Vector-like quarks for $t \to cZ$, B physics and M_W with automated 1-loop matching

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(based on 2204.05962 with Crivellin, Kitahara, Mescia)

Motivations for vector-like fermions

- Appear in many BSM theories – GUTs, extra dimensions, composite Higgs
- Can explain $(g-2)_\mu$, $b \to s\ell\ell$, CAA
- Not currently ruled out by experiment (unlike heavy chiral fermions)

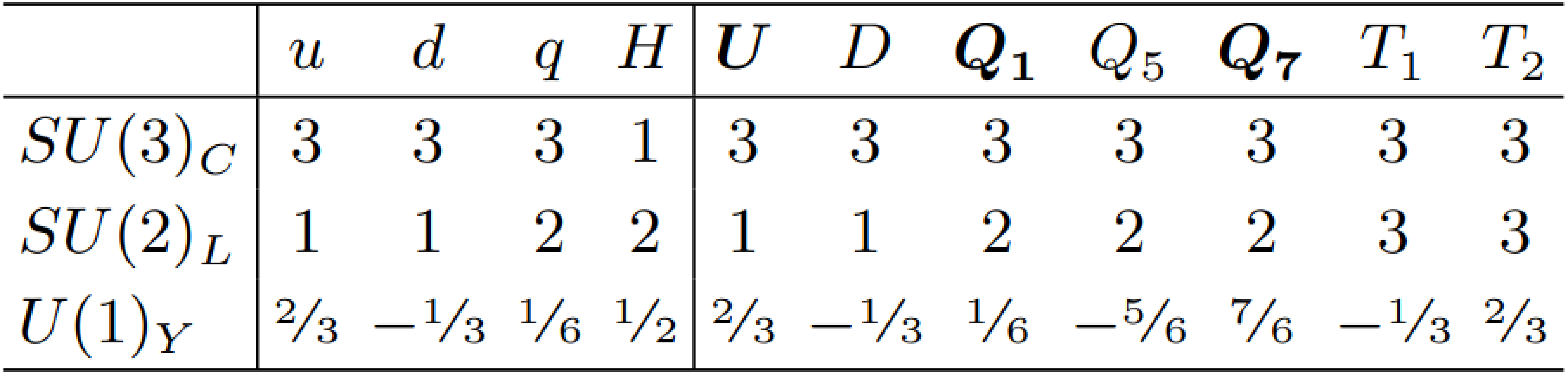
Vector-like fermions (VLFs)

- Left and right components have same gauge charges
- Allows to directly write a mass term in the Lagrangian
    - Not limited to electroweak scale

VLFs

- But after EW symmetry breaking, can mix with the SM fermions
  - So all VLFs cause shifts in many processes, already tree level!

Vector-like quarks (VLQs)



	u	d	q	H	$\boldsymbol{U}$	D	$\boldsymbol{Q_1}$	Q_5	$\boldsymbol{Q_7}$	T_1	T_2
$SU(3)_C$	3	3	3	1	3	3	3	3	3	3	3
$SU(2)_L$	1	1	2	2	1	1	2	2	2	3	3
$U(1)_Y$	$2/3$	$-1/3$	$1/6$	$1/2$	$2/3$	$-1/3$	$1/6$	$-5/6$	$7/6$	$-1/3$	$2/3$

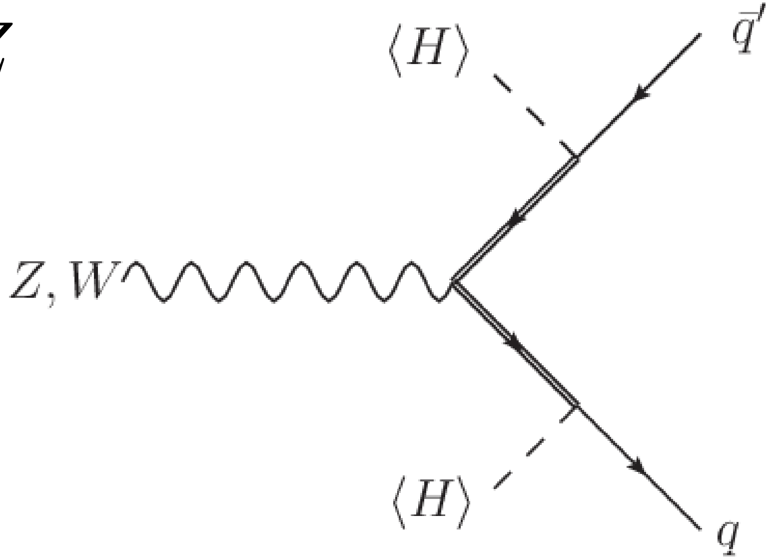
- Lots of different representations, so can mix (and therefore affect) lots of quark processes

Vector-like quarks (VLQs)

- Lots of different representations, so can mix (and therefore affect) lots of quark processes
  - Mix with 2nd/3rd gen LH down-type => $b \to s\ell\ell$ (e.g. `1403.1269`)
  - Mix with 1st/2nd gen up or down => CAA (e.g. `1906.02714`)

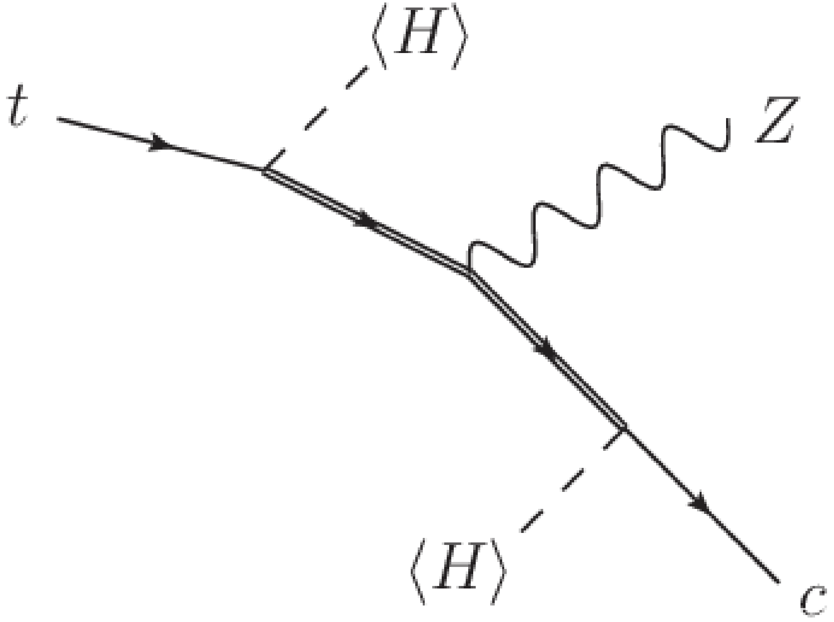
VLQs at tree level

- Affect Z and W decays => lots of effects
- One interesting case: $t \to cZ$



VLQs for $t \to cZ$

- Tiny in SM
    - $\mathcal{B} \sim 10^{-14}$
- BSM from VLQs
    - $\mathcal{B} \sim \xi^4 v^4 / M^4$
- Exp limit ~ 10^{-4}



ATLAS-CONF-2021-049

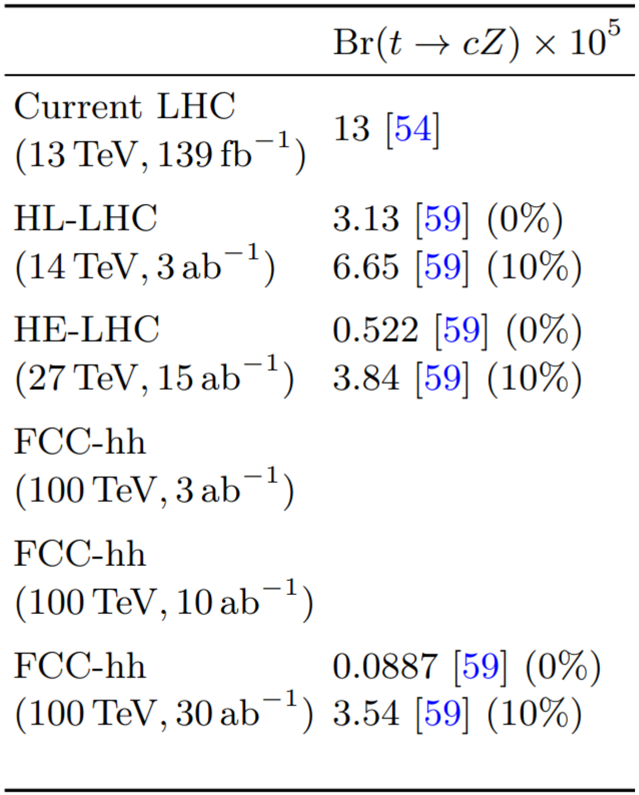
VLQs for t->cZ

- BSM from VLQs
  - $\mathcal{B} \sim \xi^4 v^4 / M^4$
- Exp limit $\sim 10^{-4}$ now

  ATLAS-CONF-2021-049
- Could be 10^{-5} from HL-LHC

  2010.05148
- 10^{-6} from FCC-hh

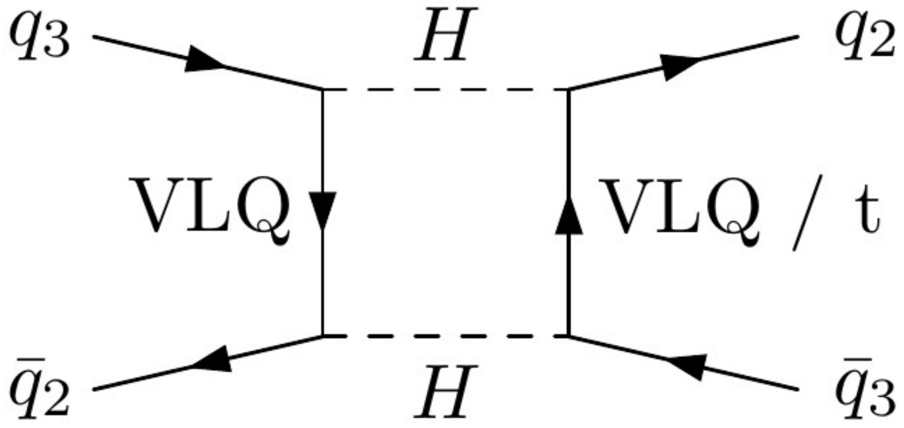
  2010.05148



	$\mathrm{Br}(t \to cZ) \times 10^5$
Current LHC $(13\,\mathrm{TeV}, 139\,\mathrm{fb}^{-1})$	13 [54]
HL-LHC $(14\,\mathrm{TeV}, 3\,\mathrm{ab}^{-1})$	3.13 [59] (0%) 6.65 [59] (10%)
HE-LHC $(27\,\mathrm{TeV}, 15\,\mathrm{ab}^{-1})$	0.522 [59] (0%) 3.84 [59] (10%)
FCC-hh $(100\,\mathrm{TeV}, 3\,\mathrm{ab}^{-1})$	
FCC-hh $(100\,\mathrm{TeV}, 10\,\mathrm{ab}^{-1})$	
FCC-hh $(100\,\mathrm{TeV}, 30\,\mathrm{ab}^{-1})$	0.0887 [59] (0%) 3.54 [59] (10%)

VLQs at 1-loop

- B_s mixing (or meson mixing in general)
- Radiative decays
- W mass!



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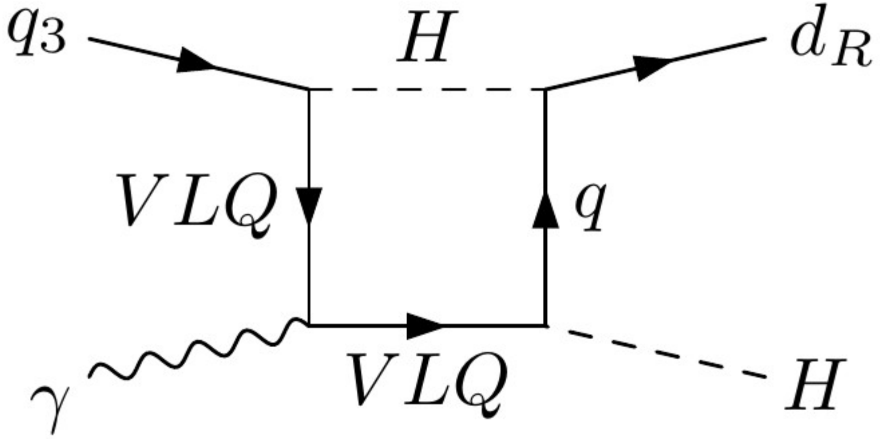

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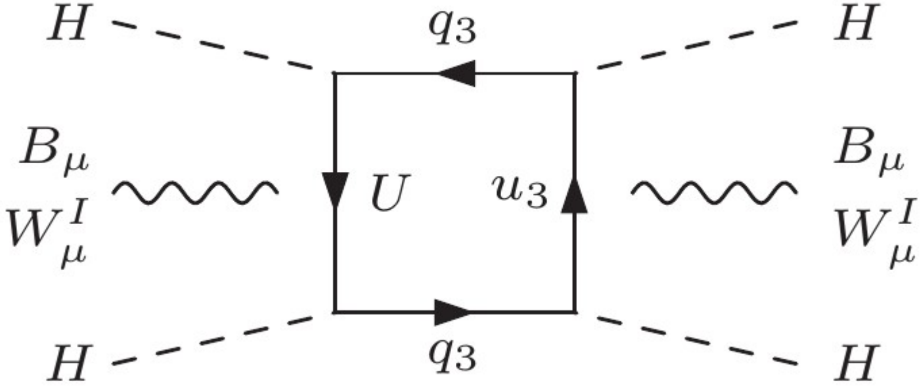
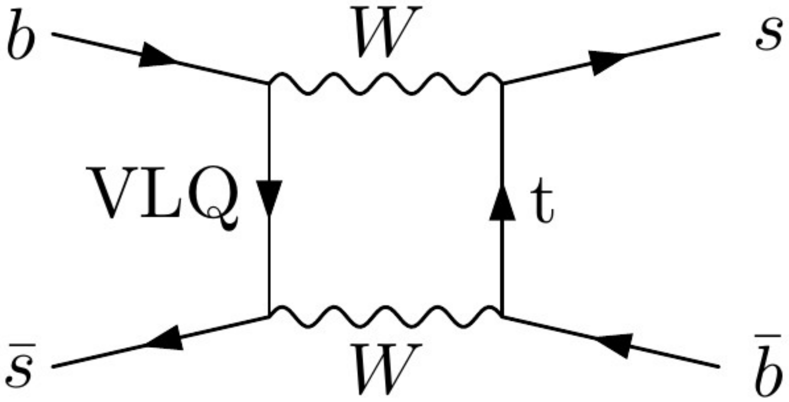


Calculating 1-loop effects

- Fixed order way
  - Directly calculated every observable
  - Large logs common e.g. B mixing: $\log(M/m_t)$



Calculating 1-loop effects

- EFT way
  - VLQs have mass far above SM scale
    - Exp limit is 1.3 TeV for 3rd gen quark couplings `1808.02343`
    - For 1st or 2nd gen, limit is similar `2006.07172`
  - So integrate them out and use the SMEFT

SMEFT

- Most general EFT which has the SM as the low energy limit
  - Second half is the caveat
- “Factorises” calculations
  - Match UV to SMEFT → RG in SMEFT (→ match SMEFT to LEFT → RG in LEFT) → observables in terms of WCs

SMEFT

- “Factorises” calculations
  - Match UV to SMEFT → RG in SMEFT (→ match SMEFT to LEFT → RG in LEFT) → observables in terms of WCs
- Each step is independent

SMEFT

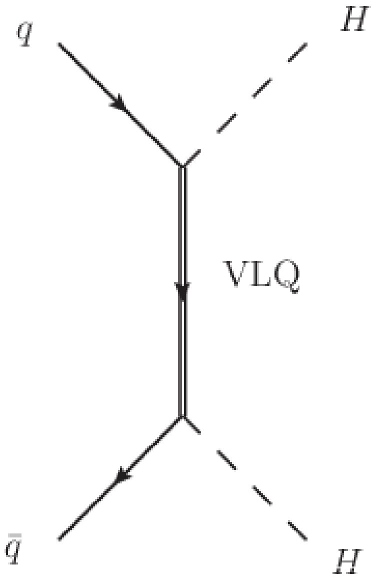
- Match UV to SMEFT
  - Model dependent
- RG in SMEFT
  - Alonso, Jenkins, Manohar, Trott
- Match SMEFT to LEFT
  - Jenkins, Manohar, Stoffer & Dekens, Stoffer
- RG in LEFT
  - Jenkins, Manohar, Stoffer
  - Plus higher orders in QCD
- Observables in terms of WCs
  - Everyone

SMEFT

- Match UV to SMEFT
  - Until recently, by hand
- RG in SMEFT:
  - DsixTools, wilson
- Match SMEFT to LEFT
  - DsixTools, wilson
- RG in LEFT
  - DsixTools, wilson
- Observables in terms of WCs
  - flavio, EOS

Matching to the SMEFT

- Tree level easy
  - C_{Hq}, C_{uH}
- 1 loop harder
  - See hep-ph/9310302, 2003.12525, 2003.05936, 2107.12133, …



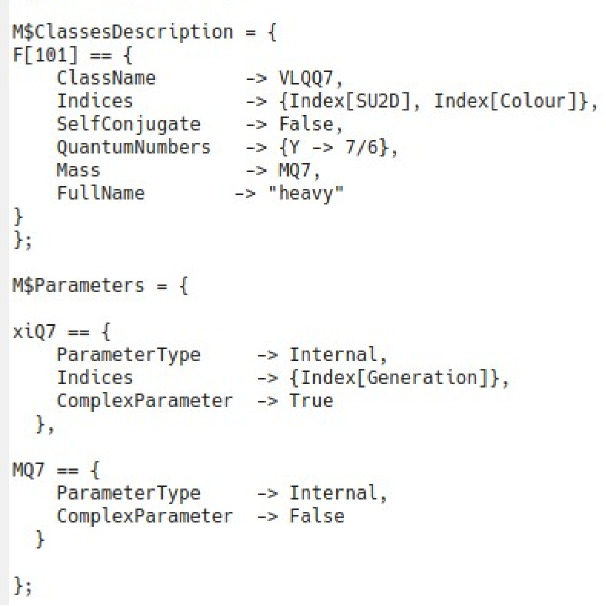
VLQs @ 1-loop

- We spent about 3 months trying to calculate all the relevant coefficients
  - (i.e. all the one we thought were relevant!)
- Lots learnt along the way

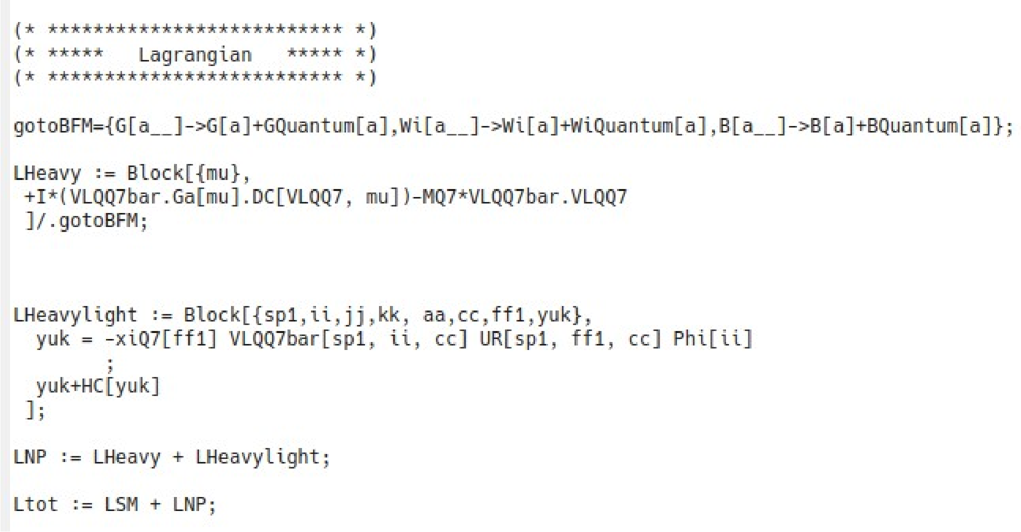
MatchMakerEFT

- Dec 2021 – paper on arXiv 2112.10787
- UV theory specified in terms of FeynRules .fr file
- Matching then proceeds totally automatically

VLQs in MatchMakerEFT



```
M$ClassesDescription = {
F[101] == {
    ClassName        -> VLQQ7,
    Indices          -> {Index[SU2D], Index[Colour]},
    SelfConjugate    -> False,
    QuantumNumbers   -> {Y -> 7/6},
    Mass             -> MQ7,
    FullName        -> "heavy"
}
};

M$Parameters = {

xiQ7 == {
    ParameterType     -> Internal,
    Indices           -> {Index[Generation]},
    ComplexParameter  -> True
  },

MQ7 == {
    ParameterType     -> Internal,
    ComplexParameter  -> False
  }

};
```

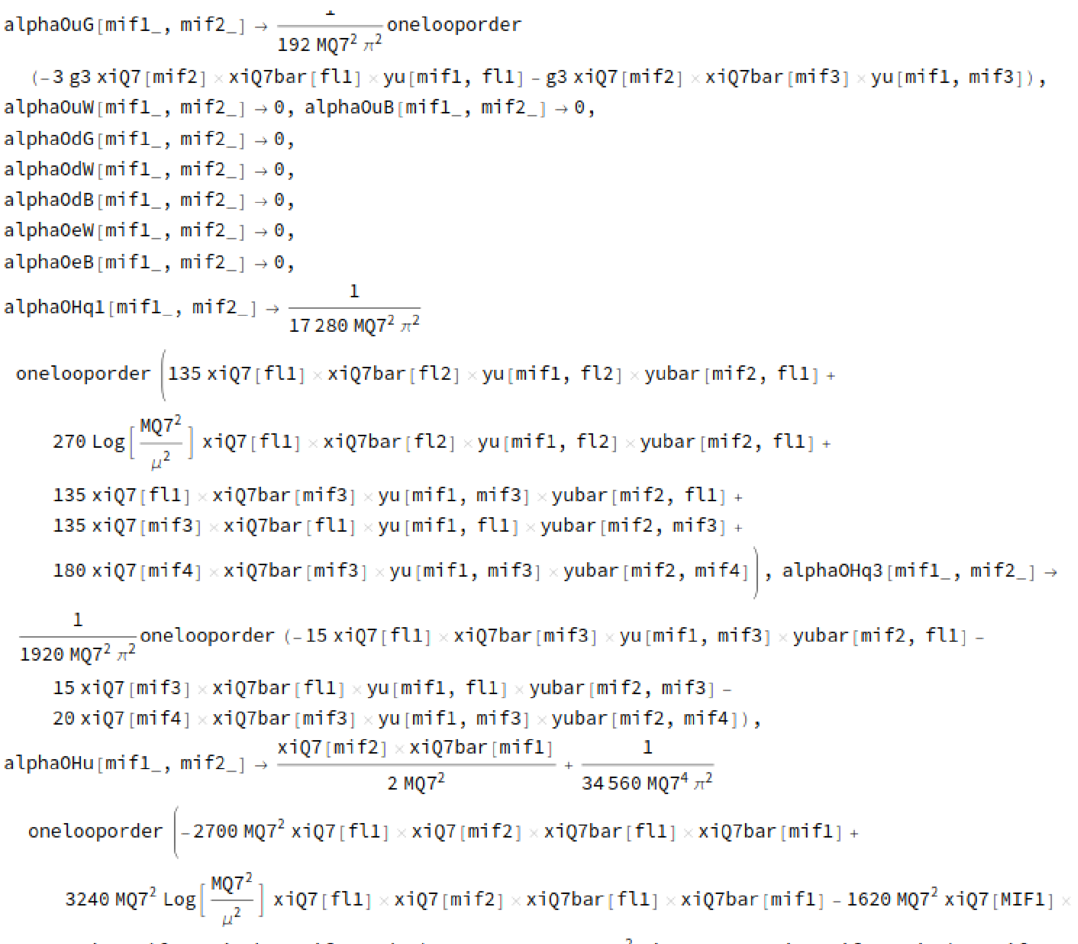


```
(* ************************** *)
(* *****   Lagrangian   ***** *)
(* ************************** *)

gotoBFM={G[a__]->G[a]+GQuantum[a],Wi[a__]->Wi[a]+WiQuantum[a],B[a__]->B[a]+BQuantum[a]};

LHeavy := Block[{mu},
 +I*(VLQQ7bar.Ga[mu].DC[VLQQ7, mu])-MQ7*VLQQ7bar.VLQQ7
 ]/.gotoBFM;



LHeavylight := Block[{sp1,ii,jj,kk, aa,cc,ff1,yuk},
  yuk = -xiQ7[ff1] VLQQ7bar[sp1, ii, cc] UR[sp1, ff1, cc] Phi[ii]
         ;
  yuk+HC[yuk]
 ];

LNP := LHeavy + LHeavylight;

Ltot := LSM + LNP;
```

VLQs in MatchMakerEFT

- Quick, no supercomputer needed!
- All algebraic

VLQs in MatchMakerEFT



$$\texttt{alphaOuG[mif1\_, mif2\_]} \rightarrow \frac{1}{192\,\texttt{MQ7}^2\,\pi^2}\texttt{onelooporder}$$

$$(-3\,\texttt{g3}\,\texttt{xiQ7[mif2]} \times \texttt{xiQ7bar[fl1]} \times \texttt{yu[mif1, fl1]} - \texttt{g3}\,\texttt{xiQ7[mif2]} \times \texttt{xiQ7bar[mif3]} \times \texttt{yu[mif1, mif3]}),$$

$$\texttt{alphaOuW[mif1\_, mif2\_]} \rightarrow 0,\ \texttt{alphaOuB[mif1\_, mif2\_]} \rightarrow 0,$$

$$\texttt{alphaOdG[mif1\_, mif2\_]} \rightarrow 0,$$

$$\texttt{alphaOdW[mif1\_, mif2\_]} \rightarrow 0,$$

$$\texttt{alphaOdB[mif1\_, mif2\_]} \rightarrow 0,$$

$$\texttt{alphaOeW[mif1\_, mif2\_]} \rightarrow 0,$$

$$\texttt{alphaOeB[mif1\_, mif2\_]} \rightarrow 0,$$

$$\texttt{alphaOHq1[mif1\_, mif2\_]} \rightarrow \frac{1}{17\,280\,\texttt{MQ7}^2\,\pi^2}$$

$$\texttt{onelooporder}\,\Big(135\,\texttt{xiQ7[fl1]} \times \texttt{xiQ7bar[fl2]} \times \texttt{yu[mif1, fl2]} \times \texttt{yubar[mif2, fl1]} +$$

$$270\,\texttt{Log}\left[\frac{\texttt{MQ7}^2}{\mu^2}\right]\texttt{xiQ7[fl1]} \times \texttt{xiQ7bar[fl2]} \times \texttt{yu[mif1, fl2]} \times \texttt{yubar[mif2, fl1]} +$$

$$135\,\texttt{xiQ7[fl1]} \times \texttt{xiQ7bar[mif3]} \times \texttt{yu[mif1, mif3]} \times \texttt{yubar[mif2, fl1]} +$$

$$135\,\texttt{xiQ7[mif3]} \times \texttt{xiQ7bar[fl1]} \times \texttt{yu[mif1, fl1]} \times \texttt{yubar[mif2, mif3]} +$$

$$180\,\texttt{xiQ7[mif4]} \times \texttt{xiQ7bar[mif3]} \times \texttt{yu[mif1, mif3]} \times \texttt{yubar[mif2, mif4]}\Big),\ \texttt{alphaOHq3[mif1\_, mif2\_]} \rightarrow$$

$$\frac{1}{1920\,\texttt{MQ7}^2\,\pi^2}\texttt{onelooporder}\,(-15\,\texttt{xiQ7[fl1]} \times \texttt{xiQ7bar[mif3]} \times \texttt{yu[mif1, mif3]} \times \texttt{yubar[mif2, fl1]} -$$

$$15\,\texttt{xiQ7[mif3]} \times \texttt{xiQ7bar[fl1]} \times \texttt{yu[mif1, fl1]} \times \texttt{yubar[mif2, mif3]} -$$

$$20\,\texttt{xiQ7[mif4]} \times \texttt{xiQ7bar[mif3]} \times \texttt{yu[mif1, mif3]} \times \texttt{yubar[mif2, mif4]}),$$

$$\texttt{alphaOHu[mif1\_, mif2\_]} \rightarrow \frac{\texttt{xiQ7[mif2]} \times \texttt{xiQ7bar[mif1]}}{2\,\texttt{MQ7}^2} + \frac{1}{34\,560\,\texttt{MQ7}^4\,\pi^2}$$

$$\texttt{onelooporder}\,\Big(-2700\,\texttt{MQ7}^2\,\texttt{xiQ7[fl1]} \times \texttt{xiQ7[mif2]} \times \texttt{xiQ7bar[fl1]} \times \texttt{xiQ7bar[mif1]} +$$

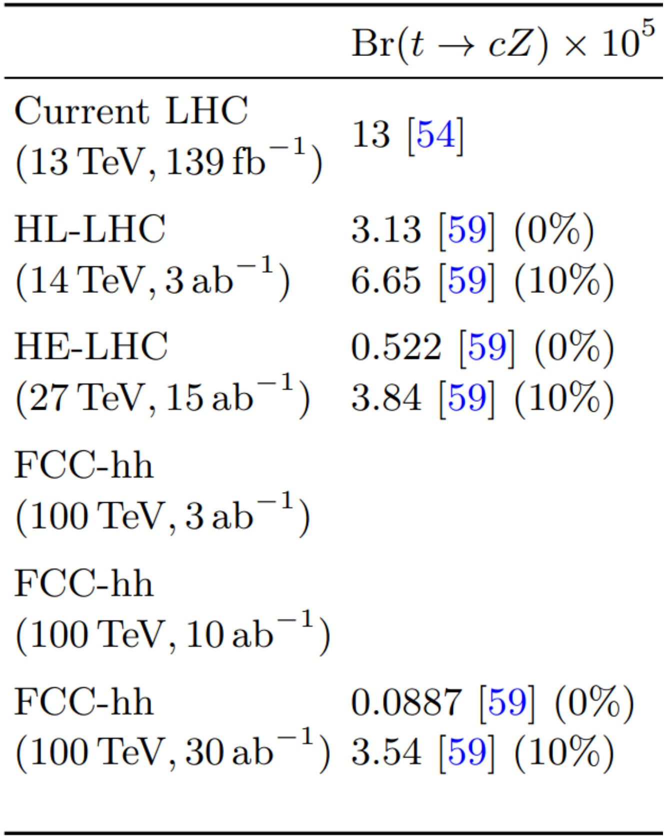
$$3240\,\texttt{MQ7}^2\,\texttt{Log}\left[\frac{\texttt{MQ7}^2}{\mu^2}\right]\texttt{xiQ7[fl1]} \times \texttt{xiQ7[mif2]} \times \texttt{xiQ7bar[fl1]} \times \texttt{xiQ7bar[mif1]} - 1620\,\texttt{MQ7}^2\,\texttt{xiQ7[MIF1]} \times$$

From UV to observables

- $t \to cZ$
- B mixing
- $b \to s\ell\ell$
- EWPO (including M_W)

$t \to cZ$

- As discussed earlier



	$\mathrm{Br}(t \to cZ) \times 10^5$
Current LHC $(13\,\mathrm{TeV}, 139\,\mathrm{fb}^{-1})$	13 [54]
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B_s mixing

- 1-loop effect
- Exp = $(17.741 \pm 0.020)\,\mathrm{ps}^{-1}$ HFLAV - PDG 2021
- SM = $(18.3^{+0.7}_{-1.2})\,\mathrm{ps}^{-1}$ 1909.11087

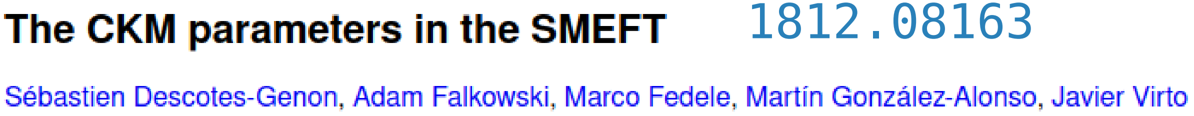
(

CKM treatment

- Theory prediction needs CKM elements
- CKM elements are determined from observables
- Observables might be affected by NP

CKM treatment

- (a) Solution



The CKM parameters in the SMEFT 1812.08163

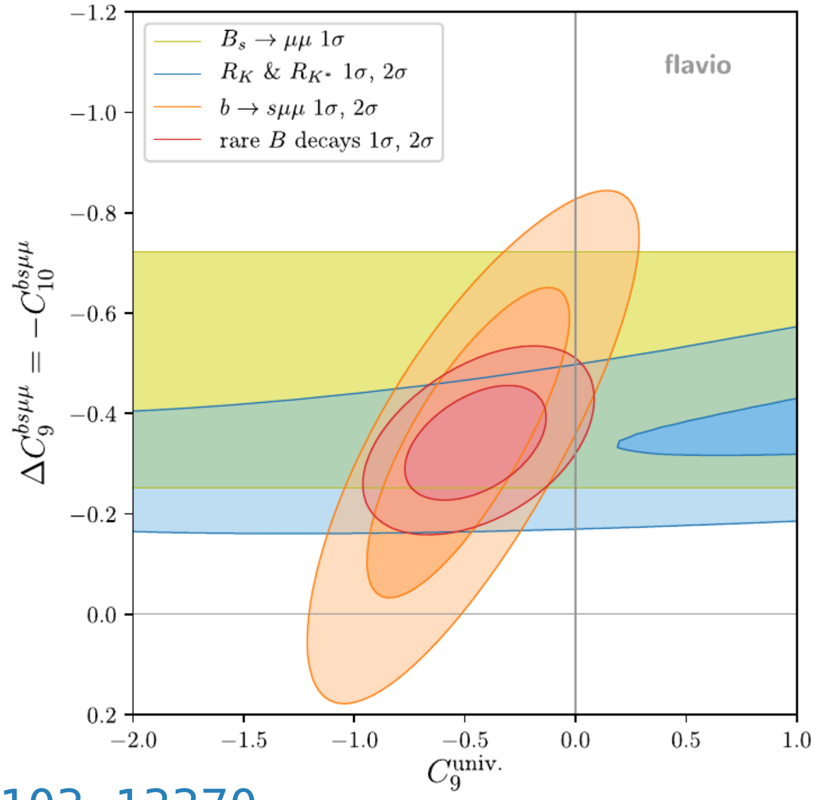
Sébastien Descotes-Genon, Adam Falkowski, Marco Fedele, Martín González-Alonso, Javier Virto

- Used by smelli with these 4 observables:
  - $\Delta M_d/\Delta M_s, B \to X_c e\nu\,, B \to \tau\nu\,, \dfrac{K \to \mu\nu}{\pi \to \mu\nu}$
- Thus these missing in fit

)

$b \to s\ell\ell$

- Data from $b \to s\ell\ell$ decays disagrees with SM
- Good fit can include universal effects in C_9 or C_{10}



2103.13370

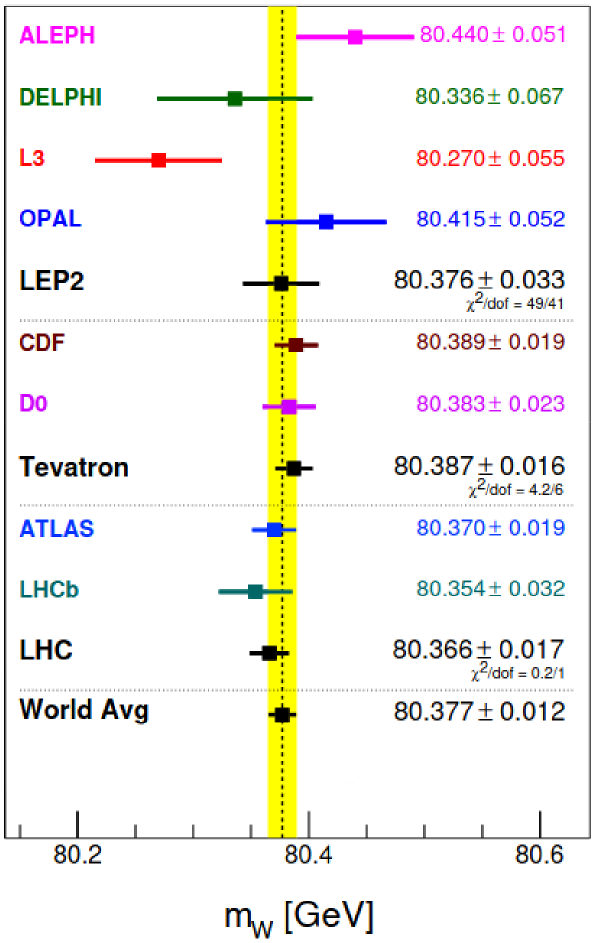
EWPO

- Z and W decays, mostly measured by LEP
- Note that smelli uses the $(\alpha_{\mathrm{EM}}, M_Z, G_F)$ SMEFT input scheme
- So M_Z is not an observable, but M_W is

M_W?

- SM
  - $(80.359 \pm 0.006)\ \mathrm{GeV}$
- PDG 2022
  - $(80.377 \pm 0.012)\ \mathrm{GeV}$

PDG 2022



M_W?

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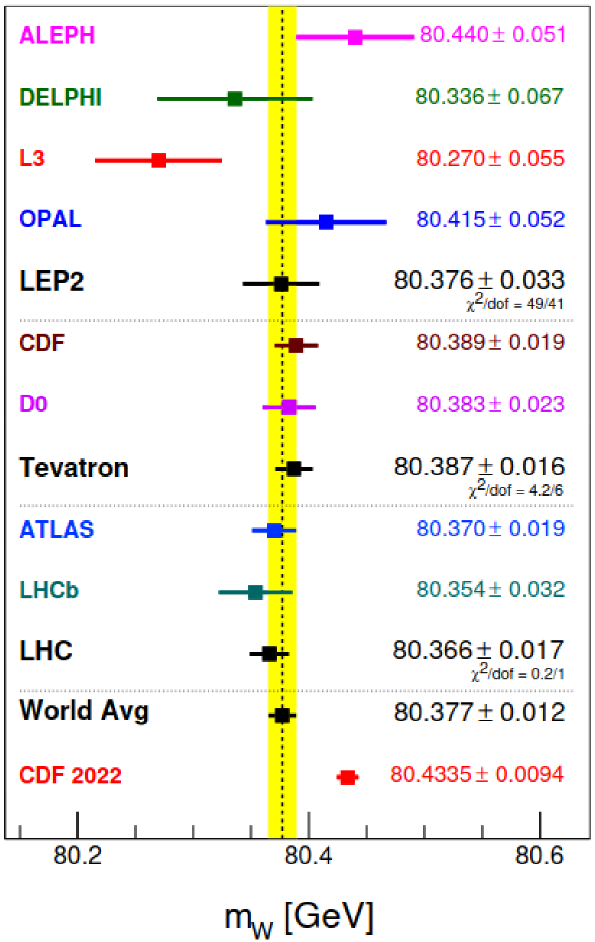
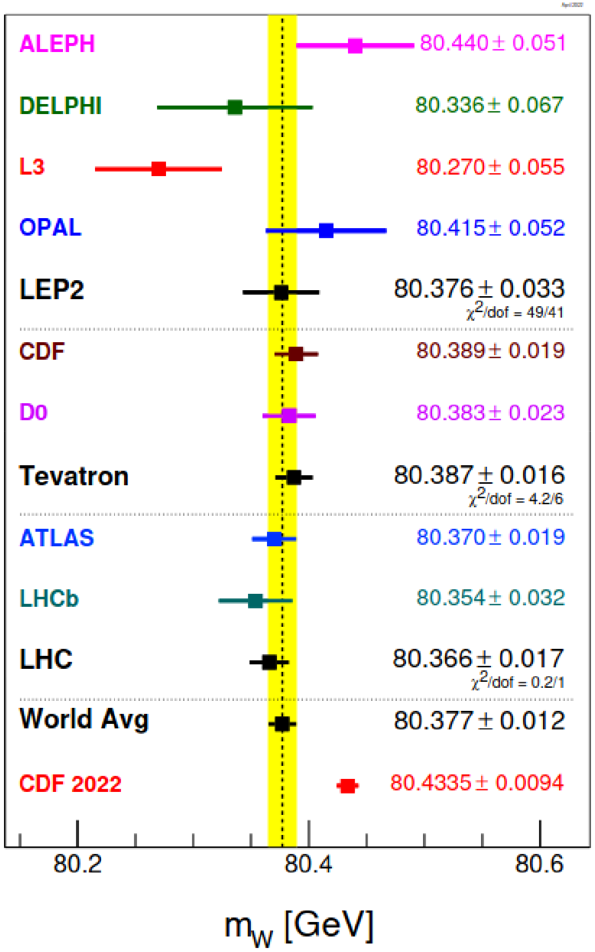
PDG 2022



M_W?

- SM
  - $(80.359 \pm 0.006)\ \mathrm{GeV}$
- PDG 2022
  - $(80.377 \pm 0.012)\ \mathrm{GeV}$
- Naive combination
  - $(80.413 \pm 0.008)\ \mathrm{GeV}$

PDG 2022

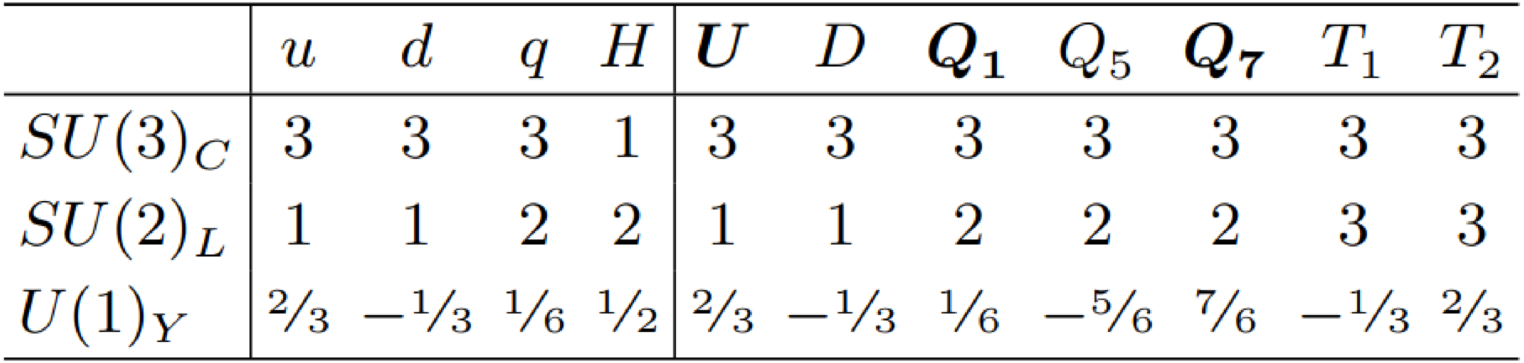


Final technicalities

- We work in the down-basis, where Y_d is diagonal, Y_u is not => $Y_u = V_{\mathrm{CKM}}^\dagger \cdot (0, 0, y_t)$
- So FCNCs in the up sector are generated by CKM rotation, but not in down sector

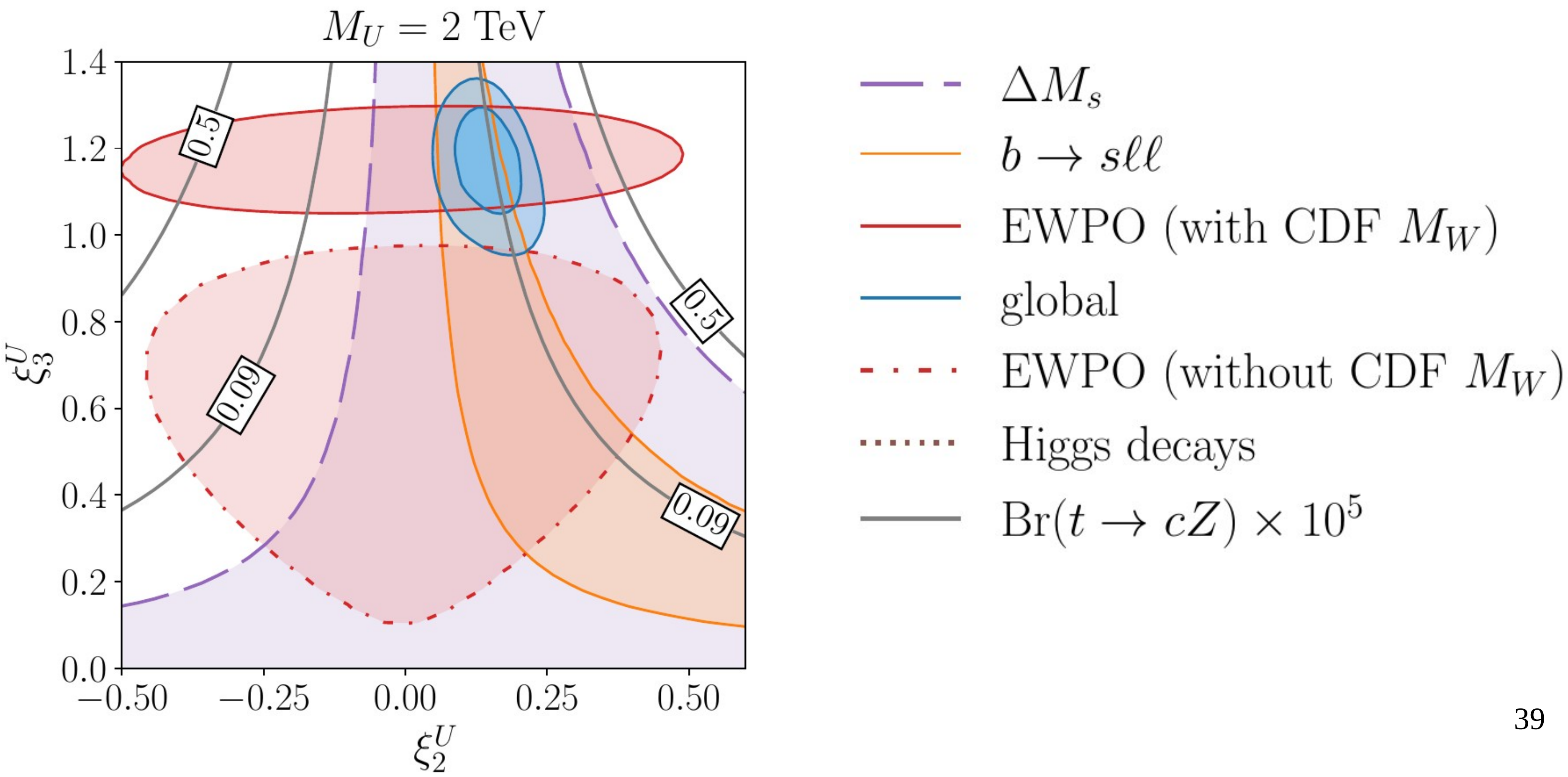
Results

- Analysis of VLQ quantum numbers tells us 3 options to modify up-type Z couplings at tree level but only down-type at 1-loop
  - i.e. to get large $t \to cZ$ but small $Z \to bb$, B_s mixing, …



	u	d	q	H	$\boldsymbol{U}$	D	$\boldsymbol{Q_1}$	Q_5	$\boldsymbol{Q_7}$	T_1	T_2
$SU(3)_C$	3	3	3	1	3	3	3	3	3	3	3
$SU(2)_L$	1	1	2	2	1	1	2	2	2	3	3
$U(1)_Y$	$2/3$	$-1/3$	$1/6$	$1/2$	$2/3$	$-1/3$	$1/6$	$-5/6$	$7/6$	$-1/3$	$2/3$

VLQ U


$M_U = 2$ TeV
ξ_3^U
ξ_2^U
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
−0.50
−0.25
0.00
0.25
0.50
0.5
0.09
0.5
0.09
ΔM_s
$b \to s\ell\ell$
EWPO (with CDF M_W)
global
EWPO (without CDF M_W)
Higgs decays
$\mathrm{Br}(t \to cZ) \times 10^5$

VLQ U B physics constraints

- Why aren't $b \to s\gamma$ or B_s mixing stronger?

VLQ U B physics constraints

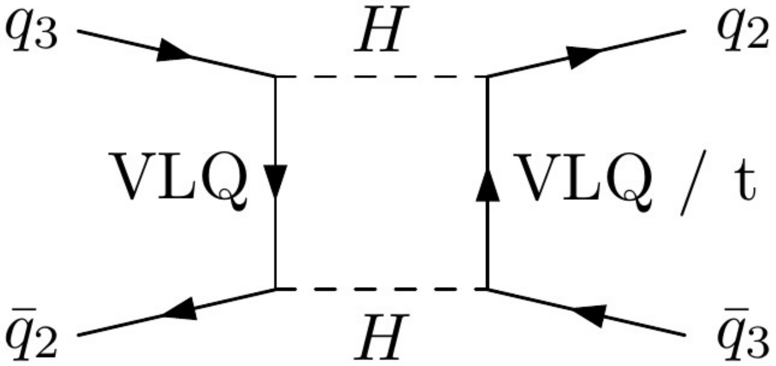
- $b \to s\gamma$ is due to cancellation in C_7 at EW scale
  - SMEFT $C_{dB,dW}$ vs quark-loop when integrating out the W
  - Both scale as ξ^2/M^2, so this is robust feature
  - Opposite sign, about 50% numerical size

VLQ U B physics constraints

- B_s mixing already cancels in SMEFT
- C_{qq} has two parts
  - ξ^4/M^2 from VLQ-VLQ box
  - $4\frac{\xi^2 y_t^2 V_{tb} V_{ts}}{M^2}\ln\frac{M^2}{m_t^2}$ from VLQ-top box
- Cancellation accidental due to mass and coupling size

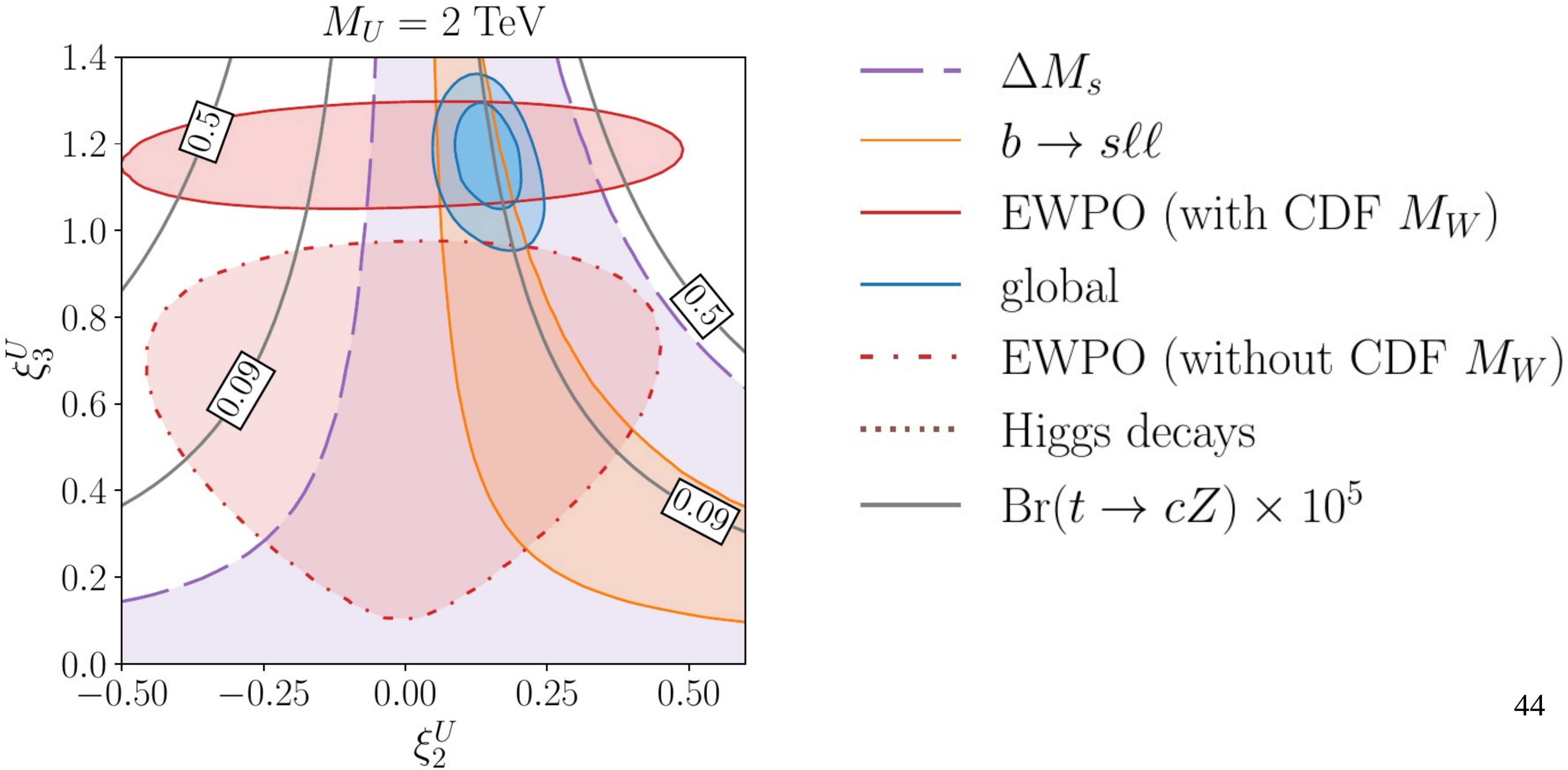
VLQ U B physics constraints

- B_s mixing already cancels in SMEFT
- C_{qq} has two parts
  - ξ^4/M^2 from VLQ–VLQ box
  - $4\frac{\xi^2 y_t^2 V_{tb} V_{ts}}{M^2} \ln\frac{M^2}{m_t^2}$ from VLQ

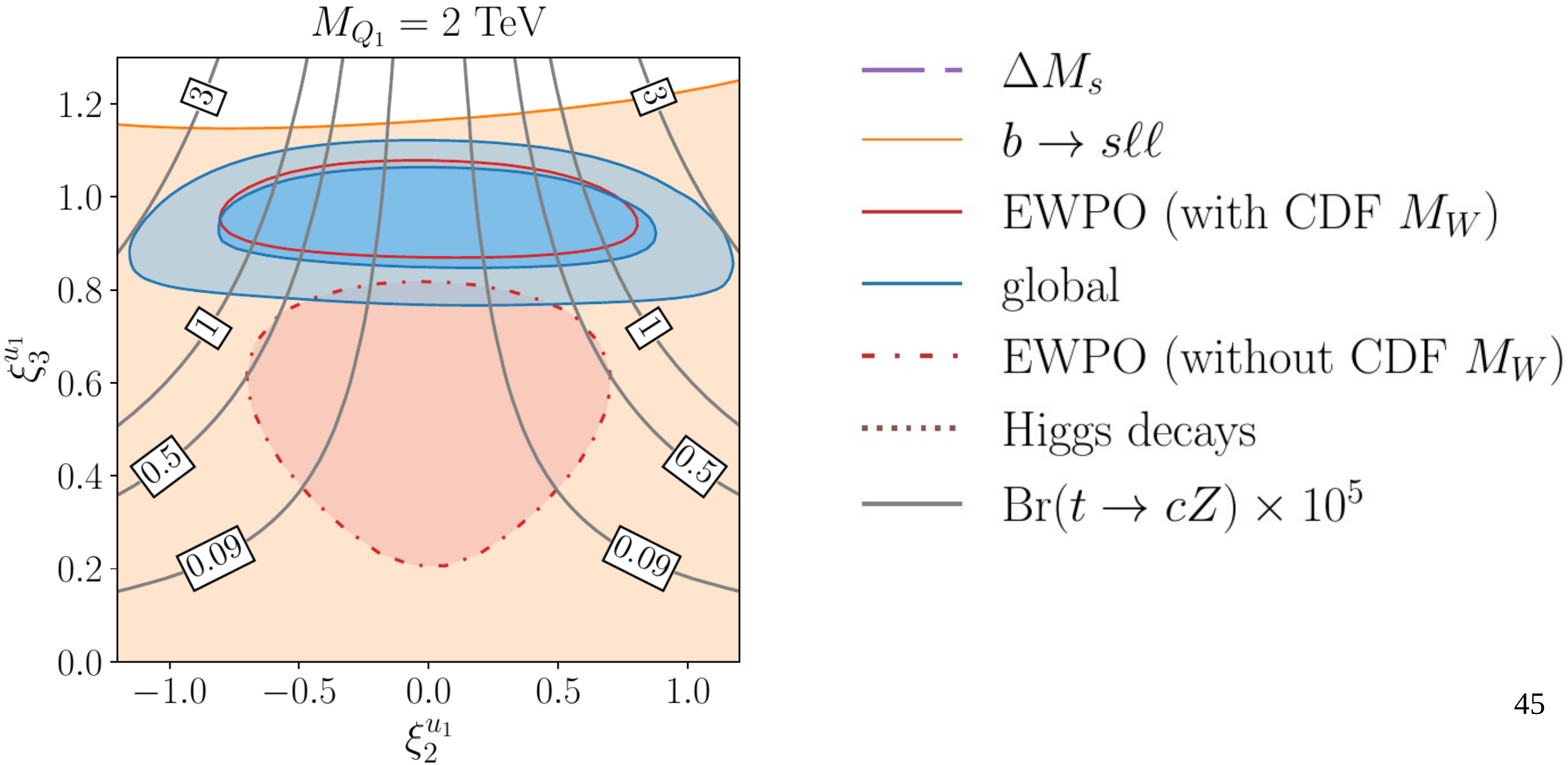


- Cancellation accidental due to mass and coupling size

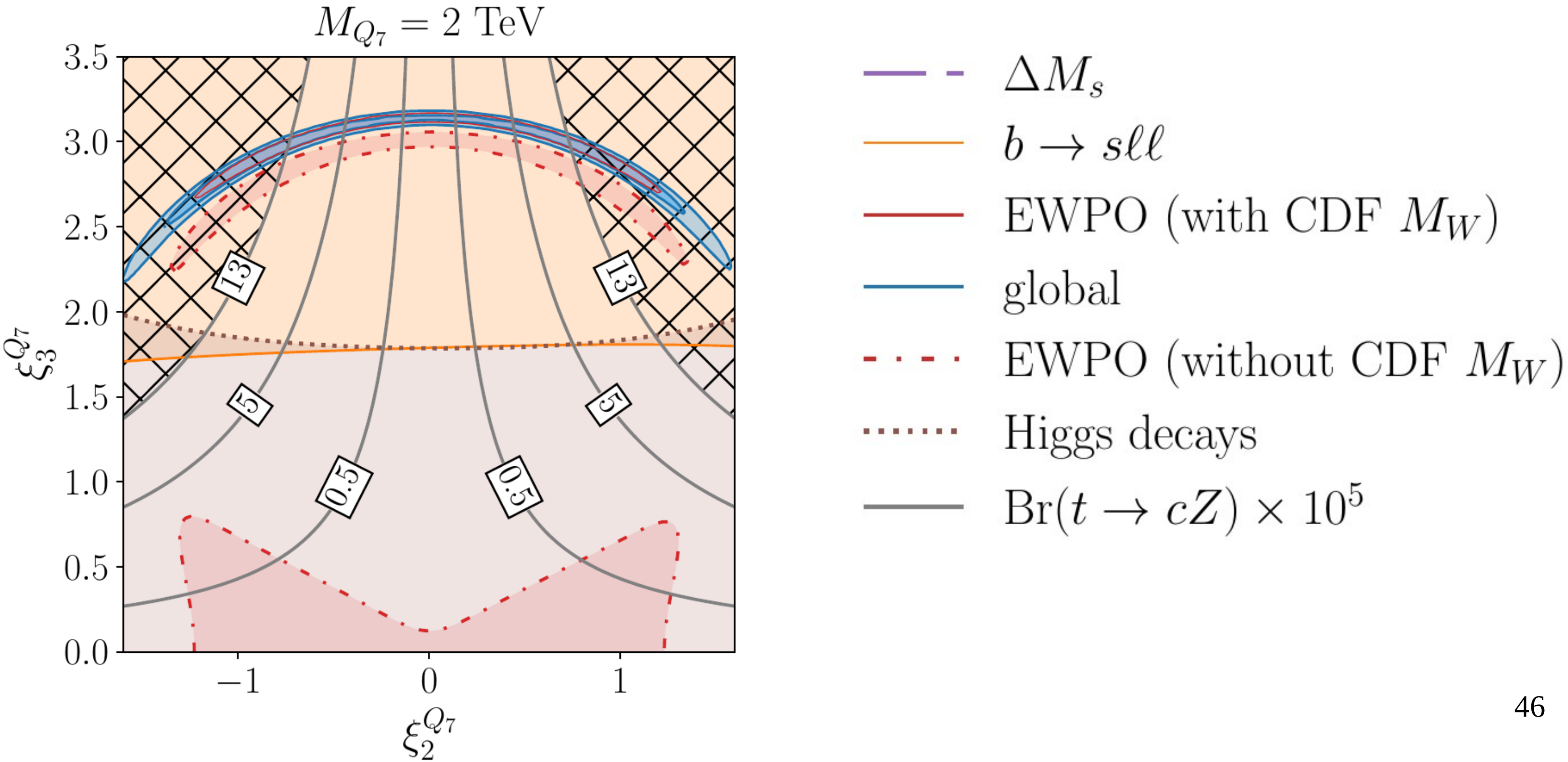
VLQ U


$M_U = 2$ TeV
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
ξ_3^U
−0.50
−0.25
0.00
0.25
0.50
ξ_2^U
0.5
0.09
0.5
0.09
ΔM_s
$b \to s\ell\ell$
EWPO (with CDF M_W)
global
EWPO (without CDF M_W)
Higgs decays
$\mathrm{Br}(t \to cZ) \times 10^5$

VLQ Q1


$M_{Q_1} = 2$ TeV
$\xi_3^{u_1}$
$\xi_2^{u_1}$
0.0
0.2
0.4
0.6
0.8
1.0
1.2
−1.0
−0.5
0.0
0.5
1.0
3
1
0.5
0.09
ΔM_s
$b \to s\ell\ell$
EWPO (with CDF M_W)
global
EWPO (without CDF M_W)
Higgs decays
$\mathrm{Br}(t \to cZ) \times 10^5$

VLQ Q7

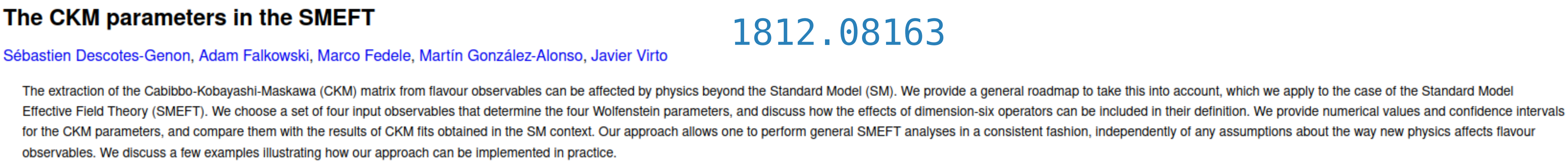

$M_{Q_7} = 2$ TeV
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
$\xi_3^{Q_7}$
−1
0
1
$\xi_2^{Q_7}$
13
13
5
5
0.5
0.5
ΔM_s
$b \to s\ell\ell$
EWPO (with CDF M_W)
global
EWPO (without CDF M_W)
Higgs decays
$\mathrm{Br}(t \to cZ) \times 10^5$

Conclusions

- VLQs are an interesting BSM model for $t \to cZ$
- Correlation with B physics and M_W studied within SMEFT
- Automated 1-loop matching makes analysis easier

Backup

CKM treatment



The CKM parameters in the SMEFT

Sébastien Descotes-Genon, Adam Falkowski, Marco Fedele, Martín González-Alonso, Javier Virto

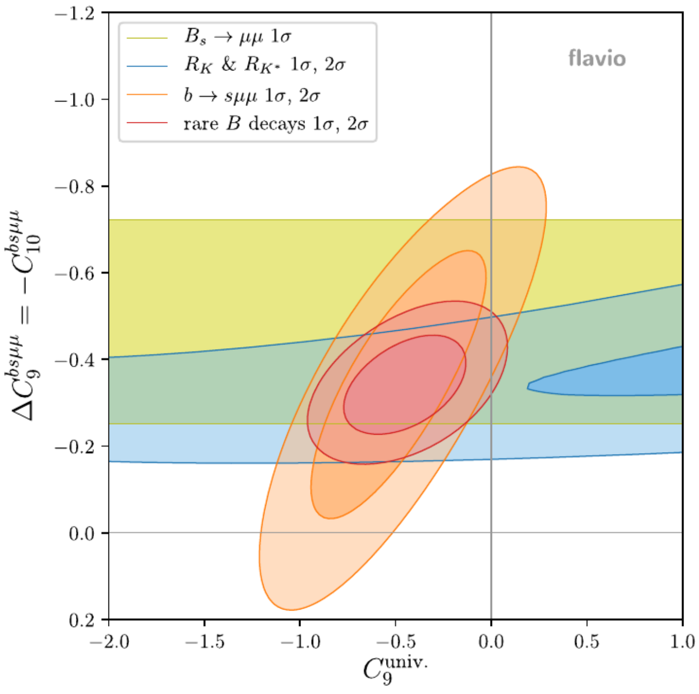
The extraction of the Cabibbo-Kobayashi-Maskawa (CKM) matrix from flavour observables can be affected by physics beyond the Standard Model (SM). We provide a general roadmap to take this into account, which we apply to the case of the Standard Model Effective Field Theory (SMEFT). We choose a set of four input observables that determine the four Wolfenstein parameters, and discuss how the effects of dimension-six operators can be included in their definition. We provide numerical values and confidence intervals for the CKM parameters, and compare them with the results of CKM fits obtained in the SM context. Our approach allows one to perform general SMEFT analyses in a consistent fashion, independently of any assumptions about the way new physics affects flavour observables. We discuss a few examples illustrating how our approach can be implemented in practice.

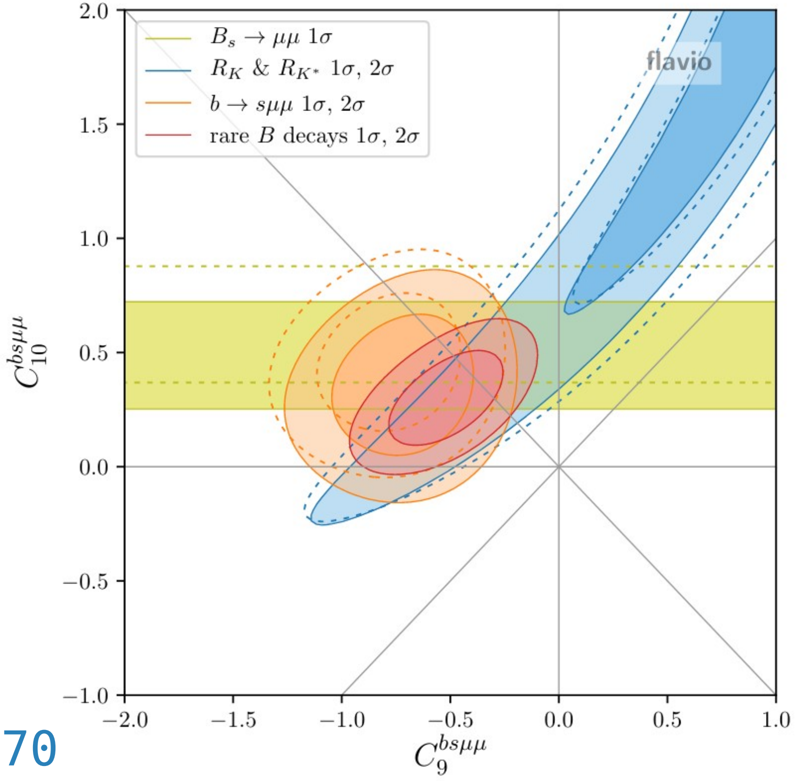
1812.08163

- smelli uses $\Delta M_d/\Delta M_s$, $B \to X_c e\nu$, $B \to \tau\nu$, $\dfrac{K \to \mu\nu}{\pi \to \mu\nu}$
- VLQs give shift in gamma of 5 deg, Vub and Vcb of ~1%

LFU in bsll

- U VLQ generates (approx) C9=-C10/4 structure





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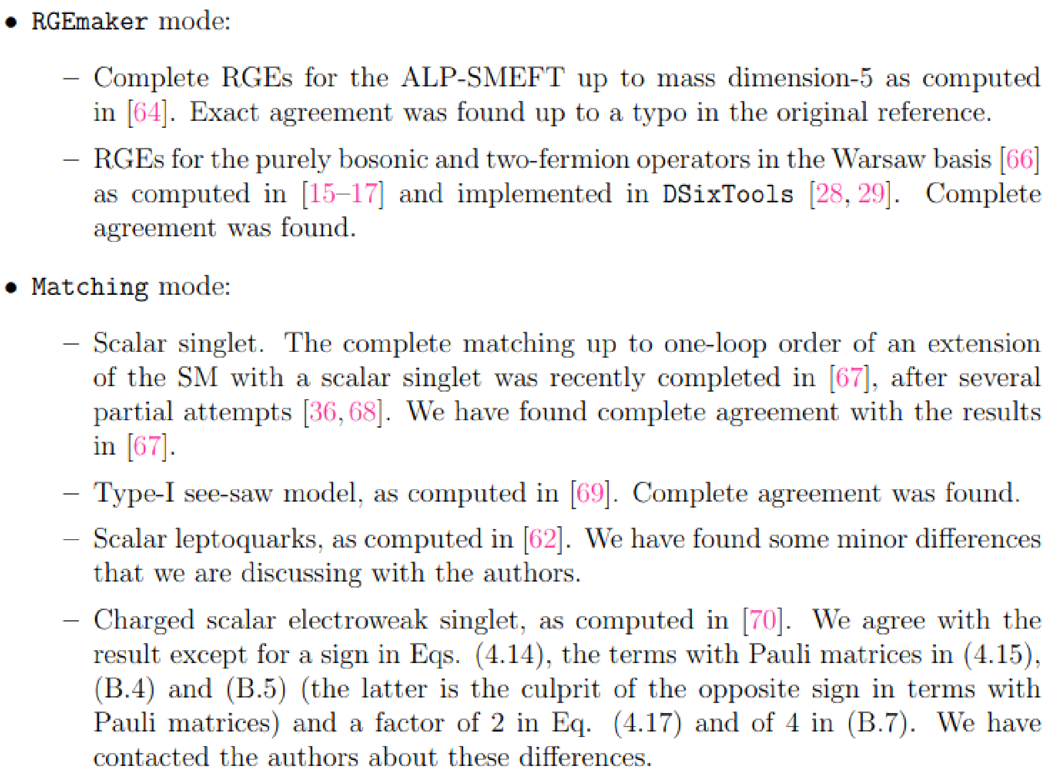
CAA

- Vud^2 + Vus^2 = 1

PDG Vud, Vus review

- PDG gives 2-3 sigma discrepancy

MatchMakerEFT



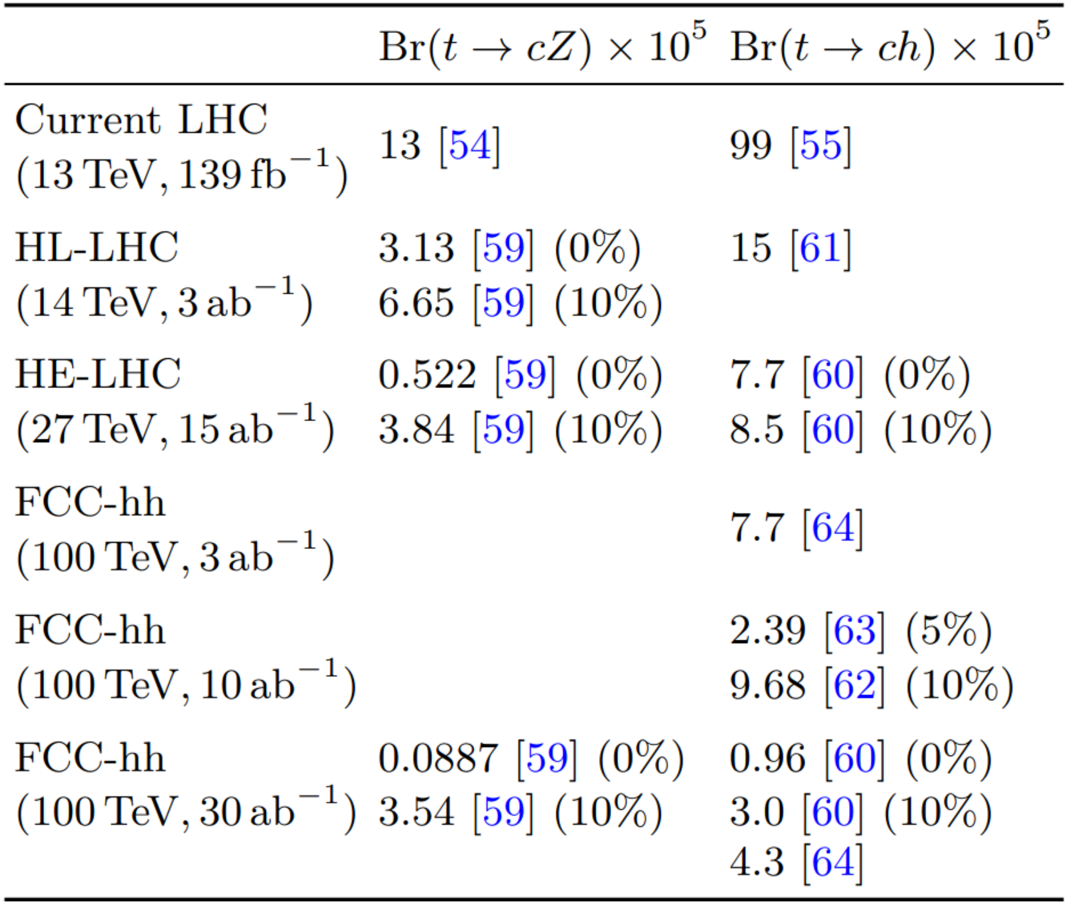
- `RGEmaker` mode:
  - Complete RGEs for the ALP-SMEFT up to mass dimension-5 as computed in [64]. Exact agreement was found up to a typo in the original reference.
  - RGEs for the purely bosonic and two-fermion operators in the Warsaw basis [66] as computed in [15–17] and implemented in `DSixTools` [28, 29]. Complete agreement was found.
- `Matching` mode:
  - Scalar singlet. The complete matching up to one-loop order of an extension of the SM with a scalar singlet was recently completed in [67], after several partial attempts [36, 68]. We have found complete agreement with the results in [67].
  - Type-I see-saw model, as computed in [69]. Complete agreement was found.
  - Scalar leptoquarks, as computed in [62]. We have found some minor differences that we are discussing with the authors.
  - Charged scalar electroweak singlet, as computed in [70]. We agree with the result except for a sign in Eqs. (4.14), the terms with Pauli matrices in (4.15), (B.4) and (B.5) (the latter is the culprit of the opposite sign in terms with Pauli matrices) and a factor of 2 in Eq. (4.17) and of 4 in (B.7). We have contacted the authors about these differences.

2112.10787

MatchMakerEFT

- Two step matching:
  1) Create model – quick, low cost
  2) Match model – slow, high cost

t→ch



	$\mathrm{Br}(t \to cZ) \times 10^5$	$\mathrm{Br}(t \to ch) \times 10^5$
Current LHC ($13\,\mathrm{TeV}, 139\,\mathrm{fb}^{-1}$)	13 [54]	99 [55]
HL-LHC ($14\,\mathrm{TeV}, 3\,\mathrm{ab}^{-1}$)	3.13 [59] (0%) 6.65 [59] (10%)	15 [61]
HE-LHC ($27\,\mathrm{TeV}, 15\,\mathrm{ab}^{-1}$)	0.522 [59] (0%) 3.84 [59] (10%)	7.7 [60] (0%) 8.5 [60] (10%)
FCC-hh ($100\,\mathrm{TeV}, 3\,\mathrm{ab}^{-1}$)		7.7 [64]
FCC-hh ($100\,\mathrm{TeV}, 10\,\mathrm{ab}^{-1}$)		2.39 [63] (5%) 9.68 [62] (10%)
FCC-hh ($100\,\mathrm{TeV}, 30\,\mathrm{ab}^{-1}$)	0.0887 [59] (0%) 3.54 [59] (10%)	0.96 [60] (0%) 3.0 [60] (10%) 4.3 [64]