[Theory] Extended Higgs sectors and high-energy flavour dynamics

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Non-minimal EWSB: singlets/doublets

Singlets/doublets

A doublet Higgs has 4 dof

Higgs = (vev + higgs particle + W/Z dofs)

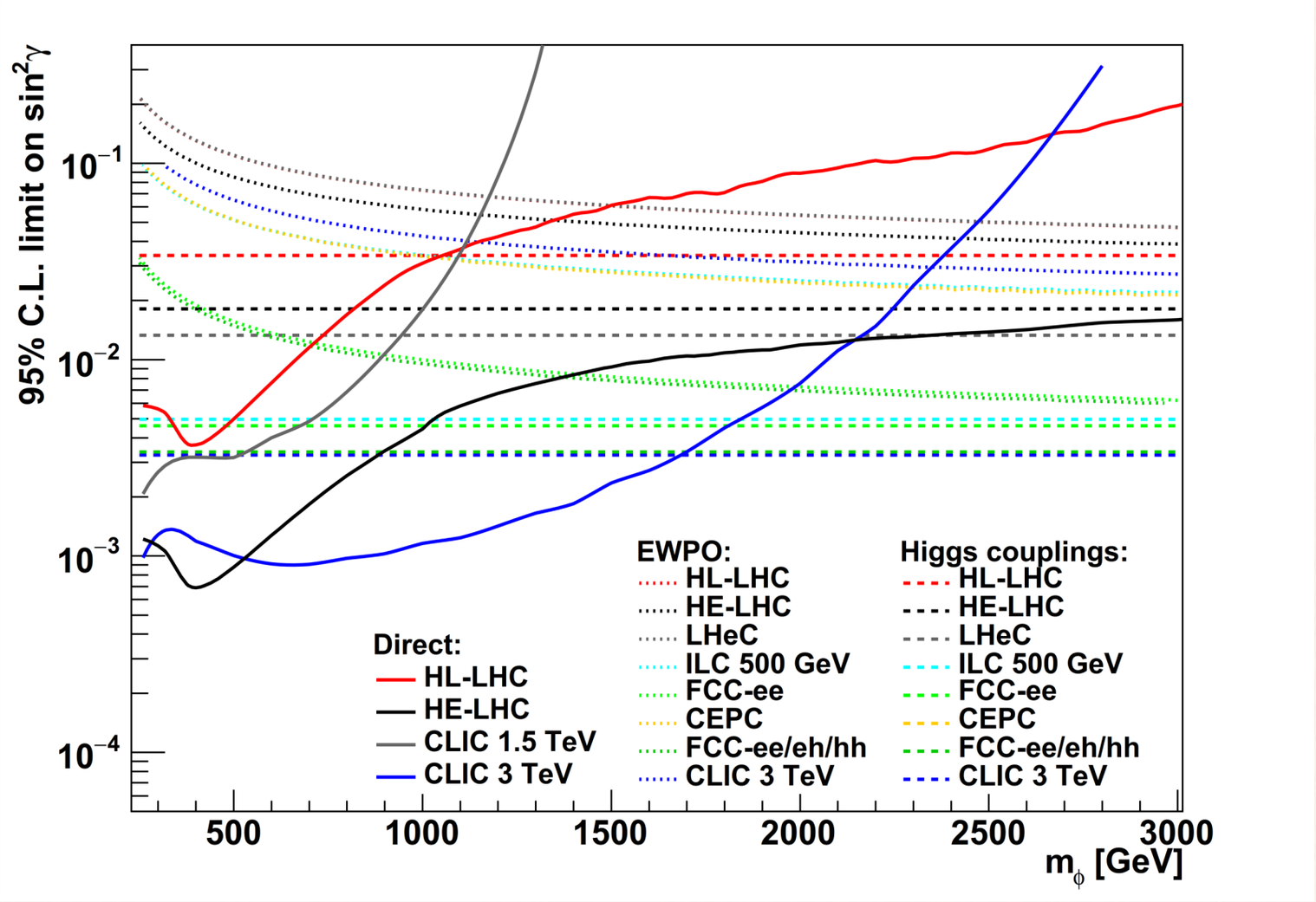
and that's all we need in the SM

Why more? Occam's razor

But in BSM models minimal EWSB is not generic
More structure/symmetries tend to need a more complex scalar sector

SUSY at least two doublets
Composite Higgs no reason for global breaking to be minimal
Scalars will mix & modify Higgs

Interplay Higgs/EWPO/direct



$$\Delta S = \frac{1}{6\pi}\,\bar{c}_H(m_\phi)\,\log\left(\frac{m_\phi}{m_Z}\right)$$

EWPO

$\propto \sin^2\gamma$ mixing

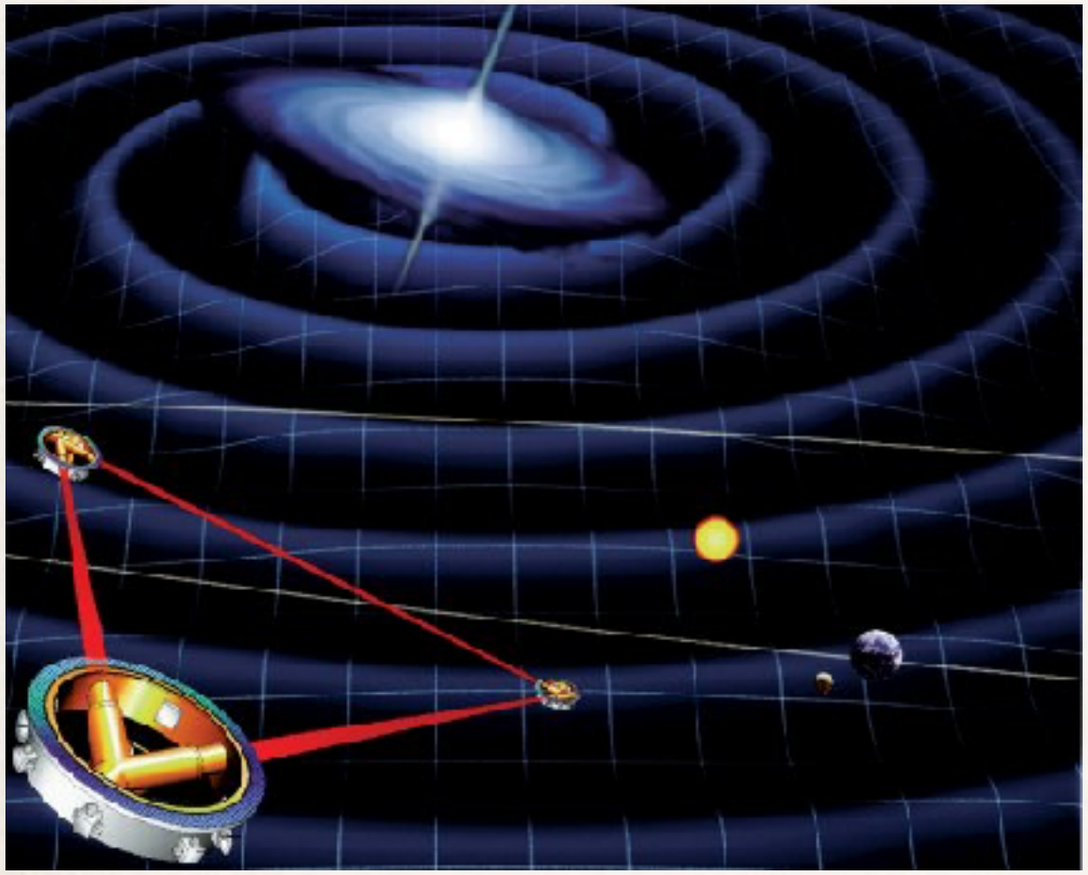
mass

Higgs

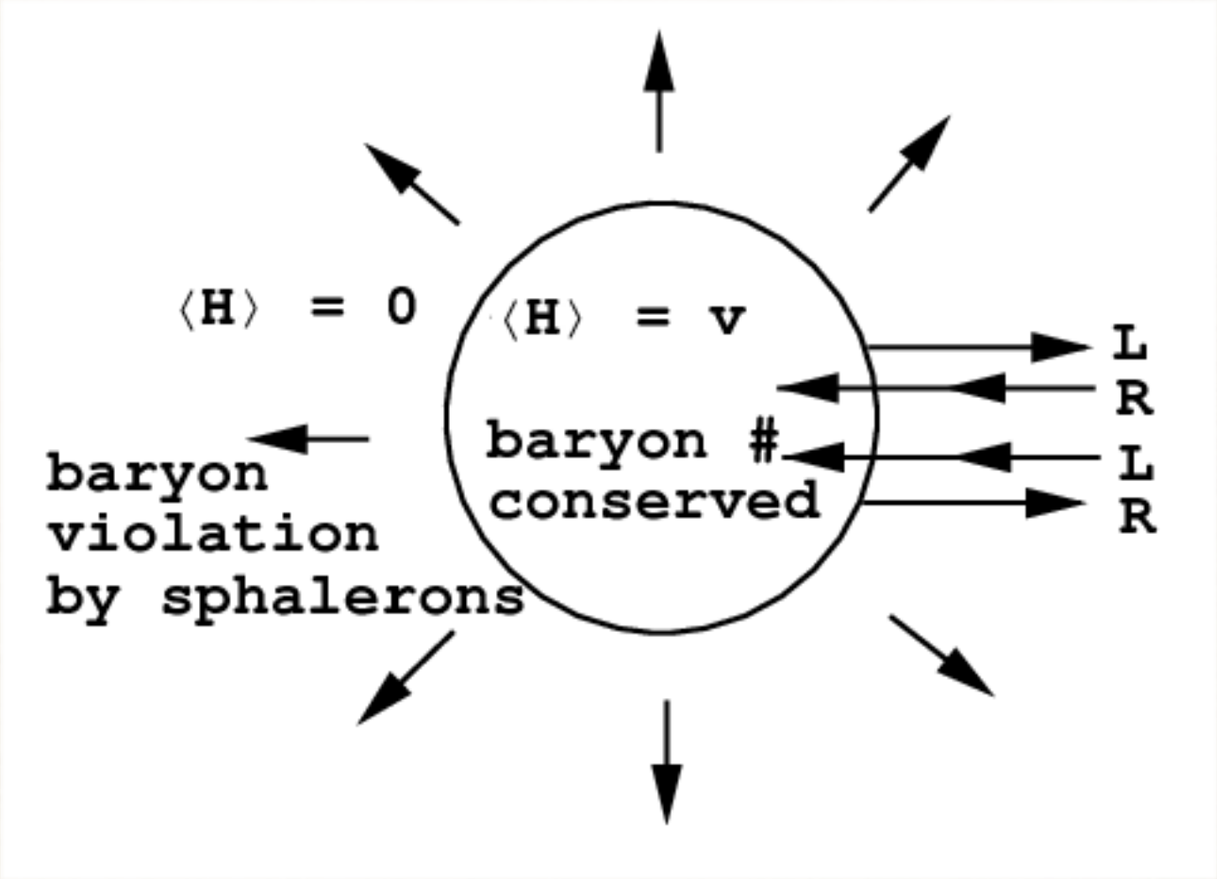
Direct

Phase transitions: a new opportunity

Additional contributions to the EW phase transition
from singlets and doublets
Reach to 1st order? Baryogenesis and Gravitational waves



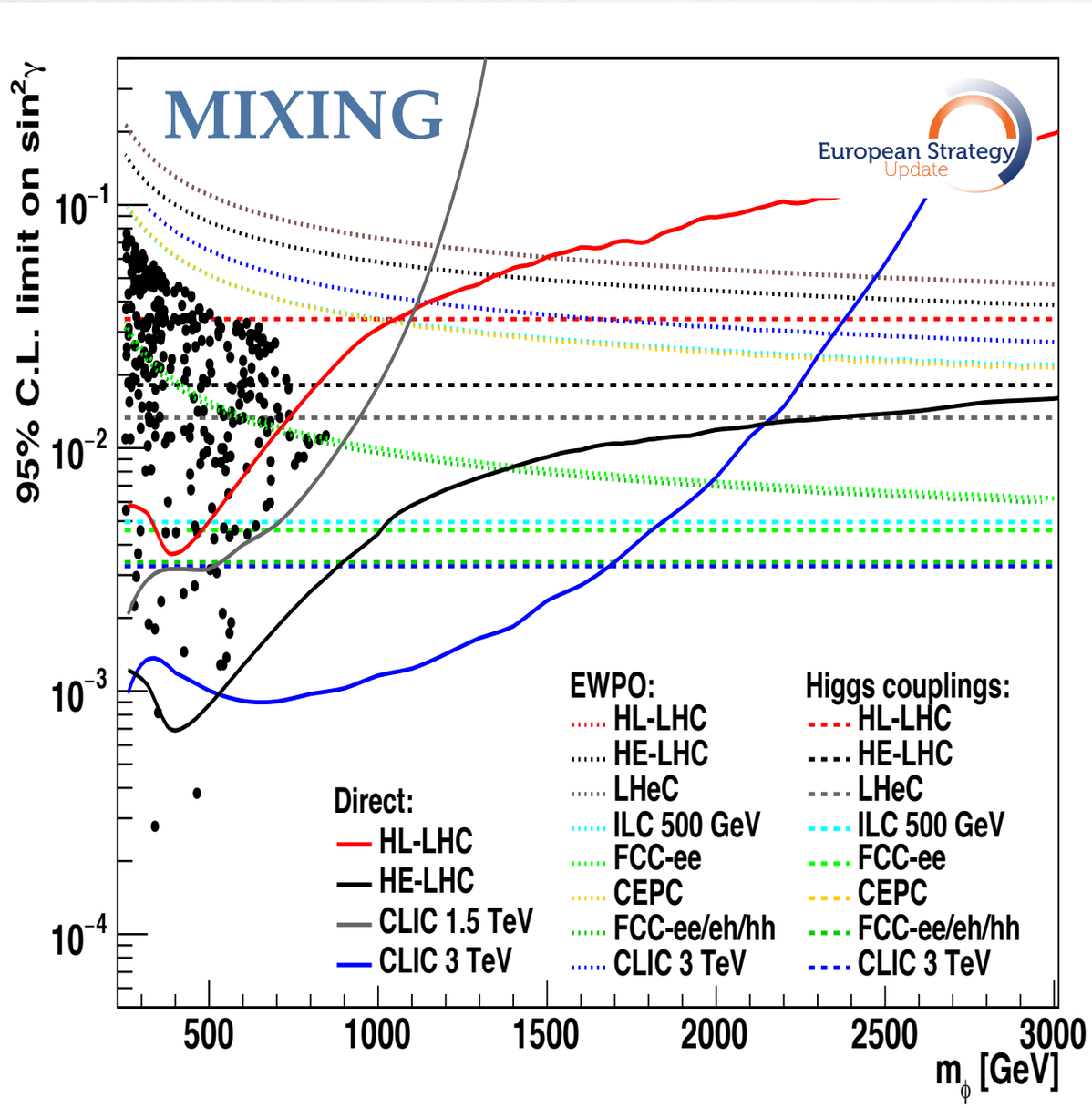
LISA'S PROPOSAL

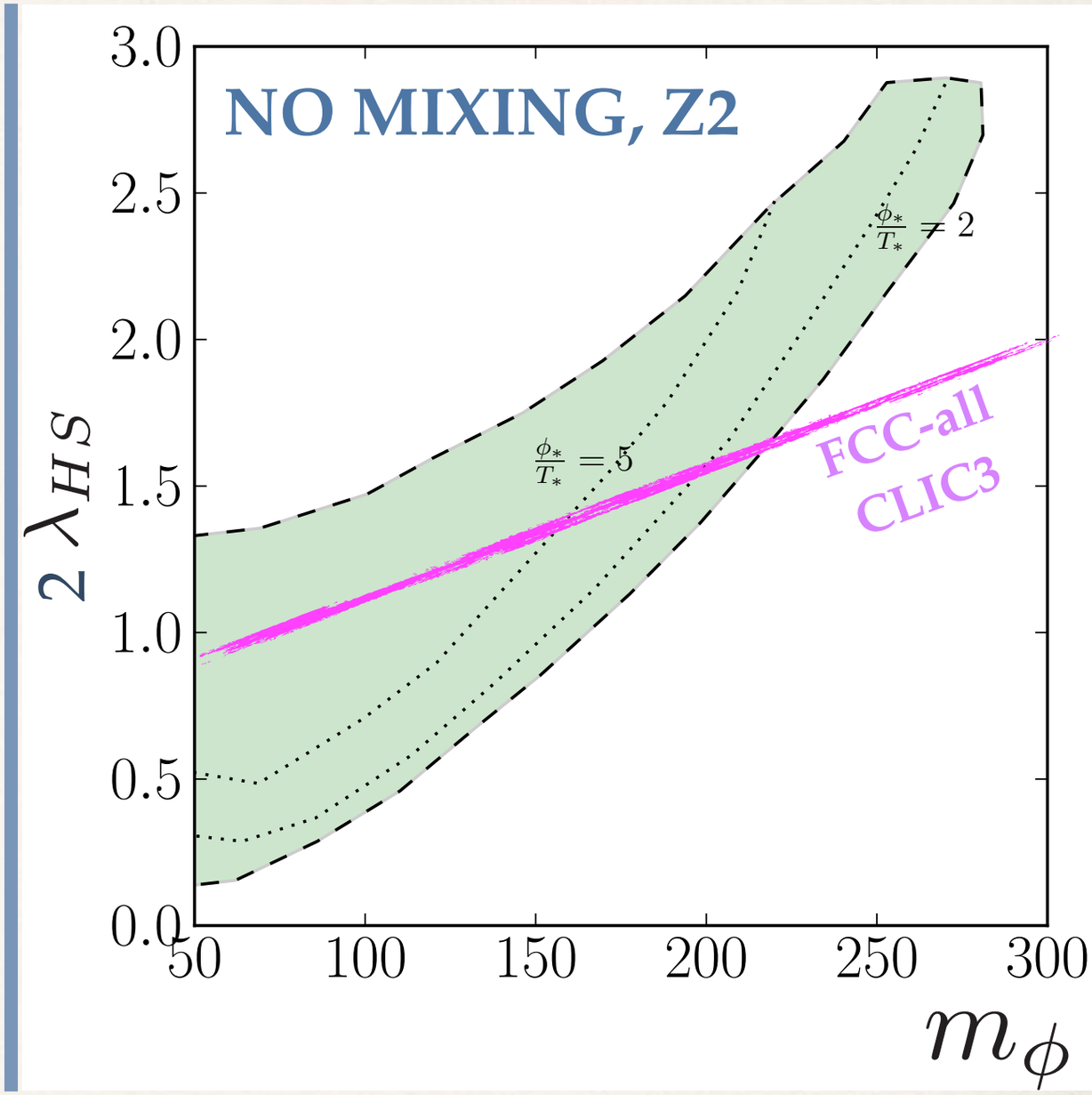


FROM CLINE

Open new opportunities at the TeV
Colliders/LISA/EDMs

Phase transitions: singlet example





Dots 1OPT from 1605.06123

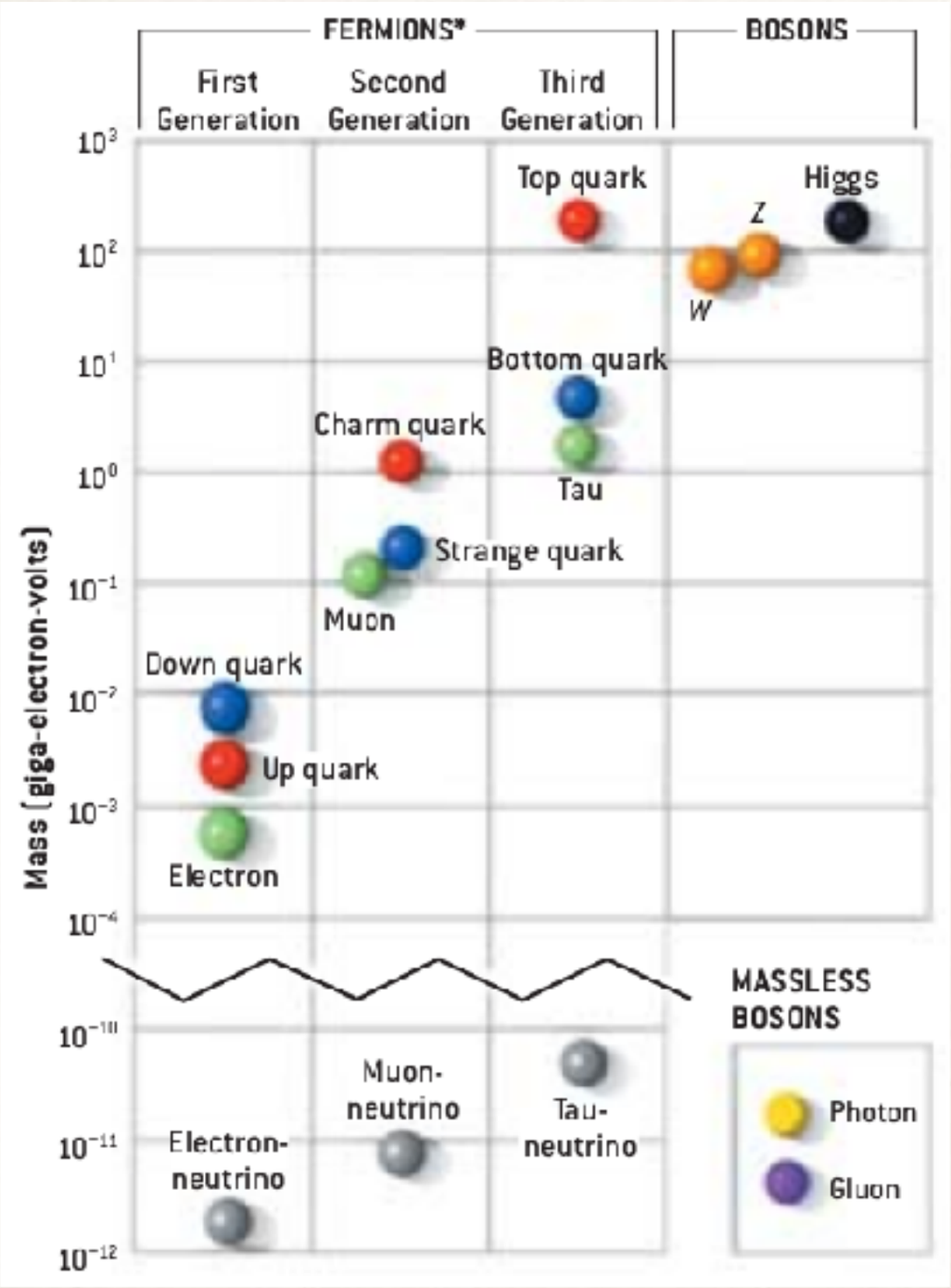
thanks to Chala, **LISA draft**

Lessons common to singlets/doublets

Upper limit on singlet mass < TeV
correlation with anomalous di-Higgs

On the UV origin of flavour

The 3rd generation & flavour



[from G Kane, Scientific American]

The structure of EWSB
(the origin of mass)
and the UV structure of flavour
are linked

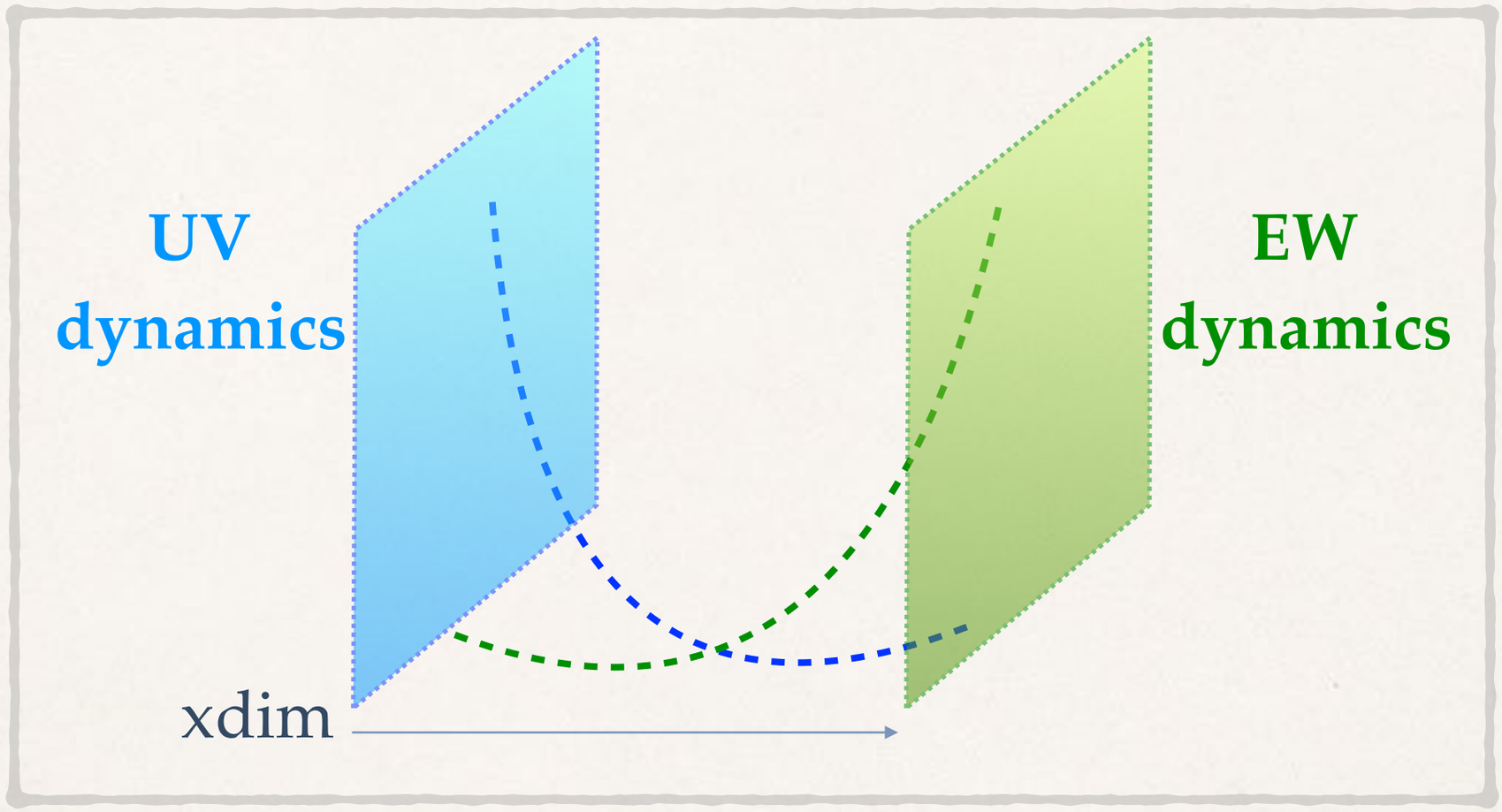
The third generation *feels*
EWSB more strongly than the other two
may be a sensitive probe into flavour

Consistent with observations: we know
of the flavour properties of the 1st and
2nd generation to be SM-like to a higher
precision

Let's make the third generation special

Example: Warped extra-dimensions

What if Nature were higher-dimensional?



Our 4D-world measurements: distributions inside the extra-dimension

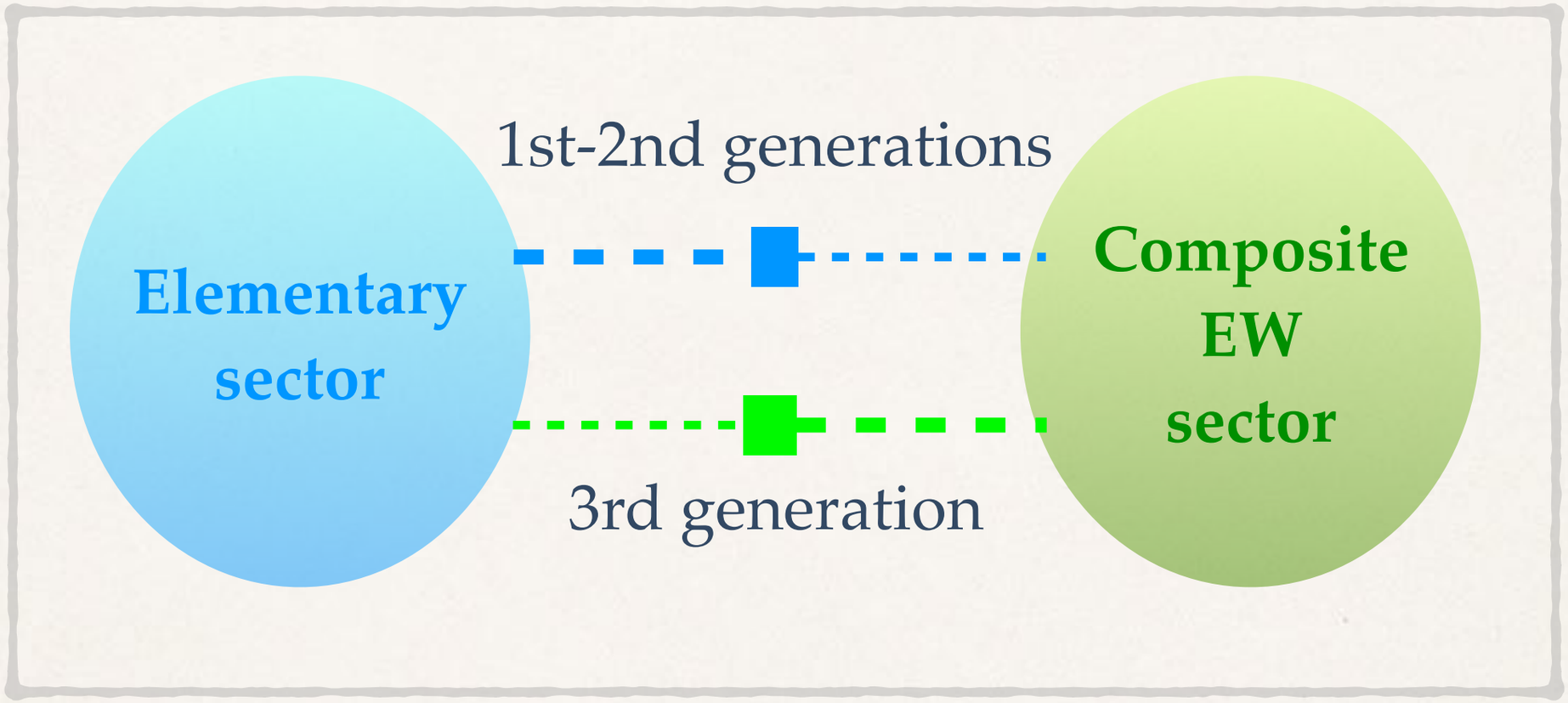
*most fermions light because they do not feel EWSB that much

*third generation ***special*** because it happens to be (spatially) closer to the place where EWSB happens

Let's make the third generation special, again

Example: Partial compositeness

What if there were a new strongly coupled sector?



Mixing of third generation with fermions from the new strong sector happens to be larger than for the 1st and 2nd generations

Higgs as a Composite Higgs

Top flavour and FCNCs

Top FCNC decays—*typical* predictions

Typical predictions (Snowmass 1311.2028)

Process	SM	2HDM(FV)	2HDM(FC)	MSSM	RPV	RS
$t \to Zu$	7×10^{-17}	–	–	$\leq 10^{-7}$	$\leq 10^{-6}$	–
$t \to Zc$	1×10^{-14}	$\leq 10^{-6}$	$\leq 10^{-10}$	$\leq 10^{-7}$	$\leq 10^{-6}$	$\leq 10^{-5}$
$t \to gu$	4×10^{-14}	–	–	$\leq 10^{-7}$	$\leq 10^{-6}$	–
$t \to gc$	5×10^{-12}	$\leq 10^{-4}$	$\leq 10^{-8}$	$\leq 10^{-7}$	$\leq 10^{-6}$	$\leq 10^{-10}$
$t \to \gamma u$	4×10^{-16}	–	–	$\leq 10^{-8}$	$\leq 10^{-9}$	–
$t \to \gamma c$	5×10^{-14}	$\leq 10^{-7}$	$\leq 10^{-9}$	$\leq 10^{-8}$	$\leq 10^{-9}$	$\leq 10^{-9}$
$t \to hu$	2×10^{-17}	6×10^{-6}	–	$\leq 10^{-5}$	$\leq 10^{-9}$	–
$t \to hc$	3×10^{-15}	2×10^{-3}	$\leq 10^{-5}$	$\leq 10^{-5}$	$\leq 10^{-9}$	$\leq 10^{-4}$

Best sensitivity to models

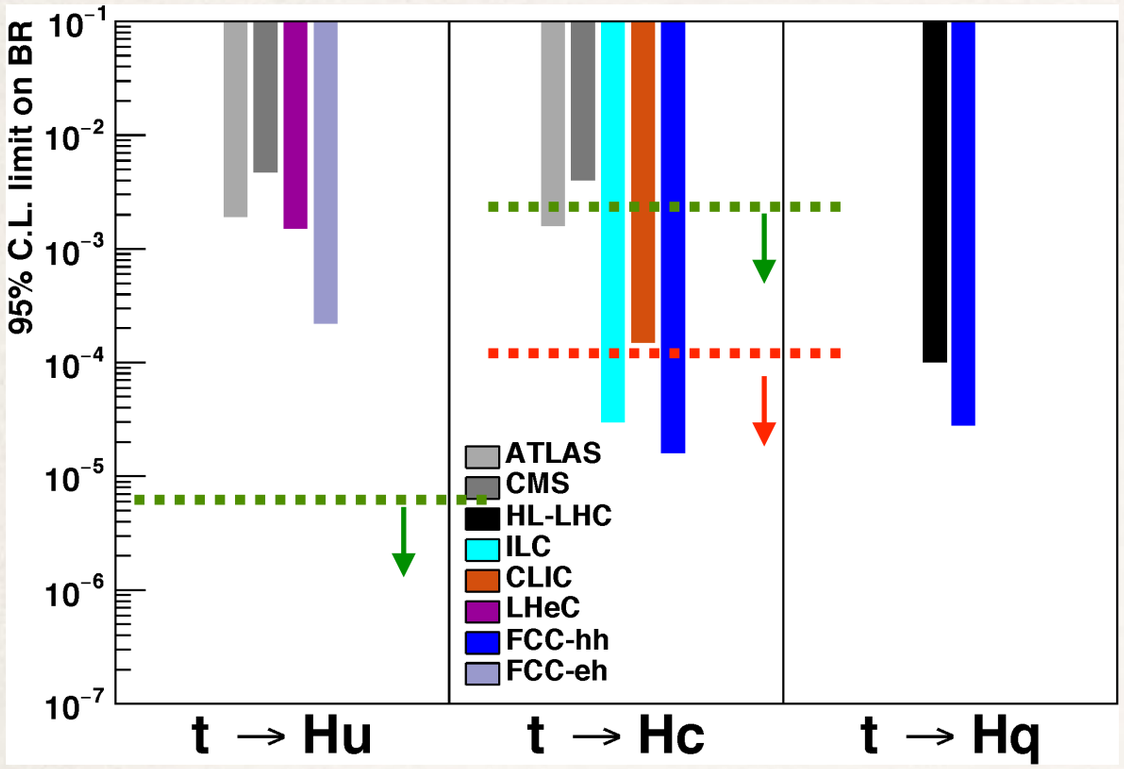
2HDM (FV) and RS

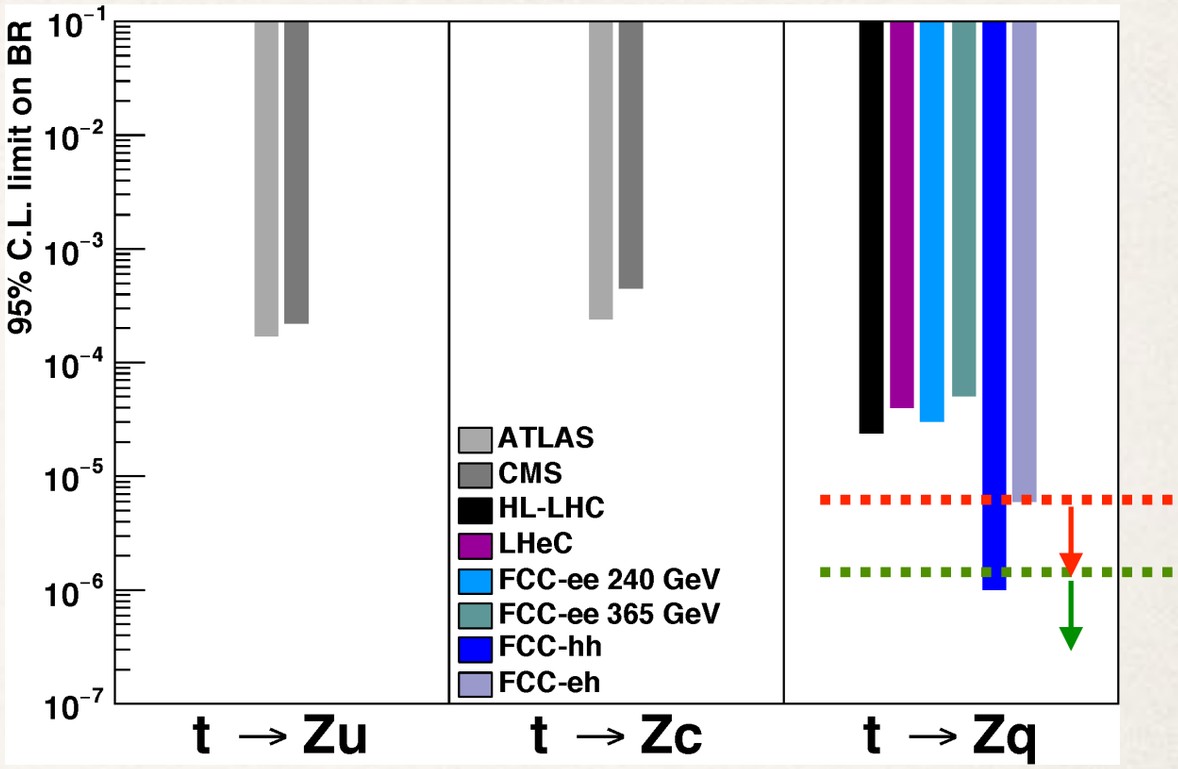
PH/9609279, PH/0606293

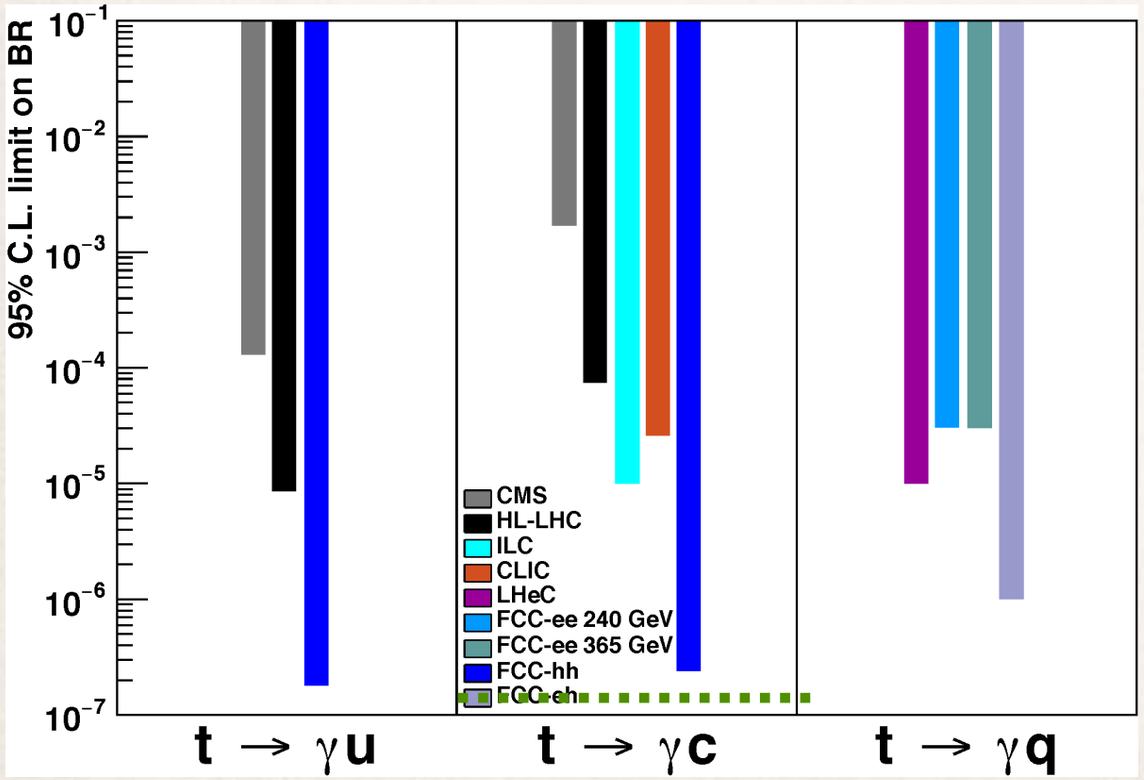
Top FCNC decays: in context

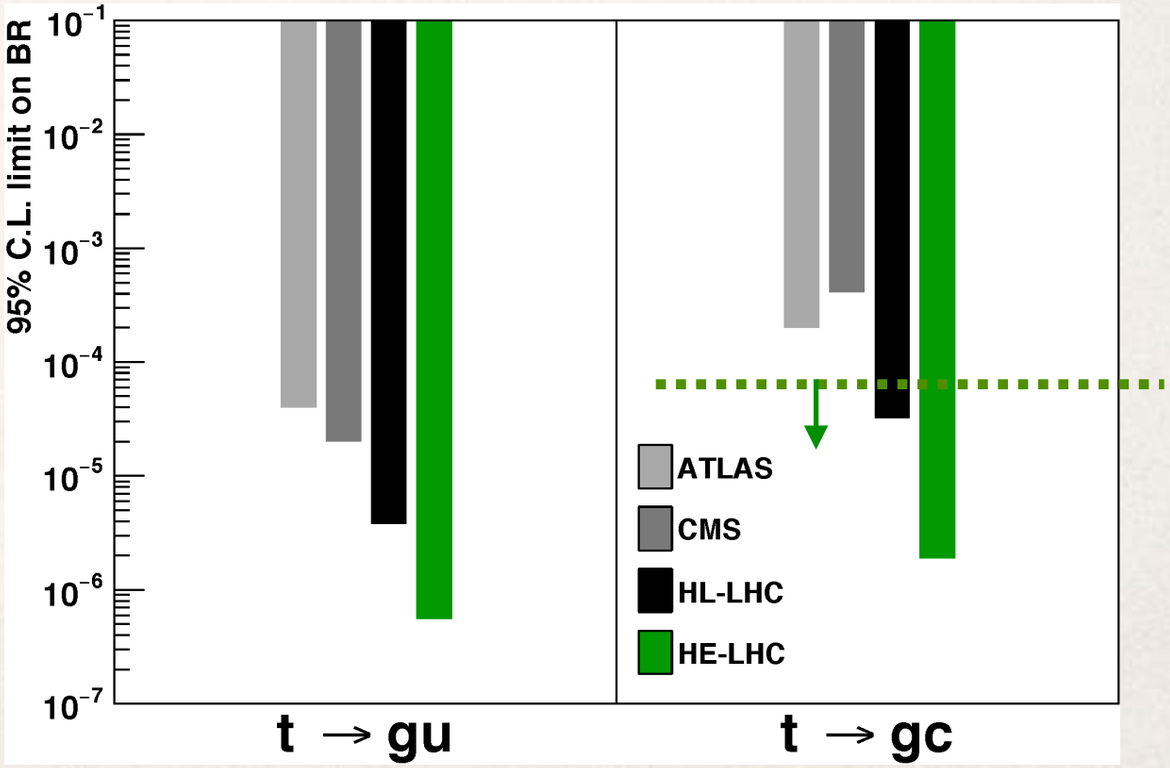
2HDM (FV)

RS





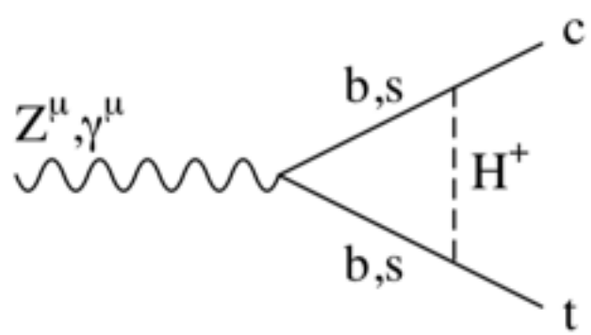




Top FCNC decays—*typical* predictions

Third generation is special, dynamically or by design

2HDM (FV)



Assuming flavour violation

$$\propto \frac{\sqrt{m_i\, m_j}}{v}$$

see recent analysis 1710.03752

RS

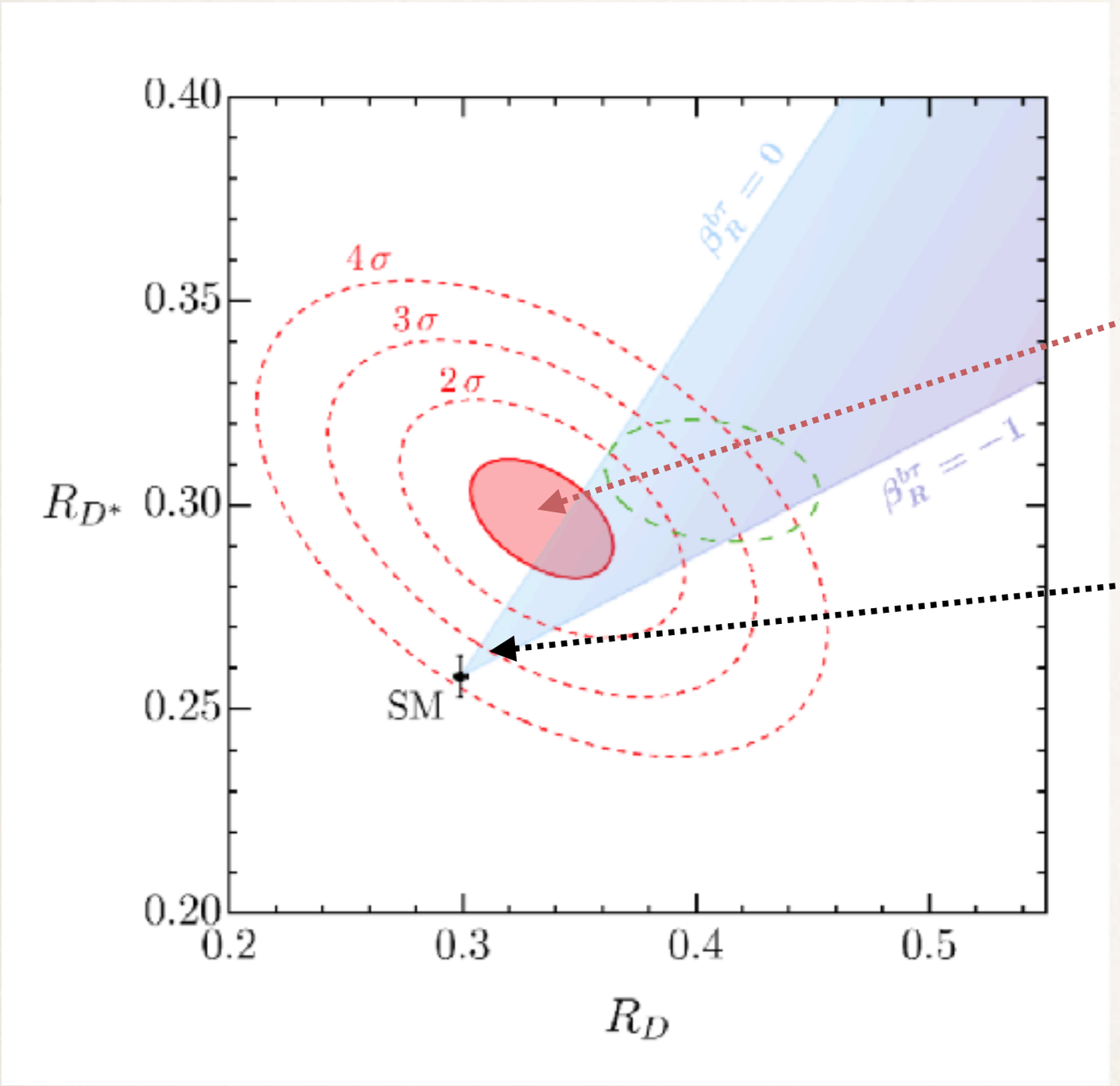
warped extra-dimensions

precursor of modern partial compositeness models

$$\mathrm{BR}\,(t \to cZ) \;\sim\; 10^{-5} \left(\frac{3\ \mathrm{TeV}}{m_{KK}}\right)^4 \left(\frac{(U_R)_{23}}{0.1}\right)^2$$

Leptoquarks and flavour anomalies

Flavour anomalies: is the SM breaking down?



current exp world average from 1903.11517

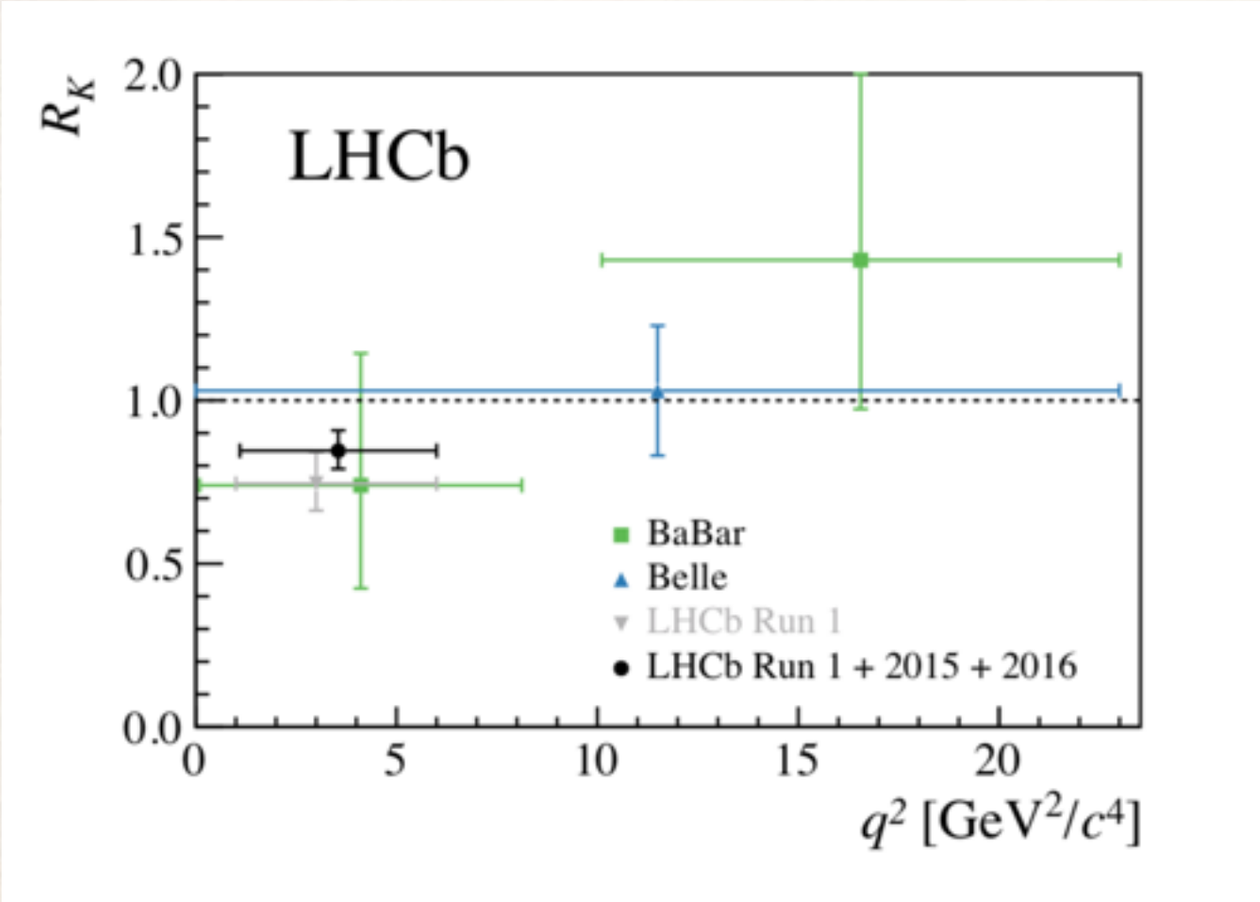
SM prediction

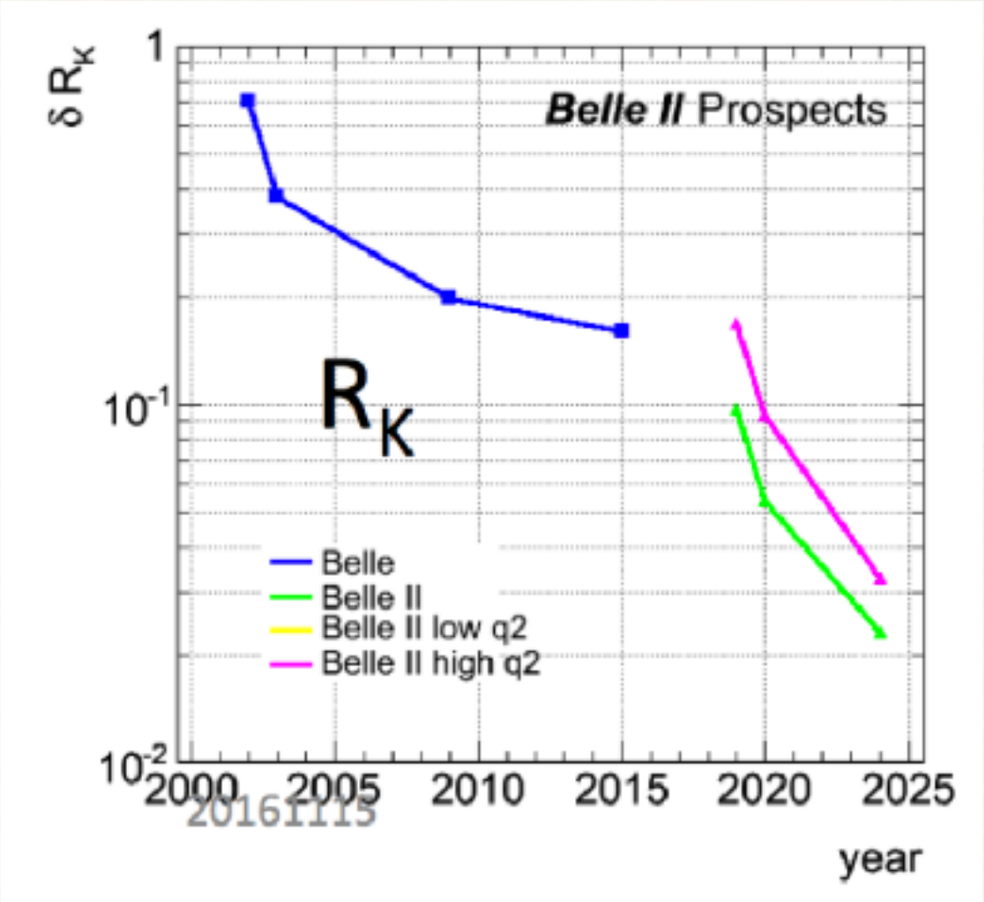
Shaded region:
U1 models

Flavour anomalies: current status

Moriond 2019, no paradigm shift

Data yet to be analysed and to be made public





One of the preferred explanations to this and other flavour anomalies is the existence of new LQs, particularly U1

Leptoquarks? That's so 80's!

Table 115.1: Possible leptoquarks and their quantum numbers.

Spin	$3B+L$	$SU(3)_c$	$SU(2)_W$	$U(1)_Y$	Allowed coupling
0	−2	$\bar{3}$	1	1/3	$\bar{q}^c_L \ell_L$ or $\bar{u}^c_R e_R$
0	−2	$\bar{3}$	1	4/3	$\bar{d}^c_R e_R$
0	−2	$\bar{3}$	3	1/3	$\bar{q}^c_L \ell_L$
1	−2	$\bar{3}$	2	5/6	$\bar{q}^c_L \gamma^\mu e_R$ or $\bar{d}^c_R \gamma^\mu \ell_L$
1	−2	$\bar{3}$	2	−1/6	$\bar{u}^c_R \gamma^\mu \ell_L$
0	0	3	2	7/6	$\bar{q}_L e_R$ or $\bar{u}_R \ell_L$
0	0	3	2	1/6	$\bar{d}_R \ell_L$
1	0	3	1	2/3	$\bar{q}_L \gamma^\mu \ell_L$ or $\bar{d}_R \gamma^\mu e_R$
1	0	3	1	5/3	$\bar{u}_R \gamma^\mu e_R$
1	0	3	3	2/3	$\bar{q}_L \gamma^\mu \ell_L$

PDG

Objects with L and B numbers

Initial motivation GUTs

possible in many models

SU(5), SO(10)

Pati/Salam

squarks in RPV

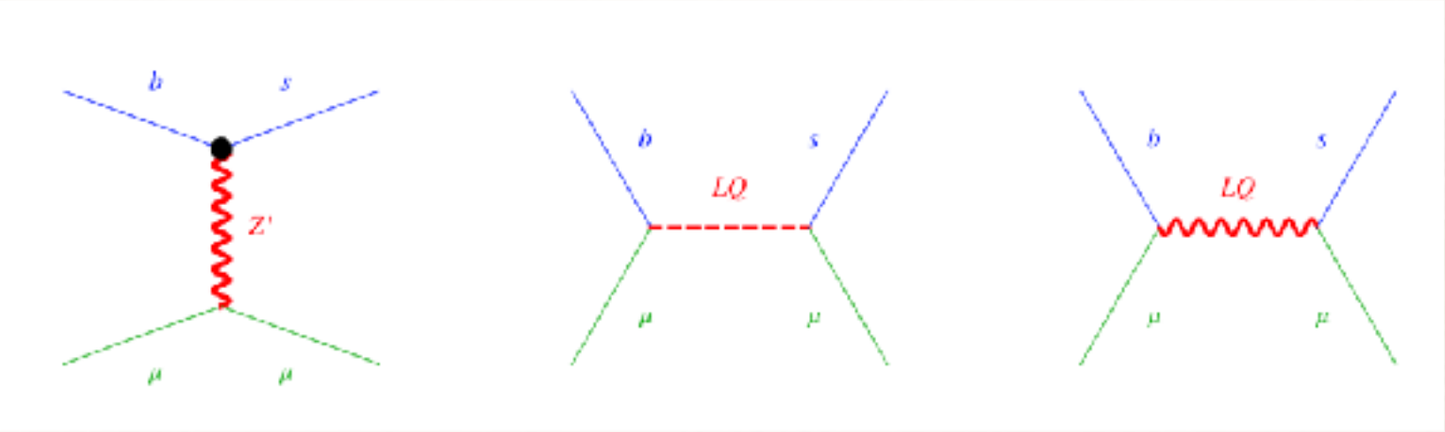
Ext TC/generic compositeness

The U1 in a nutshell

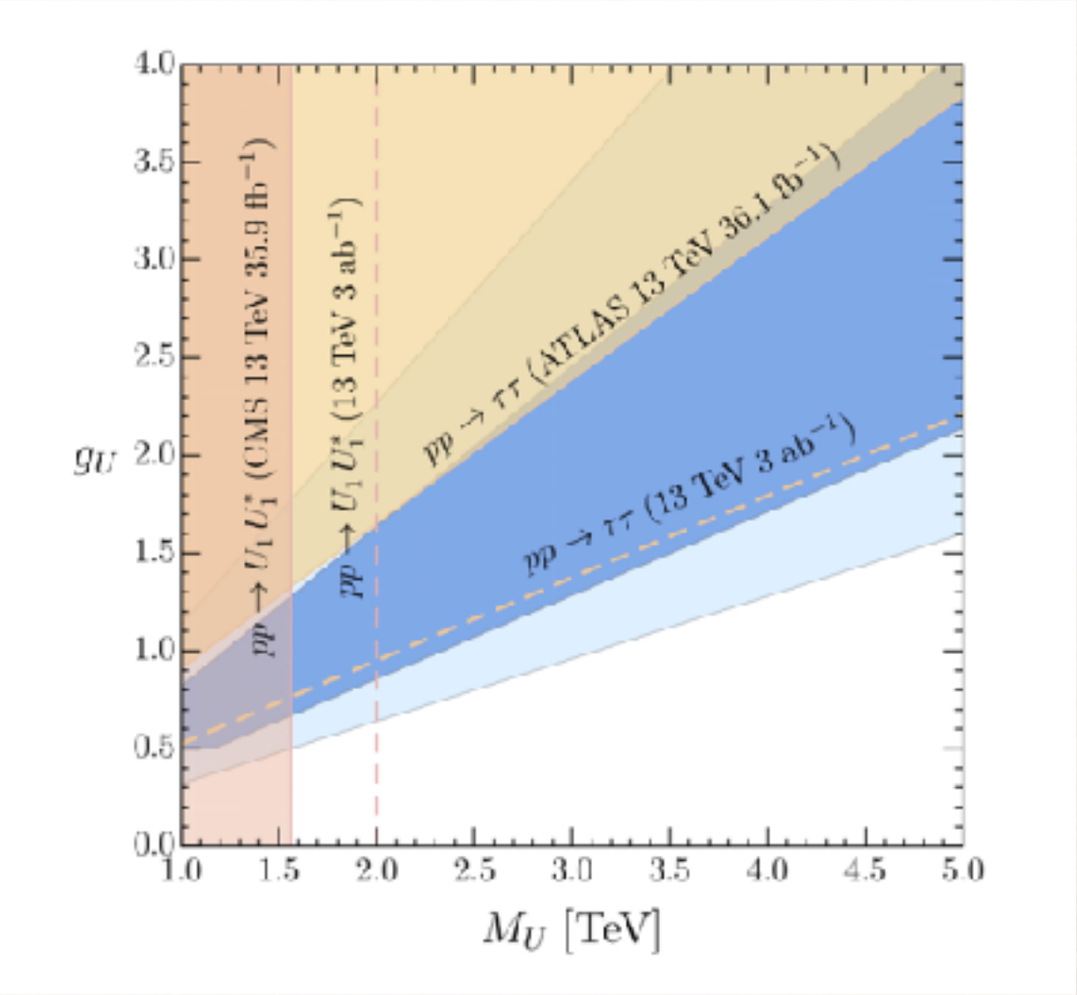
Review U1 in 1808.08179

recent 1903.11517,1704.05438**v4**

4 fermion operators
flavour observables
low-energy indirect



mass 1-2 TeV can explain the anomalies with LH couplings **direct** searches and **indirect high-pT** searches



Model building a flavour anomaly

Even if the anomalies went away
efforts to fit them in a theoretical context will remain

The U1 in a UV-complete model is a difficult exercise

flavour is difficult

E.g. `1903.11517`

Gauge group $\mathcal{G}_{4321} = SU(4) \times SU(3)' \times SU(2) \times U(1)'$

Flavour symmetry PS^3 3rd gen vs others

Occam's razor
to principles
not to matter content

Field	$SU(4)$	$SU(3)'$	$SU(2)_L$	$U(1)'$
q_L^i	**1**	**3**	**2**	1/6
u_R^i	**1**	**3**	**1**	2/3
d_R^i	**1**	**3**	**1**	−1/3
ℓ_L^i	**1**	**1**	**2**	−1/2
e_R^i	**1**	**1**	**1**	−1
ψ_L^i	**4**	**1**	**2**	0
ψ_u^i	**4**	**1**	**1**	1/2
ψ_d^i	**4**	**1**	**1**	−1/2
χ_L^i	**4**	**1**	**2**	0
χ_R^i	**4**	**1**	**2**	0
H_1	**1**	**1**	**2**	1/2
H_{15}	**15**	**1**	**2**	1/2
Ω_1	$\bar{\mathbf{4}}$	**1**	**1**	−1/2
Ω_3	$\bar{\mathbf{4}}$	**3**	**1**	1/6
Ω_{15}	**15**	**1**	**1**	0

Outlook

- Is the Higgs sector minimal? Are there other scalar resonances participating in EWSB? We tackle this question with a combination of indirect EWPT, Higgs measurements (including di-Higgs) and direct searches

- If not minimal, could the EW phase transition be strong 1st order? Scalars need to be light (< TeV) and typically modify the properties of the Higgs. Colliders have an excellent coverage to these scenarios. Exceptional opportunity to connect with GWs and theoretical approaches to fluid dynamics

- If strong 1st order, could the EW phase transition explain baryogenesis? Connection to EDM measurements and other observables sensitive to CPV

- Could we understand the UV origin of flavour with colliders? Possibly, if some preferential treatment of 3rd generation. Top FCNCs and B anomalies could provide the first clues. Theoretical efforts to fit all this in a full framework underway