juttner, Sachrajda, *et al.* '15

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

SM like

few % deviation as in $b\to s\mu\mu$

O(1) deviations in models with TeV-scale NP coupled mainly to 3[rd] gen.



Explicit examples discussed in:

Marzocca, Trifinopulos, Venturini '21
Crosas, GI, Lizana, Selimovic Stefanek, '22
...

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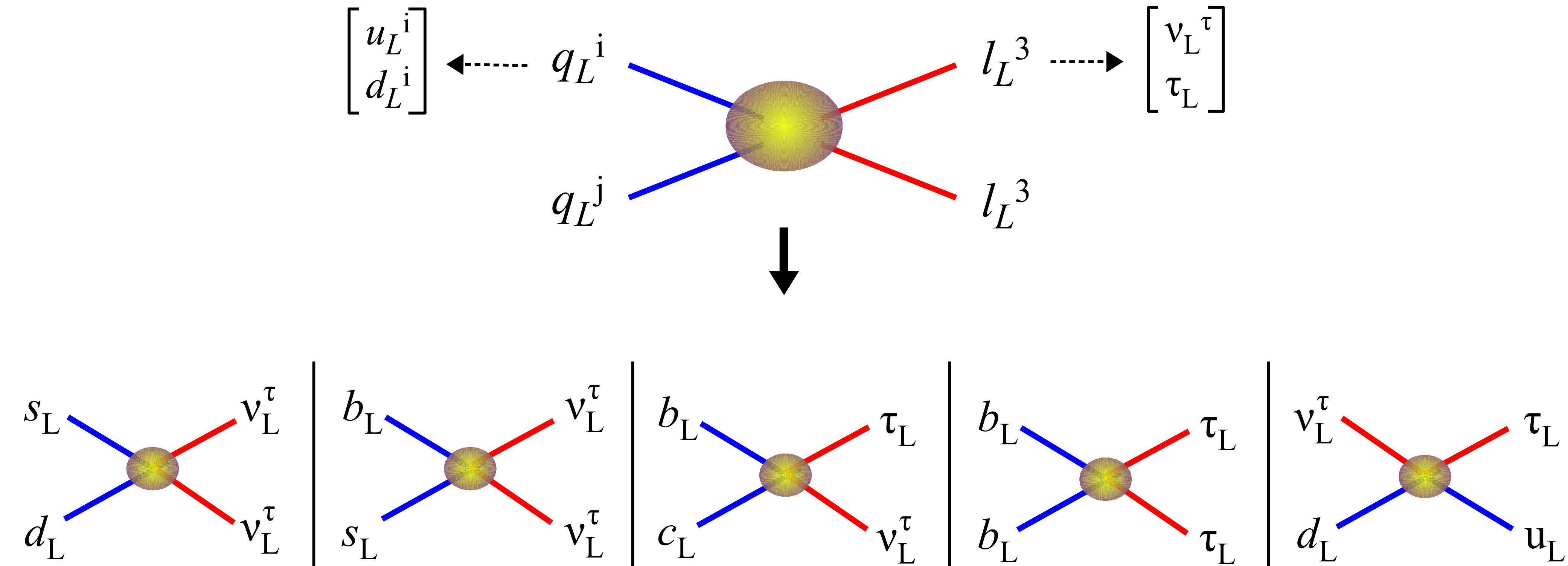
$B(K^+ \to \pi^+\nu\nu)_{SM} = (8.60 \pm 0.42)\times 10^{-11}$ Buras *et al.* '15, '21

$B(K^+ \to \pi^+\nu\nu)_{exp} = (10.6 \pm 4.0)\times 10^{-11}$ NA62 [2016+2017+2018]

$B(K_L \to \pi^0\nu\nu)_{SM} = (3.0 \pm 0.3)\times 10^{-11}$ Buras *et al.* '15

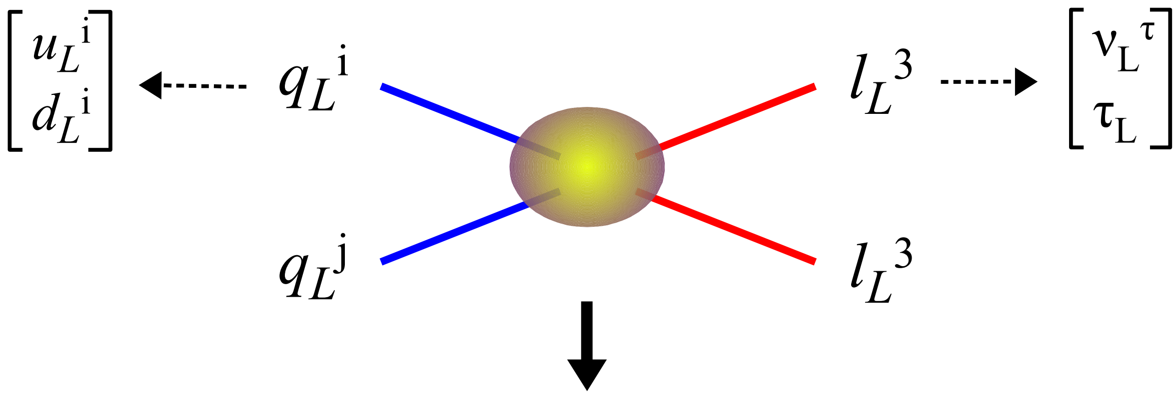
$B(K_L \to \pi^0\nu\nu)_{exp} < 3.6 \times 10^{-9}$ KOTO '19

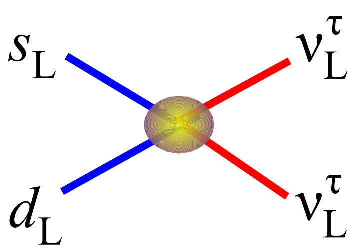
Effective-theory approach

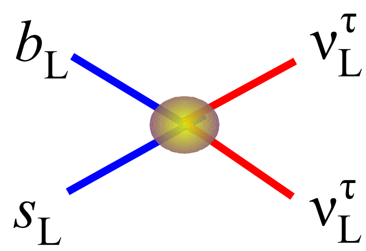


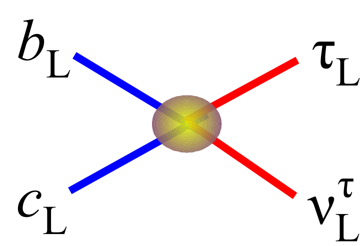
$B(K^+ \to \pi^+ \nu\nu)$	$B(B^+ \to K^+ \nu\nu)$	$R[D^{(*)}]$	$\sigma(pp \to \tau\tau)$	$\sigma(\nu^\tau N \to N'\tau)$

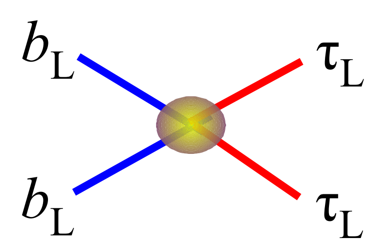
Effective-theory approach

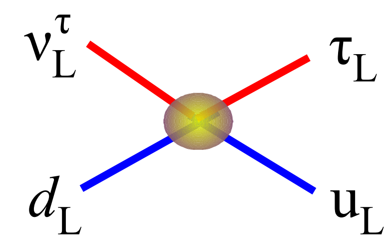






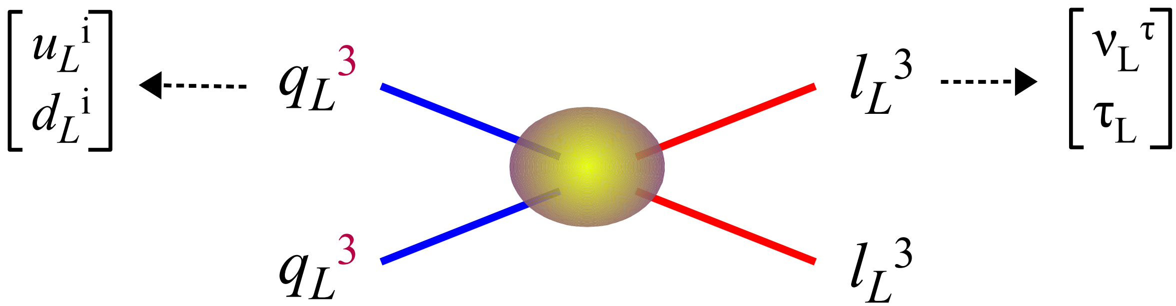


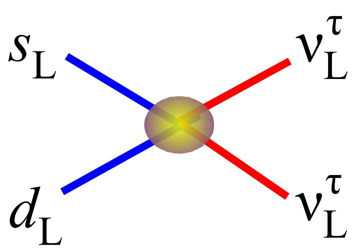
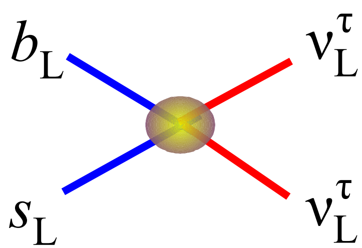
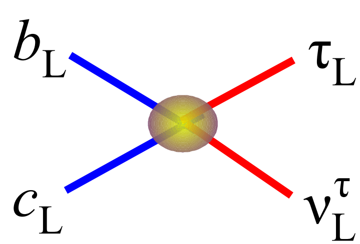
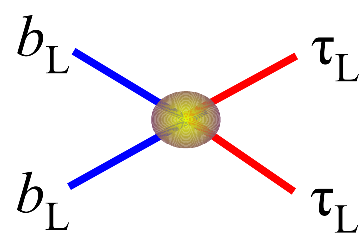
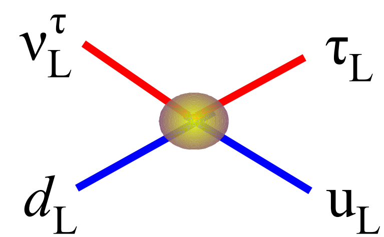




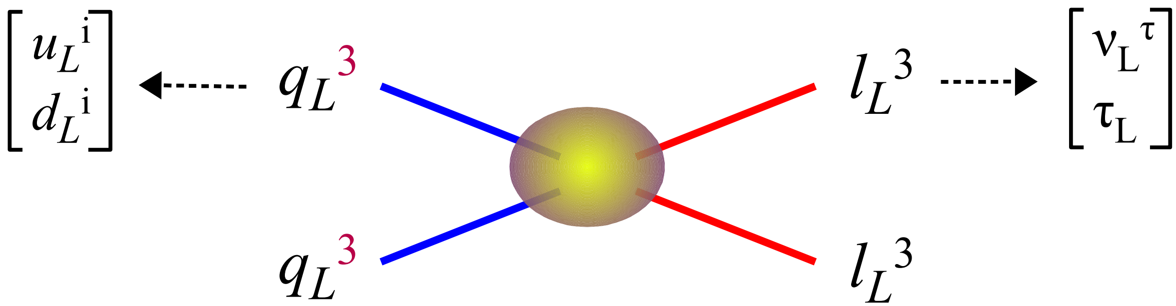
$B(K^+ \to \pi^+ \nu\nu)$	$B(B^+ \to K^+ \nu\nu)$	$R[D^{(*)}]$	$\sigma(pp \to \tau\tau)$	$\sigma(\nu^\tau N \to N'\tau)$
Now [NA62]:	Now [Belle-II]:	Now [HFLAV]:	Now [ATLAS]:	Now:
$\Lambda > 95$ TeV	$\Lambda > 6.4$ TeV	$\Lambda > 2.7$ TeV	$\Lambda > 1.2$ TeV	–
$\delta B = 5\%$ [HIKE]:	$50\,ab^{-1}$ [Belle-II]:	$50\,ab^{-1}$ [Belle-II]:	$3\,ab^{-1}$ [HL-LHC]:	$\delta\sigma = 5\%$ [*future* ?]:
$\Lambda > 270$ TeV	$\Lambda > 18$ TeV	$\Lambda > 6.0$ TeV	$\Lambda > 1.7$ TeV	$\Lambda > 0.75$ TeV

Effective-theory approach



$C \times \lvert V_{ts} \rvert \lvert V_{td} \rvert$	$C \times \lvert V_{ts} \rvert$	$C \times \lvert V_{cb} \rvert$	C	$C \times \lvert V_{ub} \rvert \lvert V_{td} \rvert$
				
$B(K^+ \to \pi^+ \nu\nu)$	$B(B^+ \to K^+ \nu\nu)$	$R[D^{(*)}]$	$\sigma(pp \to \tau\tau)$	$\sigma(\nu^\tau N \to N'\tau)$
Now [NA62]: $\Lambda > 1.7$ TeV $\delta B=5\%$ [HIKE]: $\Lambda > 4.7$ TeV	Now [Belle-II]: $\Lambda > 1.3$ TeV $50ab^{-1}$ [Belle-II]: $\Lambda > 3.6$ TeV	Now [HFLAV]: $\Lambda > 0.6$ TeV $50ab^{-1}$ [Belle-II]: $\Lambda > 1.2$ TeV	Now [ATLAS]: $\Lambda > 1.2$ TeV $3ab^{-1}$ [HL-LHC]: $\Lambda > 1.7$ TeV	Now: – $\delta\sigma=5\%$ [*future* ?]: –

Effective-theory approach



$C \times \lvert V_{ts} \rvert \lvert V_{td} \rvert$	$C \times \lvert V_{ts} \rvert$	$C \times \lvert V_{cb} \rvert$	C	$C \times \lvert V_{ub} \rvert \lvert V_{td} \rvert$
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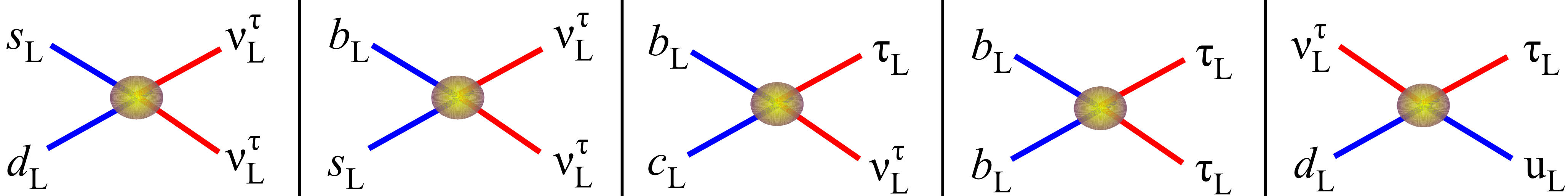
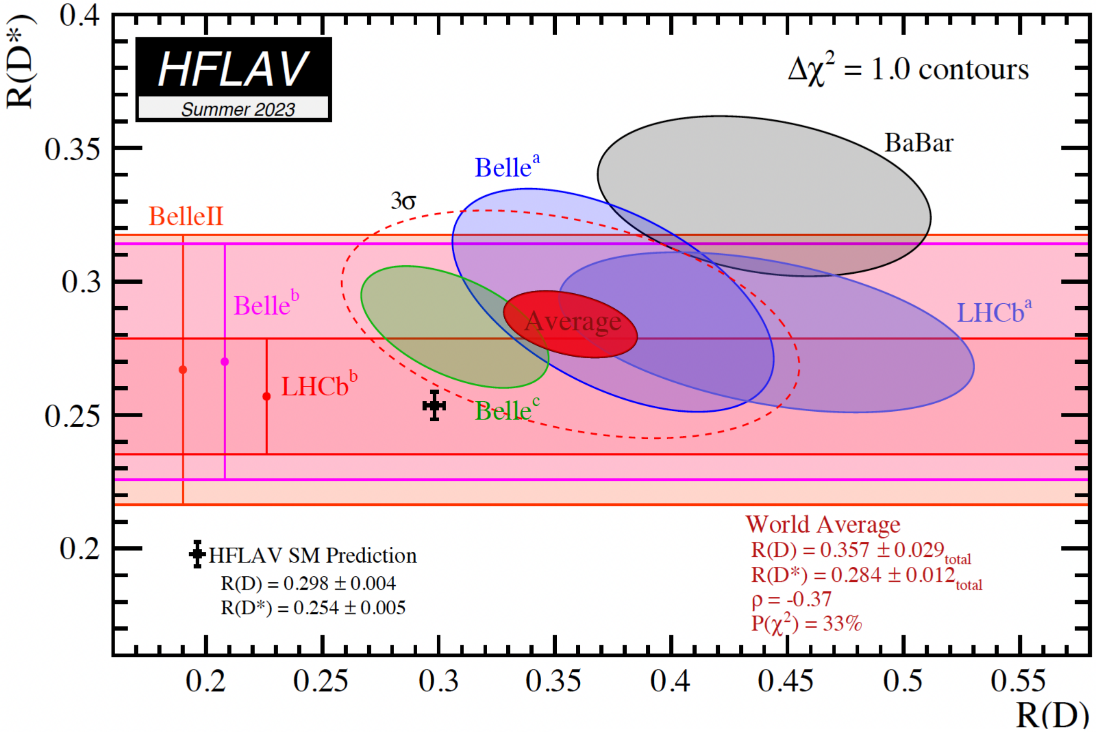
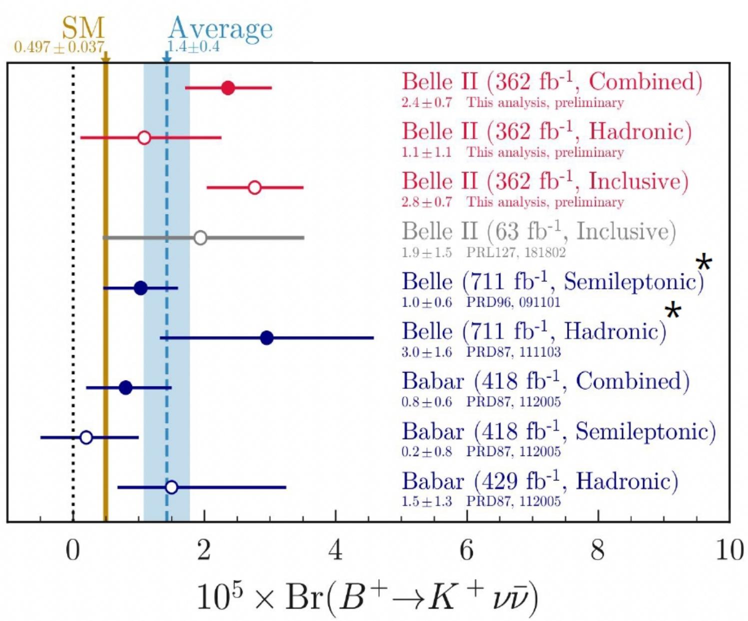


excess over SM prediction | *excess over SM prediction* | *excess over SM prediction*


HFLAV
Summer 2023
$\Delta\chi^2 = 1.0$ contours
BaBar
Belle[a]
3σ
BelleII
Belle[b]
Average
LHCb[a]
LHCb[b]
Belle[c]
HFLAV SM Prediction
R(D) = 0.298 ± 0.004
R(D*) = 0.254 ± 0.005
World Average
R(D) = 0.357 ± 0.029 total
R(D*) = 0.284 ± 0.012 total
ρ = -0.37
P(χ²) = 33%
R(D*)
R(D)


SM
0.497 ± 0.037
Average
1.4±0.4
Belle II (362 fb-1, Combined)
2.4±0.7 This analysis, preliminary
Belle II (362 fb-1, Hadronic)
1.1±1.1 This analysis, preliminary
Belle II (362 fb-1, Inclusive)
2.8±0.7 This analysis, preliminary
Belle II (63 fb-1, Inclusive)
1.9±1.5 PRL127, 181802
Belle (711 fb-1, Semileptonic) *
1.0±0.6 PRD96, 091101
Belle (711 fb-1, Hadronic) *
3.0±1.6 PRD87, 111103
Babar (418 fb-1, Combined)
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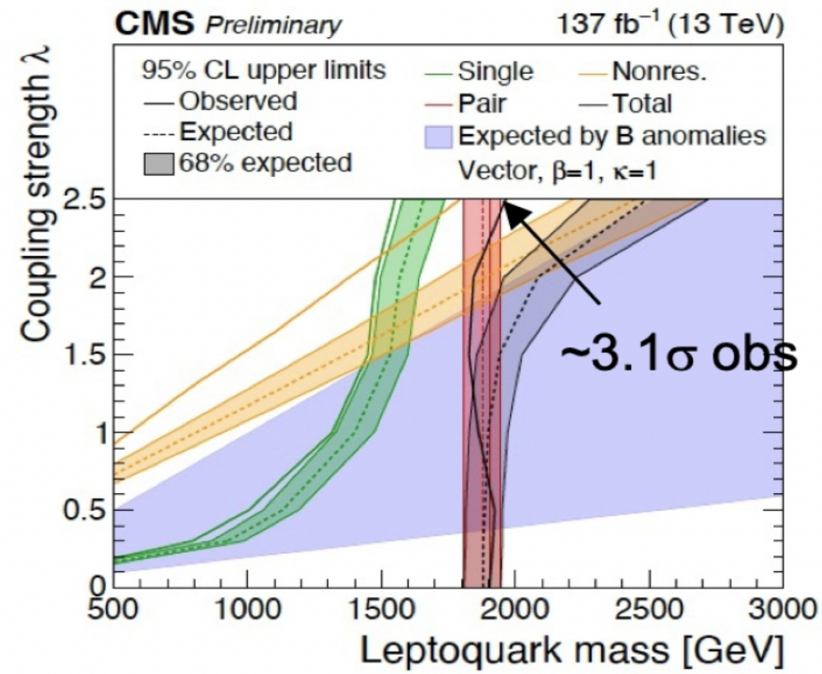
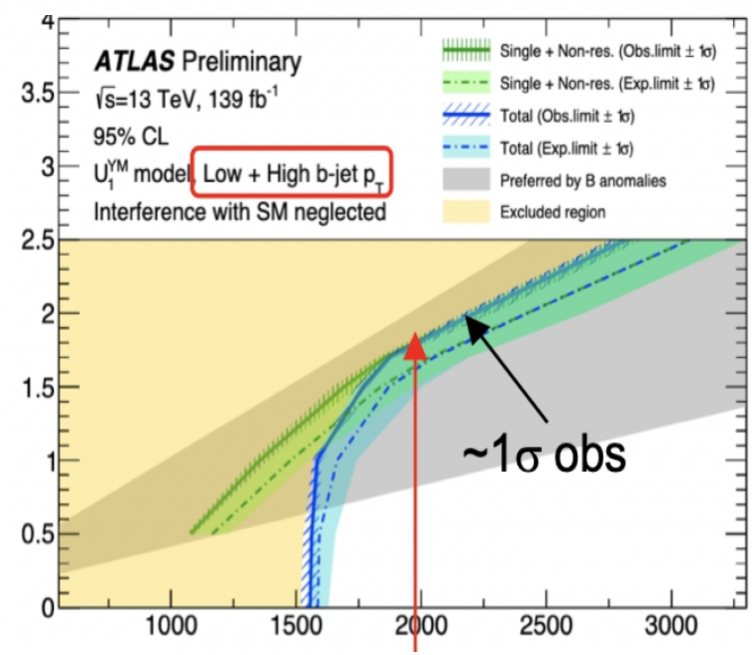
Babar (429 fb-1, Hadronic)
1.5±1.3 PRD87, 112005
$10^5 \times \mathrm{Br}(B^+ \to K^+ \nu\bar{\nu})$

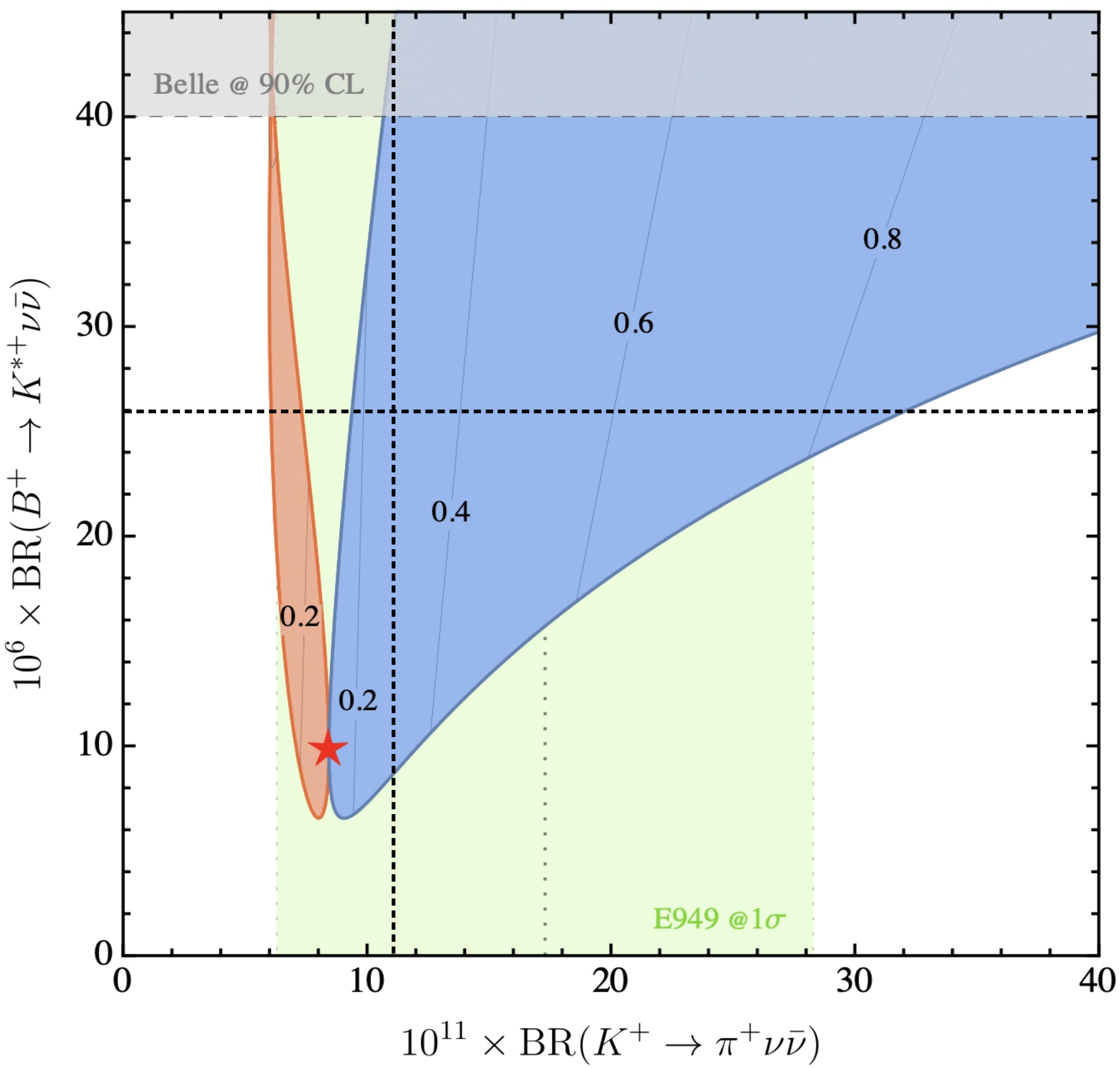
σ(pp → ττ)

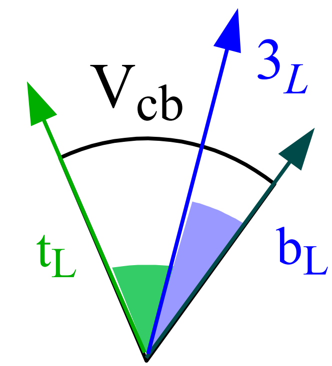

CMS Preliminary
137 fb-1 (13 TeV)
95% CL upper limits
Observed
Expected
68% expected
Single
Pair
Nonres.
Total
Expected by B anomalies
Vector, β=1, κ=1
~3.1σ obs
Coupling strength λ
Leptoquark mass [GeV]


ATLAS Preliminary
√s=13 TeV, 139 fb-1
95% CL
U1YM model Low + High b-jet pT
Interference with SM neglected
Single + Non-res. (Obs.limit ± 1σ)
Single + Non-res. (Exp.limit ± 1σ)
Total (Obs.limit ± 1σ)
Total (Exp.limit ± 1σ)
Preferred by B anomalies
Excluded region
~1σ obs

Effective-theory approach

In models with NP coupled mainly to the 3rd gen. a key aspect in comparing flavor-conserving vs. flavor-violating processes is the orientation in flavor space [alignment *of the 3rd gen.*]





$B(K^+ \to \pi^+ \nu\nu)$ vs. $B(B \to K^{(*)} \nu\nu)$ provide a clean direct constraint on this key parameter

Bordone, Buttazzo, GI, Monnard '16

Effective-theory approach

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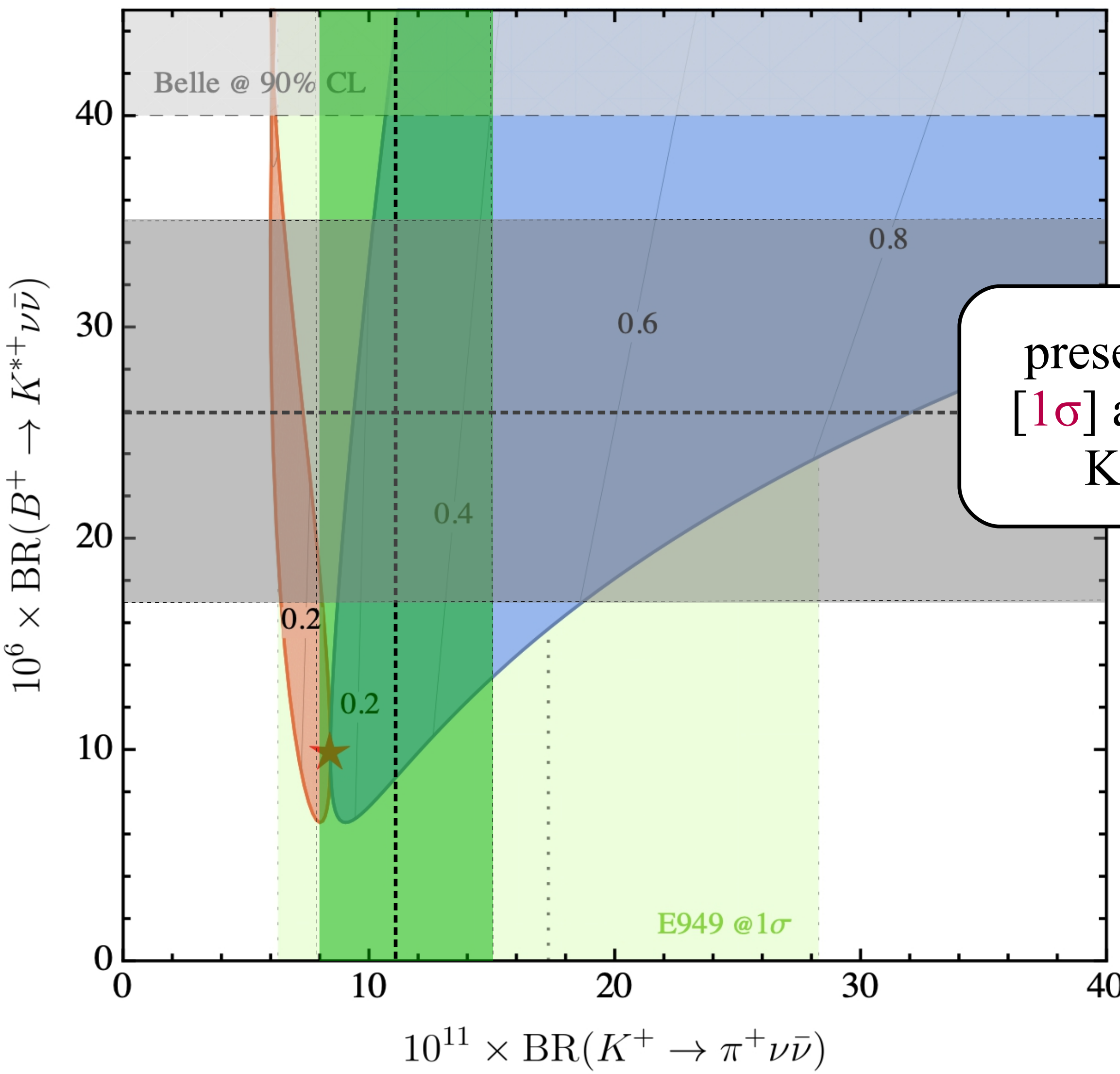
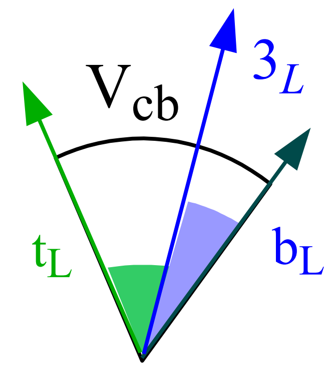


present range [1σ] averaging K & K*



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Bordone, Buttazzo, GI, Monnard '16

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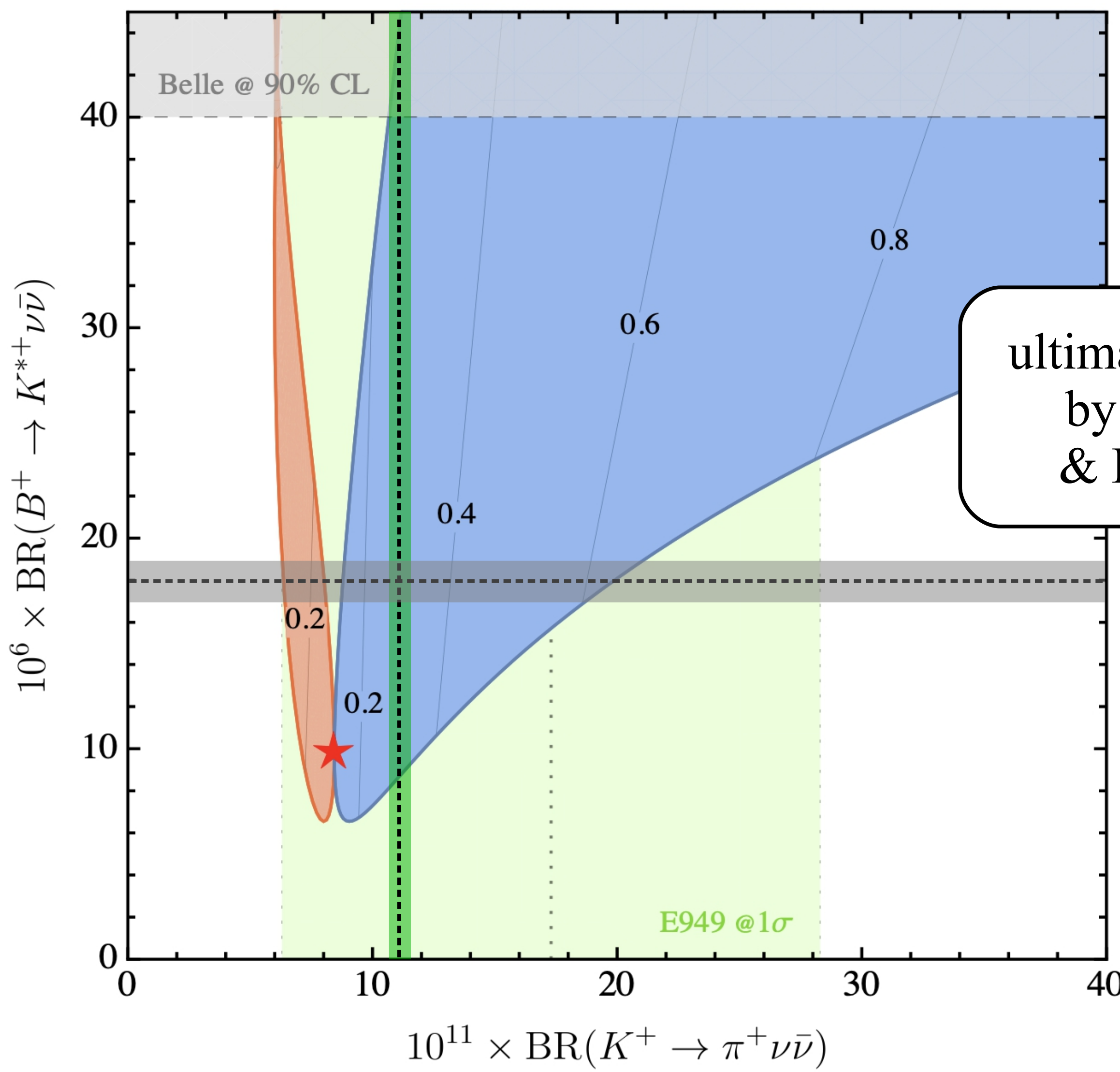
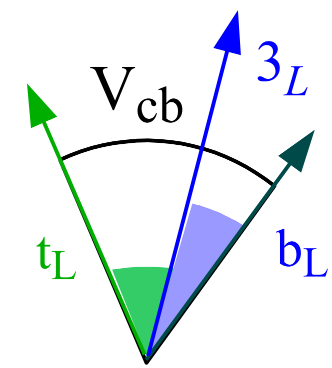


ultimate errors by HIKE & Belle-II



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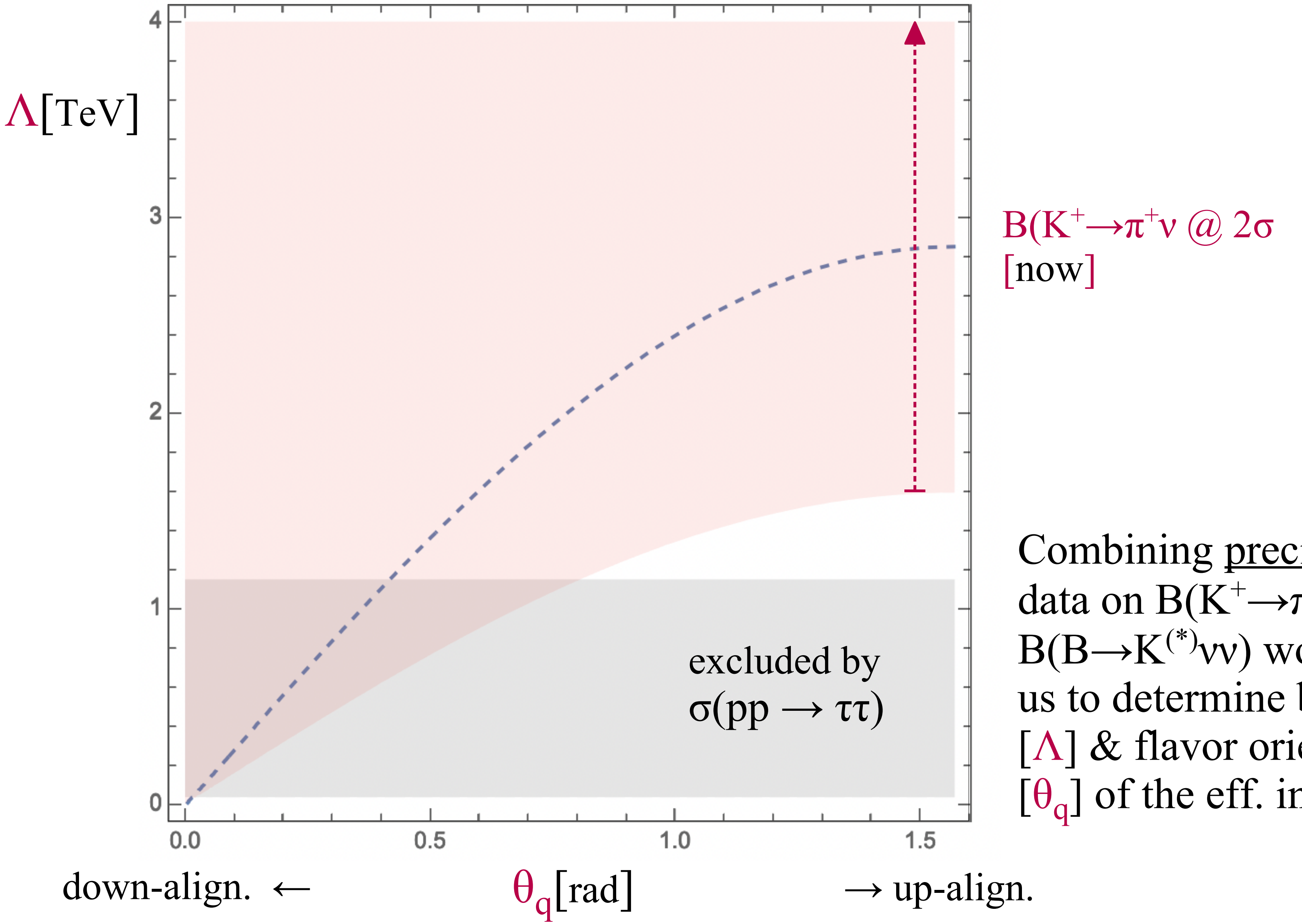
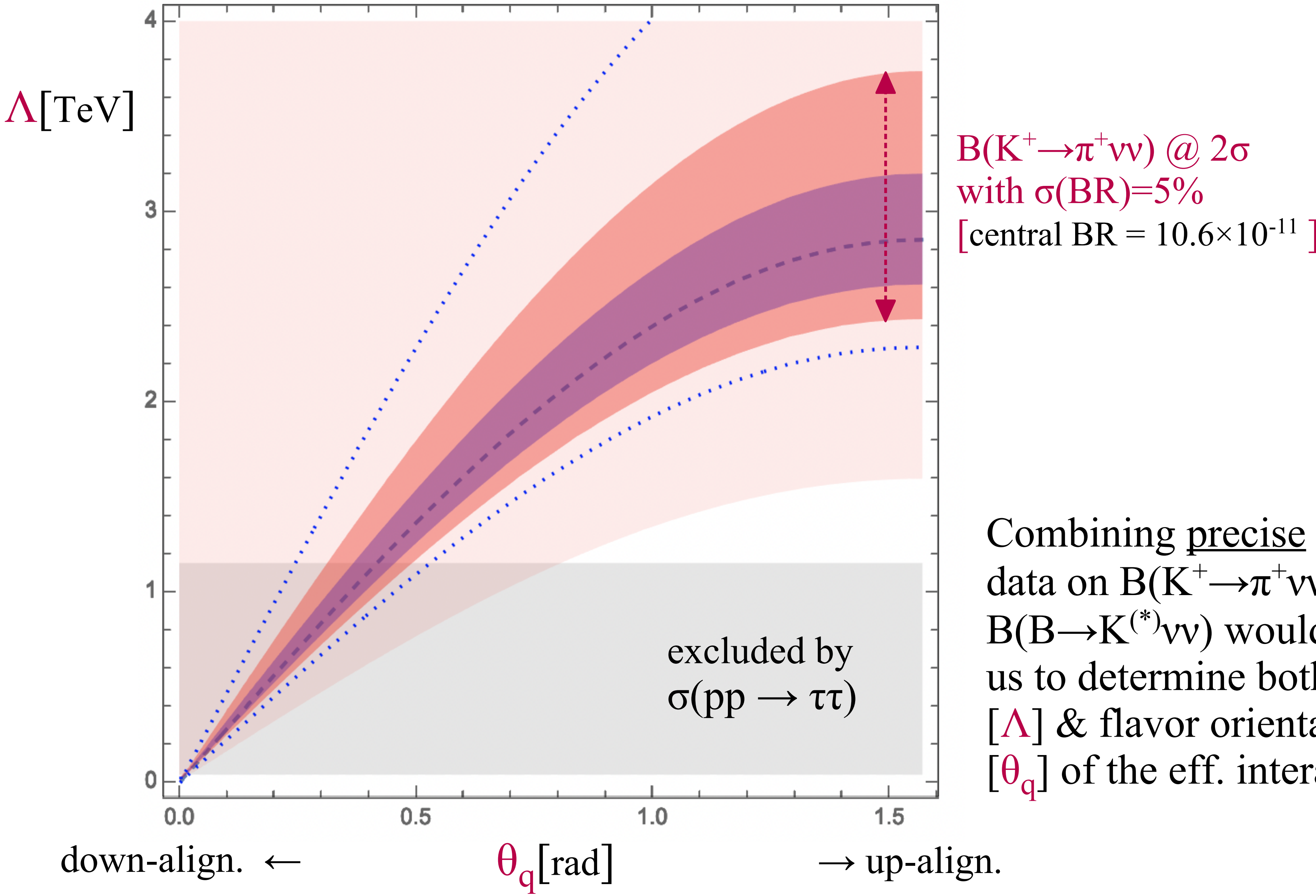
Effective-theory approach



Combining precise exp. data on $B(K^+\to\pi^+\nu\nu)$ & $B(B\to K^{(*)}\nu\nu)$ would allow us to determine both scale [Λ] & flavor orientation [θ_q] of the eff. interaction

Effective-theory approach



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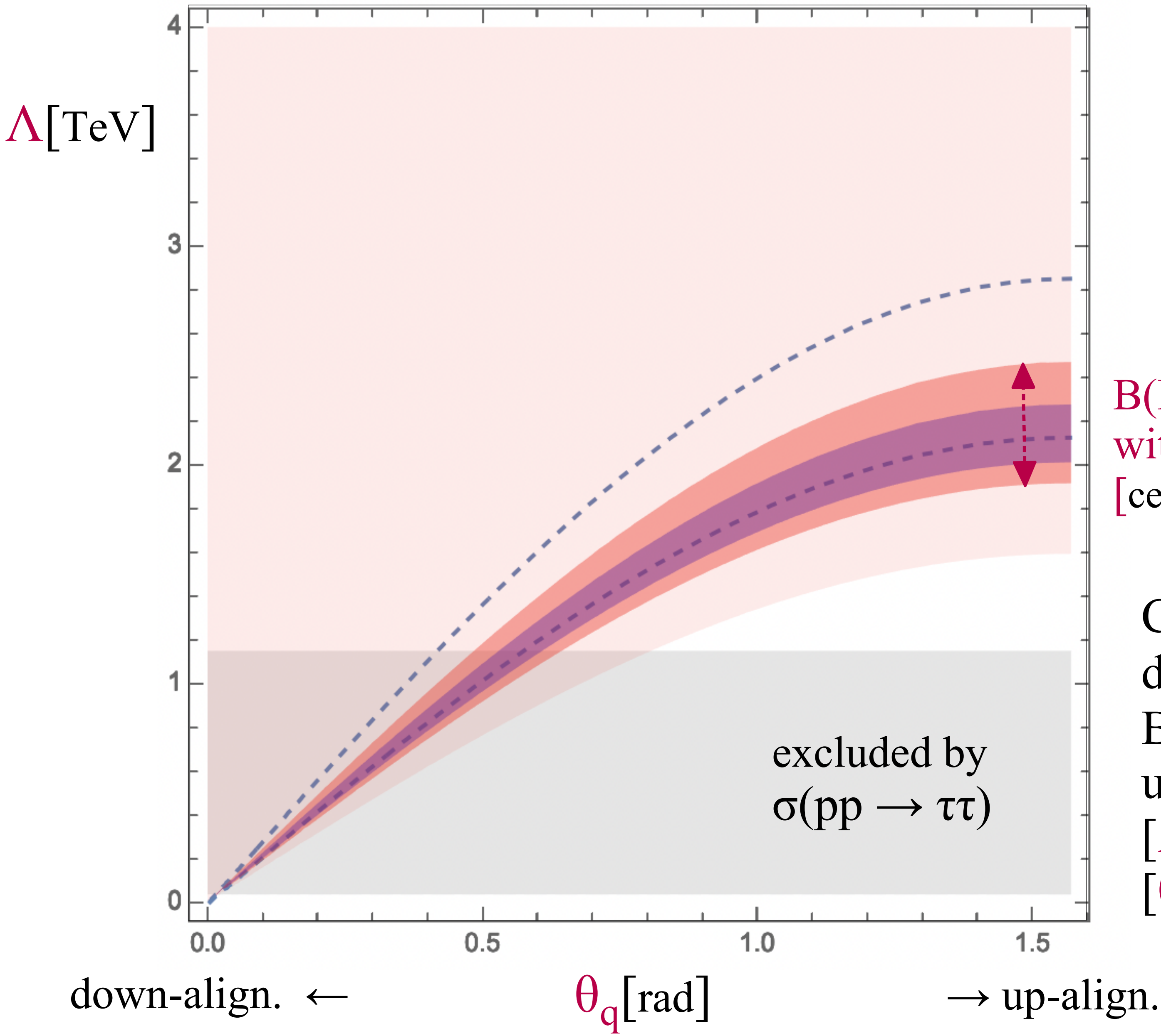
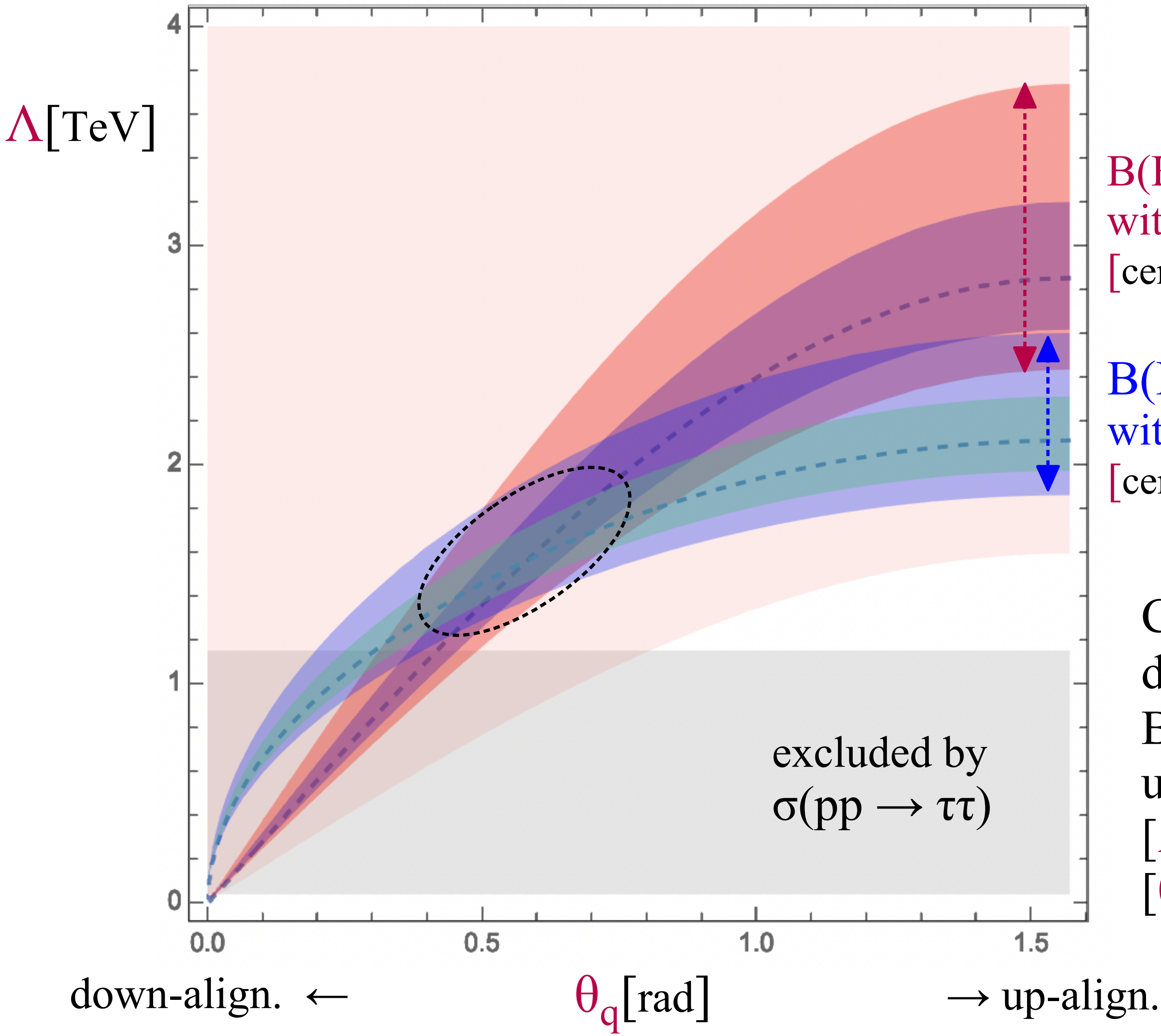


$B(K^+\to\pi^+\nu\nu)$ @ 2σ
with $\sigma(BR)=5\%$
[central BR = 12.5×10^{-11}]

Combining precise exp. data on $B(K^+\to\pi^+\nu\nu)$ & $B(B\to K^{(*)}\nu\nu)$ would allow us to determine both scale [Λ] & flavor orientation [θ_q] of the eff. interaction

Effective-theory approach



$B(K^+ \to \pi^+ \nu\nu)$ @ 2σ
with $\sigma(BR)=5\%$
[central BR = 10.6×10^{-11}]

$B(B \to K^{(*)} \nu\nu)$ @ 2σ
with $\sigma(BR)=10\%$
[central BR = 1.8×BR]

Combining <u>precise</u> exp. data on $B(K^+ \to \pi^+ \nu\nu)$ & $B(B \to K^{(*)} \nu\nu)$ would allow us to determine both scale [Λ] & flavor orientation [θ_q] of the eff. interaction

A motivated BSM example

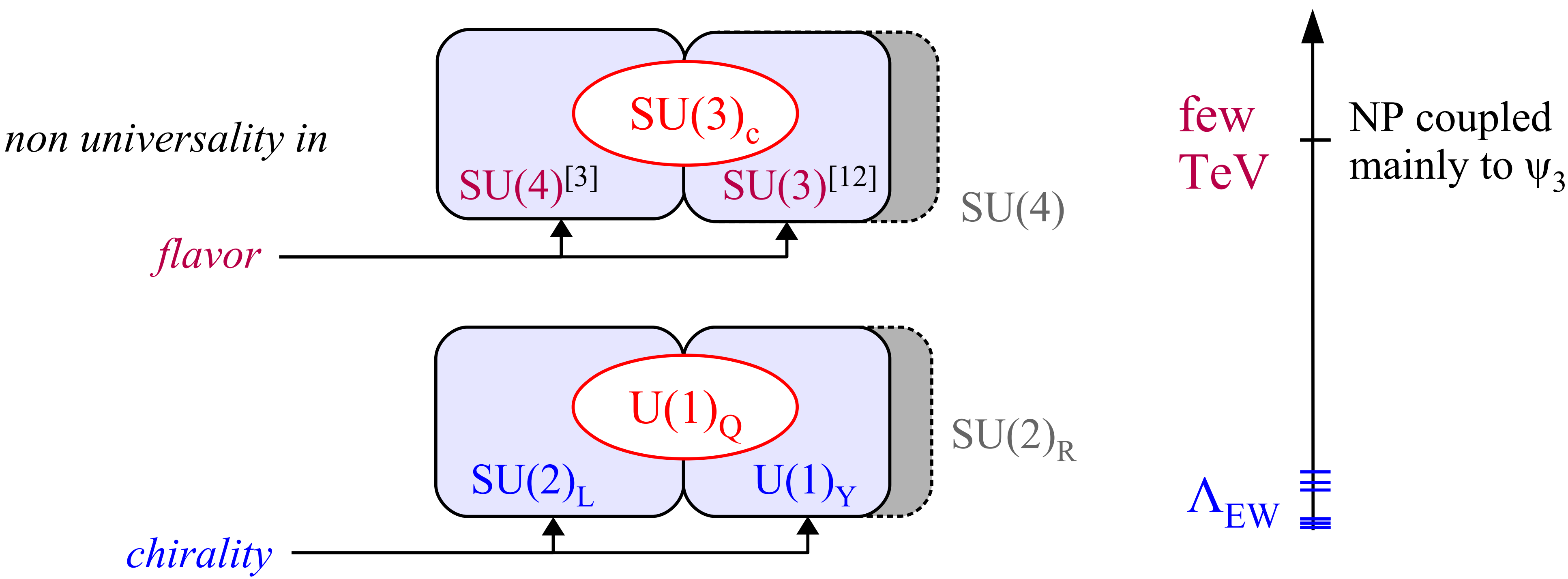
Among models with flavor non-universal gauge interactions, a particularly interesting set up is provided by "4321 models" [*natural "last step" in the SSB chain down to SM of various motivate UV completions*]

Virtues [*theory*]:

- natural Yukawa structure
- quantization of electric charge
- UV complete

Virtues [*pheno*]:

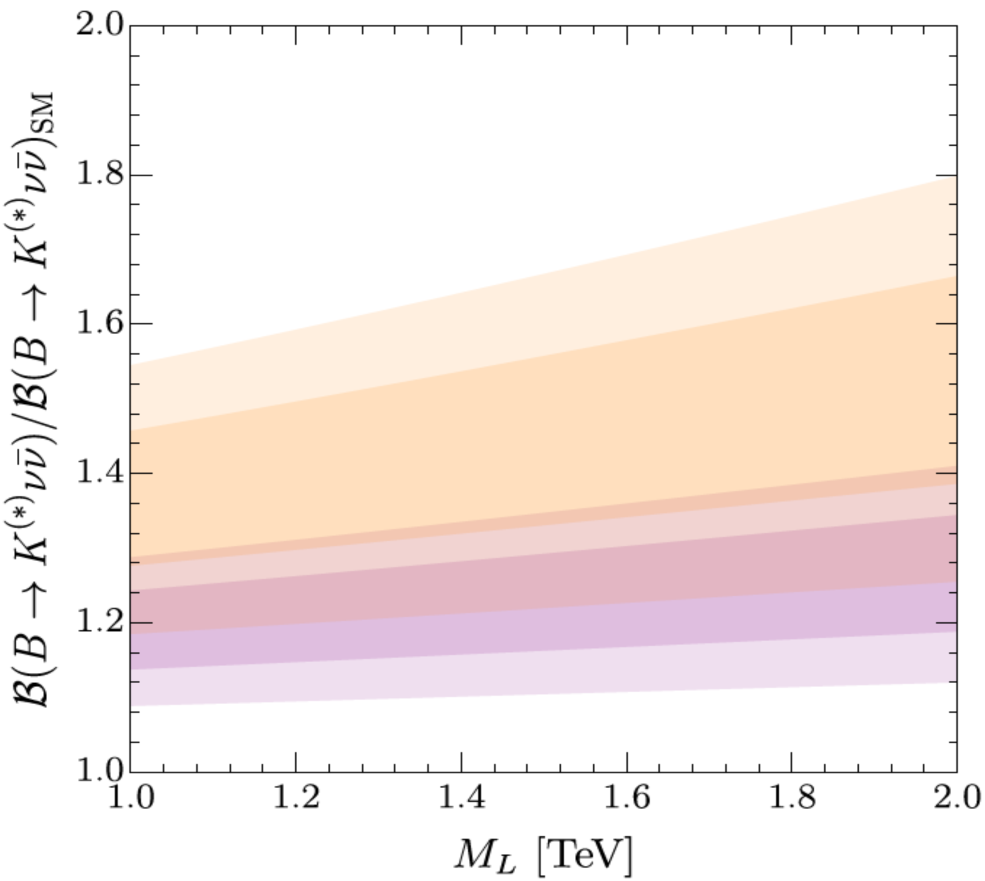
- addresses R(D) anomalies
- addresses LU $b \to s\ell\ell$ anomalies



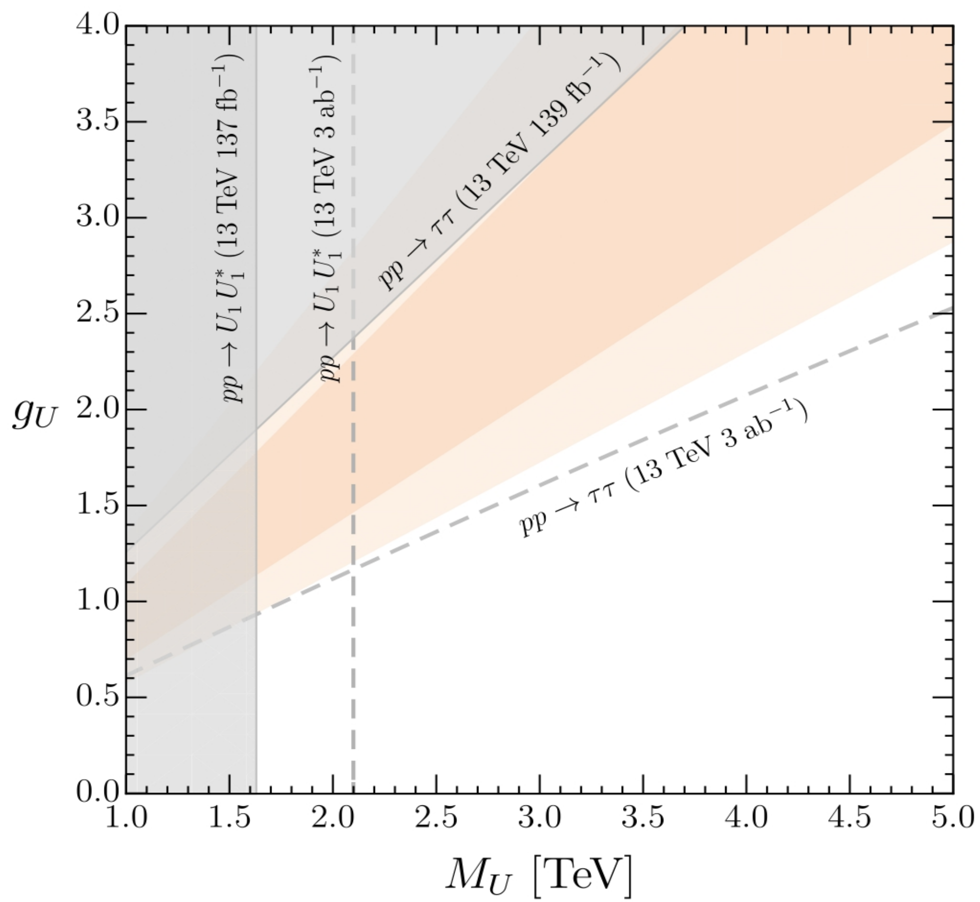
A motivated BSM example

Two clean predictions of this setup following from present data on R(D) & R(D*):

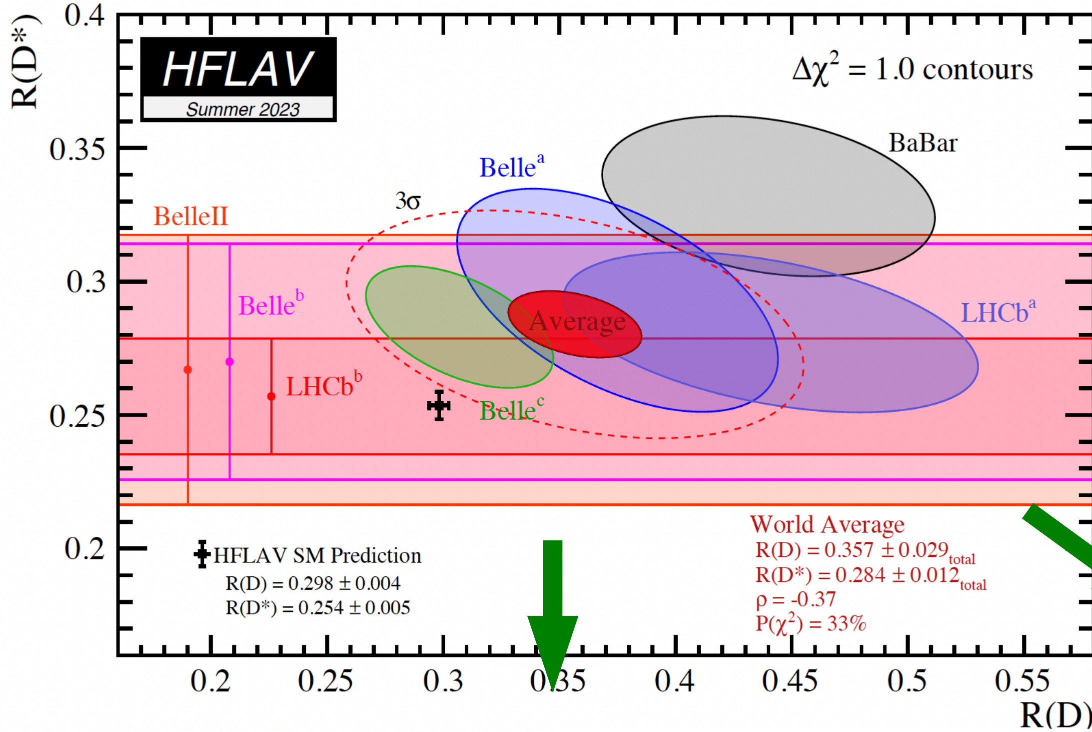
1) enhancement of B($B\to K\nu\nu$) & B($B\to K^*\nu\nu$)
2) enhancement of σ(pp → ττ)



Fuentes-Martin, GI, Konig, Selimovic, '20



Cornella *et al.* '21


HFLAV
Summer 2023
$\Delta\chi^2 = 1.0$ contours
BaBar
Belle[a]
Belle[b]
Belle[c]
BelleII
LHCb[a]
LHCb[b]
Average
3σ
HFLAV SM Prediction
R(D) = 0.298 ± 0.004
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World Average
R(D) = 0.357 ± 0.029 total
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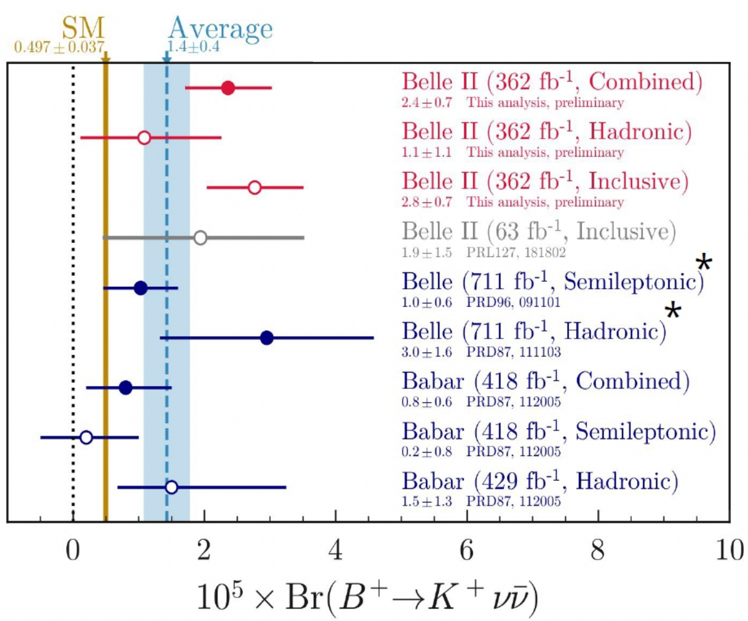
ρ = -0.37
P(χ²) = 33%
R(D)
R(D*)


SM
0.497 ± 0.037
Average
1.4±0.4
Belle II (362 fb-1, Combined)
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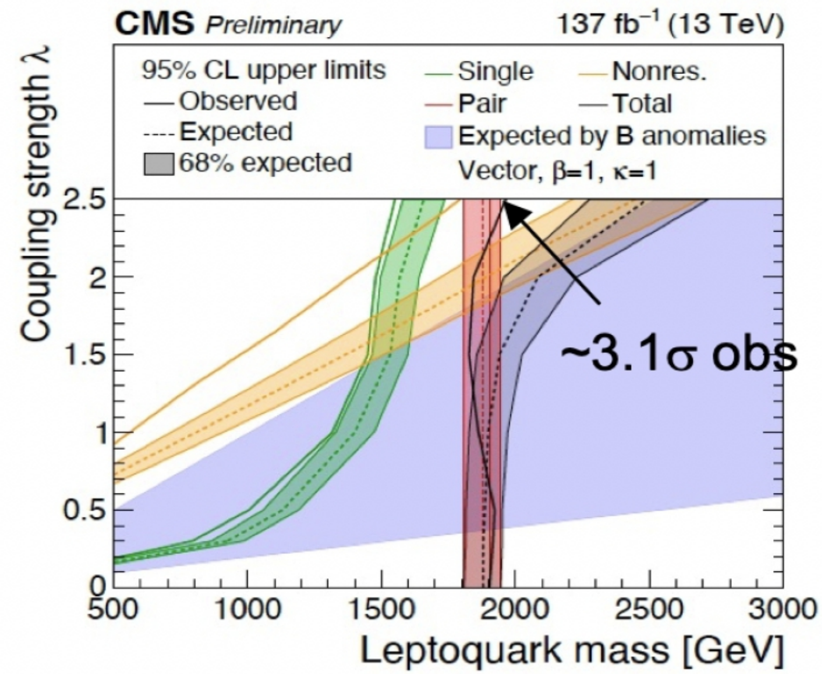
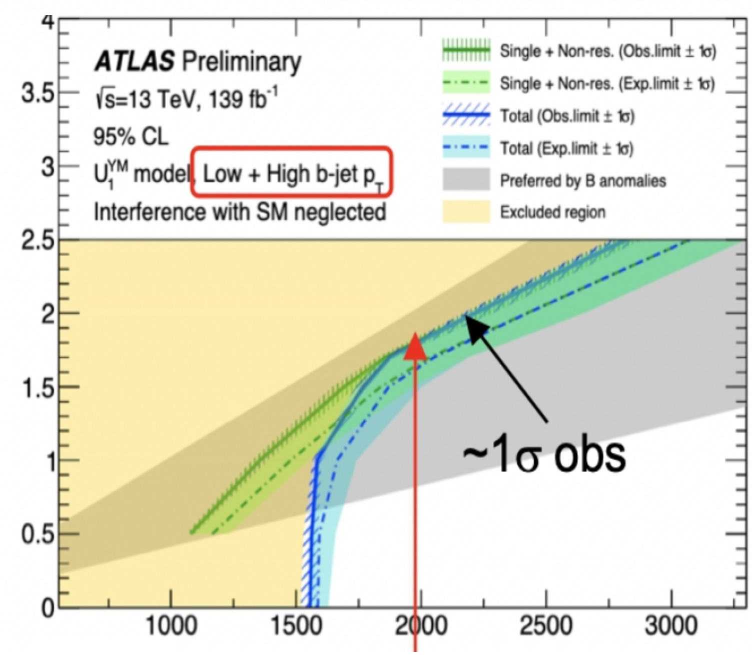
$10^5 \times \mathrm{Br}(B^+ \to K^+ \nu\bar{\nu})$

σ(pp → ττ)


CMS Preliminary
137 fb-1 (13 TeV)
95% CL upper limits
Observed
Expected
68% expected
Single
Pair
Nonres.
Total
Expected by B anomalies
Vector, β=1, κ=1
~3.1σ obs
Coupling strength λ
Leptoquark mass [GeV]


ATLAS Preliminary
√s=13 TeV, 139 fb-1
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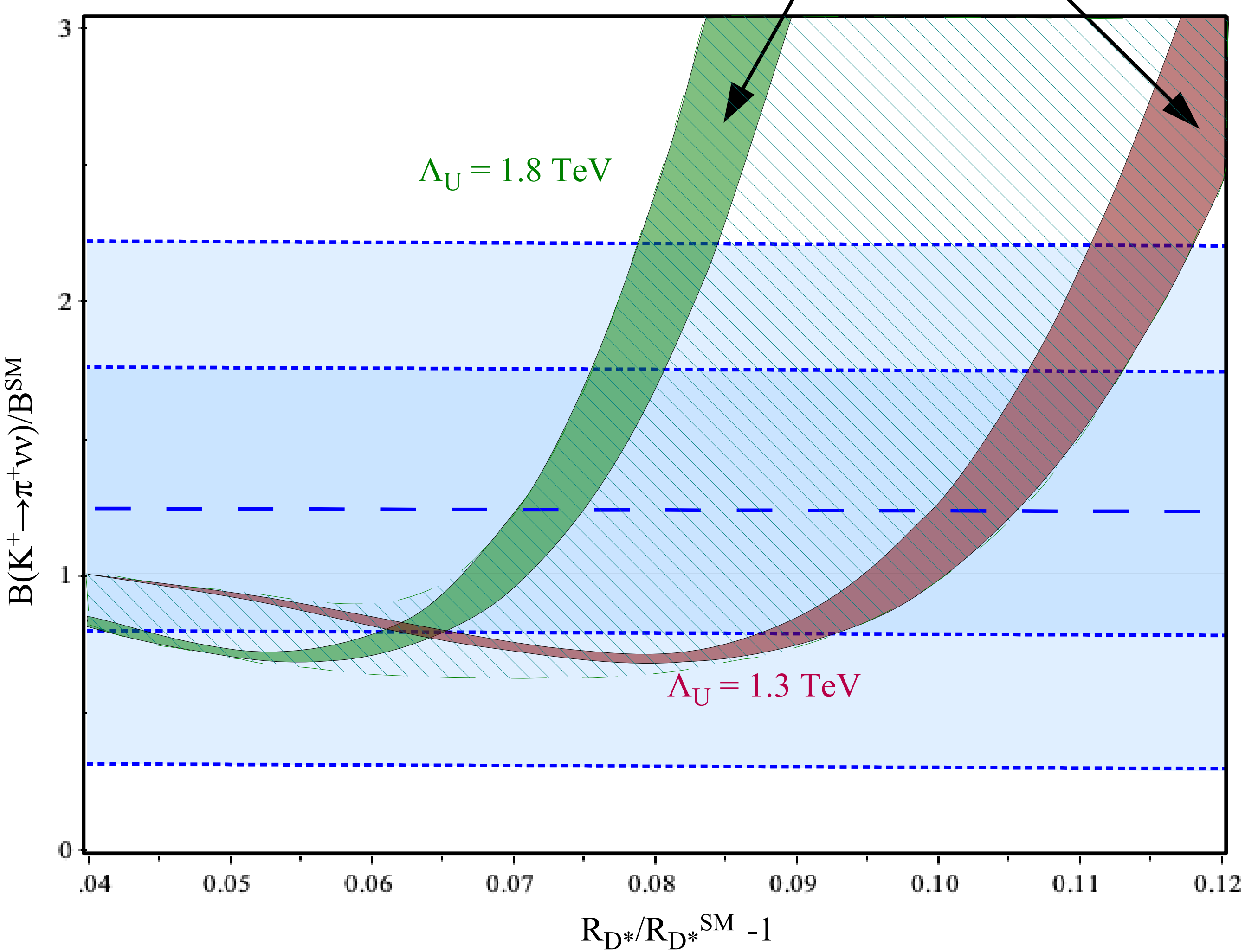
U1YM model Low + High b-jet pT
Interference with SM neglected
Single + Non-res. (Obs.limit ± 1σ)
Single + Non-res. (Exp.limit ± 1σ)
Total (Obs.limit ± 1σ)
Total (Exp.limit ± 1σ)
Preferred by B anomalies
Excluded region
~1σ obs

A motivated BSM example

Ref. values for LQ mass and coupling ($\Lambda_U = \sqrt{2} M_U / g_U$)
from B physics + high-energy searches (*max & min values*)

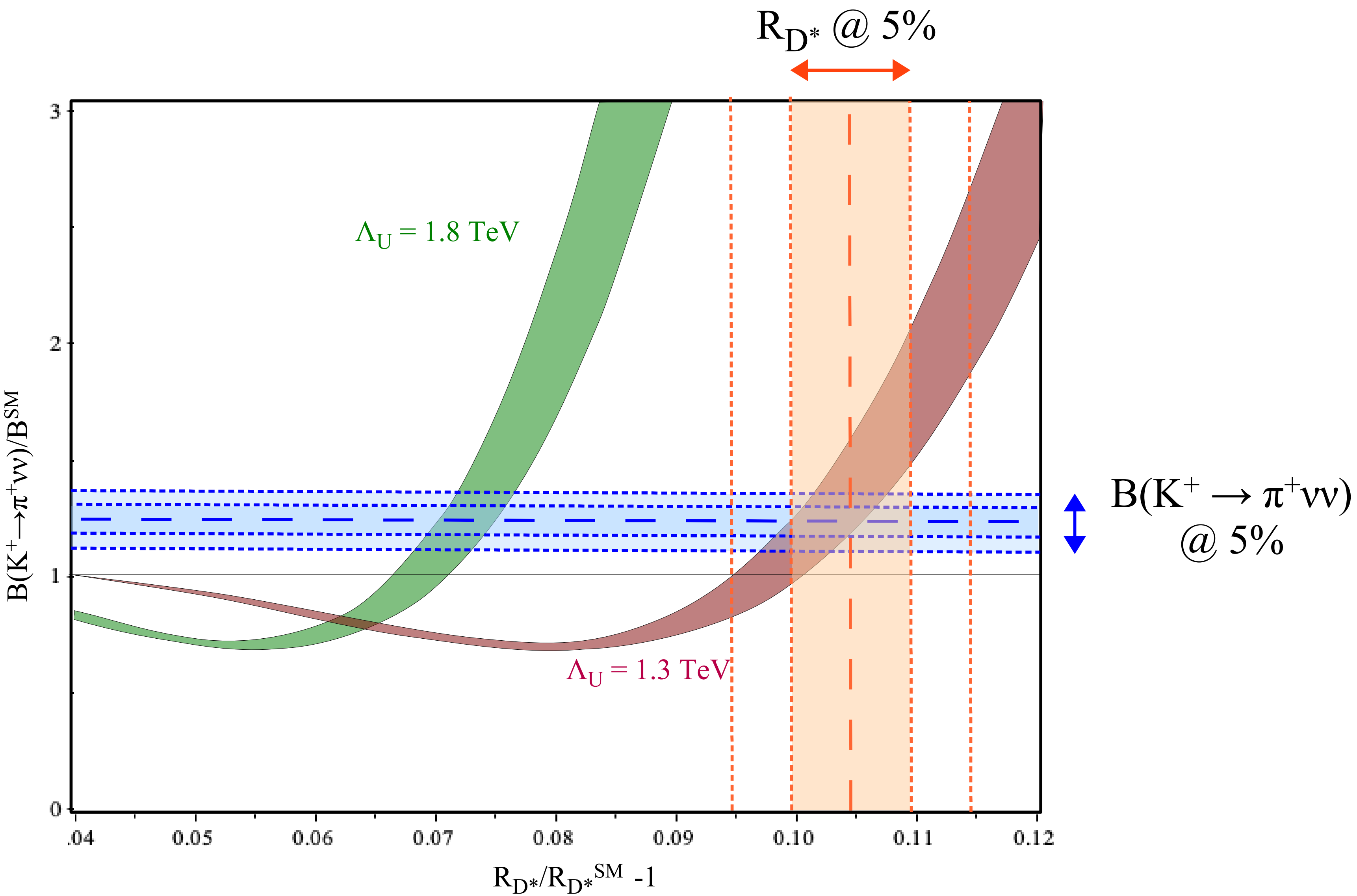


Present 2σ range for $B(K^+ \to \pi^+ \nu\nu)$

Crosas, GI, Lizana, Selimovic Stefanek '22

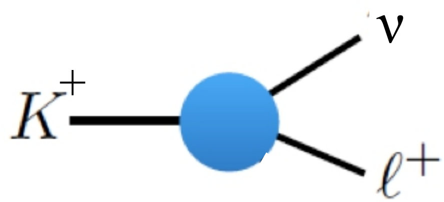
A motivated BSM example

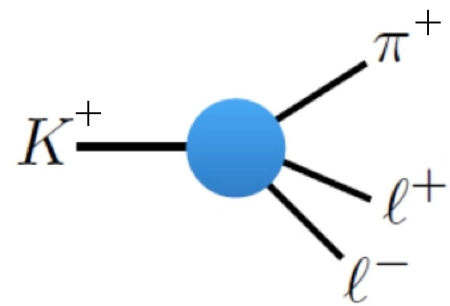
Possible impact of future precision measurements.



Crosas, GI, Lizana, Selimovic Stefanek '22

Other modes





→ More in the talk by Yuval Grossman...

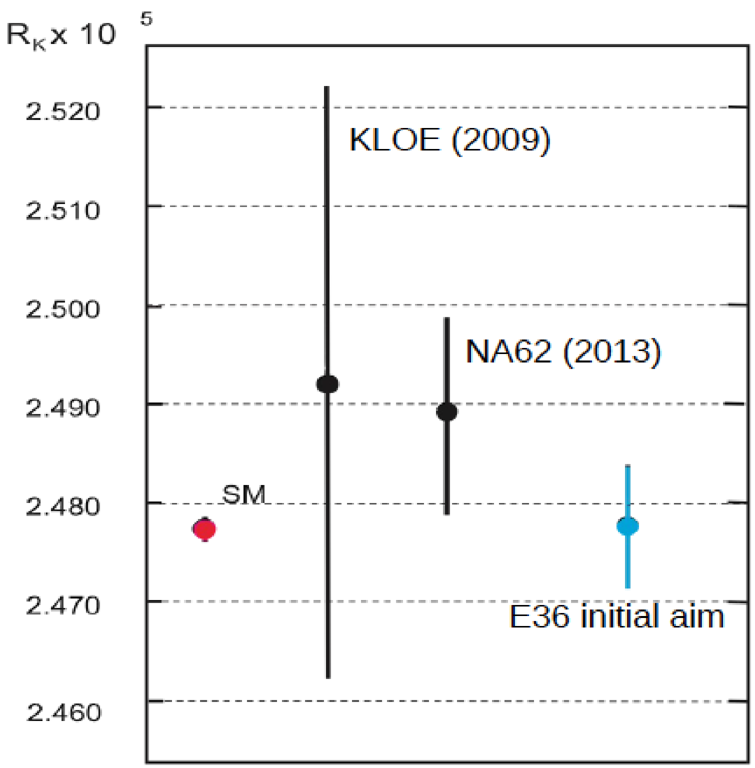
+

Other modes

I. Tests of μ/e universality in $s \to u$ transitions

A very sensitive probe of μ/e universality in the kaon system is
$R_K = \Gamma(K^+ \to e^+\nu) / \Gamma(K^+ \to \mu^+\nu)$ [→ *high-sensitivity to scalar amplitudes*]

Using simple EFT considerations, we can expect violations from SM in $R_K(K)$ up to $\sim 10^{-3}$



- **Highly Precise SM value**
  $R_K = (2.477 \pm 0.001 \quad) \times 10^{-5}$
  [V. Cirigliano, I. Rosell, Phys. Rev. Lett. 99, 231801

- **World Average (2013)**
  $R_K = (2.488 \pm 0.01) \times 10^{-5}$ $\Delta R_K/R_K \approx 0.4\%$

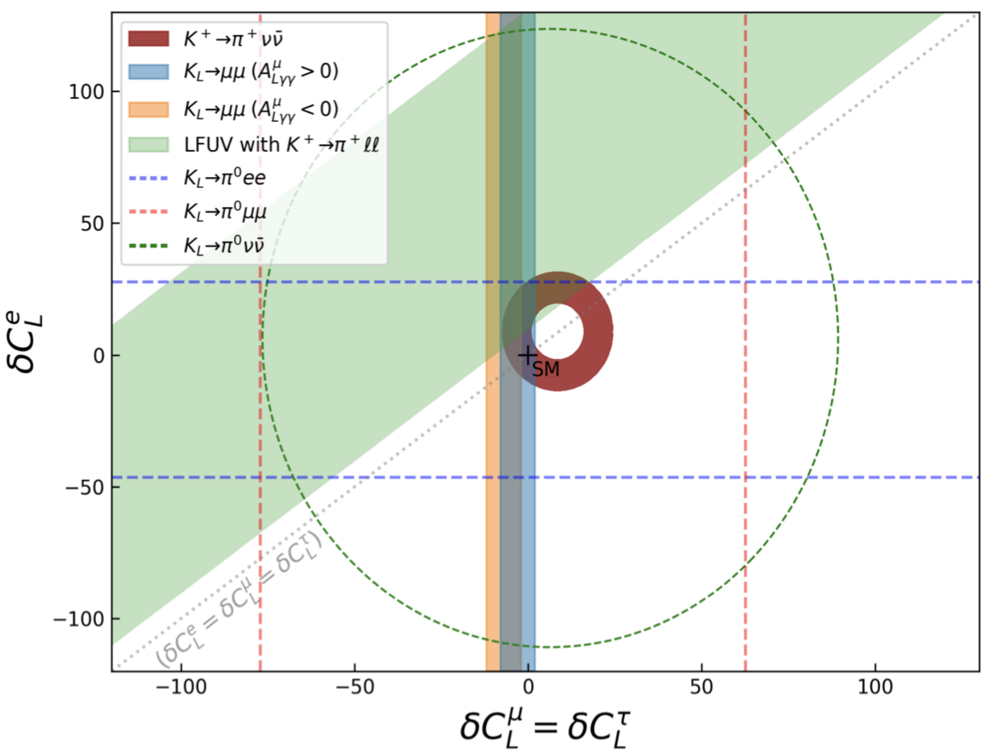
Sizable NP parameter space still to probed

Other modes

II. Tests of μ/e universality in $s \to d$ (FCNC) transitions

In $K^+ \to \pi^+ ll$ we can probe μ/e universality in vector-type amplitudes.

Given present bounds on $R_K(B)$ → simple EFT considerations imply LFU violations at the per-mil level in the coefficients (slopes) of the $K^+ \to \pi^+ ll$ form factors [vs. current exp. bounds @ 10% level]



While it is impossible to reach this NP benchmark, there is still a large room for improvement on a very "clean" SM test

D'Ambrosio, Iyer, Mahmoudi, Neshatpour '22

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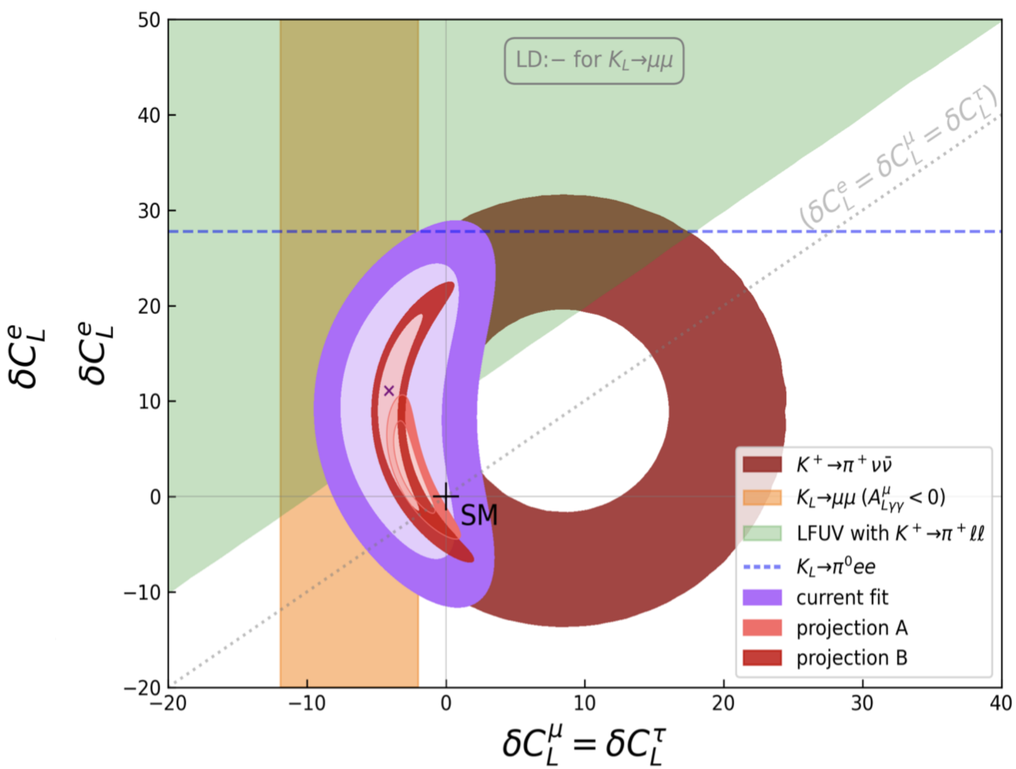

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D'Ambrosio, Iyer, Mahmoudi, Neshatpour '22

Conclusions

- Flavor is an essential ingredient to understand the structure of physics beyond the SM.

- Measuring $B(K^+ \rightarrow \pi^+ \nu\nu)$ @ 5% relative error is a milestone in this respect: unique probe of flavor mixing among the light generations at the electroweak scale and above.

- Present data are fully compatible with a "flavor-full" extension of the SM, where NP is dominantly coupled to the 3rd generation at the TeV scale.
  In this general (*and well-motivated*) context, the key role of a precise measurement of $B(K \rightarrow \pi\nu\nu)$ is further reinforced.

- While the role of $K \rightarrow \pi\nu\nu$ decays is somehow unique, other rare K decays do offer complementary windows on more specific SM extensions