BSM lessons from flavor

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Physics at long distances

- Ignore the short-distance details (degrees of freedom)

Law of physics become simpler

+

Accidental symmetries

credits: R. Rattazzi

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Accidental symmetries

SO(3) symmetry

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Physics at long distances

- Ignore the short-distance details (degrees of freedom)

Law of physics become simpler

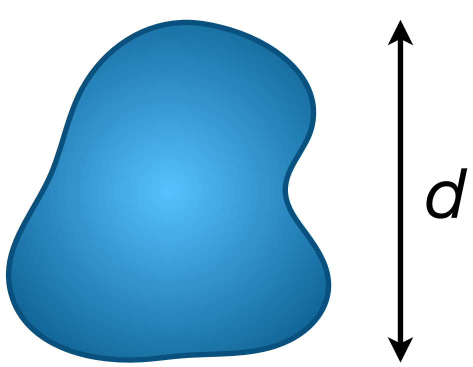
+

Accidental symmetries

SO(3) symmetry

- Example: electrostatic potential at long distances

credits: R. Rattazzi



SO(3) $\longrightarrow$ SO(2) $\longrightarrow$ $\varnothing$

1/R   *d/R²*   *d²/R³*

$$V(\vec{R}) = \int \frac{\rho(\vec{r})}{|\vec{R}-\vec{r}|} d^3r \xrightarrow{R \gg d} \frac{Q}{R} + \frac{\vec{Q}_1 \cdot \vec{R}}{R^3} + \frac{Q_2^{ij} R_i R_j}{R^5} + \cdots$$

The Standard Model EFT

The SM is an Effective Theory valid up to a scale Λ; expansion in E/Λ

$$\mathcal{L}_{\rm SM} = \mathcal{L}_{d\leq 4} + \frac{1}{\Lambda}\mathcal{L}_{d=5} + \frac{1}{\Lambda^2}\mathcal{L}_{d=6} + \cdots$$

- d = 4: $\mathcal{L}_{\rm kin} + g A_\mu(\bar\psi\gamma^\mu\psi) + Y_{ij} H\bar\psi^i\psi^j + \lambda|H|^4$

  the “spherical cow”: renormalizable SM Lagrangian, accounts for all what we see!

  Accidental symmetries of SM: B, L, custodial SO(4)

- d = 5: $\frac{b_{ij}}{\Lambda} L_i L_j H H$

- d = 6: $\frac{c_{ijkl}}{\Lambda^2}\psi_i\psi_j\psi_k\psi_l + \frac{c_{ij}}{\Lambda^2}(\psi_i\sigma_{\mu\nu}\psi_j)F^{\mu\nu} + \cdots$

  (the head, tail, horns of the cow…)

- …

Flavor is crucial!

The "spherical cow"

I. The SM is valid up to $\Lambda \gg m_W$

- Neutrino masses determined by dim. 5 term $\mathcal{L}_5 = \frac{b_{ij}}{\Lambda} L_i L_j H H$

  very high scale $\Lambda \sim 10^{14}$ GeV explains why $m_\nu \ll m_{q,l}$

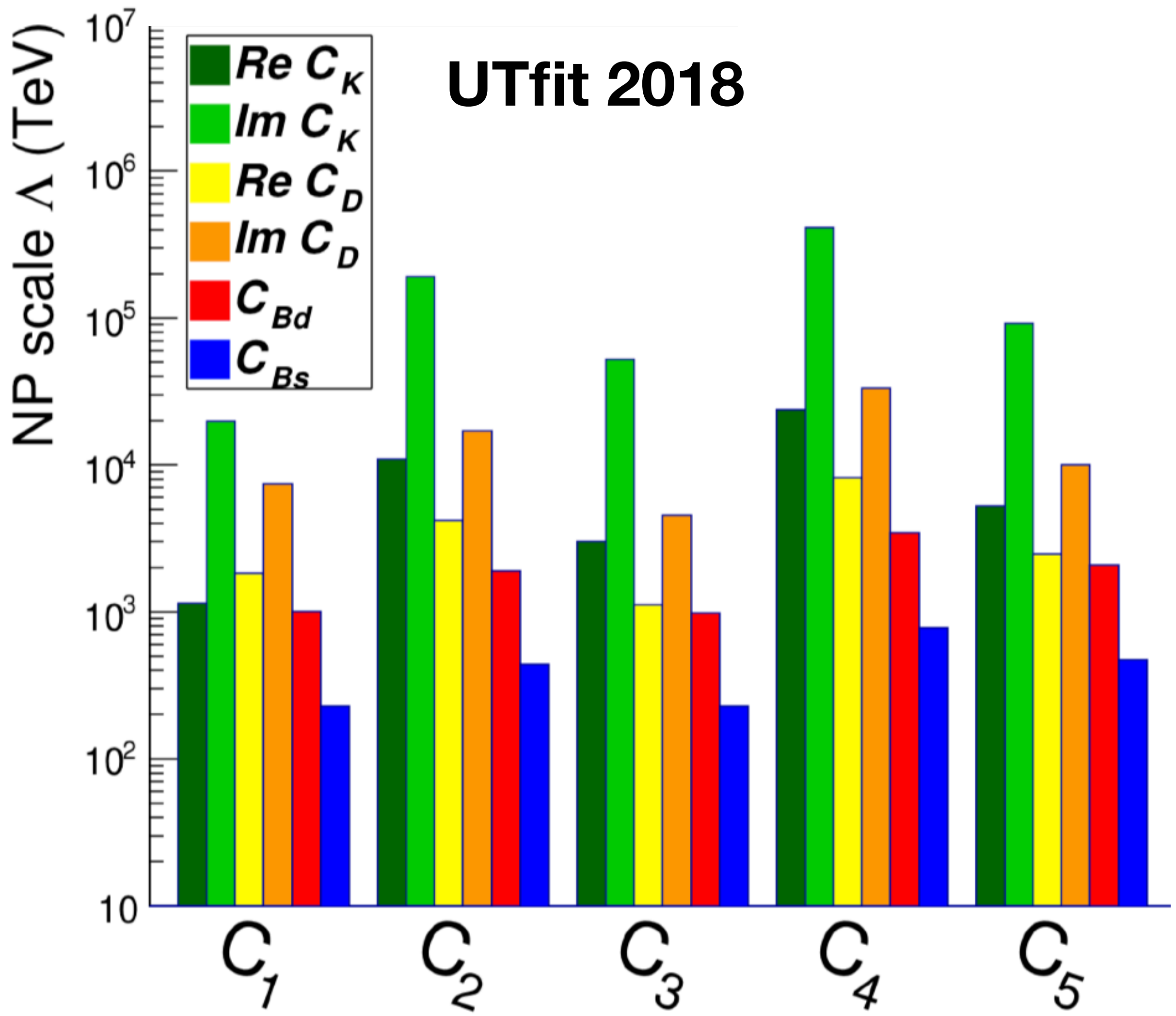
- All other physical effects much more suppressed (dim. 6 operators):

  B, L automatically conserved

  Flavor in agreement with CKM

  Agreement with all experiments!

  (but we'll never see anything new)

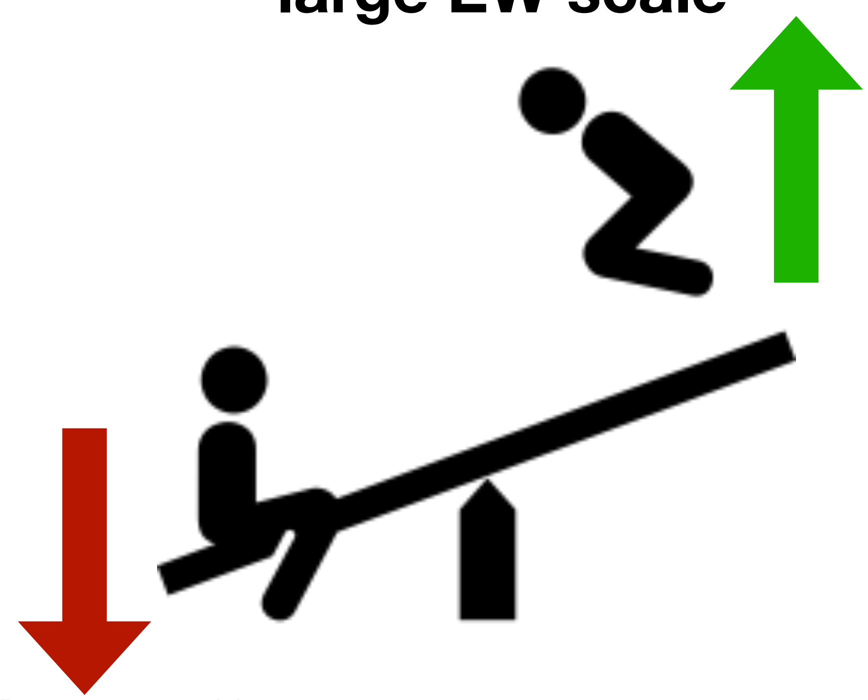


however… indications that this might not be the correct picture

The hierarchy paradox

The only dim. 2 term in the Lagrangian: Higgs mass

$$\mathcal{L} = c_2\Lambda^2|H|^2 + \mathcal{L}_4 + \frac{1}{\Lambda}\mathcal{L}_5 + \frac{1}{\Lambda^2}\mathcal{L}_6 + \cdots$$



1. EW scale expected of order Λ,
   unless c_2 suppressed by some symmetry

   (no such symmetry in SM)

2. Higher dimension terms could be small for other reasons:

   ✦ Dim. 5: neutrino mass violates L

   ✦ Dim. 6: maybe complex flavor structure / flavor symmetries

   Need to complicate the theory: impose symmetries, model building

☞ But flavor exists! We'll need to find an explanation anyway, at some point…

The importance of precision measurements

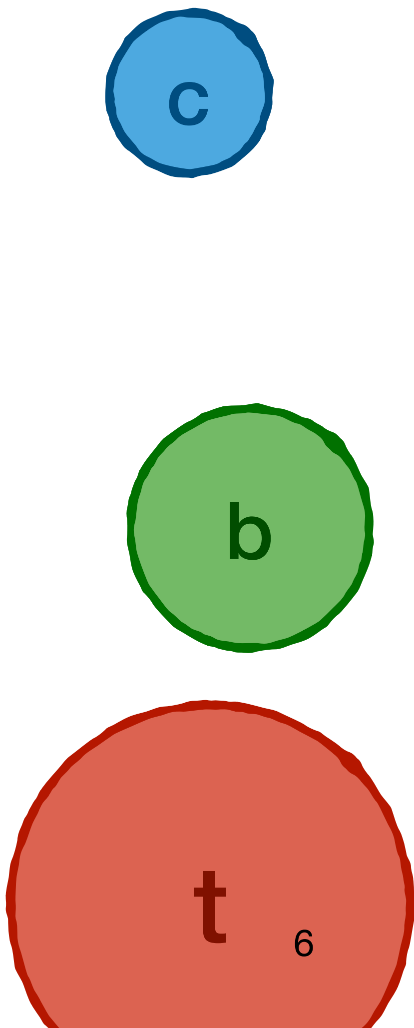
Rare (flavor) processes are the ideal place to look for New Physics!

$$\mathcal{L}_{\mathrm{SM+NP}} \xrightarrow{E \ll m_W} \mathcal{L}_{\mathrm{eff}} = \sum_i \mathcal{O}_i \left(\frac{C_i^{\mathrm{NP}}}{\Lambda^2} + \frac{C_i^{\mathrm{SM}}}{v^2} \right)$$

usually suppressed by loops & CKM factors

Several examples of great indirect discoveries in the past:

- Small $K_L \to \mu\mu$ branching ratio: existence of charm (GIM)
  Glashow, Iliopoulos, Maiani 1970
- Frequency of K-K oscillations: prediction of charm mass
  Lee, Gaillard 1974
- CPV in K system: existence of 3rd generation
  Kobayashi, Maskawa 1973
- Frequency of B-B oscillations: prediction of large top mass
  late 1980's
- (ElectroWeak Precision Tests: prediction of Higgs mass)
  late 1990's

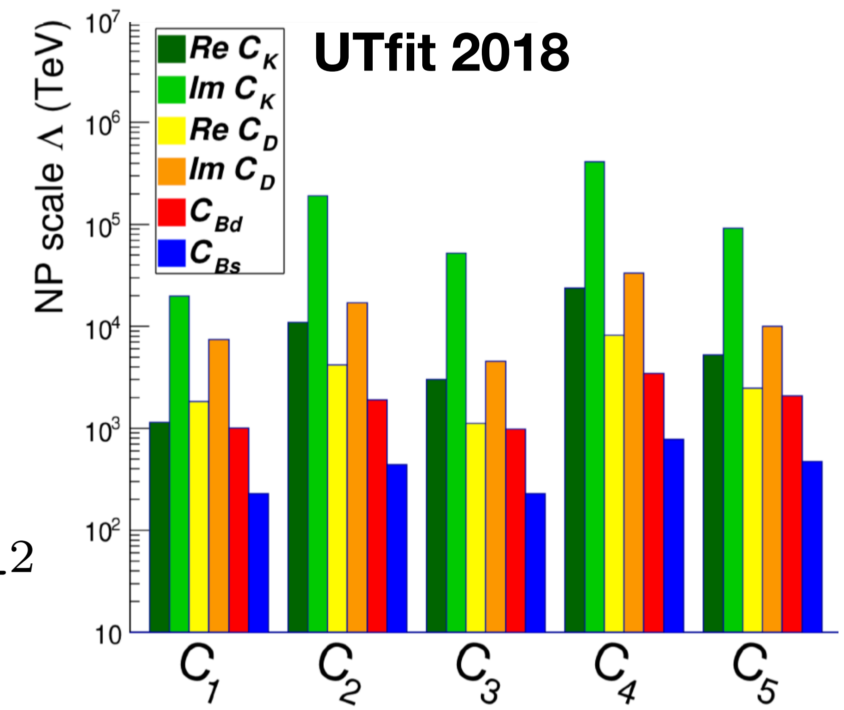


Flavor symmetries

- Insisting on Λ ~ TeV requires a suppression of FCNC by means of **symmetries**

$$\mathcal{L}_{\text{eff}} = \sum_i \mathcal{O}_i \left(\frac{C_i^{\text{NP}}}{\Lambda^2} + \frac{C_i^{\text{SM}}}{v^2} \right)$$

In the SM, the only source of flavor transitions are **Yukawa couplings** $C_{i \to j}^{\text{SM}} \approx Y_{ik} Y_{jk}^* / 16\pi^2$



- In the limit Y → 0, the SM has an exact *flavor symmetry*

$$\text{SU}(3)_q \times \text{SU}(3)_u \times \text{SU}(3)_d \times \text{SU}(3)_\ell \times \text{SU}(3)_e$$

broken by $Y_{u,d,\ell}$

- Maximal amount of suppression: NP also breaks symmetry **only with Y**

$$C_{i \to j}^{\text{NP}} \approx Y_{ik} Y_{jk}^*$$

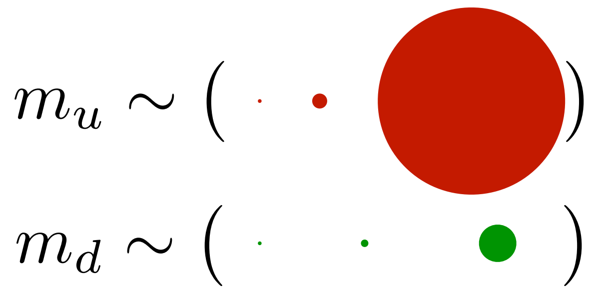
NP with CKM-like flavor structure

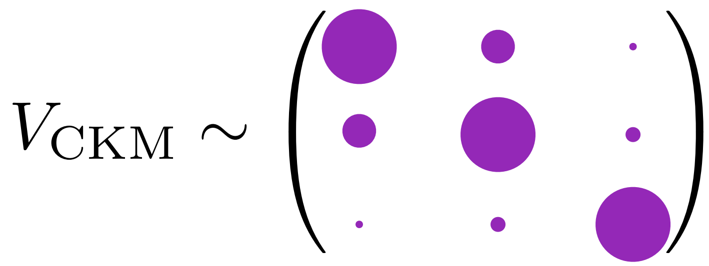
$$\Lambda^2 \approx (4\pi v)^2 \times (\Delta\mathcal{O}/\mathcal{O}) \approx \text{few TeV}^2$$

Minimal Flavor Violation

U(2) symmetry

SM quark Yukawa couplings exhibit an approximate U(2)³ flavour symmetry:





$$U(2)_{q_L} \times U(2)_{u_R} \times U(2)_{d_R}$$

$$\psi_i = (\underbrace{\psi_1 \;\; \psi_2}_{\mathbf{2}}\; \underbrace{\psi_3}_{\mathbf{1}})$$

- ✦ Good approximation of SM spectrum: $m_{\rm light} \sim 0$, $V_{\rm CKM} \sim 1$

Breaking pattern:

$$Y_{u,d} \approx \begin{pmatrix} 0 & 0 \\ 0 & 1 \end{pmatrix} \longrightarrow Y_{u,d} \approx \begin{pmatrix} \Delta & V_q \\ 0 & 1 \end{pmatrix}$$

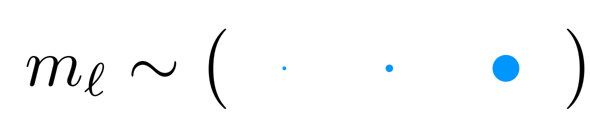
$$\Delta \sim (\mathbf{2}, \mathbf{2}, \mathbf{1})$$
$$V_q \sim (\mathbf{2}, \mathbf{1}, \mathbf{1})$$

Barbieri, B, Sala, Straub, 2012

- ✦ The *assumption* of a suitable breaking ensures MFV-like FCNC protection
- ✦ The most general symmetry that gives **“CKM-like” interactions** in a model-independent way

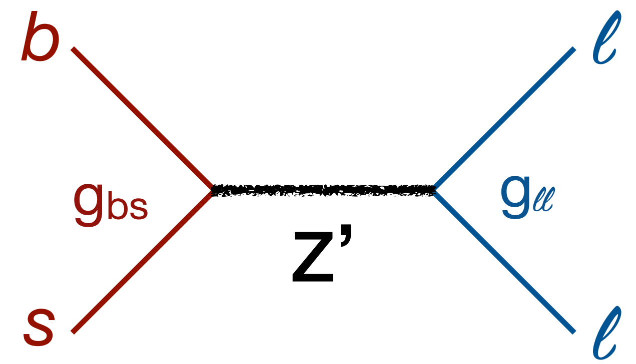
Barbieri, B, Sala, Straub, 2014

- ✦ Can be extended to charged lepton sector $(\mathrm{U}(2)_\ell \times \mathrm{U}(2)_e)$



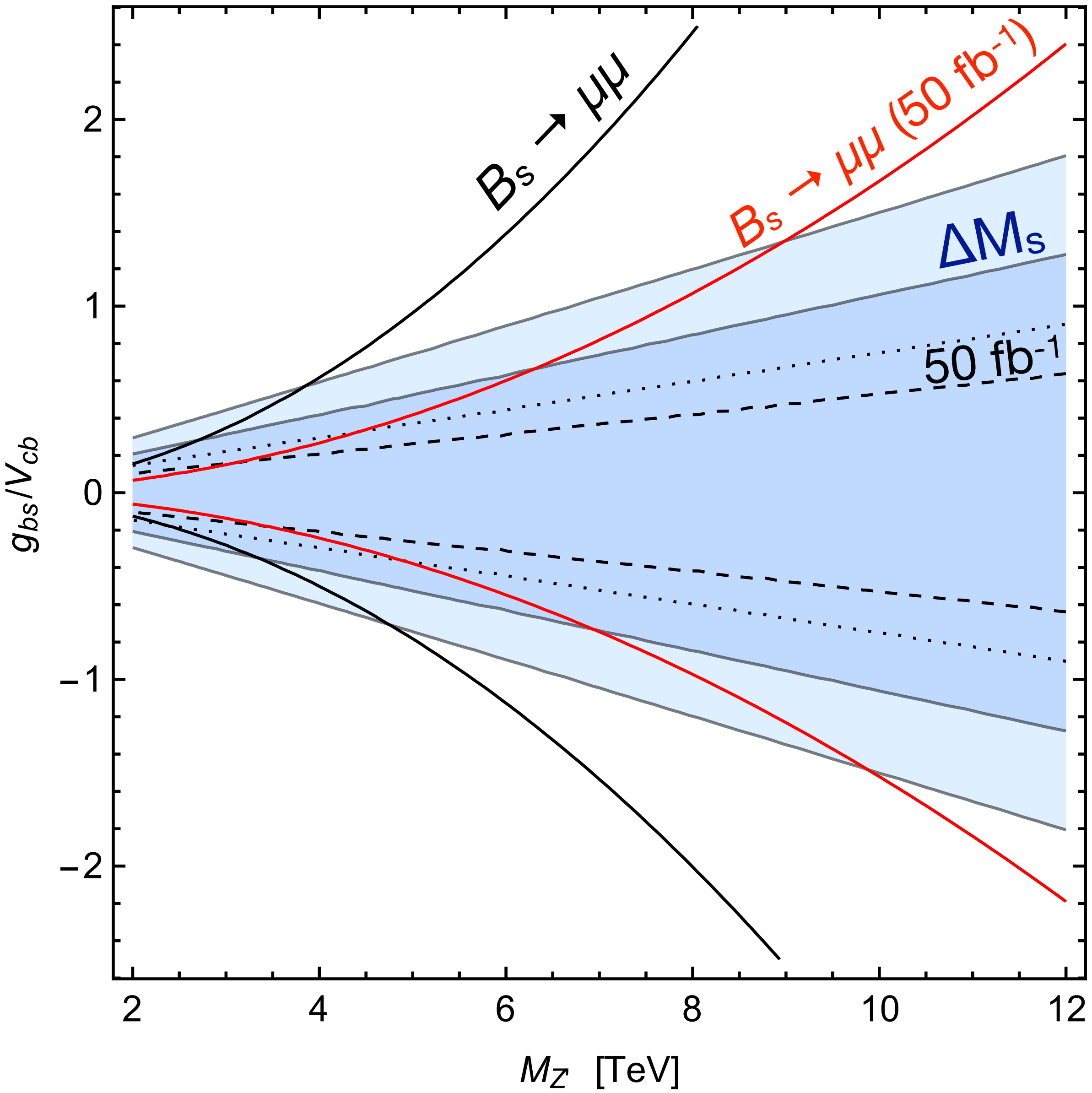
Rare decays

What energy scales can be probed through B physics, *under the most restrictive flavor assumptions (MFV / U(2))?*



Example: heavy Z' with flavour-violating *bs* coupling

$B_s \to \mu\mu$ @ LHCb



B_s mixing can probe mass scales up to ~ 10 TeV (for coupling ~ V_{cb})

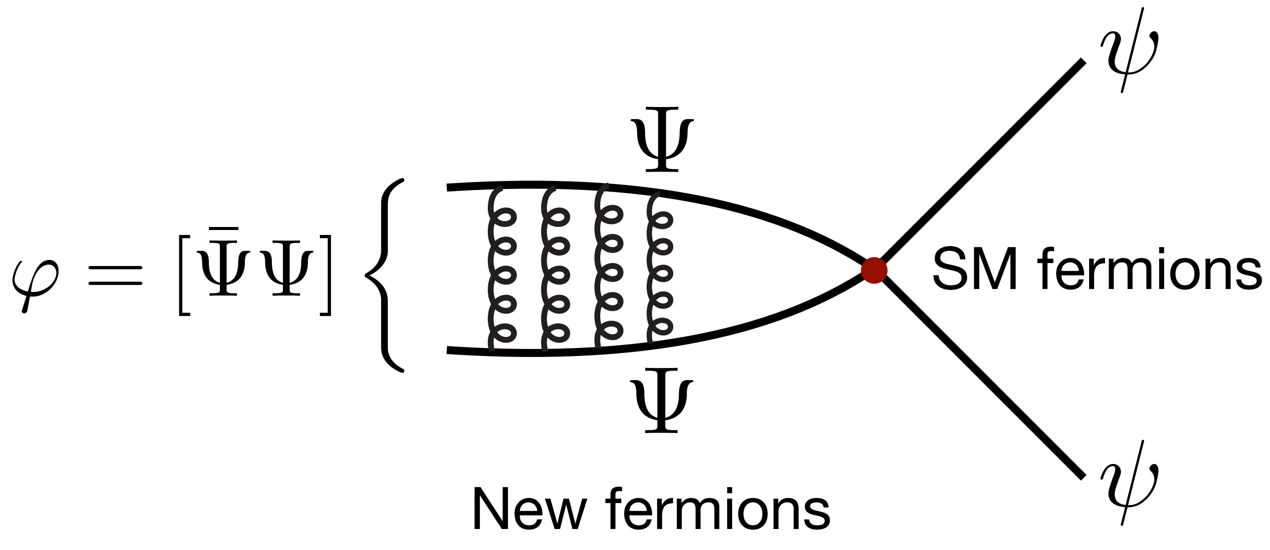
$$\Delta M_s \approx \left(g_{bs}^2/\Lambda^2\right)$$

Rare decays (e.g. $B_s \to \mu\mu$) almost competitive at high luminosity

$$\mathcal{A}(B_s \to \mu^+\mu^-) \approx \left(g_{bs}/\Lambda^2\right) \times g_{\mu\mu}$$

A natural example: Composite Higgs

- The Higgs could be composite, due to new strong interaction at $\Lambda \sim$ TeV



EW scale dynamically generated when $g_* \to 4\pi$

- Naturally light if it's a (pseudo-)Goldstone boson

Like the pion in QCD!

When $g_* \to 4\pi$, $\langle \bar{\Psi}^i \Psi^j \rangle = -f^2 B_0 \delta^{ij}$

breaks a global symmetry G $\to$ H

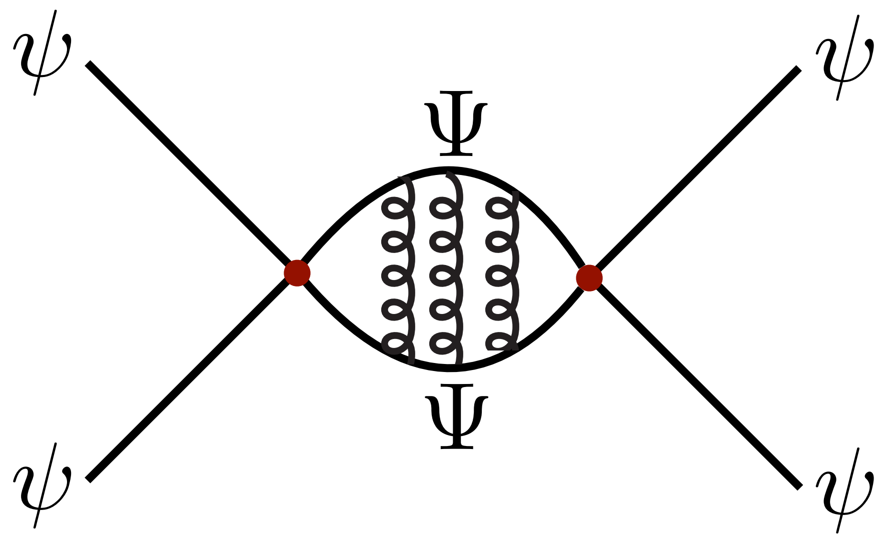
"pion" decay constant

➡ Modification of Higgs properties ~ v^2/f^2

➡ Other composite resonances with mass $m_\rho \sim g_* f < 4\pi f$ (analogous of ρ meson, nucleons, …)

Flavour bounds in Composite Higgs

- SM quarks interact with the strong sector (Higgs) $\Rightarrow$ large flavor effects!



- Natural suppression: interaction through Yukawa couplings
- Usually not enough: need **flavor symmetry**

different flavor symm. ↓

Minimal fermion resonance mass [TeV]			
	doublet	triplet	bidoublet
Ⓐ	$4.9^{\dagger}$	$1.7^{\dagger}$	$1.2^{*\dagger}$
$U(3)^3_{\mathrm{LC}}$	6.5	6.5	5.3
$U(3)^3_{\mathrm{RC}}$	-	-	3.3
$U(2)^3_{\mathrm{LC}}$	$4.9^{\ddagger}$	$0.6^{\ddagger}$	$0.6^{\ddagger}$
$U(2)^3_{\mathrm{RC}}$	-	-	1.1^{*}

← different models

* $f > 500$ GeV and $g_\psi \approx 2.5$
† excluding ε_K, up to O(1) factors
‡ $r_b = 0.2$

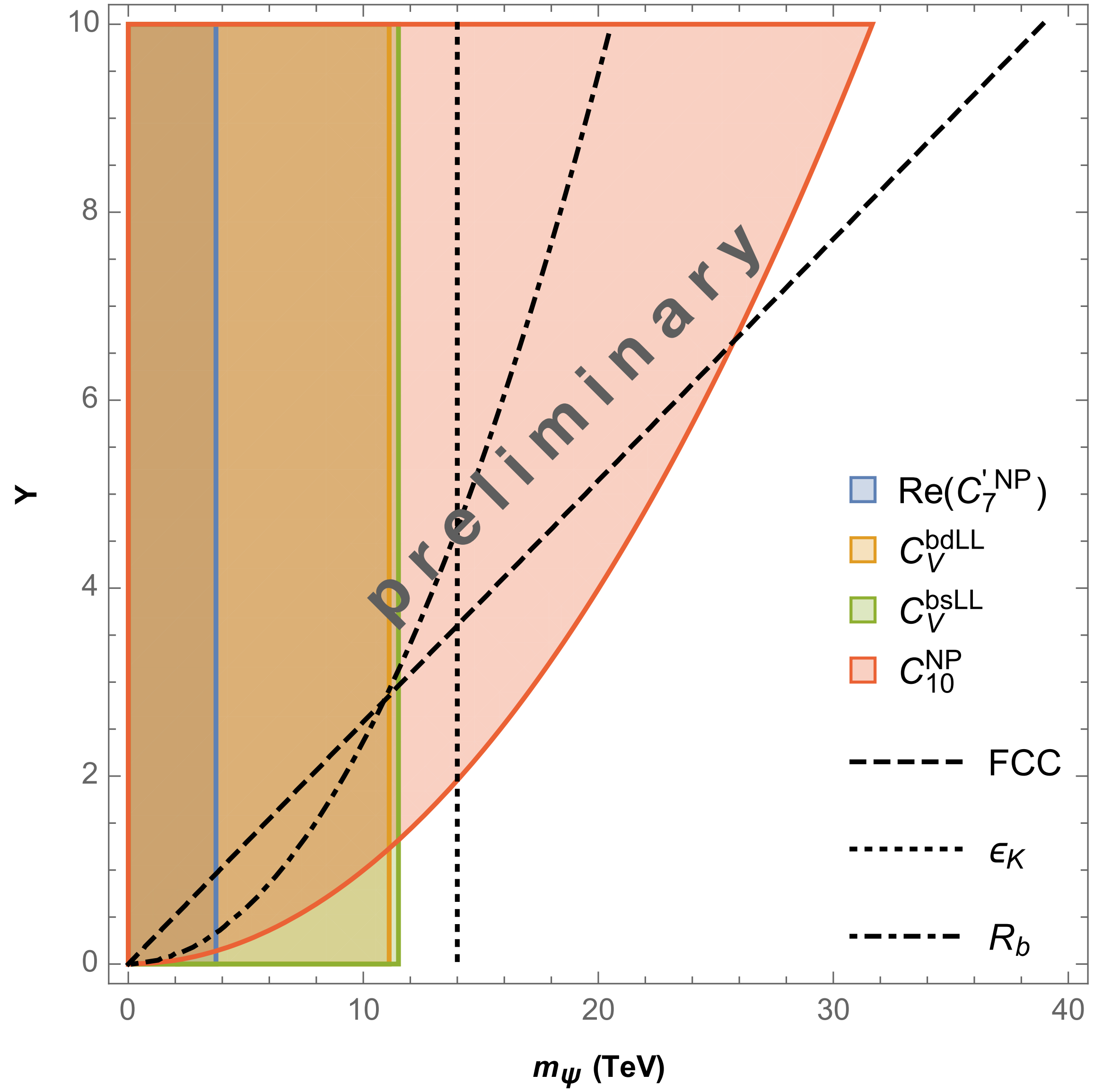
Barbieri, B, Sala, Straub, Tesi 1211.5085

Future projections

- Significant improvement in flavor measurements in the next (few) years!

LHCb (upgrade 1 & 2) Belle II NA62

- Will flavor bounds on NP scale compete with a next-generation collider?



- Higgs factory precision on h couplings (~ 10^{-3}, i.e. f > 8 TeV)
- direct searches at 100 TeV (roughly M > 10 TeV)

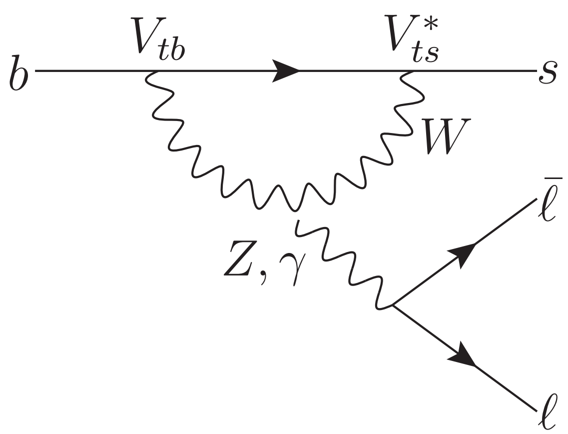
projections for
LHCb 300 fb^{-1} & Belle II

O(10 y) timescale!

work in progress with L. Vittorio

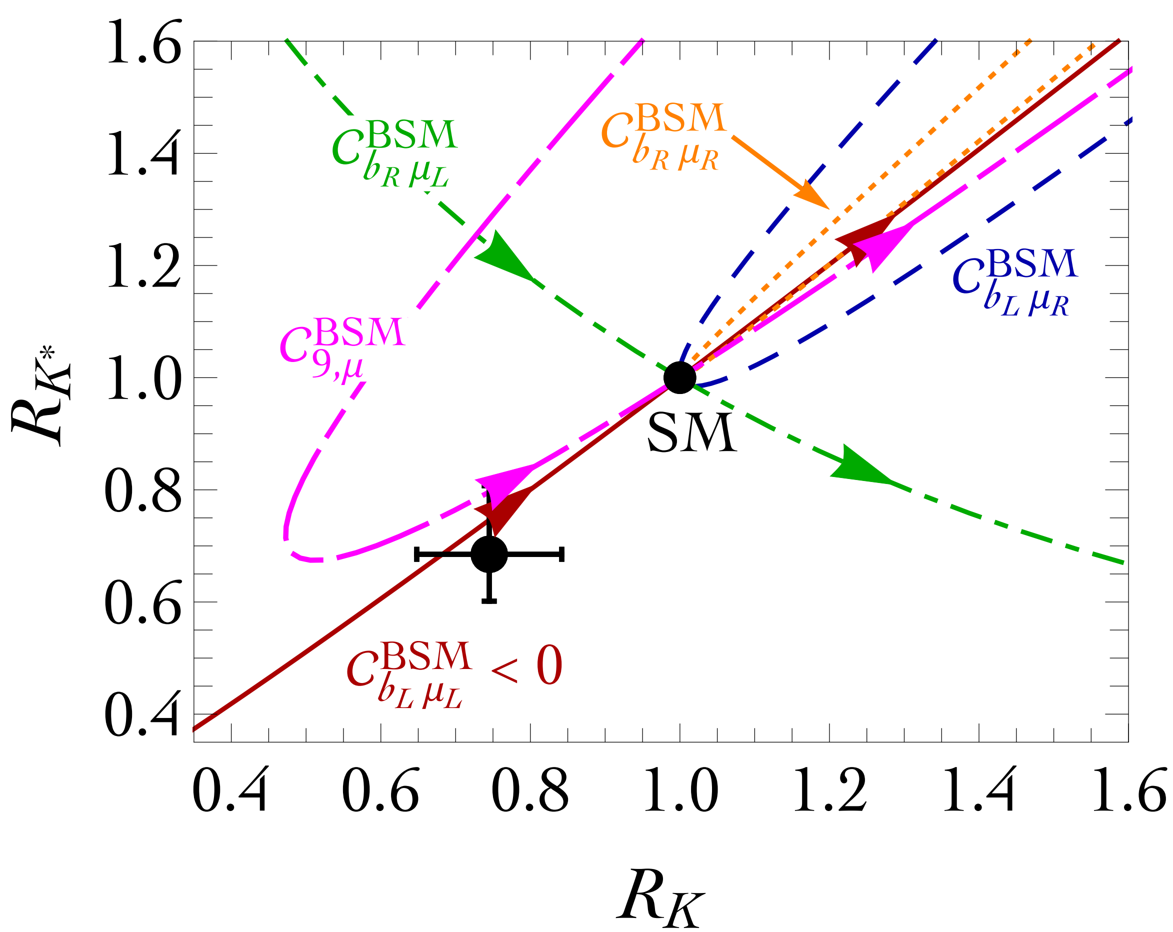
Lepton Flavor Universality

The B-physics anomalies



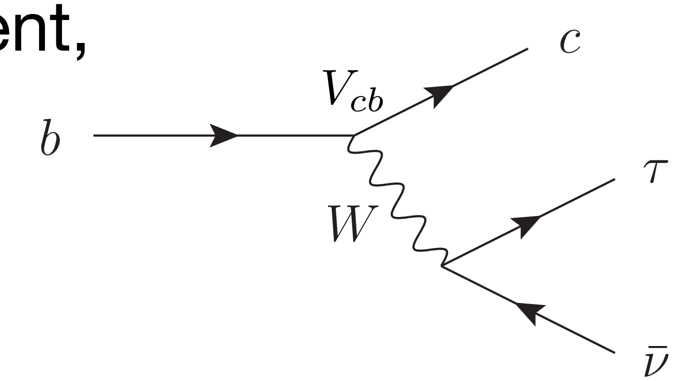
FCNC: only at loop-level in SM

Deviation from SM in several observables: $R_K^{(*)}$, P_5', various BR's



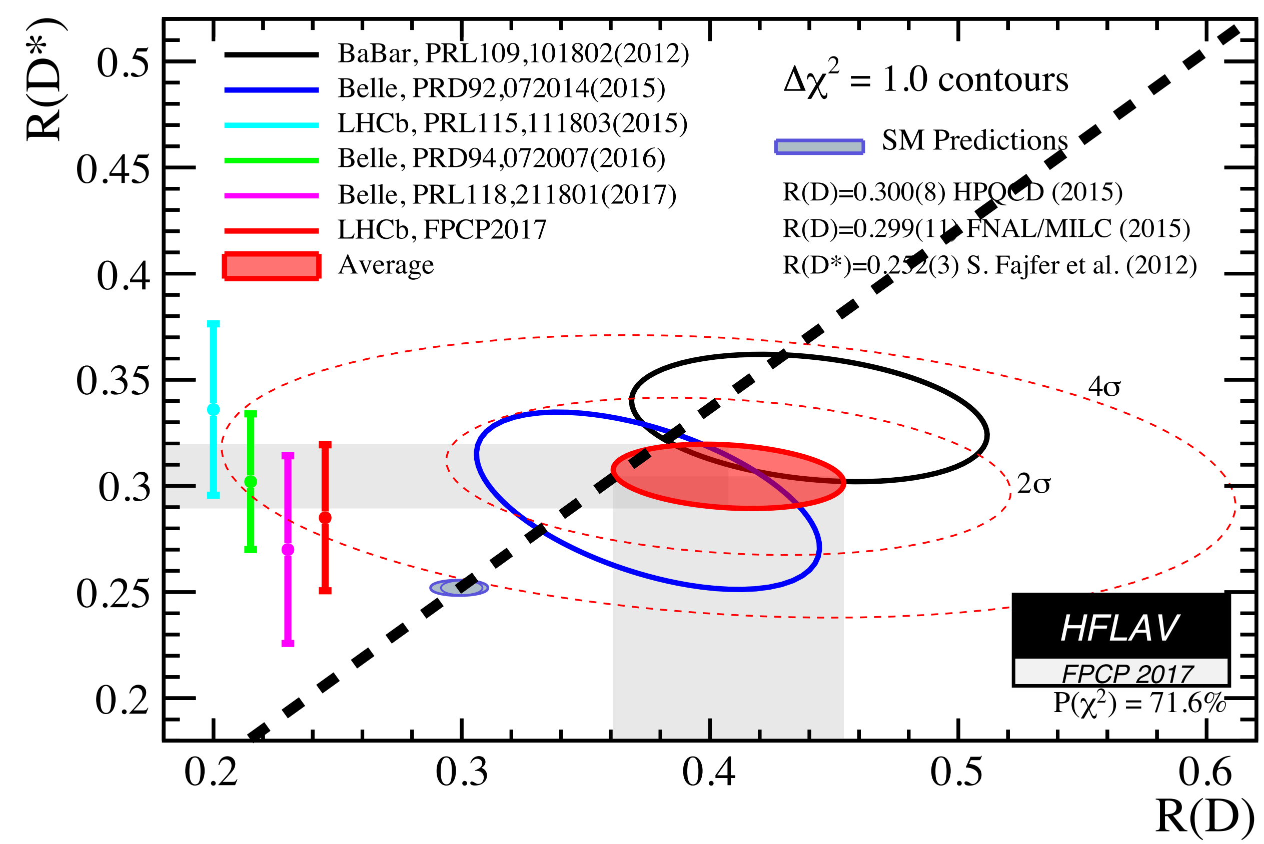
~5σ from SM

Charged-current interaction: left-handed current, tree-level in SM



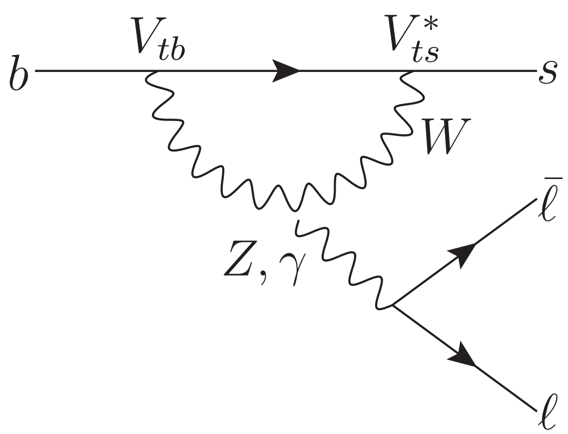
LFU ratios:

$$R_{D^{(*)}} = \frac{\mathrm{BR}(B \to D^{(*)}\tau\bar{\nu})/\mathrm{SM}}{\mathrm{BR}(B \to D^{(*)}\ell\bar{\nu})/\mathrm{SM}}$$



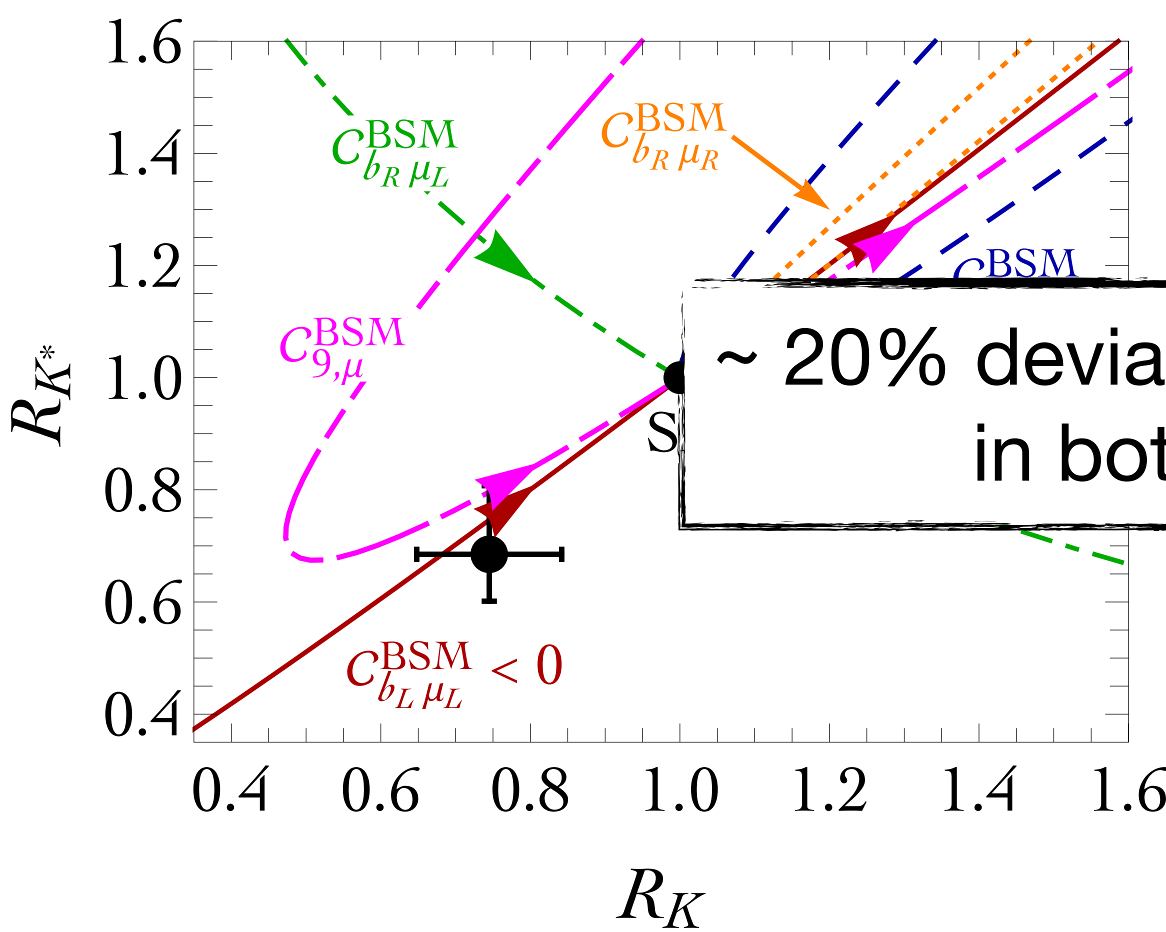
~ 3σ from SM

The B-physics anomalies



FCNC: only at loop-level in SM

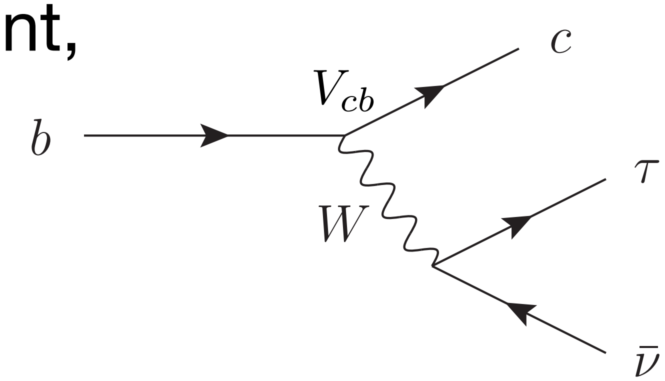
Deviation from SM in several observables: $R_{K^{(*)}}$, P_5', various BR's



~ 20% deviation in LH currents in both channels

~5σ from SM

Charged-current interaction: left-handed current, tree-level in SM



LFU ratios:

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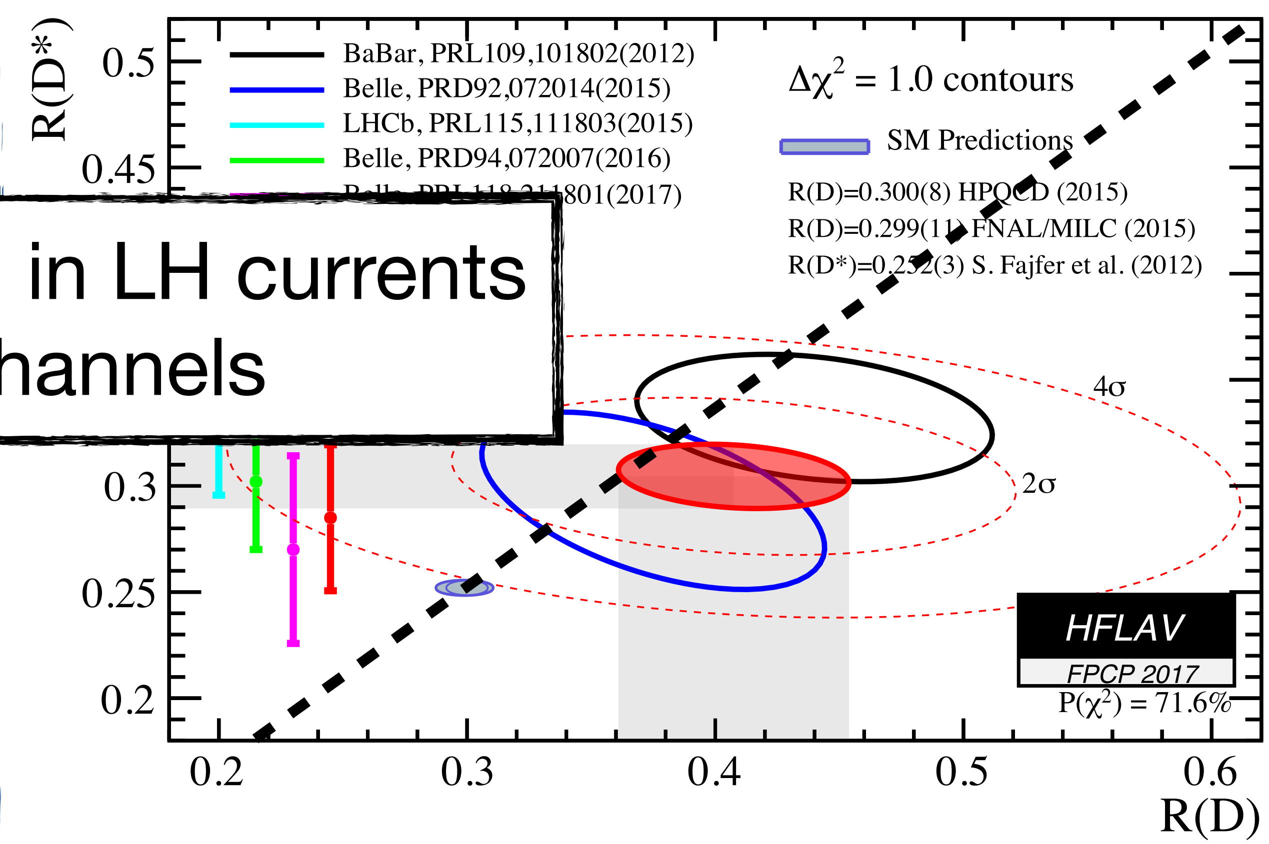


~ 3σ from SM

Lepton Flavour Universality: a remark

- (Lepton) flavour universality is an accidental property of the gauge Lagrangian, not a fundamental symmetry of nature

$$\mathcal{L}_{\text{gauge}} = i \sum_{j=1}^{3} \sum_{q,u,d,\ell,e} \bar{\psi}_j \not{D} \psi_j$$

- The only non-gauge interaction in the SM violates LFU maximally

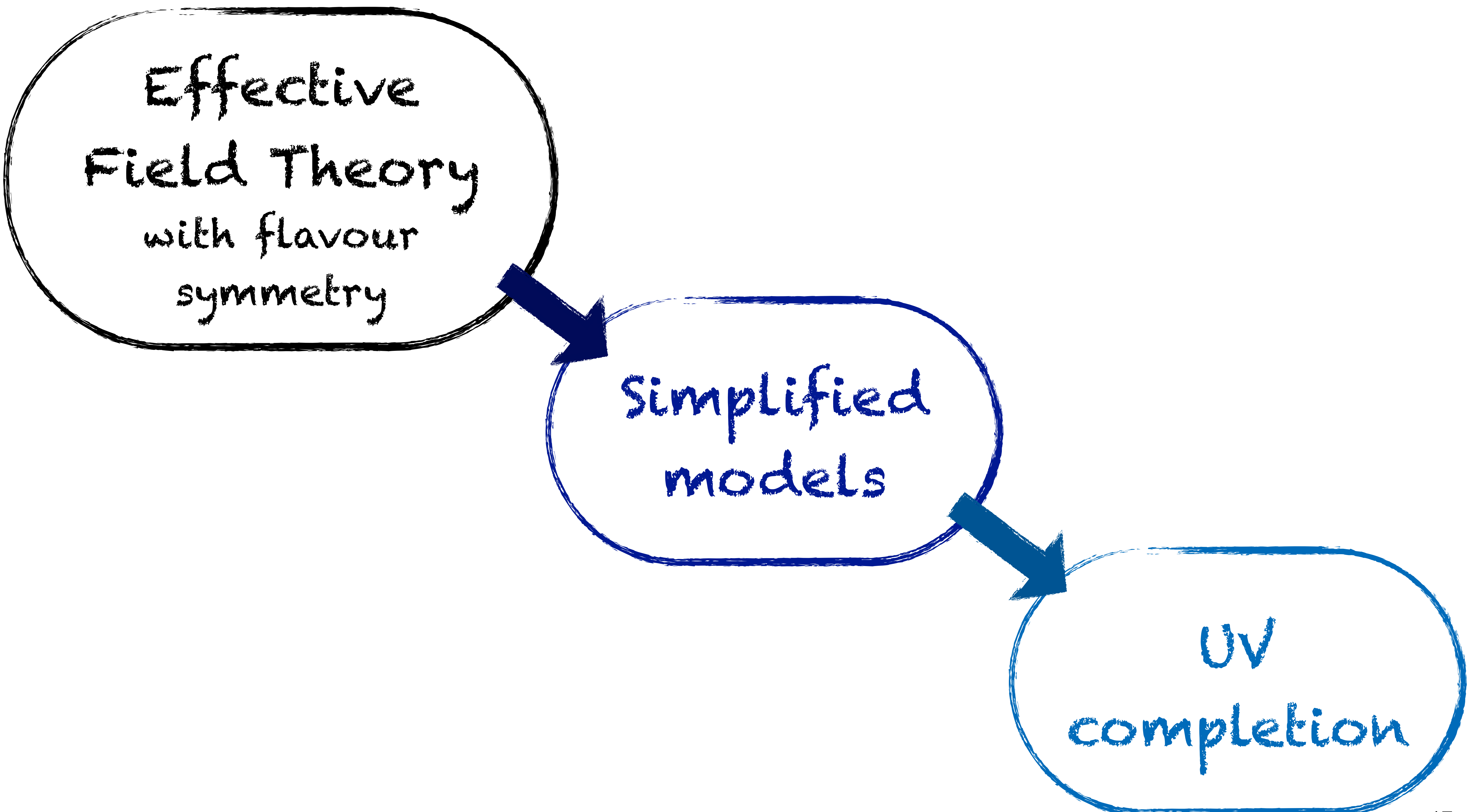
$$\mathcal{L}_{\text{Yuk}} = \bar{q}_L Y_u u_R H^* + \bar{d}_L Y_d d_R H + \bar{\ell}_L Y_e e_R H \qquad Y_{u,d,e} \approx \text{diag}(0,0,1)$$

- LFU approximately satisfied in SM processes because lepton Yukawa couplings are small

$$y_\mu \approx 10^{-3} \qquad y_\tau \approx 10^{-2}$$

➡ natural to expect LFU and flavour violations in BSM physics

Is it possible to explain the whole set of anomalies in a coherent picture?



What do we know?

1. Anomalies seen only in semi-leptonic processes: **quarks** x **leptons**

   nothing observed in pure **quark** or **lepton** processes

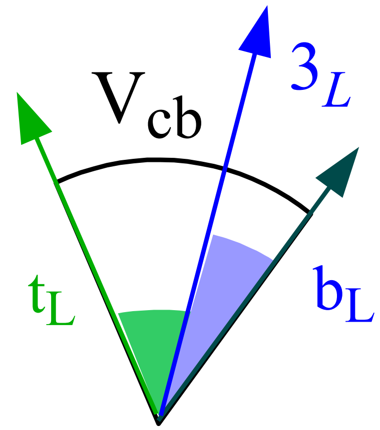
2. Large effect in **3rd generation**: b quarks, $\tau\nu$ competes with SM tree-level

   smaller non-zero effect in **2nd generation**: $\mu\mu$ competes with SM FCNC,

   no effect in 1st generation

3. **Flavour alignment** with down-quark mass basis

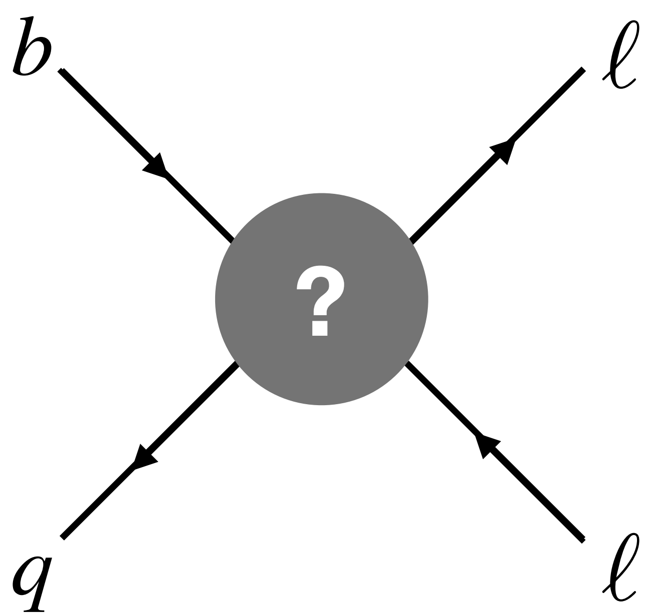
   to avoid large FCNC (true in general for BSM physics)



4. **Left-handed** four-fermion interactions

   RH and scalar currents disfavoured: can be present, but do not fit the anomalies (both in charged and neutral current), Higgs-current small or not relevant

EFT explanations of flavour anomalies



$$\frac{1}{\Lambda_D^2}(\bar{b}_L\gamma_\mu c_L)(\bar{\tau}_L\gamma^\mu\nu_\tau)$$

$\Lambda_D = 3.4\,\mathrm{TeV}$

$$\frac{1}{\Lambda_K^2}(\bar{b}_L\gamma_\mu s_L)(\bar{\mu}_L\gamma^\mu\mu_L)$$

$\Lambda_K = 31\,\mathrm{TeV}$

I. The two processes are related by $SU(2)_L$ gauge symmetry

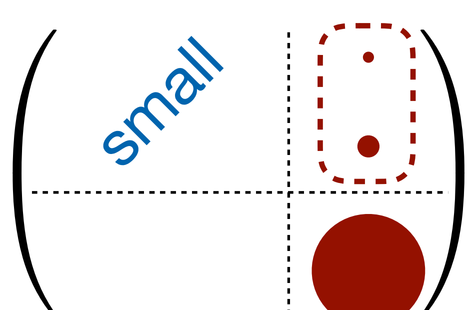
$$\frac{1}{\Lambda^2_{\text{singlet}}}(\bar{q}_L^i\gamma_\mu q_L^j)(\bar{\ell}_L^\alpha\gamma^\mu\ell_L^\beta) + \frac{1}{\Lambda^2_{\text{triplet}}}(\bar{q}_L^i\gamma_\mu\sigma^a q_L^j)(\bar{\ell}_L^\alpha\gamma^\mu\sigma^a\ell_L^\beta)$$

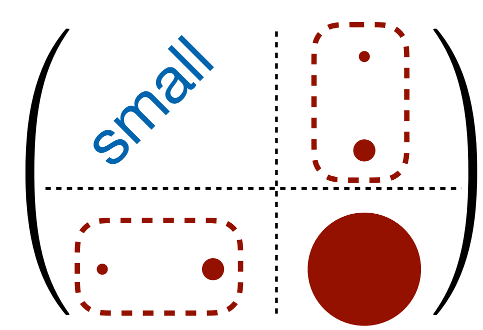
triplet operator can explain both!

II. NP structure reminds of the Yukawa hierarchy: $\Lambda_D \ll \Lambda_K, \qquad \lambda_{\tau\tau} \gg \lambda_{\mu\mu}$

large coupling to 3rd generation, couplings to light generations suppressed

→ **U(2) symmetry**

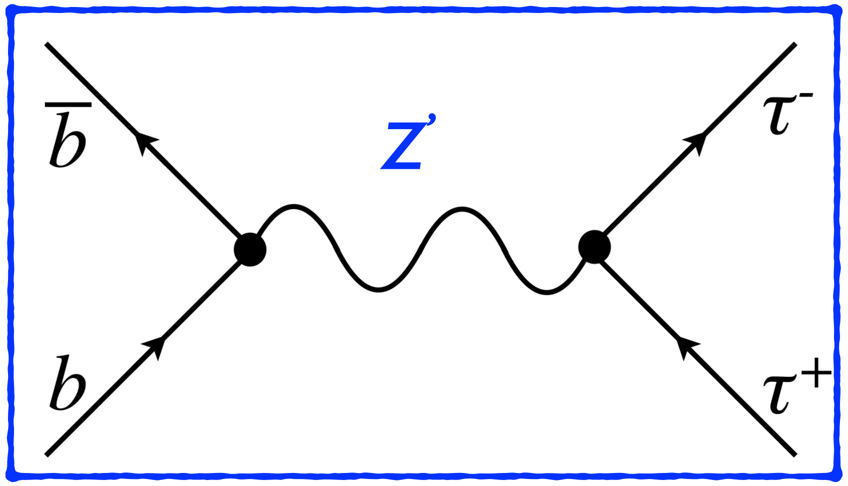
$Y_u \approx$ 

$\lambda_q \approx$ 

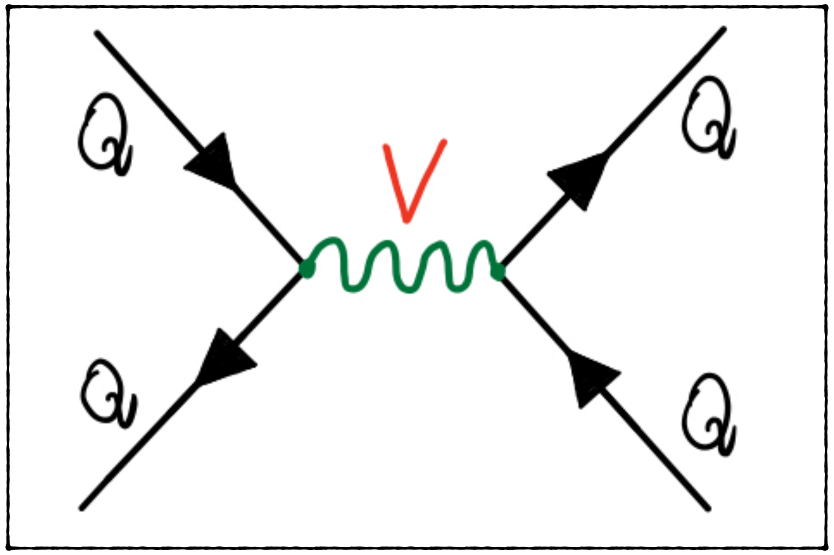
Problems

- **Direct searches:** large signal at high-pT

  $\Lambda_D \simeq 3.4\,\mathrm{TeV}$

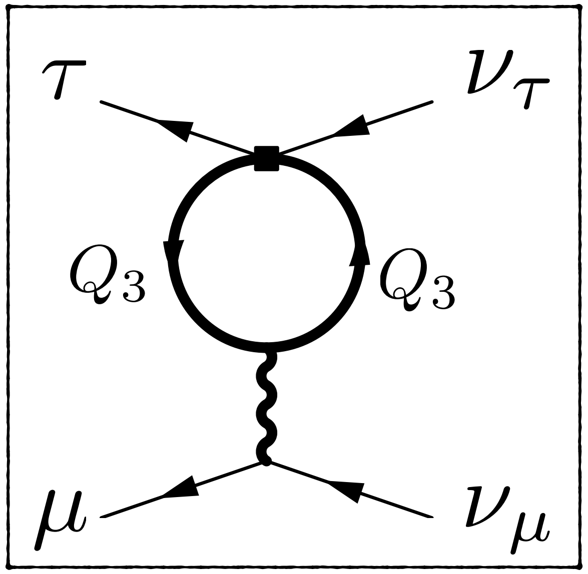


- **Flavour observables:**
  - other semi-leptonic observables
    model independent
  - meson mixing, lepton flavour violation
    depend on the model, generally present



- **ElectroWeak precision tests:**

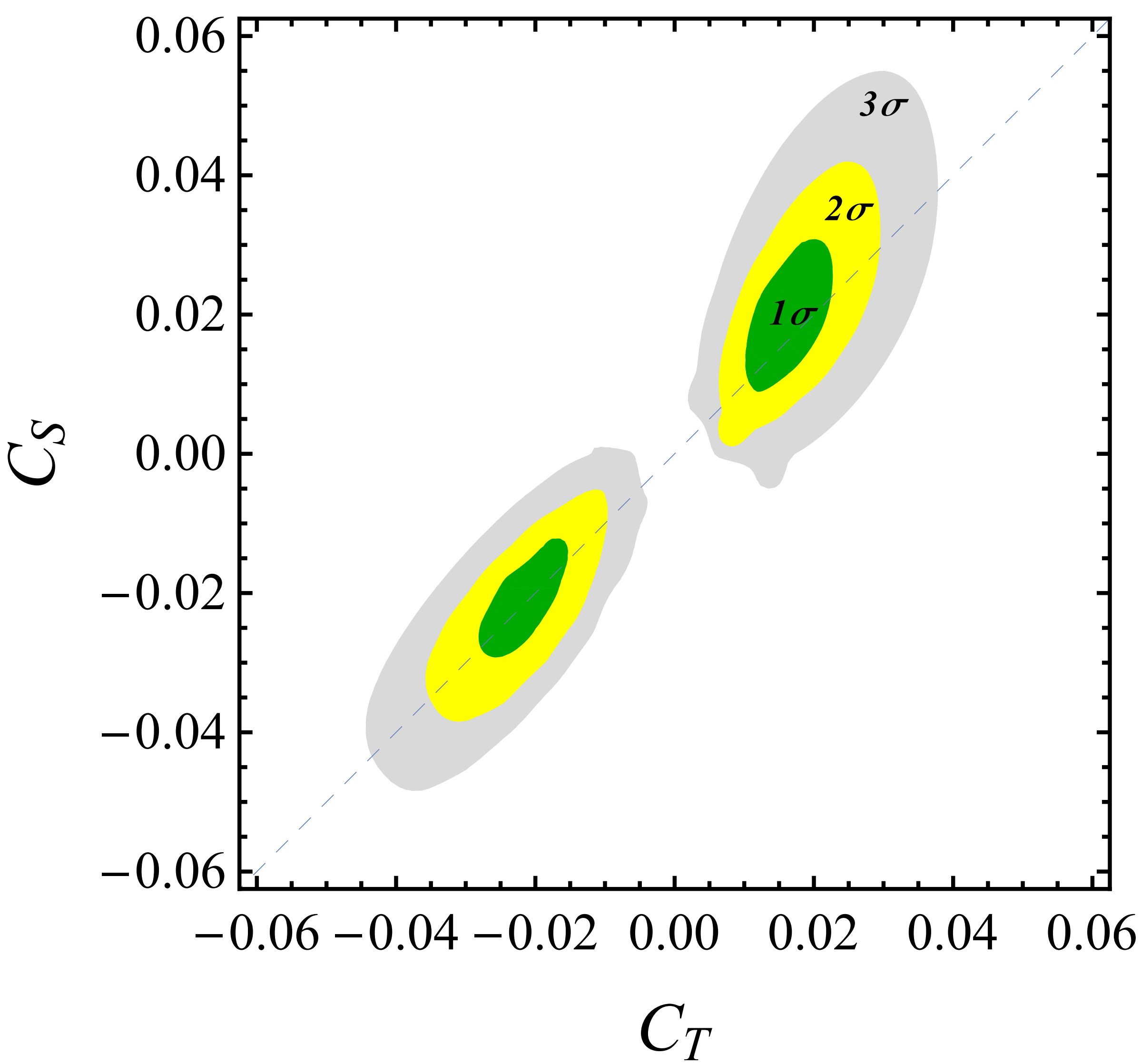
  W, Z couplings, τ decays, …
  generated radiatively at one-loop



Fit to semi-leptonic observables

- EFT fit to all semi-leptonic observables + radiative corrections to EWPT
- Don't include any UV contribution to other operators
  (they will depend on the dynamics of the specific model)

B, Greljo, Isidori, Marzocca, 2017



R_D, R_{D^*}
C_T x V_q

τ decays, EWPT
(1 loop) x $C_{T,S}$

R_K, R_{K^*}, $b \to s\mu\mu$
(C_T + C_S) x V_q x V_ℓ^2

$b \to s\nu\nu$
(C_T - C_S) x V_q

Good fit to all anomalies, with couplings compatible with the U(2) assumption

Fit to semi-leptonic observables

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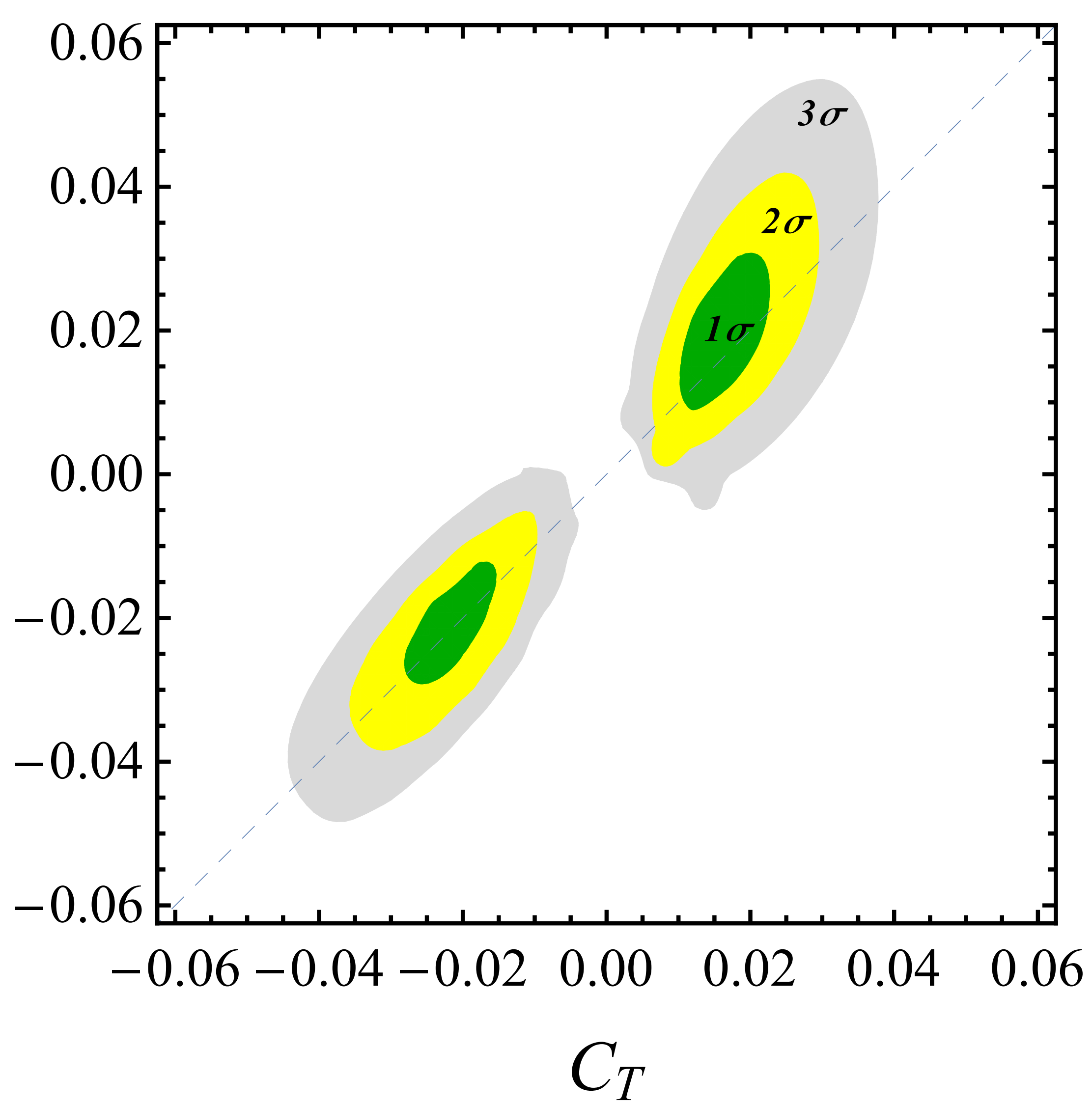
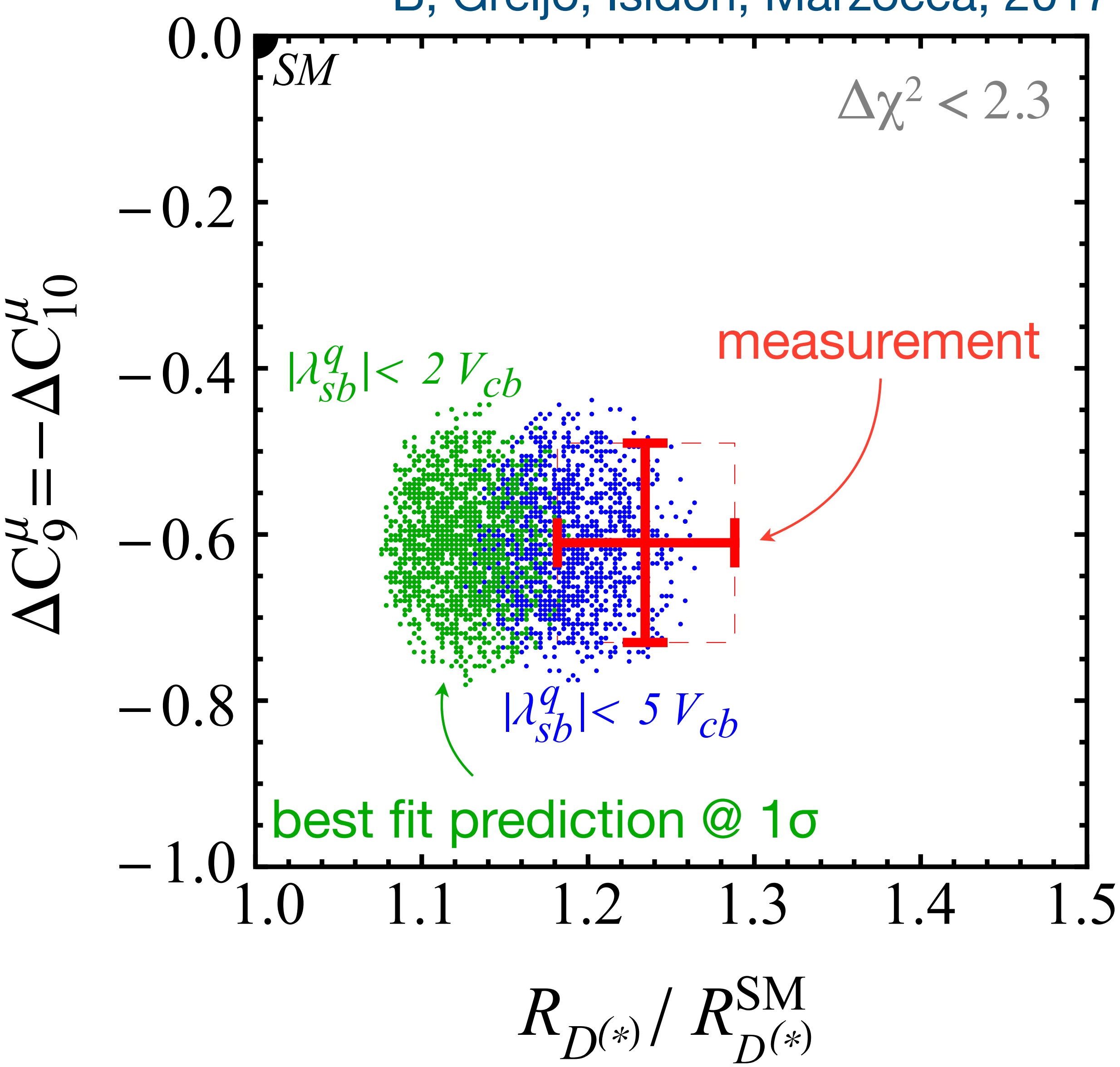




Good fit to all anomalies, with couplings compatible with the U(2) assumption

Relation to other observables: neutral currents

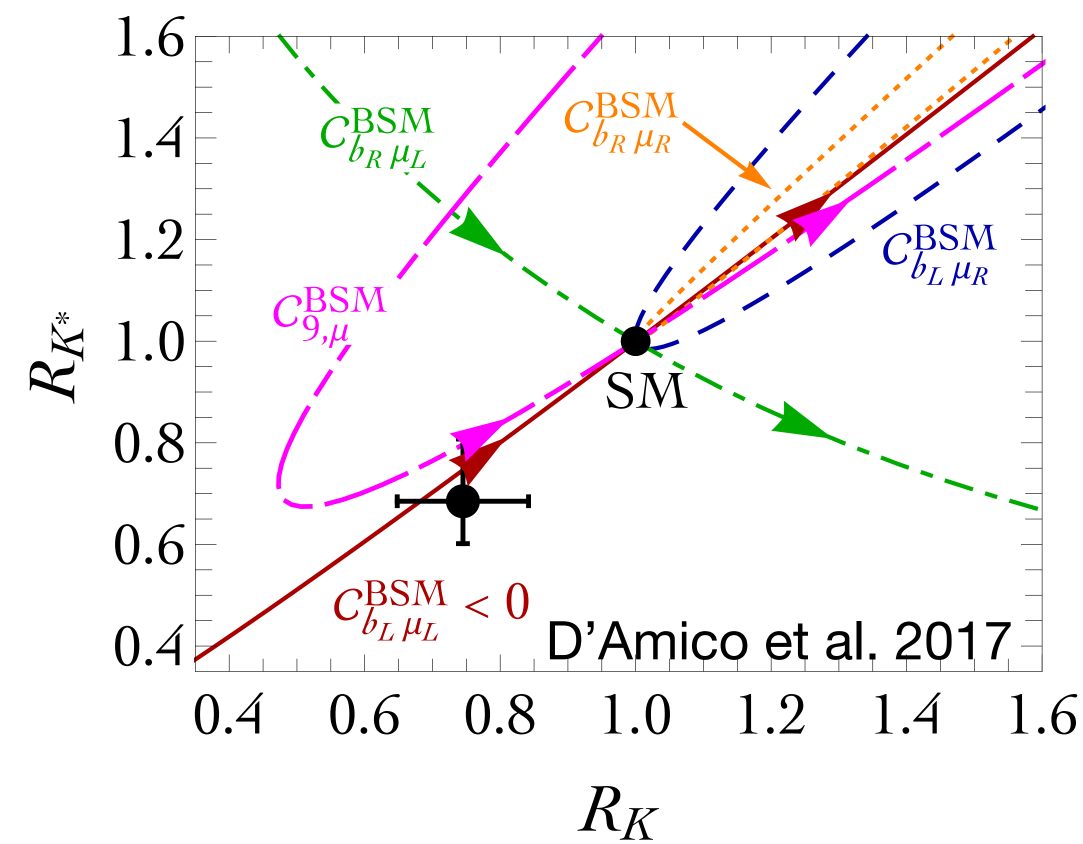
credits: G. Isidori

Quark flavour ↓ — U(2) symmetry

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

+ any other observable with the same quark-level transition…

independent of R_D



- the presence of RH/scalar currents breaks the correlation with the SM: e.g. $B \to \mu\mu$, $B \to \tau\tau$, $B \to \tau\mu$ could be enhanced

Relation to other observables: neutral currents

Lepton flavour →

credits: G. Isidori

Quark flavour ↓ — U(2) symmetry (b → s, b → d); SU(2) ($\tau\tau$, $\nu\nu$)

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

cannot suppress both channels

size determined by $R_{D^{(*)}}$

Several correlated effects in other flavour observables.

High-intensity program *is crucial* to test the flavour structure!

Relation to other observables: neutral currents

credits: G. Isidori

Lepton flavour →

Quark flavour ↓

U(2) symmetry (groups $b \to s$ and $b \to d$); SU(2) (groups $\tau\tau$ and $\nu\nu$)

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

Several correlated effects in other flavour observables.

<u>High-intensity program *is crucial* to test the flavour structure!</u>

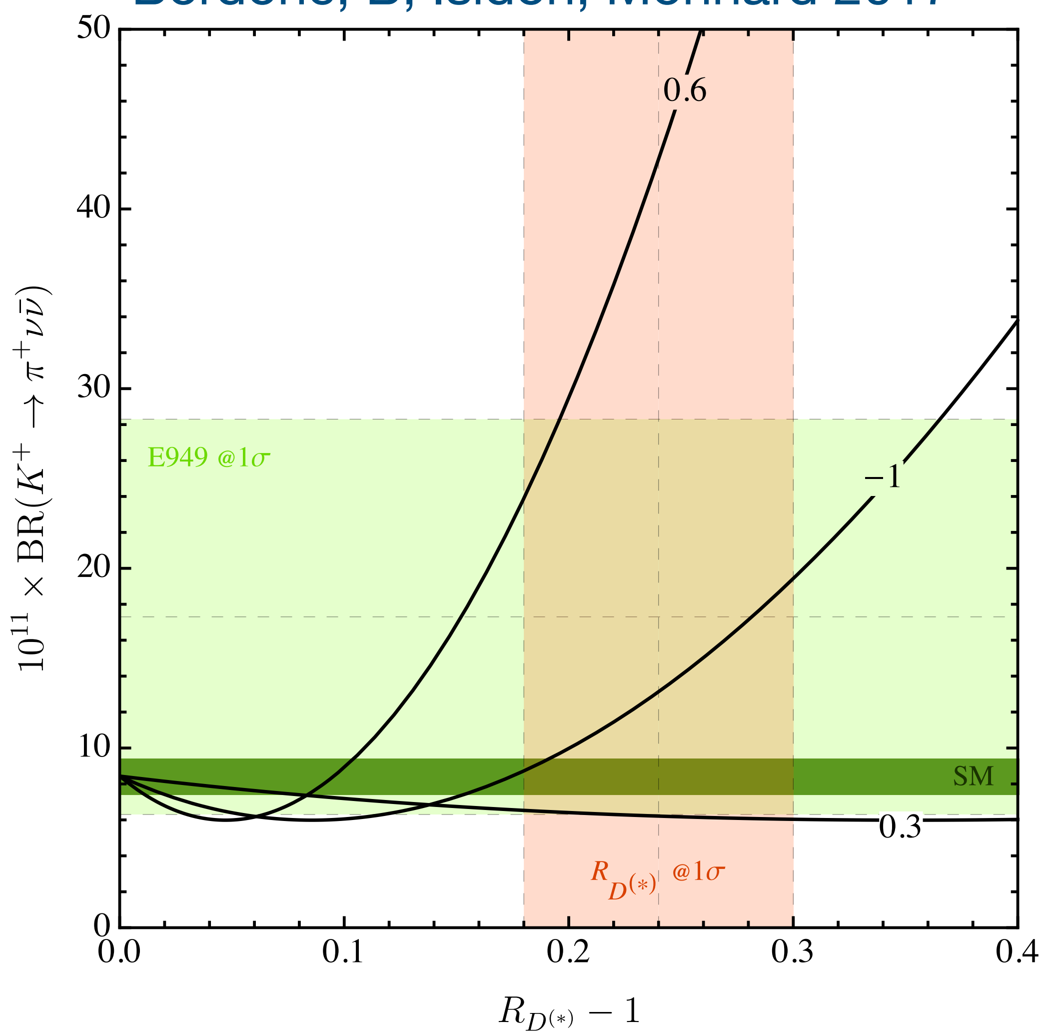
K → πνν

- The only *s* → *d* decay with 3rd generation leptons in the final state (ν_τ): sizeable deviations can be expected

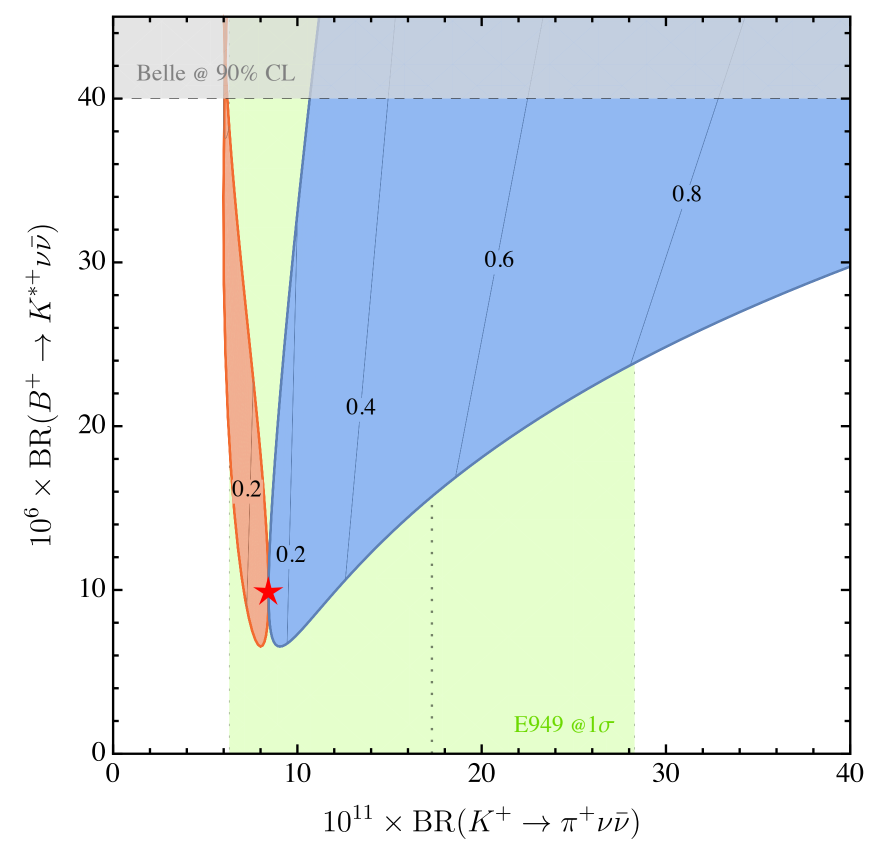
- U(2) symmetry relates *b* → *q* transitions also to *s* → *d*
  but there are model-dependent parameters of order 1 (rotation in *sd* sector):

$$\lambda_{sd} \sim V_q V_q^* \sim V_{ts}^* V_{td} \qquad \lambda_{bq} \sim V_q \sim V_{tq}^*$$

Bordone, B, Isidori, Monnard 2017



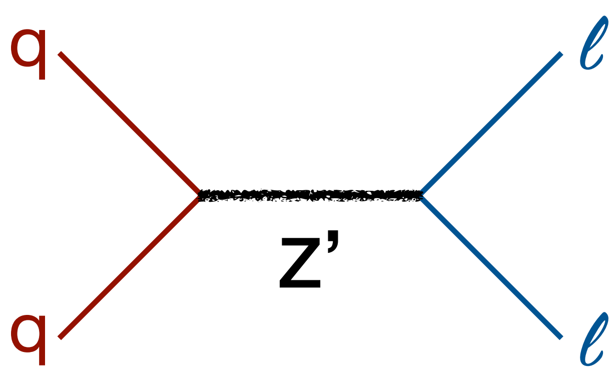
correlation between K → πνν and B → Kνν

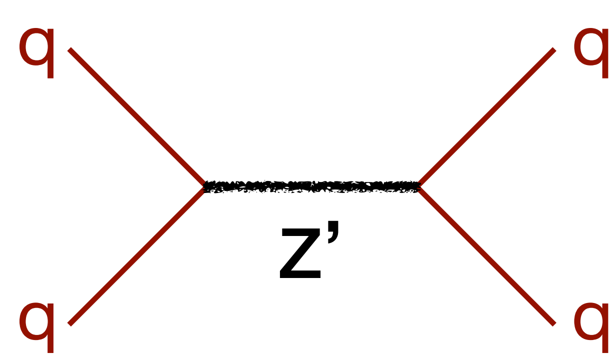


$b \to c\tau\nu$: mediators

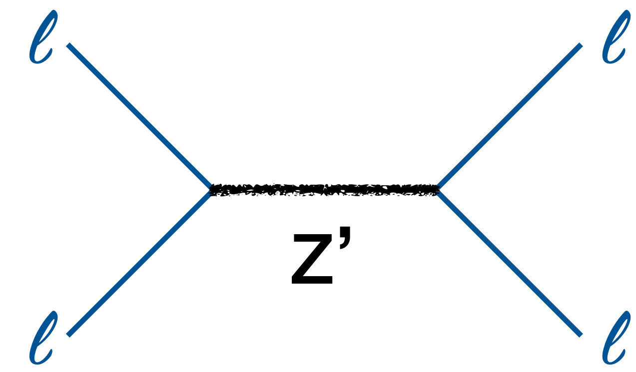
Mediators that can give rise to the LH $b \to c\ell\nu$ and $b \to s\ell\ell$ amplitudes:

- **Vector resonances W', Z':**





meson mixing

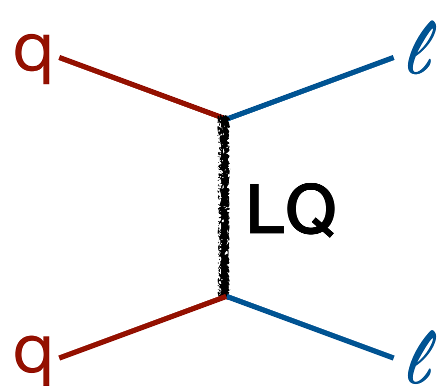


τ decays

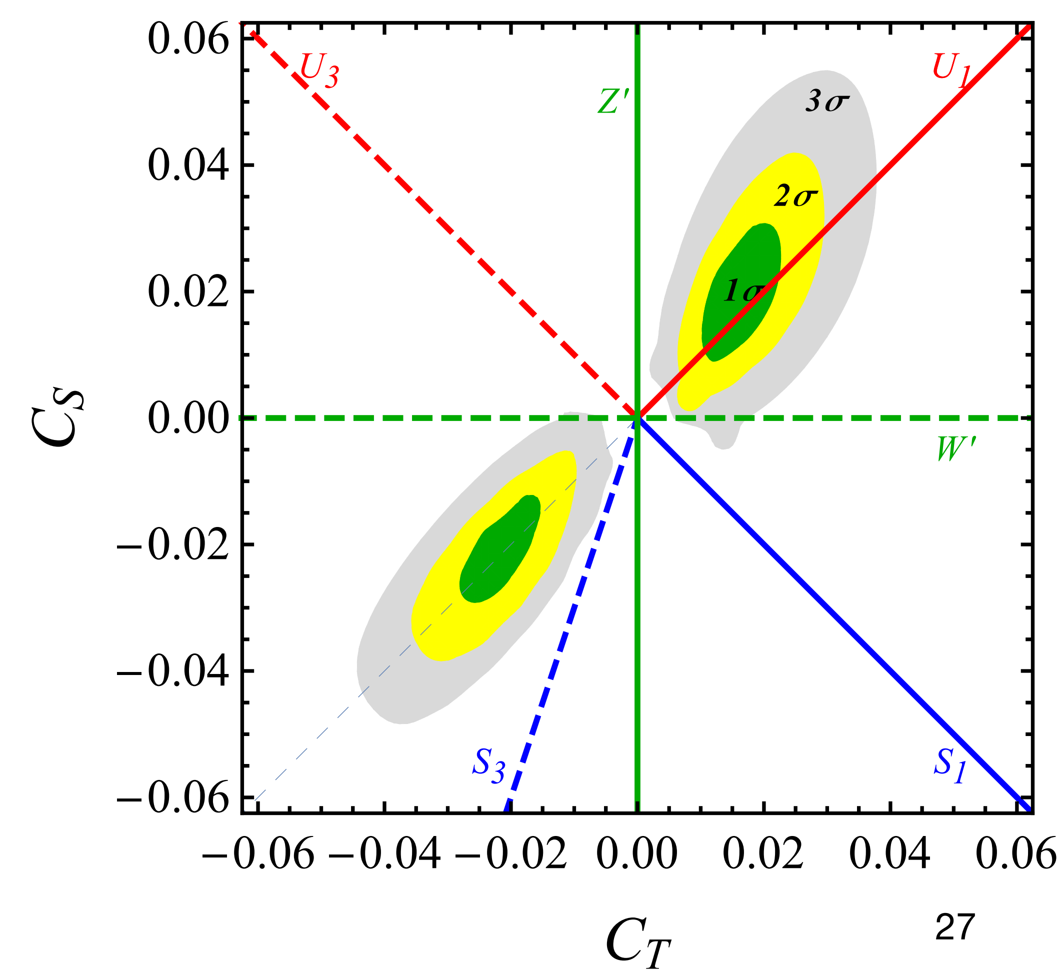
+ bounds from LHC Z' searches 

- **Leptoquarks:**

  can be scalar or vector



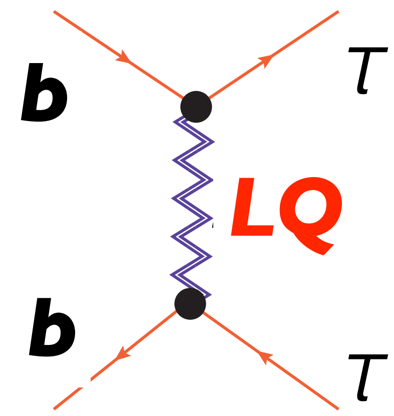
- No B mixing at tree-level ✓
- Weaker bounds from direct searches ✓
- Vector LQ fits all anomalies, no $b \to s\nu\nu$ ✓



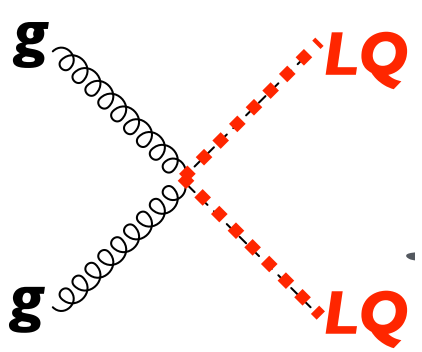
High-pT searches at LHC

- Large couplings to 3rd generation: searches in $bb \to \tau\tau$, or LQ $\to b\tau$, $t\nu$

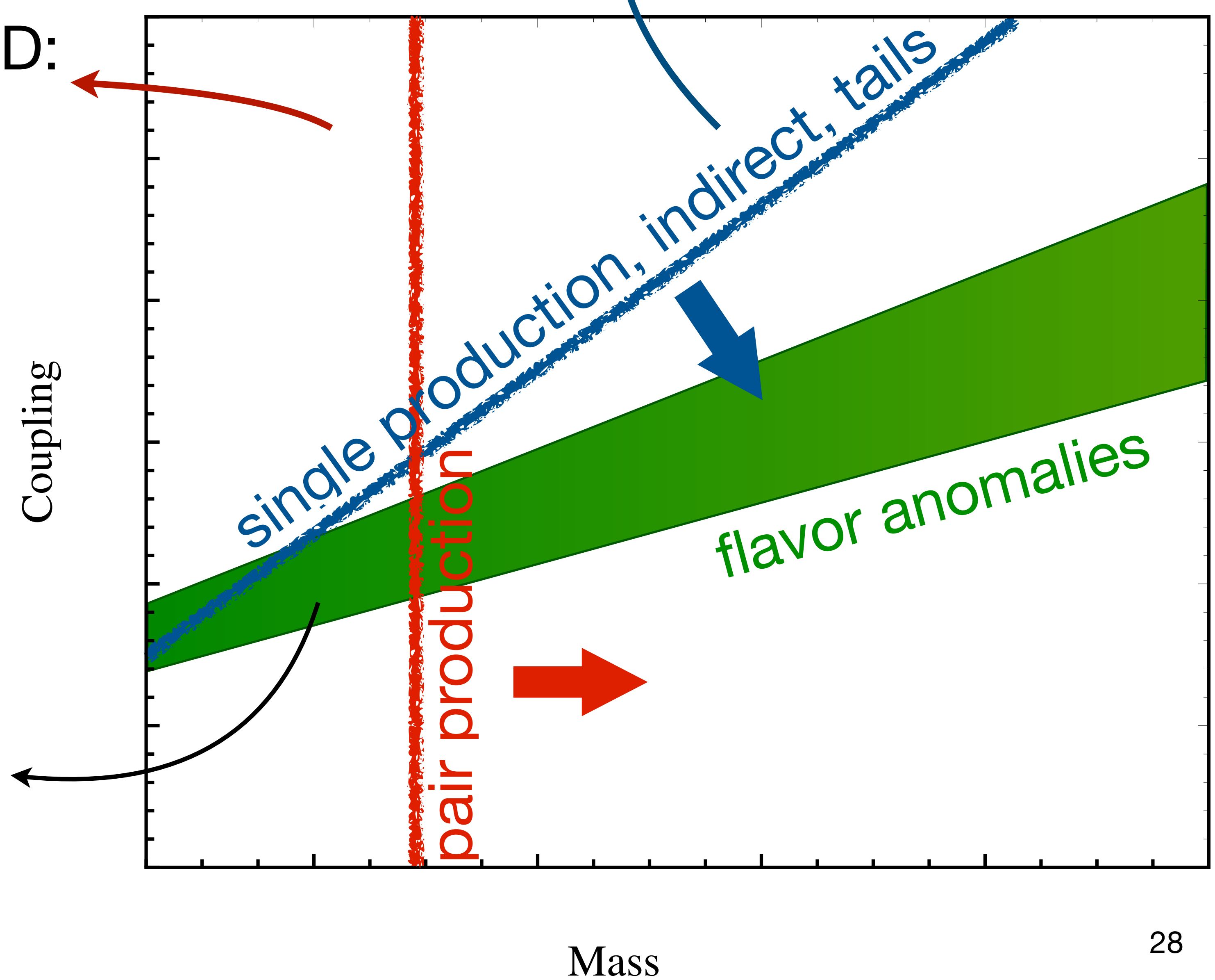
Faroughy, Greljo, Kamenik 2016



- Pair-production through QCD: model-independent



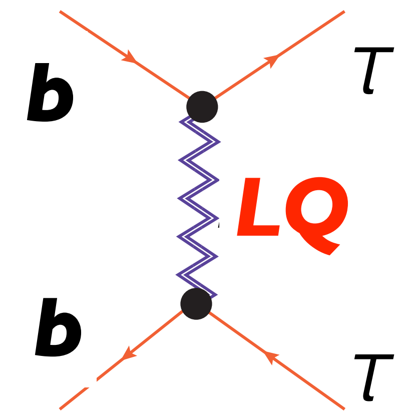
$$\Lambda^{-2} \approx \frac{\text{coupling}^2}{\text{mass}^2}$$



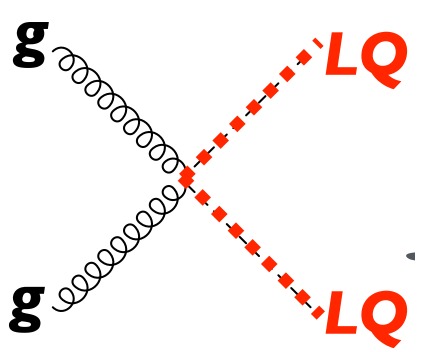
High-pT searches at LHC: vector leptoquarks

- Large couplings to 3rd generation: searches in $bb \to \tau\tau$, or LQ $\to b\tau$, $t\nu$

Faroughy, Greljo, Kamenik 2016

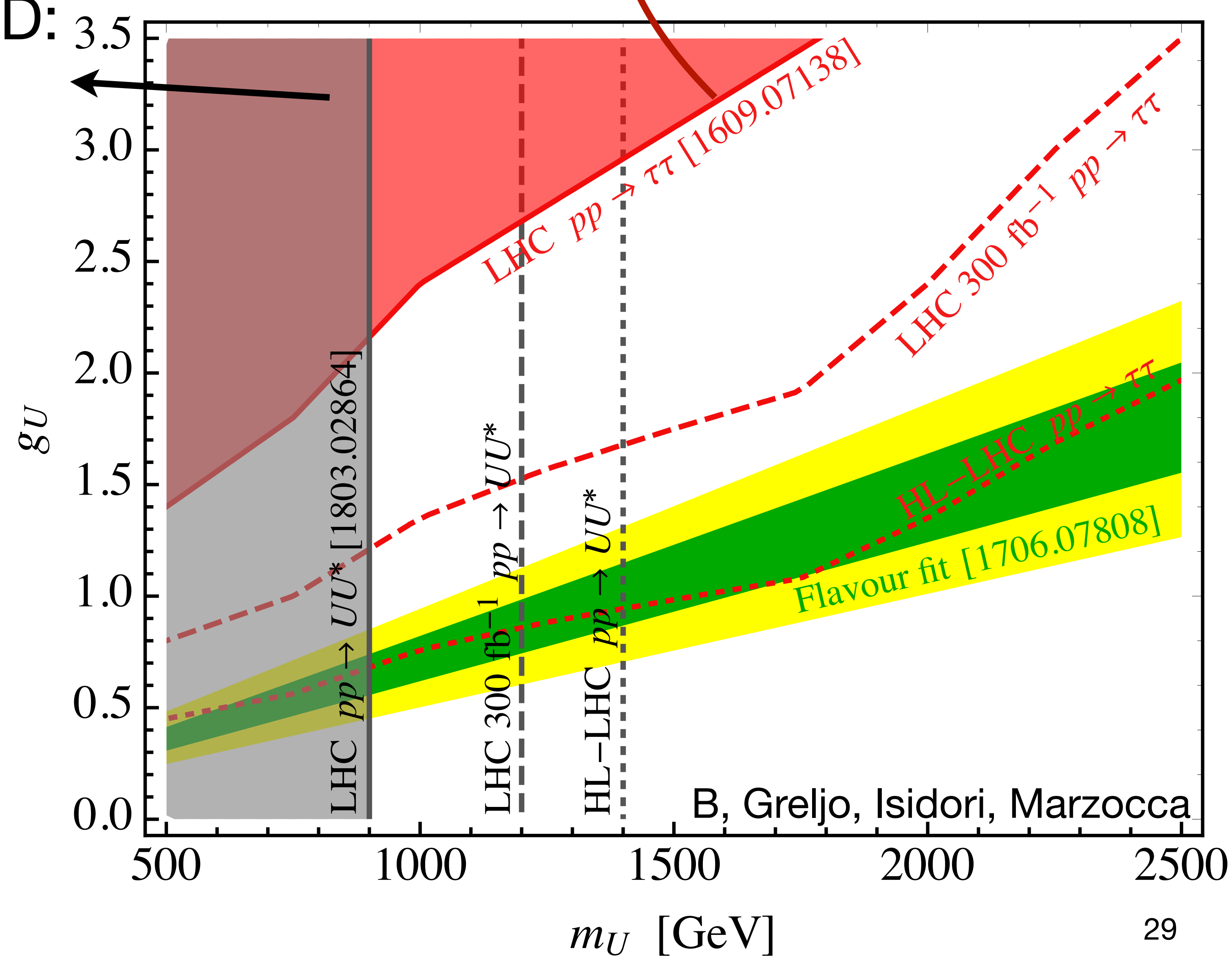


- Pair-production through QCD: model-independent



Difficult searches at the LHC:

HL-LHC will not probe the full parameter space!



A composite UV completion: scalar leptoquarks

- New strong interaction that confines at a scale Λ ~ few TeV

  $\Psi \quad \bar{\Psi}$ new (vector-like) fermions

  $\langle \bar{\Psi}^i \Psi^j \rangle = -f^2 B_0 \delta^{ij}$ breaks a global symmetry ⟶ **Goldstones**

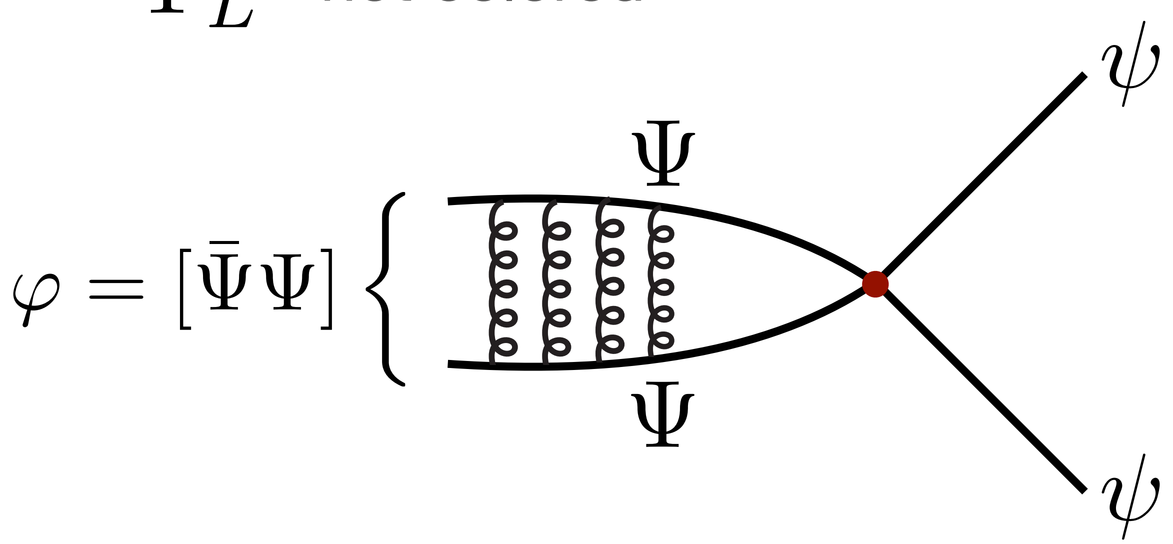
- If the fermions are charged under SM gauge group,
  then also the pseudo Nambu-Goldstone bosons have SM charges:

  Ψ_Q colored $\qquad \Psi_L$ not colored

  $[\bar{\Psi}_Q \Psi_L]$ **scalar Leptoquarks**

  $[\bar{\Psi}_L \Psi_L]$ **composite Higgs**

  \+ other states …



- Goldstones naturally light and couple to fermions

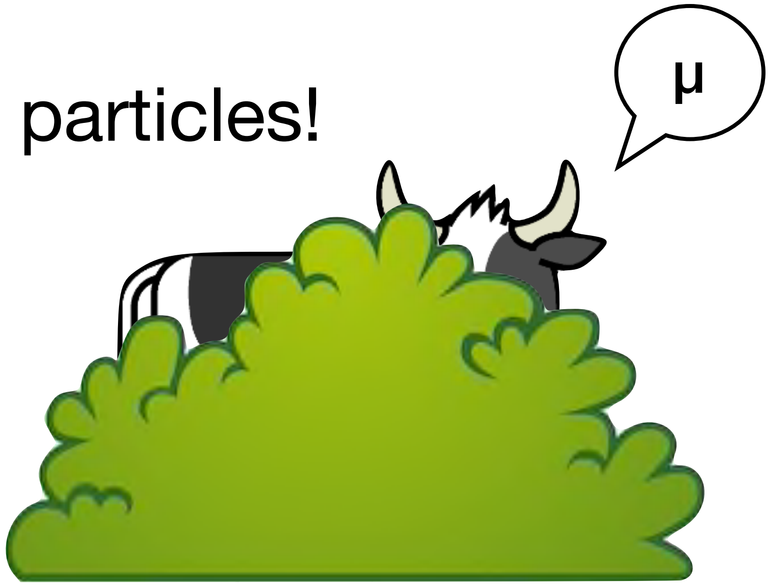
B, Greljo, Isidori, Marzocca 2017
➡ Marzocca, 2018

- Heavier vector resonances (with the same quantum numbers)


and now for something completely different...

A different example: light New Physics

- EFT description does not work if there are light new particles!



$$\mathcal{L}_{E<\Lambda} \neq \mathcal{L}_{\rm SM} + \frac{1}{\Lambda}\mathcal{L}_{d=5} + \frac{1}{\Lambda^2}\mathcal{L}_{\rm d=6} + \cdots$$

- Need to be very weakly interacting, otherwise already seen

Dark photon

ALP

Axions

RH Neutrino

Light DM

Dark sectors

- Example: light pseudo-scalar *a* (also called ALP) coupled to SM

$$\mathcal{L} = c_f \frac{\partial_\mu a}{\Lambda}(\bar{f}\gamma_\mu\gamma_5 f) + c_{\gamma\gamma}\frac{a}{\Lambda}F_{\mu\nu}\widetilde{F}^{\mu\nu}$$

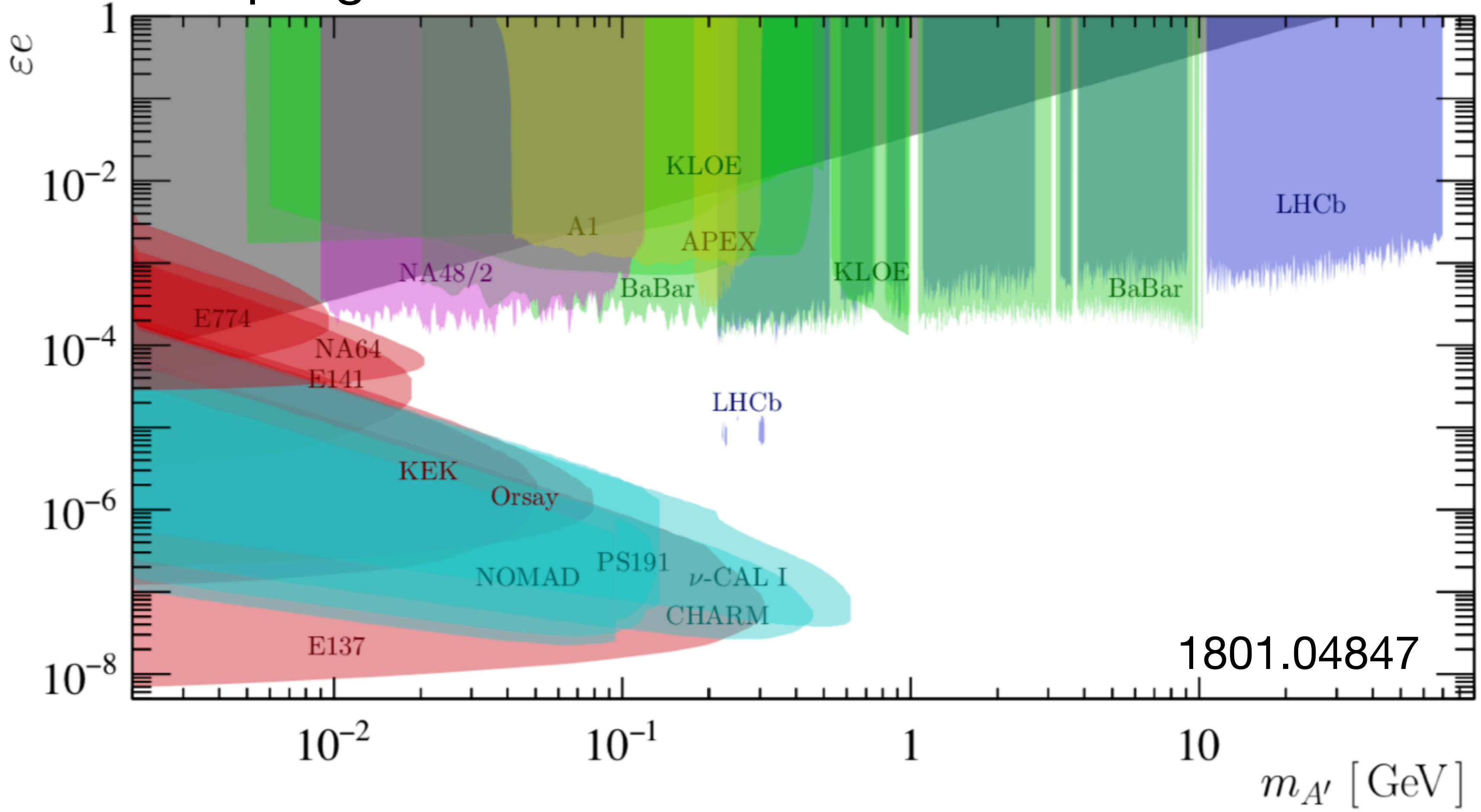
goldstone boson of some broken symmetry

same as a neutral pion!

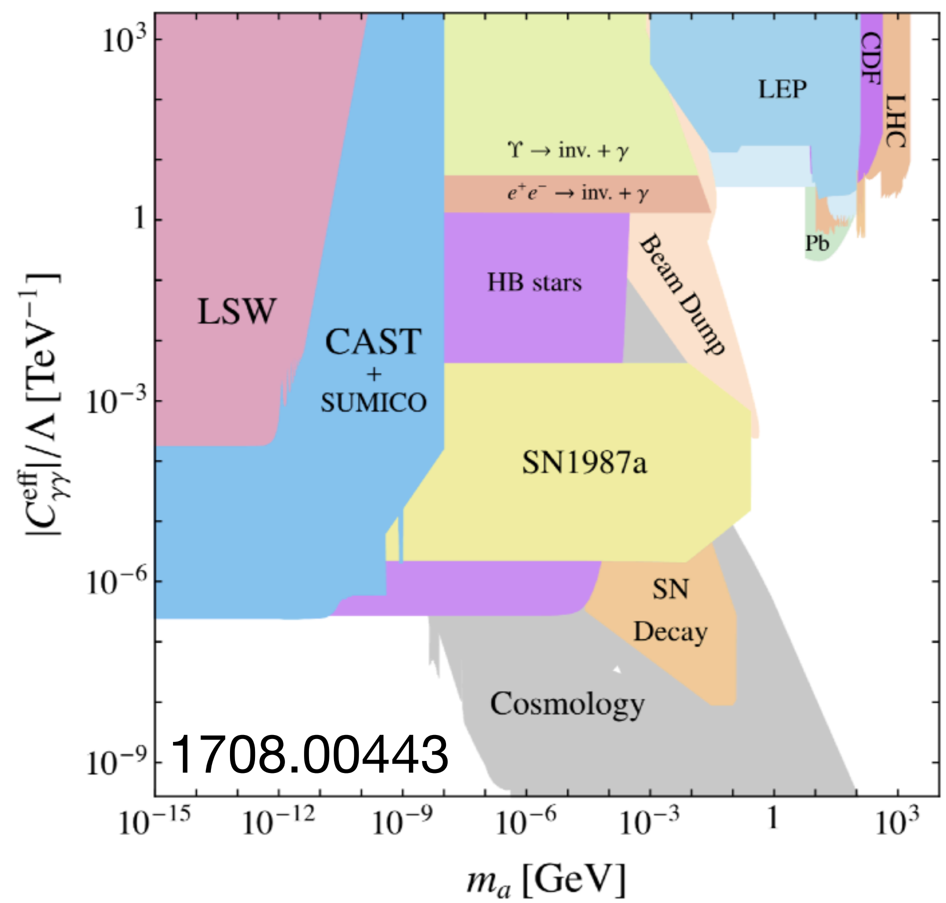
Flavor bounds on invisible particles

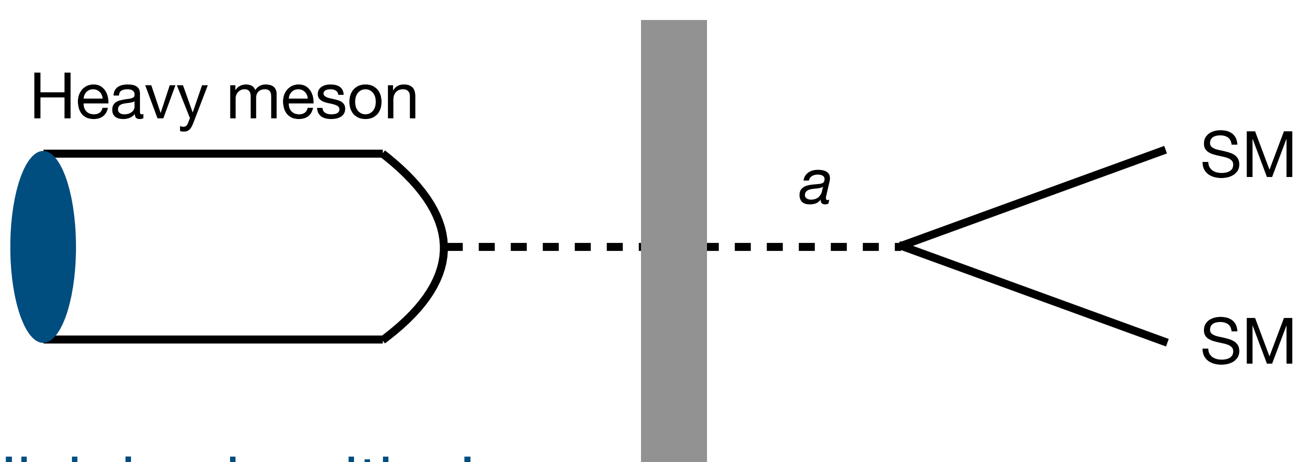
- Very strong constraints from various flavor (and other) experiments!

Coupling to fermions



Coupling to photons





High luminosities!

NB: these bounds are typically model-dependent

(no EFT description!)

Model: couplings only to leptons

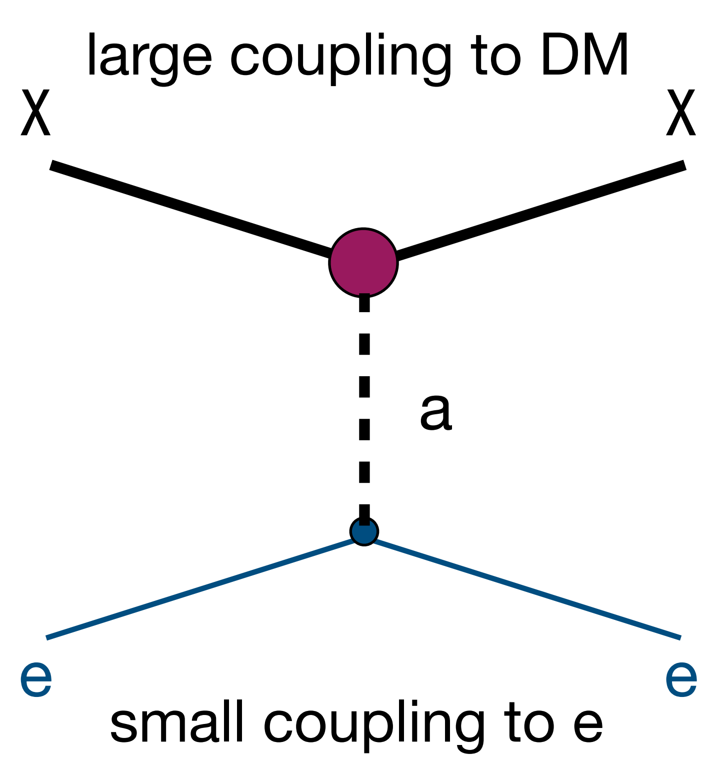
- Consider coupling to leptons only

  Flavor & collider constraints become weaker (but not absent!)

- Add a coupling to fermionic DM χ

$$\mathcal{L} = c_\chi \frac{\partial_\mu a}{\Lambda}(\bar{\chi}\gamma_\mu\gamma_5\chi) + c_e \frac{\partial_\mu a}{\Lambda}(\bar{e}\gamma_\mu\gamma_5 e) + c_{\gamma\gamma}\frac{a}{\Lambda}F_{\mu\nu}\widetilde{F}^{\mu\nu}$$

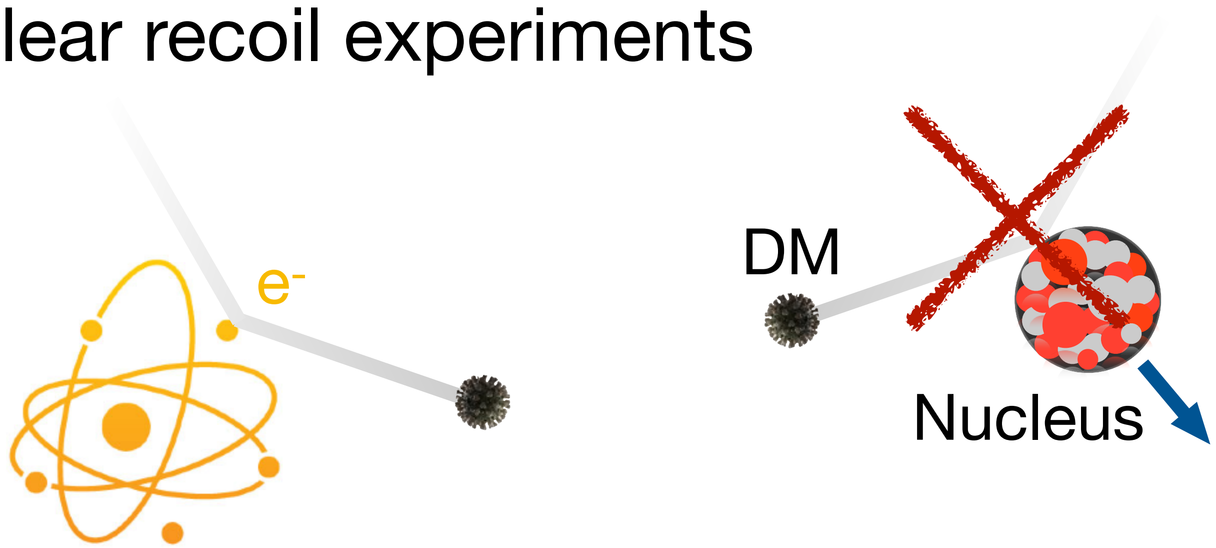
➡ DM that interacts only with electrons through a pseudoscalar mediator!



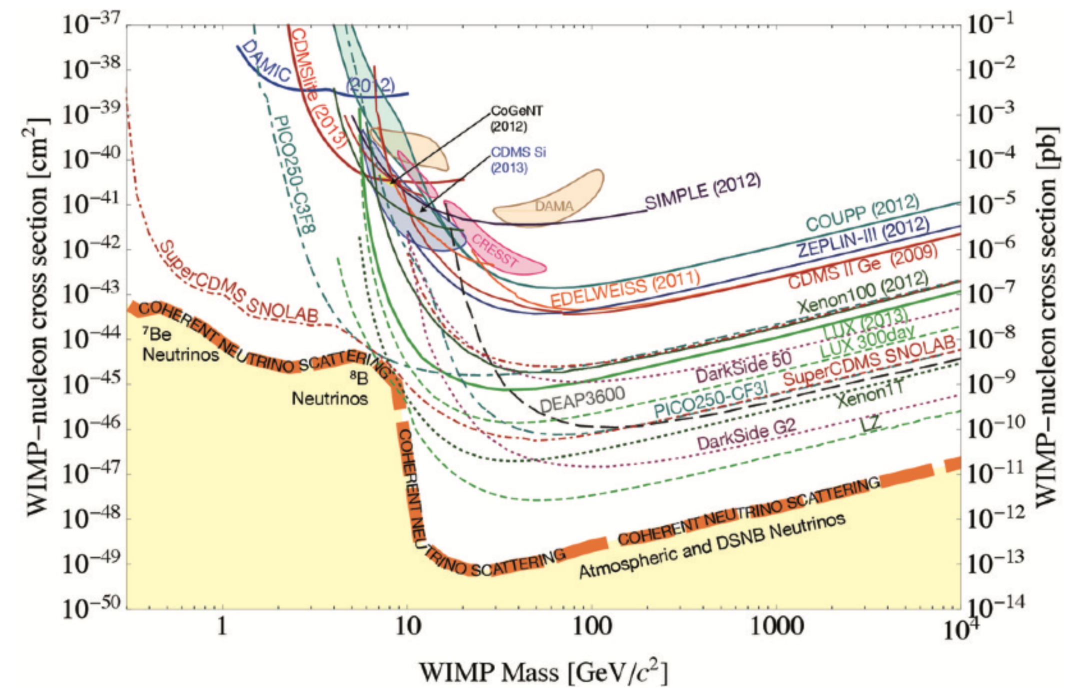
see also Alves, Weiner 1710.03764

Direct Detection

- No Direct Detection constraints from nuclear recoil experiments



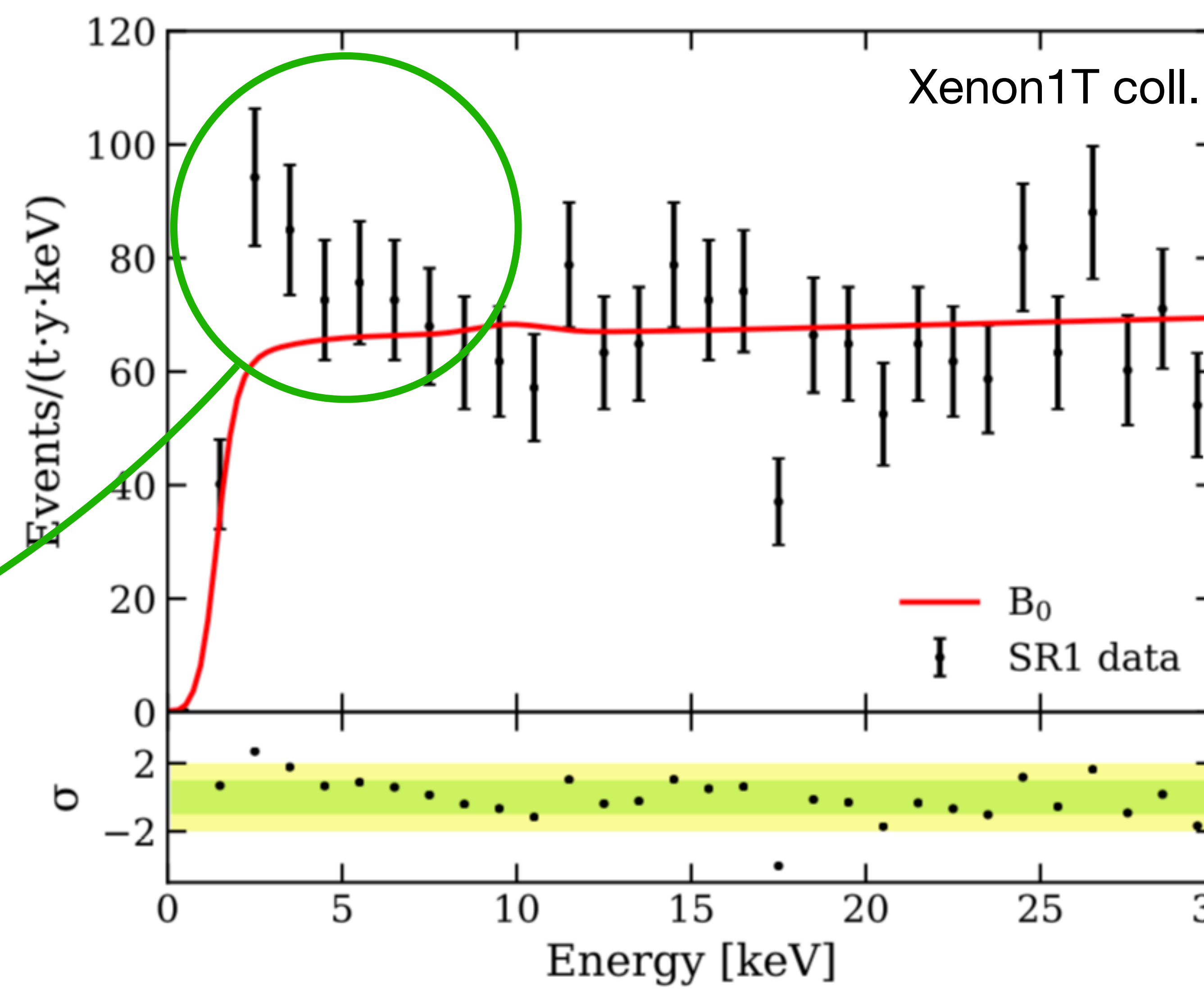
Only electron recoils



- Xenon1T has observed an excess of electron-recoil events

2006.09721

3.2σ at ~ 1-5 keV



DM-electron scattering

- Typical explanations for the Xenon signal: **keV recoil energy**
  - Non-thermal DM, more energetic (like solar axions)
  - Absorption of light DM with m_{DM} ~ keV
  - Other rather exotic models

See e.g. 2006.09721 (Xenon coll.)

- Why not “standard” WIMP scattering off electrons?

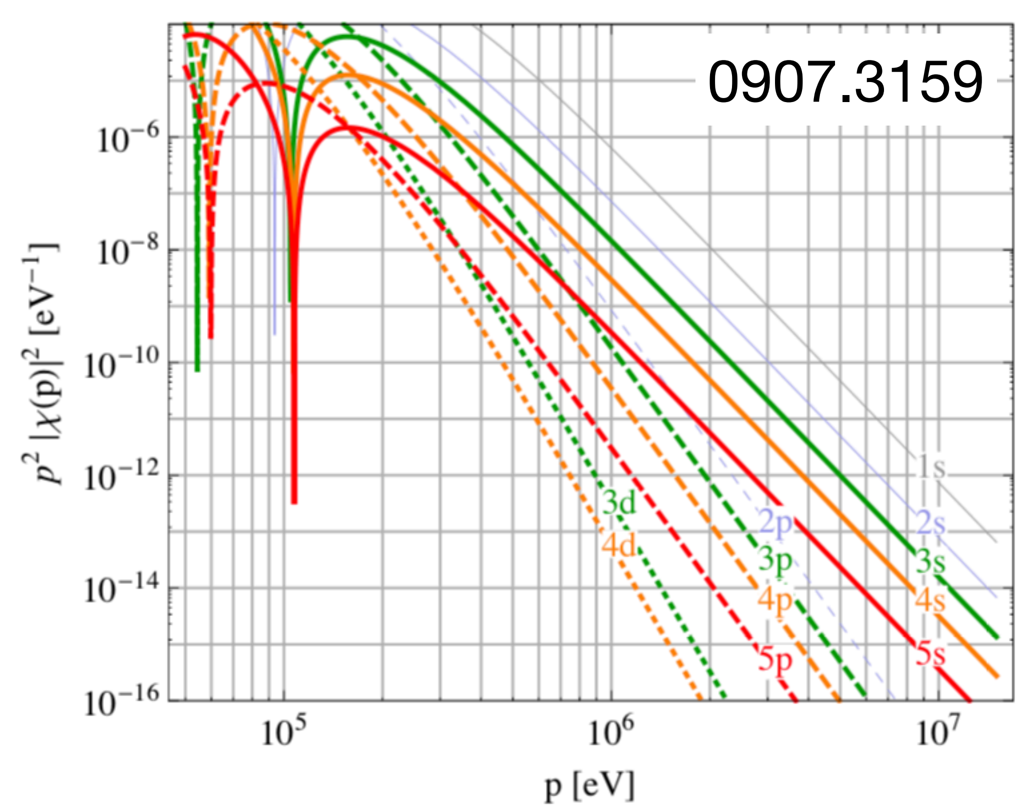
Problem: maximal recoil energy for scattering off slow electrons

$E_R \sim 2 m_e v^2 \sim$ eV **too small!**

for $v \sim 10^{-3} c$ (typical DM velocity in our Galaxy)

But electrons *bound in atoms* can have large momentum *p* ~ MeV!

$E_R \sim pv \sim$ keV



Fit to Xenon1T

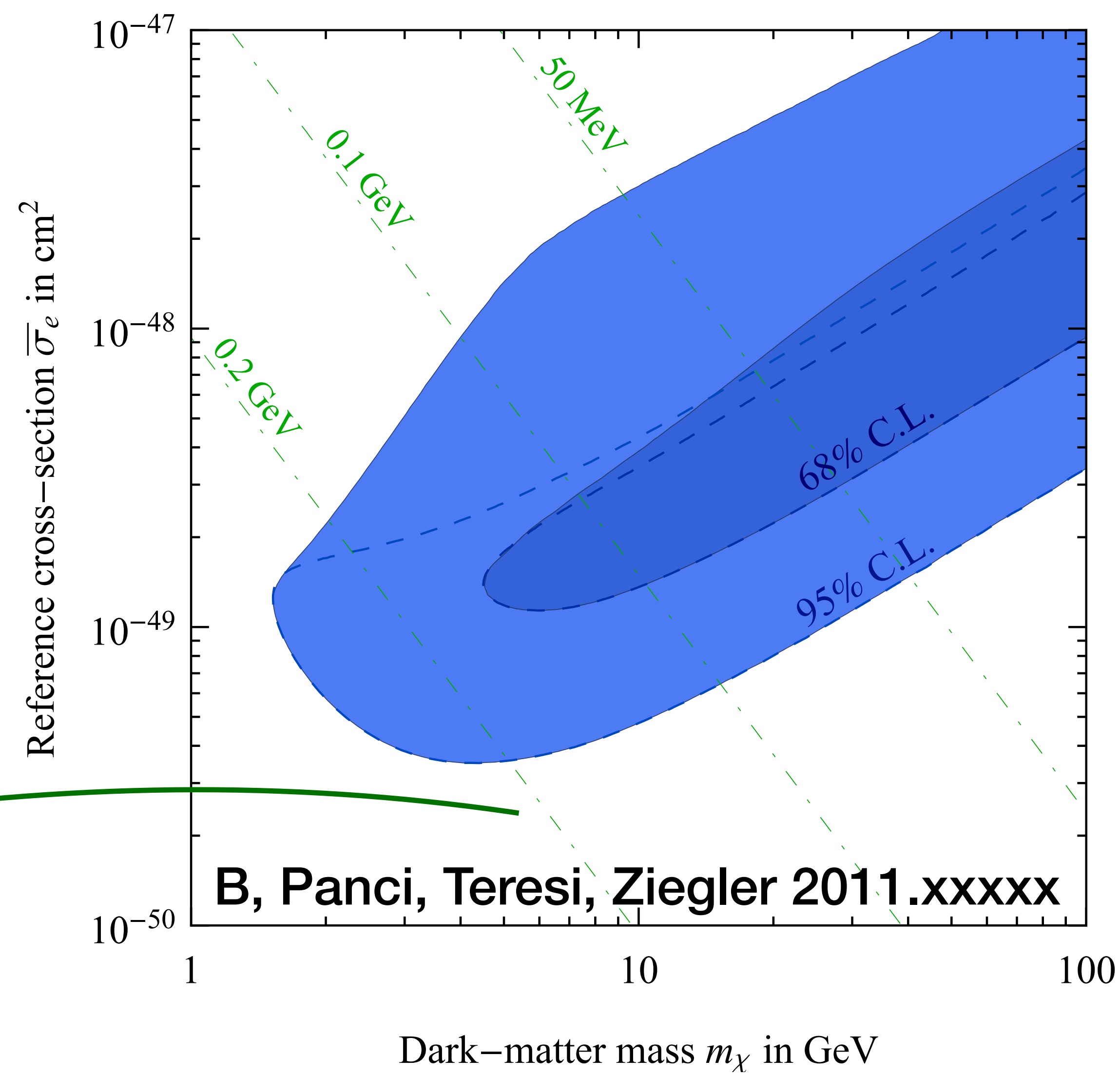
- Scattering amplitude χe → χe

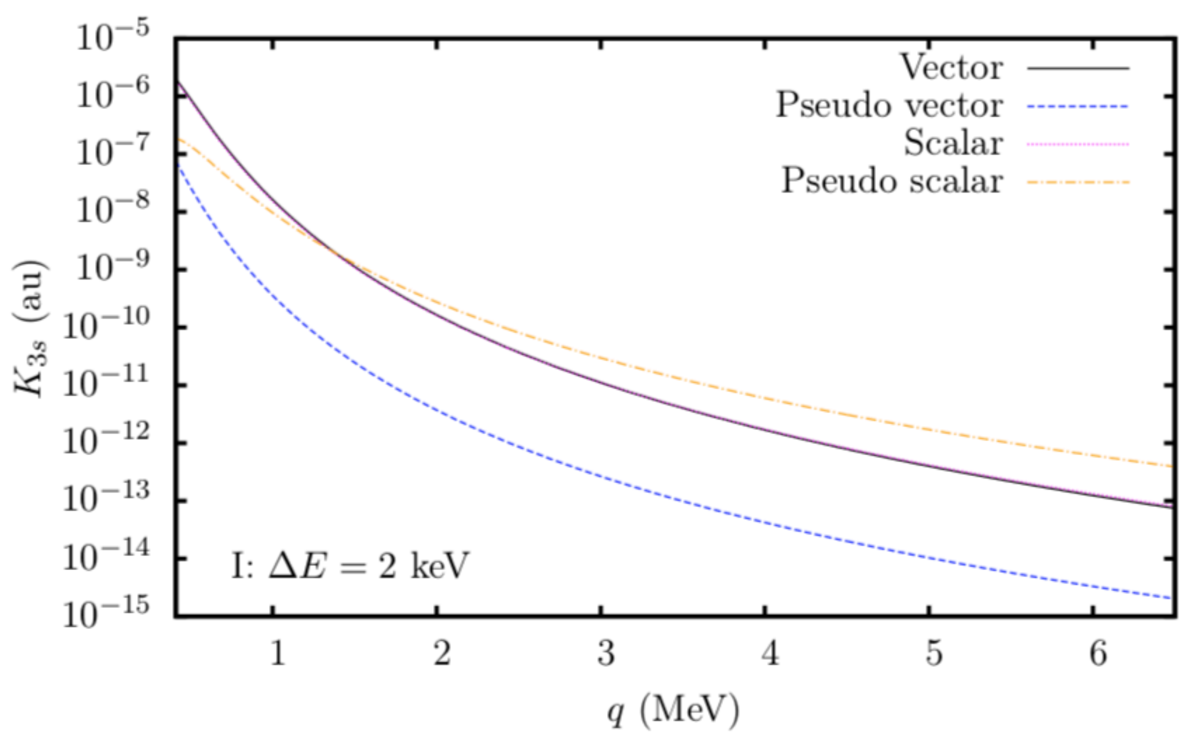
$$\mathcal{A} = (\bar{\chi}\gamma_5\chi)\frac{g_\chi g_e}{q^2 + m_e^2}(\bar{e}\gamma_5 e)$$

couplings $g_{\chi,e} = 2c_{\chi,e}/\Lambda$

- We include 3s and 4s Xe orbitals

New physics scale low, limit of contact-interaction does not apply





- Pseudo-scalar ionization function

$K_{PS}(q) \sim K_S(q)\ (q/2m_e)^2$

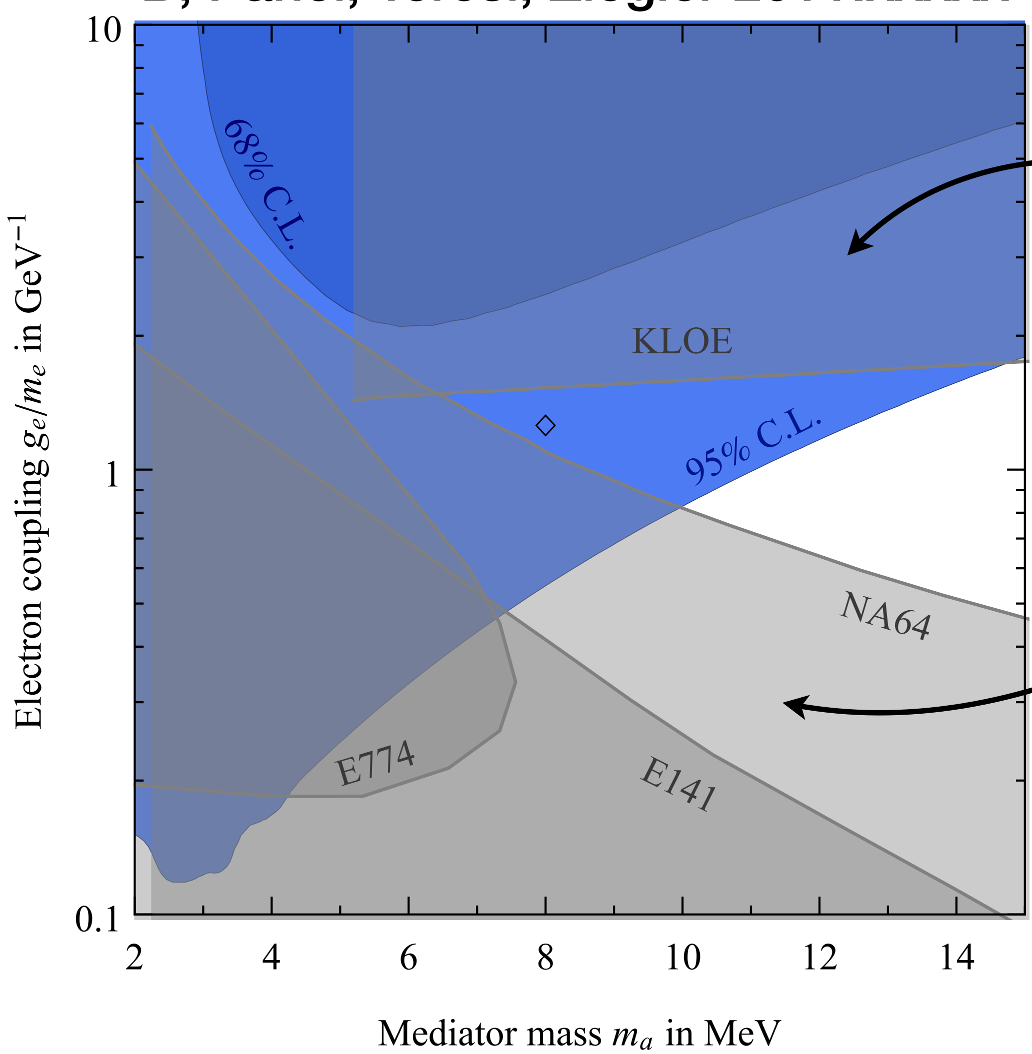
suppressed in non-relativistic limit

➡ low-energy S2-only events don't impose constraint

Bounds on the mediator

✦ Light pseudo-scalar coupled to electrons: flavor / collider / beam dump!

B, Panci, Teresi, Ziegler 2011.xxxxx



$e^+e^- \to \gamma a \to \gamma e^+ e^-$

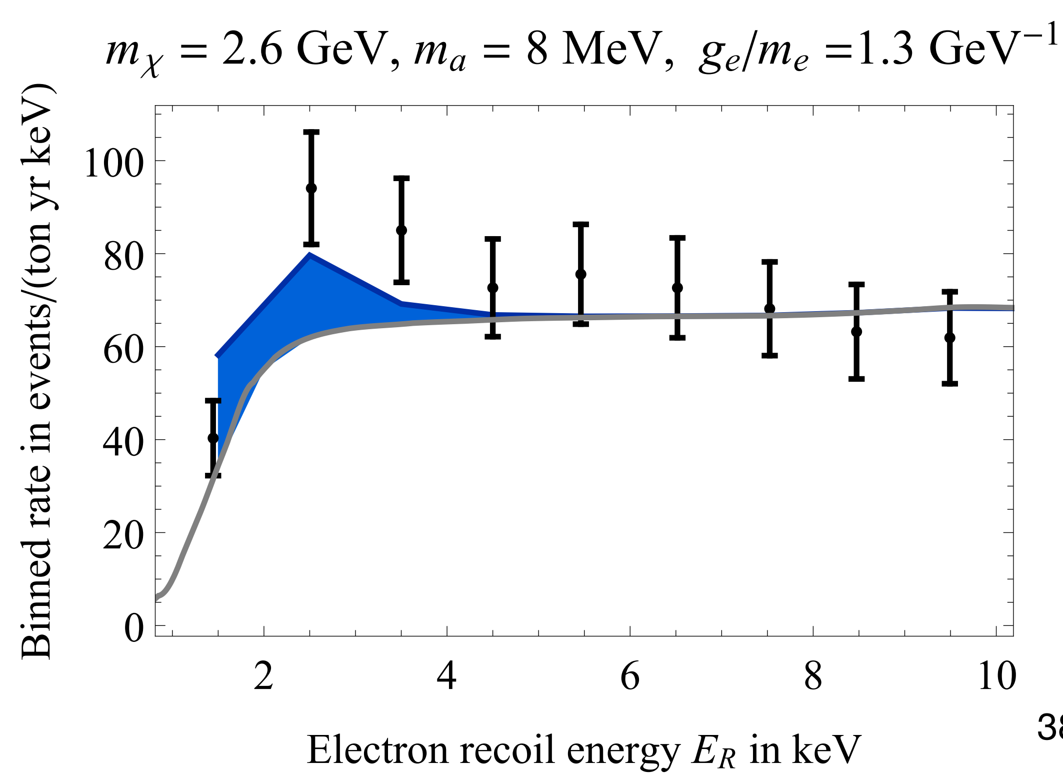
at J/ψ resonance

$a \to \gamma e^+ e^-$

from electron beam dumps

✦ BR(a → γγ) very small

✦ Portions of parameter space allowed, that give good fit to the signal!

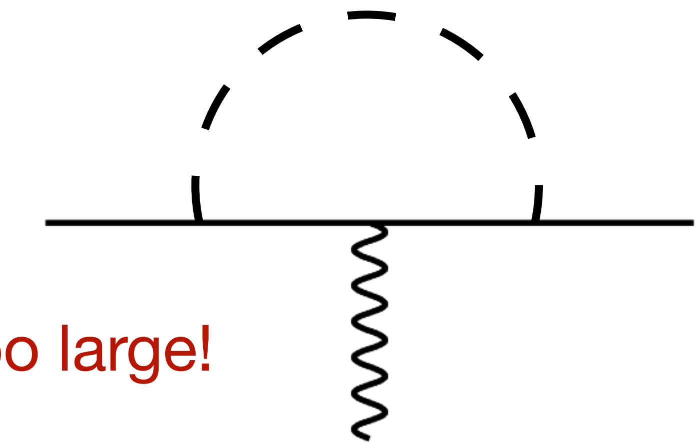


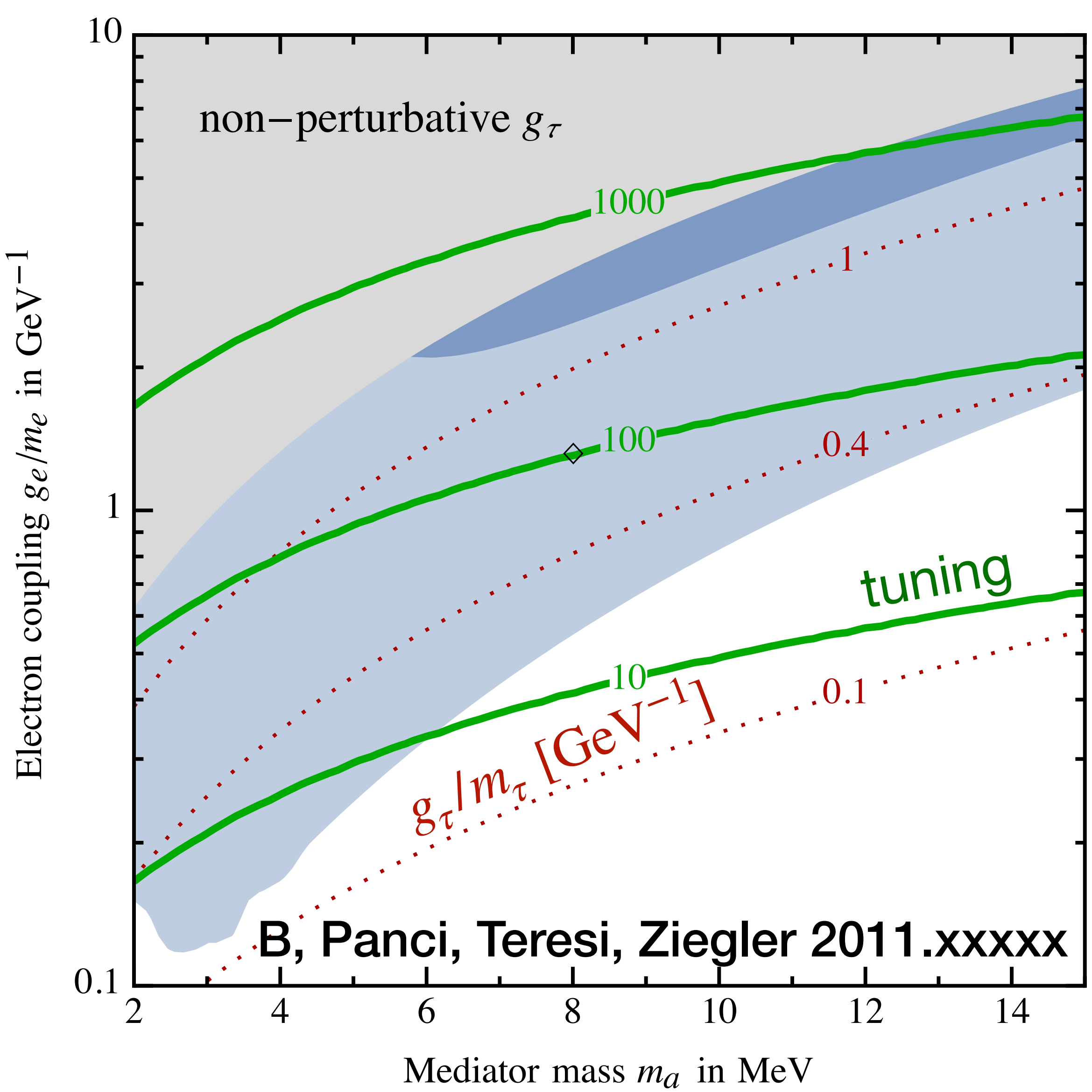
Electron g-2

- Light pseudo-scalar gives contribution to lepton g-2

$$\Delta a_e^{1\text{loop}} = -\frac{m_e^2}{4\pi^2\Lambda^2}|c_e|^2 f(m_a^2/m_e^2) \approx 10^{-10}$$

100 x too large!

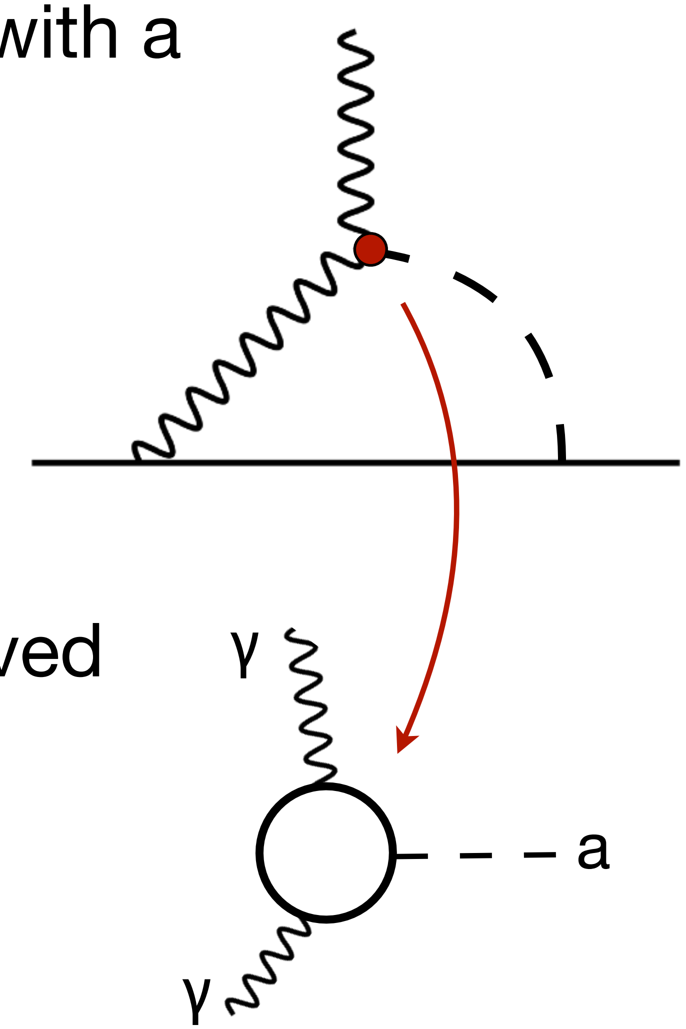




- Can be canceled with a non-zero coupling to photons

(at the price of tuning)

- This can be achieved coupling *a* to just SM leptons, including μ and τ!



- Bonus: muon g-2 can also be explained

Model: couplings only to leptons

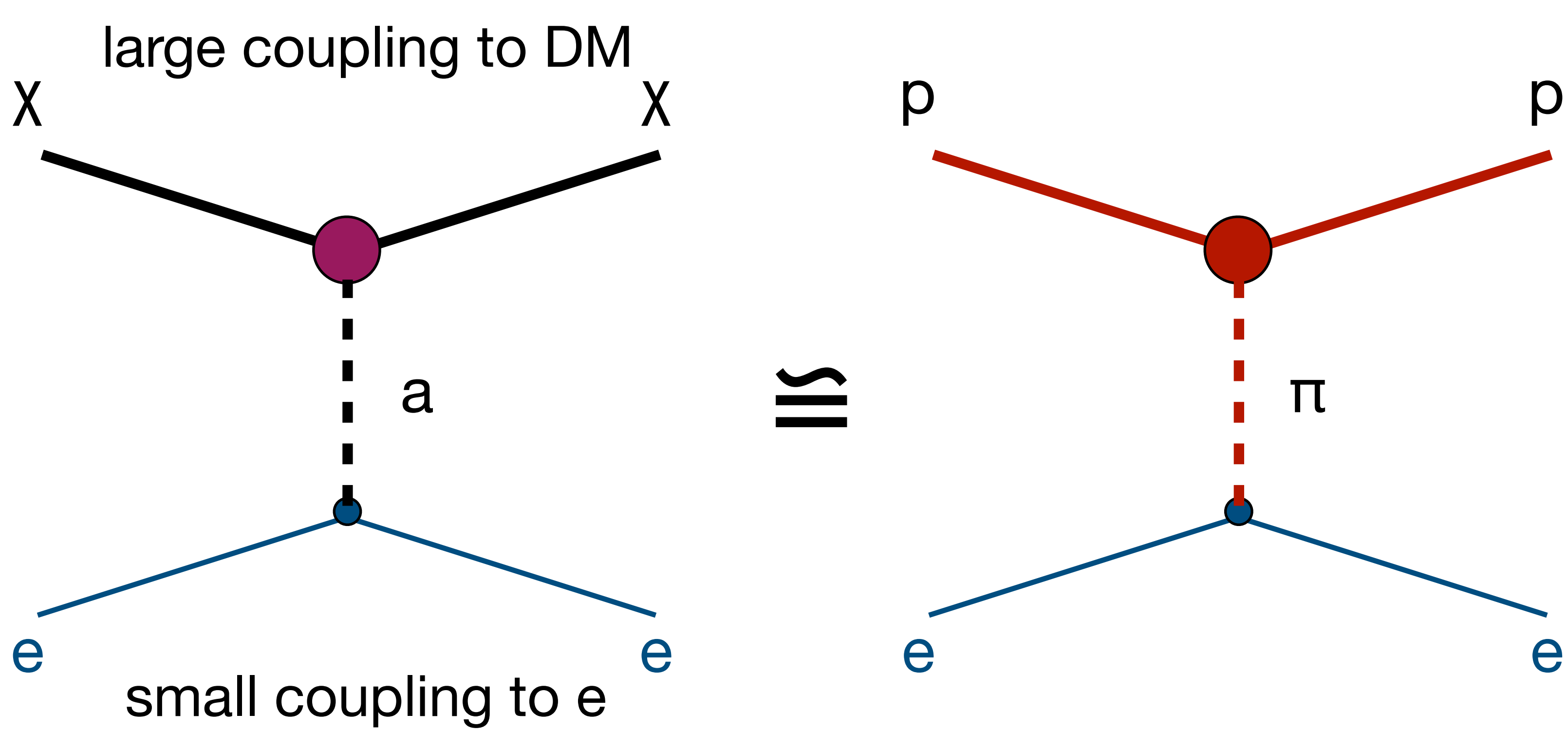
- Consider coupling to leptons only

  Flavor & collider constraints become weaker (but not absent!)

- Add a coupling to fermionic DM χ

$$\mathcal{L} = c_\chi \frac{\partial_\mu a}{\Lambda} (\bar{\chi}\gamma_\mu\gamma_5\chi) + c_e \frac{\partial_\mu a}{\Lambda} (\bar{e}\gamma_\mu\gamma_5 e) + c_{\gamma\gamma} \frac{a}{\Lambda} F_{\mu\nu}\widetilde{F}^{\mu\nu}$$

➡ DM that interacts only with electrons through a pseudoscalar mediator!



a composite dark sector?

low scale: building a full model might be difficult!

or an axion, or …

Flavor physics is a crucial ingredient of high-energy physics

Test high scales beyond direct reach

Even with largest flavor symmetries, competes with FCC reach (but in near future!)

New directions in model building

Leptoquarks, non-minimal composite sectors, …

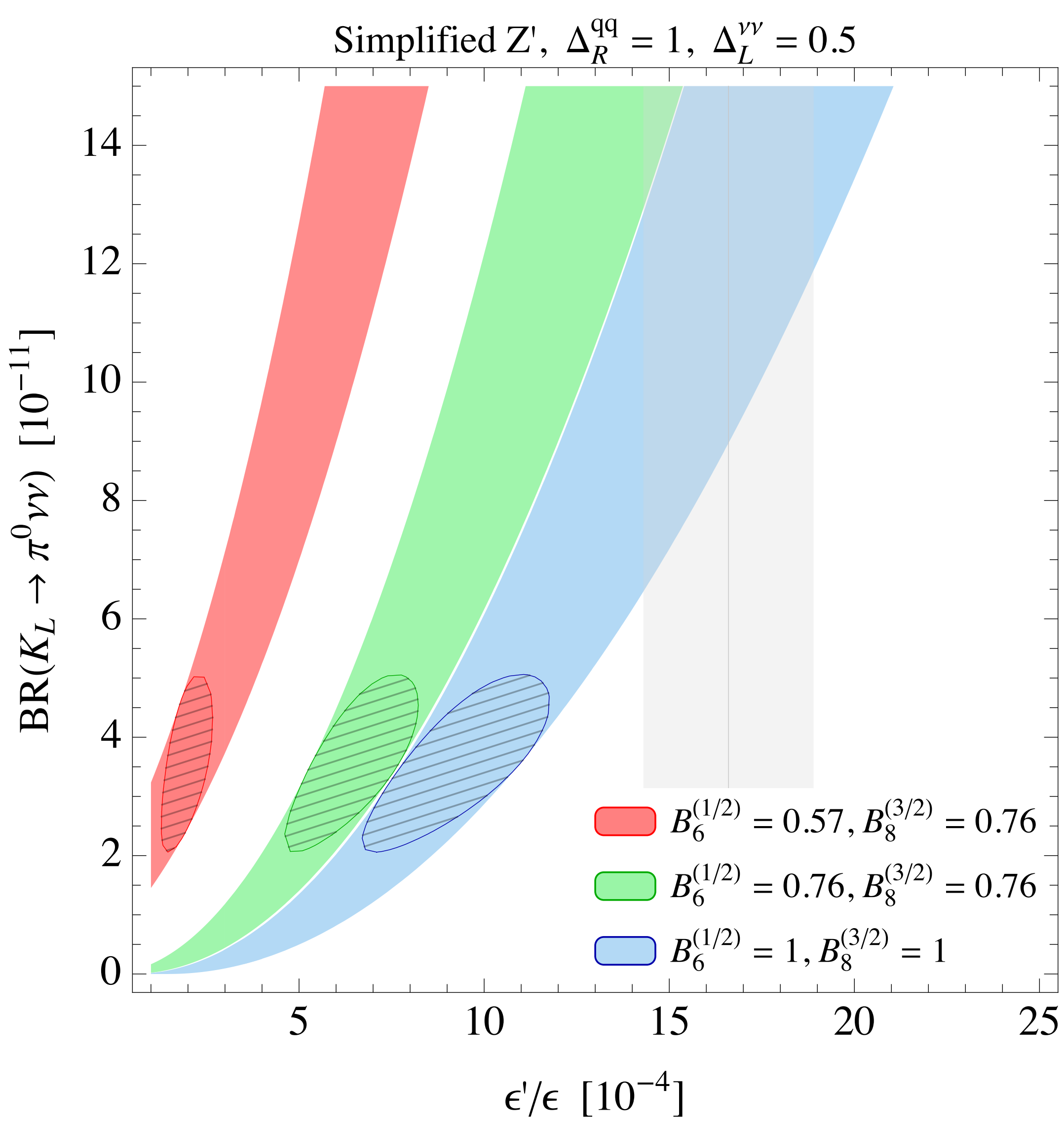
Even without a discovery we learn a lot (but a discovery is better!!)

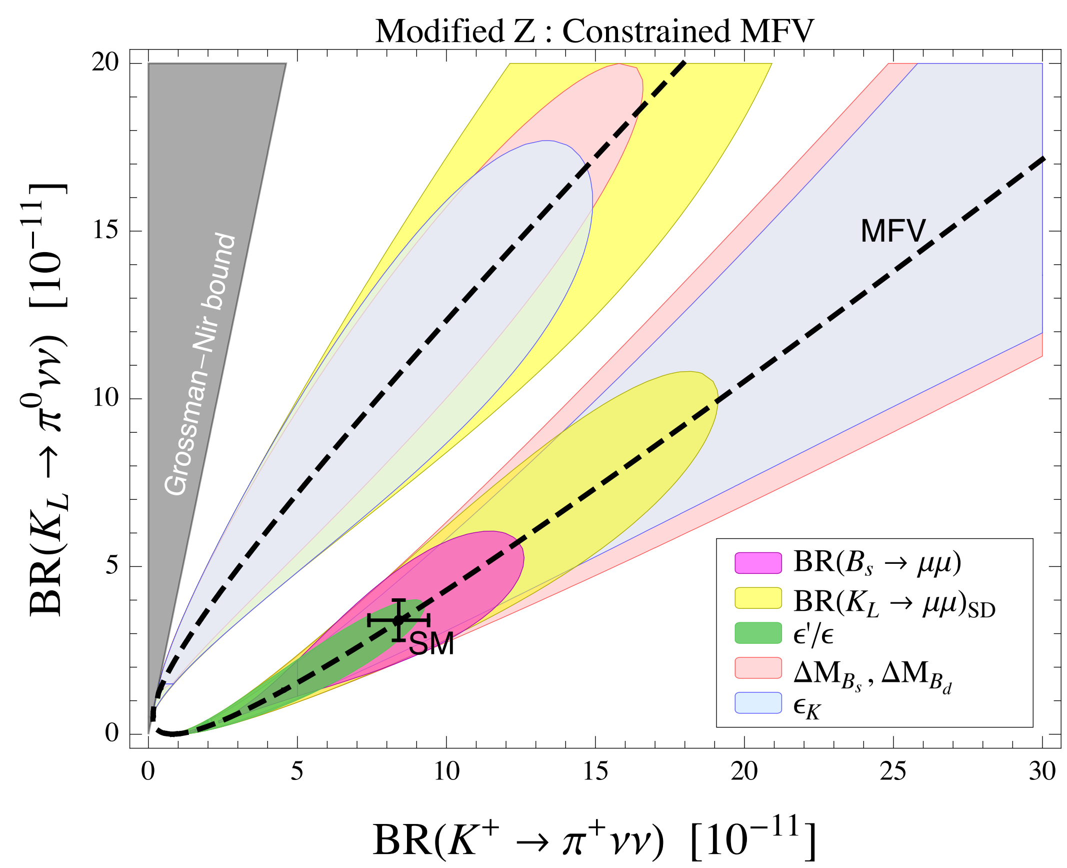
Backup

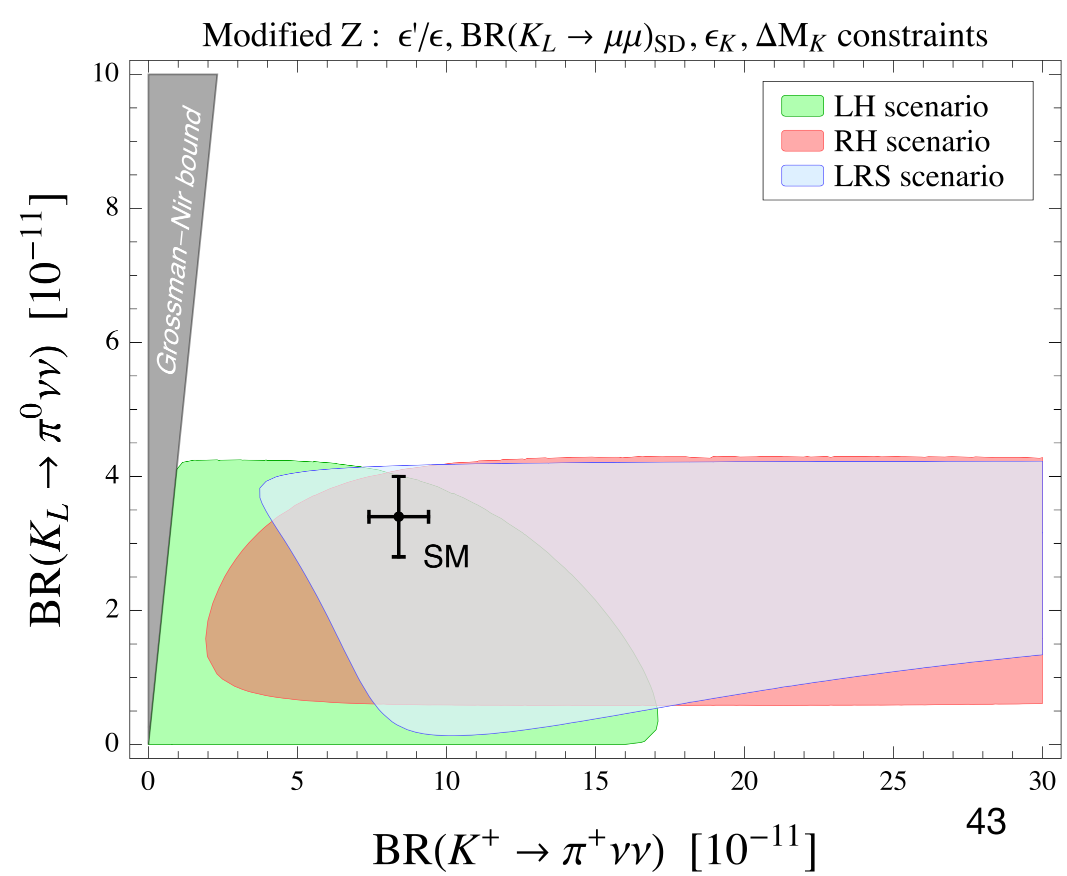
Rare decays: the importance of correlations

Many observables, many models

Correlations between different observables are crucial to distinguish them!







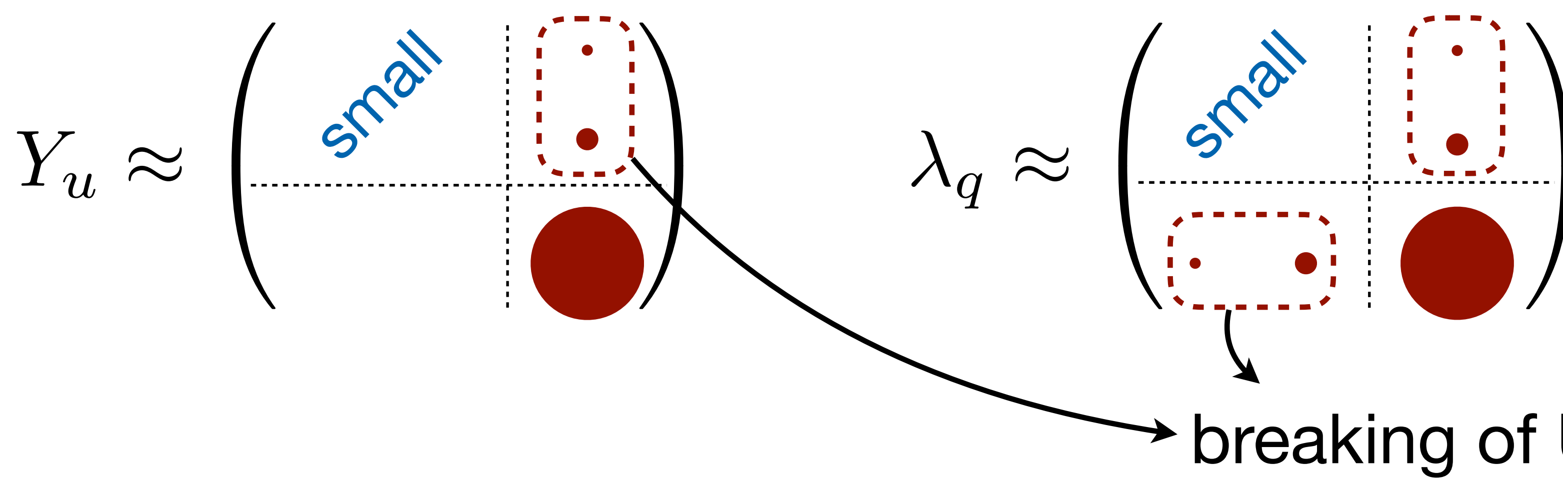
Effective Field Theory for semi-leptonic interactions

1. Left-handed semi-leptonic interactions: two possible operators in SM-EFT

$$C_S(\bar{q}_L^i \gamma_\mu q_L^j)(\bar{\ell}_L^\alpha \gamma^\mu \ell_L^\beta) \qquad\qquad C_T(\bar{q}_L^i \gamma_\mu \sigma^a q_L^j)(\bar{\ell}_L^\alpha \gamma^\mu \sigma^a \ell_L^\beta)$$

— SU(2) singlet — — SU(2) triplet —

2. CKM-like flavour pattern: U(2) symmetry for both quarks & leptons



$$\psi_i = ((\psi_1 \;\; \psi_2)^{\mathbf{2}} (\psi_3)^{\mathbf{1}})$$

i.e. coupling to third generation only: $Q_L^{(3)} \sim \begin{pmatrix} V_{ib}^* u_L^i \\ b_L \end{pmatrix}$ + small terms (~ V_{CKM})

$$\lambda_{ij}^q \approx \begin{pmatrix} \cdot & \cdot & \cdot \\ \cdot & \cdot & V_{ts} \\ \cdot & V_{ts}^* & 1 \end{pmatrix} \qquad \lambda_{\alpha\beta}^\ell \approx \begin{pmatrix} \cdot & \cdot & \cdot \\ \cdot & |V_{\tau\mu}|^2 & V_{\tau\mu} \\ \cdot & V_{\tau\mu}^* & 1 \end{pmatrix}$$

4 parameters relevant for the anomalies

B, Greljo, Isidori, Marzocca, 2017

Effective Field Theory

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

LFU ratios in ***b*** **→** ***c*** charged currents:

***τ* vs *l*:** $R^{\tau\ell}_{D^{(*)}} \simeq 1 + 2C_T\left(1 + \frac{\lambda^q_{bs}}{V_{cb}}\right) = 1.237 \pm 0.053$

***μ* vs *e*:** $R^{\mu e}_{D^{(*)}} \simeq 1 + 2C_T\left(1 + \frac{\lambda^q_{bs}}{V_{cb}}\right)\lambda_{\mu\mu} < 0.02$ → $\lambda_{\mu\mu} \lesssim 0.1$

Neutral currents: ***b*** **→** $s\nu_\tau\nu_\tau$ transitions not suppressed by lepton spurion

$$\Delta C_\nu \simeq \frac{\pi}{\alpha V^*_{ts}V_{tb}}\lambda^q_{sb}(C_S - C_T)$$

strong bounds from $B \to K^*\nu\nu$

→ $C_T \sim C_S$

b **→** $s\tau\tau$ ~ $C_T + C_S$ is large (100 x SM), weak experimental constraints

b **→** $s\mu\mu$ is an independent quantity: fixes the size of $\lambda_{\mu\mu} \sim 10^{-2}$

$$\Delta C_{9,\mu} = -\frac{\pi}{\alpha V^*_{ts}V_{tb}}\lambda^q_{sb}\lambda_{\mu\mu}(C_T + C_S)$$

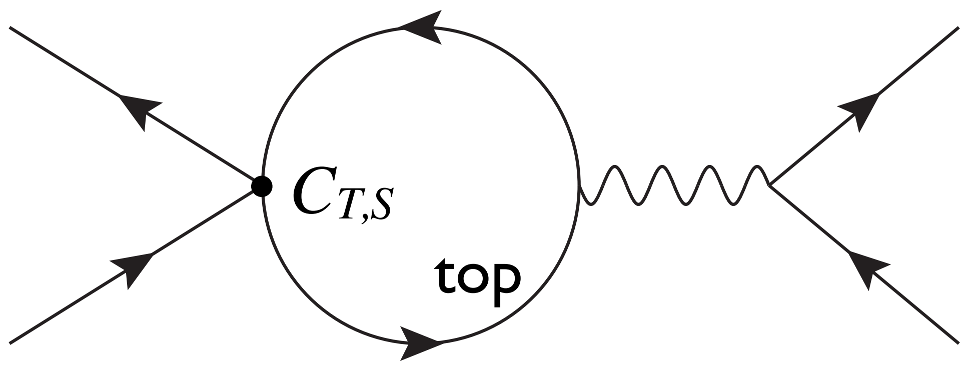
Radiative corrections

Purely leptonic operators generated at the EW scale by RG evolution

Feruglio et al. 2015

- **LFU in τ decays** $\tau \to \mu\nu\nu$ vs. $\tau \to e\nu\nu$ (effectively modification of W couplings)

$$\delta g_\tau^W = -0.084\, C_T = (9.7 \pm 9.8) \times 10^{-4}$$



- ***Z*$\tau\tau$ couplings**

$$\delta g_{\tau_L}^Z = -0.047 C_S + 0.038 C_T = -0.0002 \pm 0.0006$$

- ***Zνν* couplings** (number of neutrinos)

$$N_\nu = 3 - 0.19\, C_S - 0.15\, C_T = 2.9840 \pm 0.0082$$

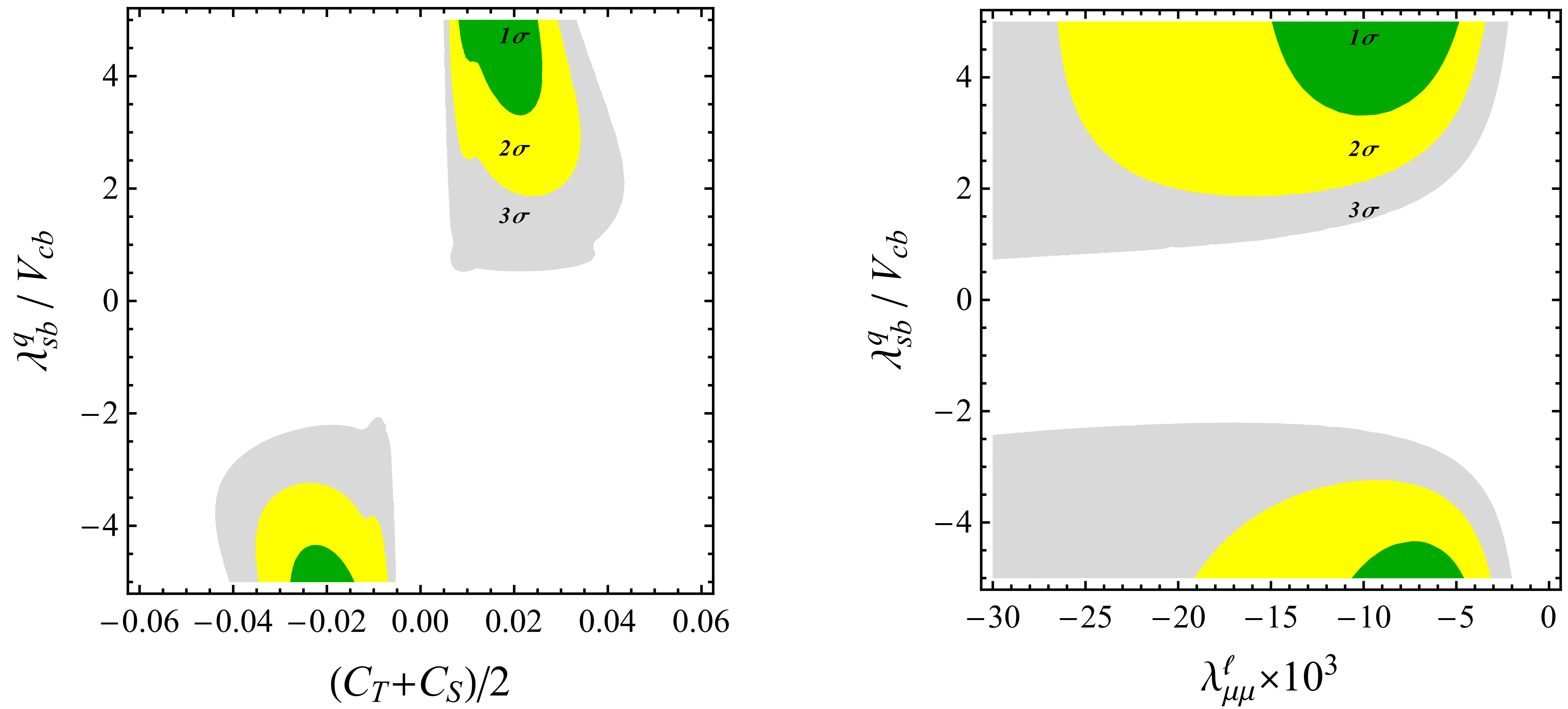
(RG-running corrections to four-quark operators suppressed by the τ mass)

→ strong bounds on the scale of NP ($C_{S,T} \lesssim$ 0.02-0.03)

Fit to semi-leptonic observables

- EFT fit to all semi-leptonic observables + radiative corrections to EWPT
- Don't include any UV contribution to other operators
  (they will depend on the dynamics of the specific model)

B, Greljo, Isidori, Marzocca, 2017



Good fit to all anomalies, with couplings compatible with the U(2) assumption

Testing chirality and flavour structure: charged currents

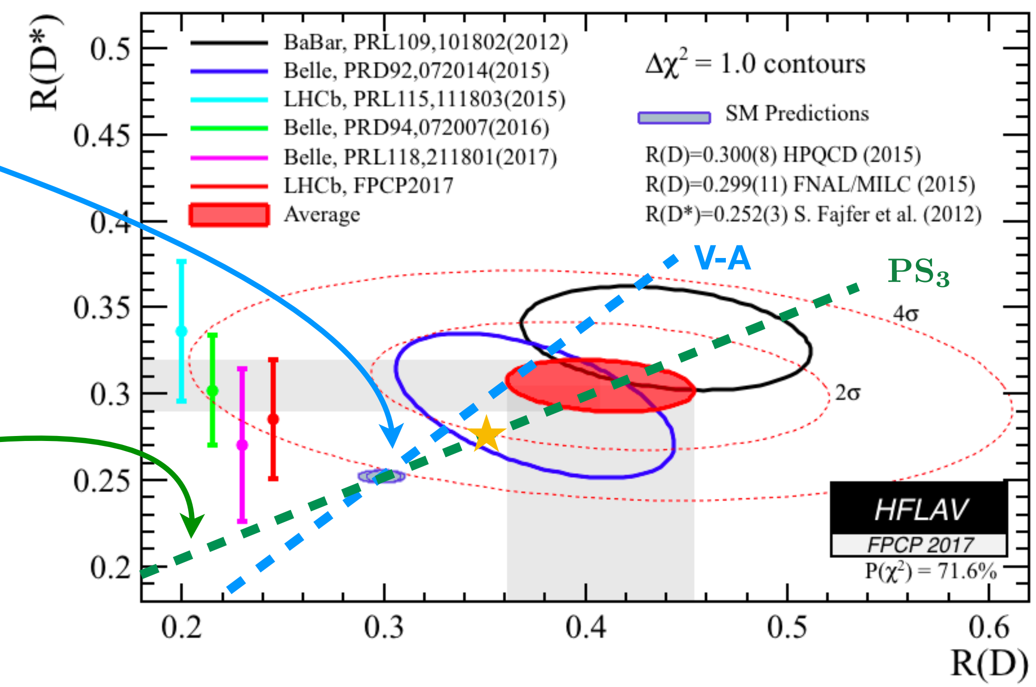
- **LH charged currents:** universality of all $\boldsymbol{b \to c}$ transitions:

$$\mathrm{BR}(B \to D\tau\nu)/\mathrm{BR}_{SM} = \mathrm{BR}(B \to D^*\tau\nu)/\mathrm{BR}_{SM} = \mathrm{BR}(B_c \to \psi\tau\nu)/\mathrm{BR}_{SM}$$

$$= \mathrm{BR}(\Lambda_b \to \Lambda_c\tau\nu)/\mathrm{BR}_{SM} = \ldots$$

  - the presence of RH/scalar currents breaks the correlation

    example: Bordone et al. 1712.01368



- **U(2) symmetry:** $\boldsymbol{b \to c}$ vs. $\boldsymbol{b \to u}$ universality

$$\mathrm{BR}(B \to D^{(*)}\tau\nu)/\mathrm{BR}_{SM} = \mathrm{BR}(B \to \pi\tau\nu)/\mathrm{BR}_{SM} = \mathrm{BR}(B^+ \to \tau\nu)/\mathrm{BR}_{SM}$$

$$= \mathrm{BR}(B_s \to K^*\tau\nu)/\mathrm{BR}_{SM} = \mathrm{BR}(\Lambda_b \to p\tau\nu)/\mathrm{BR}_{SM} = \ldots$$

✓ $\mathrm{BR}(B_u \to \tau\nu)_{exp}/\mathrm{BR}_{SM} = 1.31 \pm 0.27$ (UTfit 2016)

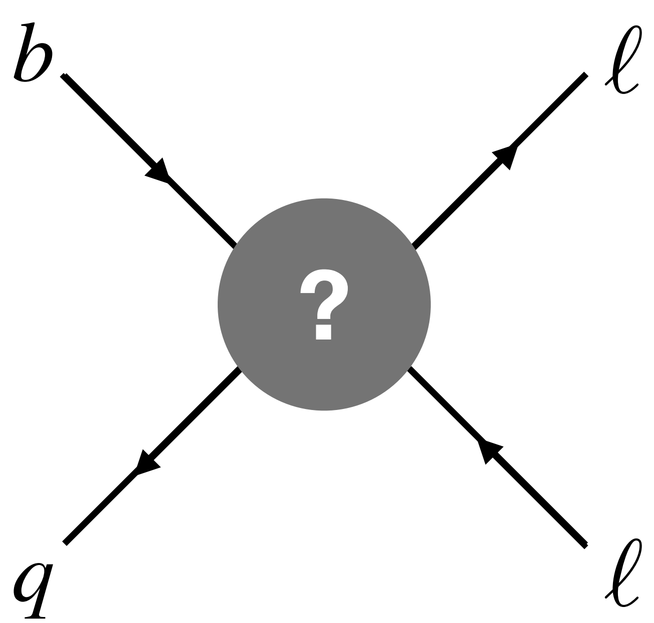
$$\lambda^q_{ij} \approx \begin{pmatrix} \cdot & \cdot & V_{td} \\ \cdot & \cdot & V_{ts} \\ V^*_{td} & V^*_{ts} & 1 \end{pmatrix}$$

small

CKM matrix

Scale of new physics

Perturbative unitarity of 2 → 2 scattering amplitudes sets upper limit on the scale where the theory breaks down (i.e. mass of new resonances)



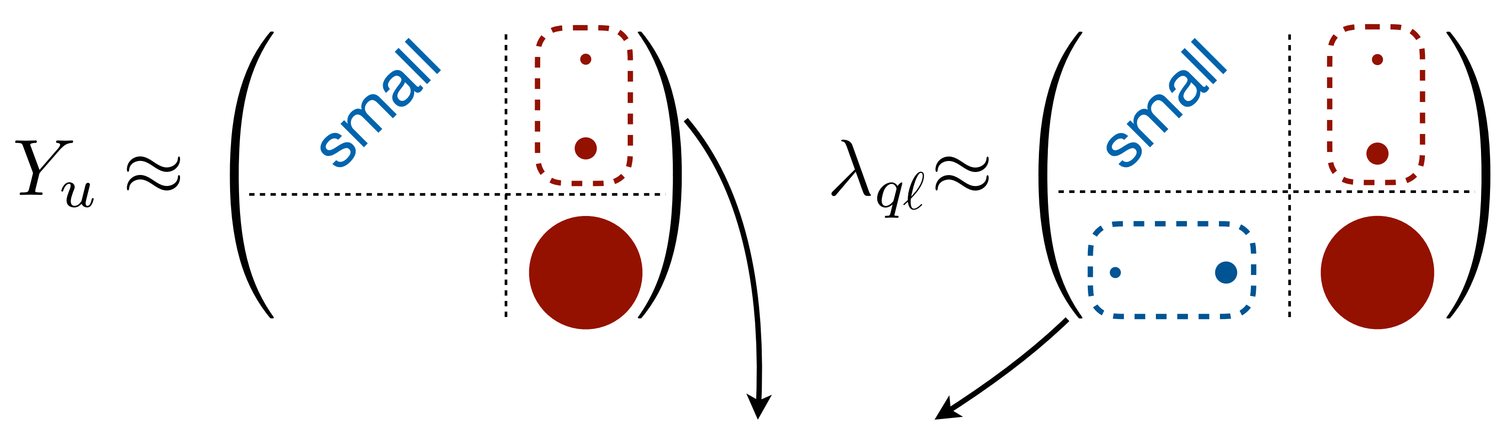
$$\frac{1}{\Lambda^2}(\bar{b}_L\gamma_\mu q_L)(\bar{\ell}_L\gamma^\mu \ell_L)$$

[Di Luzio, Nardecchia 2017]

$$|\mathrm{Re}\,(a^0_{ii})^{\mathrm{Born}}| \leq \frac{1}{2} \quad \rightarrow \quad \Lambda < 9\,\mathrm{TeV}$$

(Λ < 84 TeV for b → sμμ alone)

Assumption on flavour structure: CKM-like flavour pattern for quarks & leptons



$$\rightarrow \quad \Lambda < 2\,\mathrm{TeV}$$

(Λ < 17 TeV for b → sμμ alone)

small, of the order of CKM
(breaking of $U(2)_q$ x $U(2)_\ell$ symmetry)

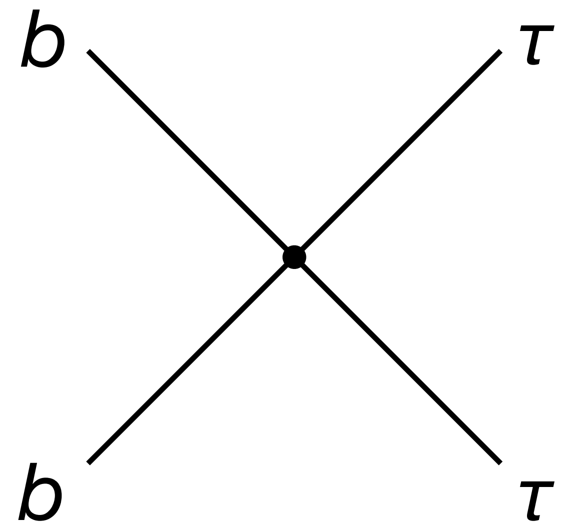
Bounds from present and future colliders?

High-pT searches at LHC

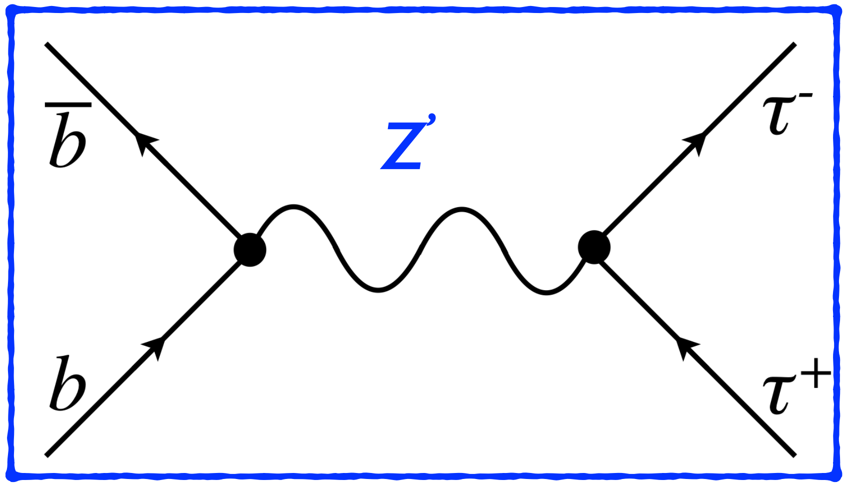
A general feature of any model: large coupling to *b* and *τ*

➡ searches in *ττ* final state at high energy at LHC

PDF of *b* quark small, but still dominant
if compared to flavour suppression

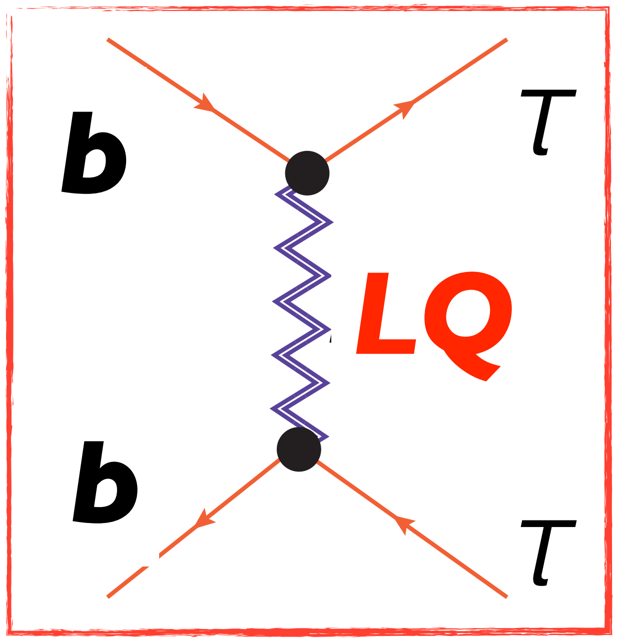


✦ s-channel resonances



must be broad to escape searches
if below ~ 2 TeV

✦ t-channel exchange: leptoquarks



UV completions: vector leptoquark

Leptoquark quantum numbers are consistent with **Pati-Salam unification**

$$SU(4) \times SU(2)_L \times SU(2)_R \supset SU(3)_c \times SU(2)_L \times U(1)_Y$$

Lepton number = 4th color

$$\psi_L = (q_L^1, q_L^2, q_L^3, \ell_L) \sim (\mathbf{4}, \mathbf{2}, \mathbf{1}),$$
$$\psi_R = (q_R^1, q_R^2, q_R^3, \ell_R) \sim (\mathbf{4}, \mathbf{1}, \mathbf{2}).$$

Gauge fields: $\mathbf{15} = \mathbf{8}_0 \oplus \mathbf{3}_{2/3} \oplus \bar{\mathbf{3}}_{-2/3} \oplus \mathbf{1}_0$

→ vector leptoquark U_1^μ

$$\begin{pmatrix} (G_\mu^a)^\alpha_\beta & U_\mu^\alpha \\ (U_\mu^\alpha)^\dagger & Z'_\mu \end{pmatrix}$$

- ✦ No proton decay: protected by gauge $U(1)_{B-L} \subset SU(4)$
- ✦ U_μ gauge vector: universal couplings to fermions!
  - ➡ bounds of O(100 TeV) from light fermion processes, e.g. $K \to \mu e$

UV completions: vector leptoquark

Non-universal couplings to fermions needed!

- **Elementary vectors:** extended gauge group
  color can't be completely embedded in SU(4)

$$SU(4) \times SU(3) \to SU(3)_c$$

Di Luzio et al. 2017
Isidori et al. 2017

only the 3rd generation is charged under SU(4)

- **Composite vectors:** resonances of a strongly interacting sector
  with global $SU(4) \times SU(2) \times SU(2)$

Barbieri, Tesi 2017

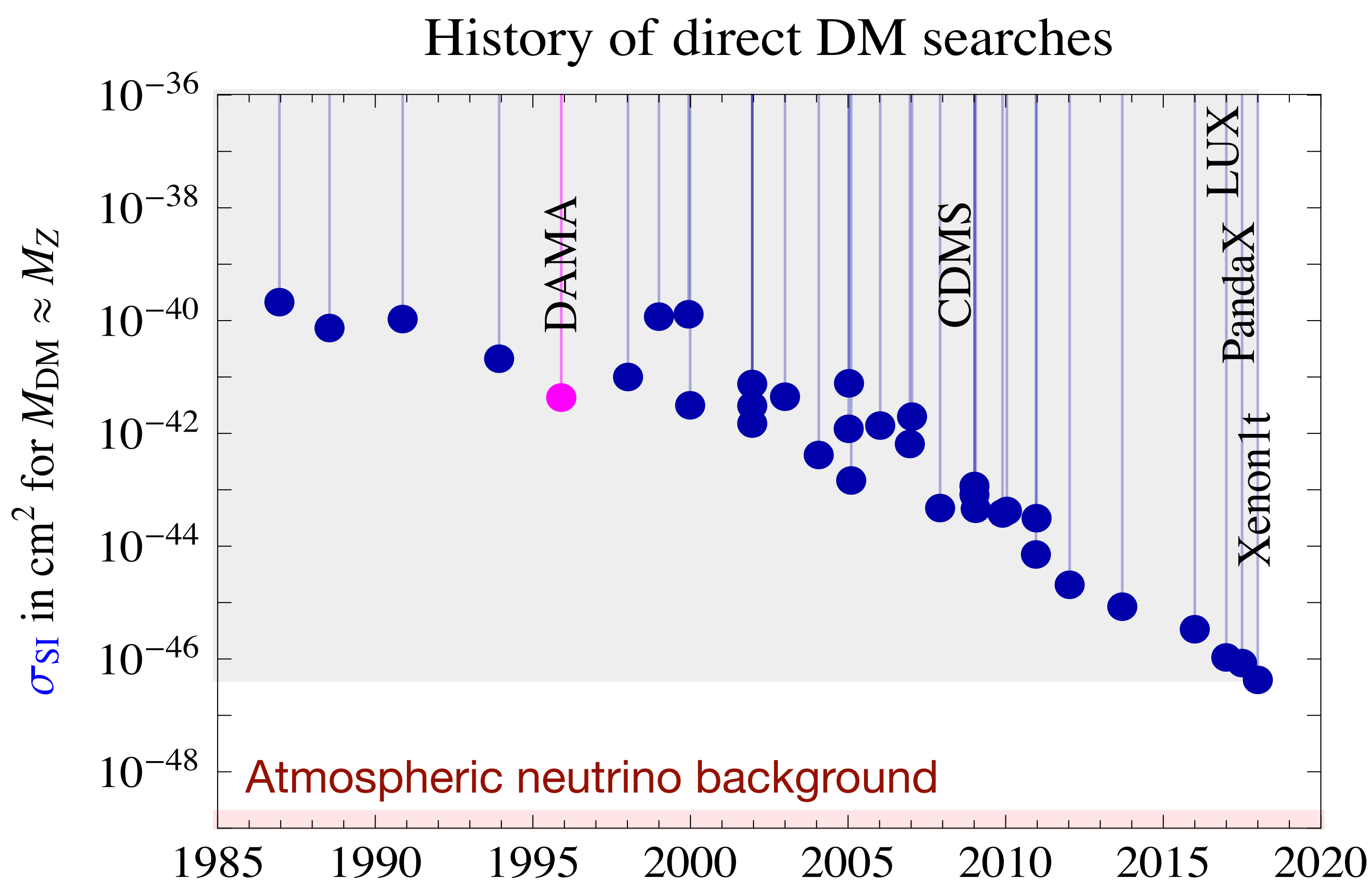
the couplings to fermions can be different (e.g. partial compositeness)

In all cases, additional heavy vector resonances (color octet and Z') are present

Searches at LHC!

$$\begin{pmatrix} (G^a_\mu)^\alpha_\beta & U^\alpha_\mu \\ (U^\alpha_\mu)^\dagger & Z'_\mu \end{pmatrix}$$

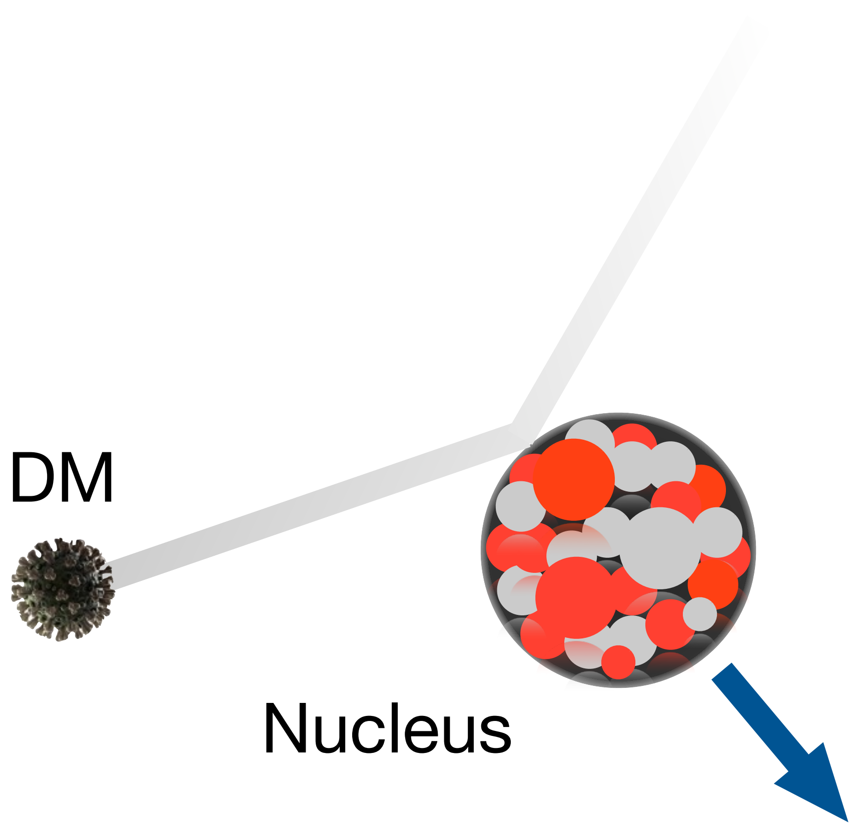
Dark Matter direct detection



- DM scatterings are very rare events
- Not easy to fully understand backgrounds at low recoil energy

➡ most experiments aim at reducing backgrounds as much as possible

No evidence for DM found until now



Rate for contact interactions:

DM velocity distribution

$$\frac{dR}{dE_{\rm rec}} = ({\rm mass}) \times \frac{\sigma_0 F(q)^2}{2\mu^2 m_{\rm DM}} \rho_{\rm DM} \int_{v_{\rm min}}^{v_{\rm esc}} d^3v \frac{f(\mathbf{v},t)}{v}$$

$$v_{\rm min} = \sqrt{M_{\rm nucl} E_{\rm rec}/2\mu^2}$$

for elastic scattering