FCC-ee: More than just Higgs physics

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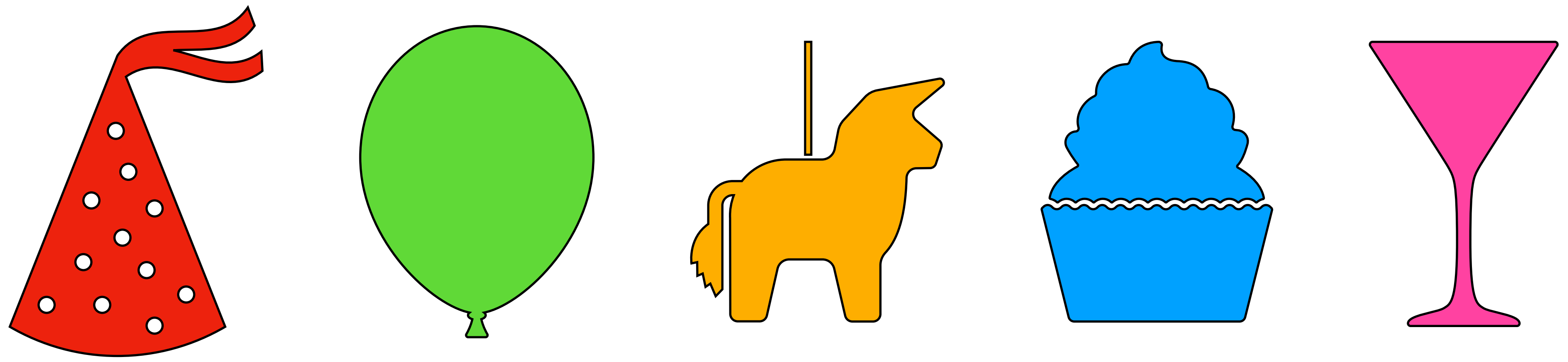
UK Research and Innovation

UK HEP Forum, 26 November 2024

University of Glasgow

Particle physics after the LHC...

Option 1: something new

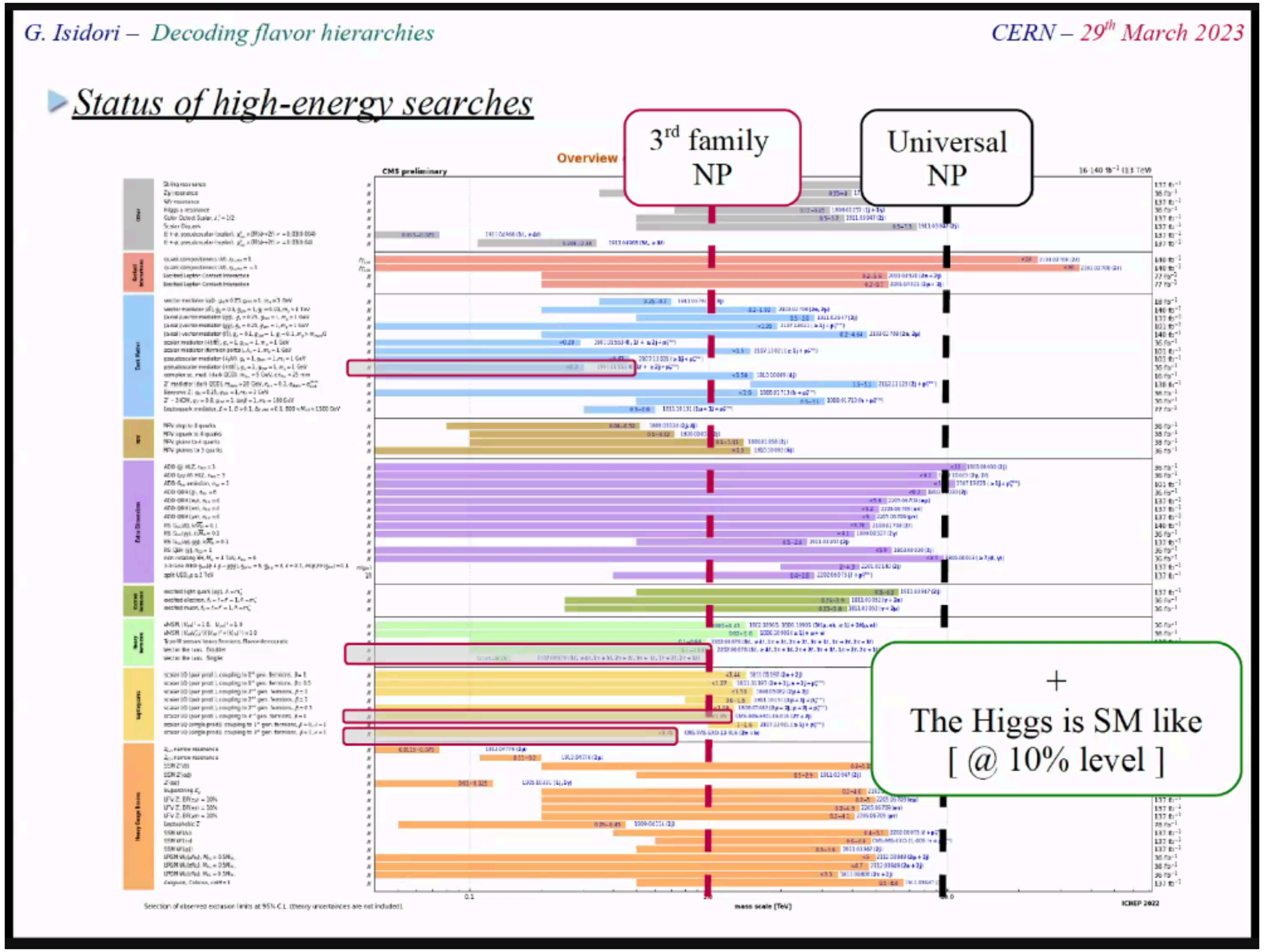


⇨ Understand the new thing

Option 2: SM still reigns

Is there still space for TeV-ish new physics? - where to look?

Best case scenario: flavourful physics



Slide from Gino Isidori, CERN Theory Colloquium, 29/3/2023

If BSM physics couples differently to different flavours, bounds change

In particular, lowest bounds if NP couples only to 3rd family

At LHC: PDF suppression
Low energy: 3rd generations less precisely measured

What this means for a future collider

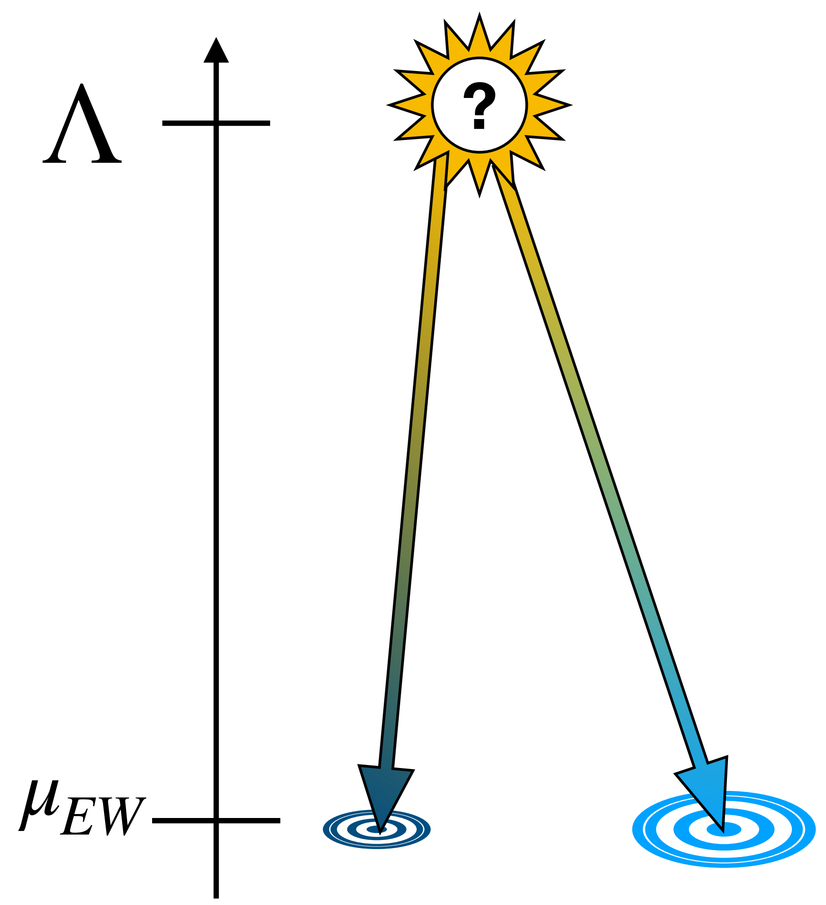
Points to some aims for a new collider:

- ★ Testing the Yukawa sector Higgs couplings to fermions, CKM tests
- ★ Searching for new interactions involving 3rd generation fermions
- ★ Precision tests that are sensitive to NP independent of flavour structure

Examples of how FCC-ee addresses these and what it might mean for BSM

The Standard Model Effective Field Theory

Approximate the effects of all possible heavy particles by writing down all possible new interactions between SM particles



$$\mathscr{L}_{\mathrm{SMEFT}} = \frac{1}{\Lambda^2} \sum_i C_i O_i + \mathcal{O}\left(\frac{1}{\Lambda^4}\right)$$

Operators are suppressed by BSM scale

$$\Lambda$$

Different classes of operators built from SM fields...

$$X^3 \quad H^6 \quad H^4 D^2 \quad \psi\bar{\psi}H^2 D \quad \psi\bar{\psi}H^3 \quad \psi\bar{\psi}XH \quad X^2H^2 \quad \bar{\psi}^2\psi^2$$

$$X = B_{\mu\nu}, G^A_{\mu\nu}, W^I_{\mu\nu}$$
$$\psi = Q, u, d, L, e$$

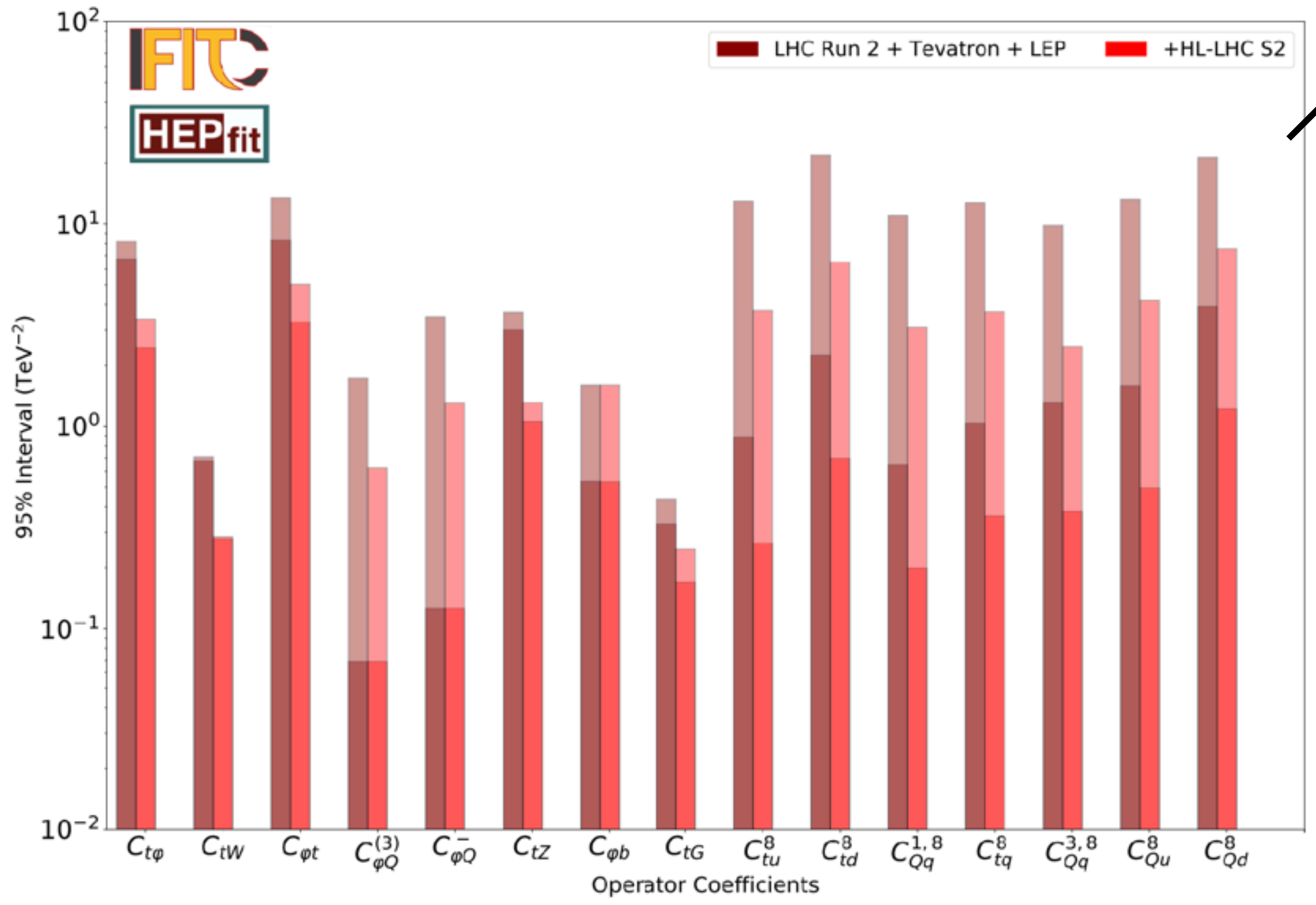
Parameters of the theory are contained in the Wilson coefficients

The search for new physics can be translated into searches in Wilson coefficient space

SMEFT in 2040

Projected fit to top-containing operators

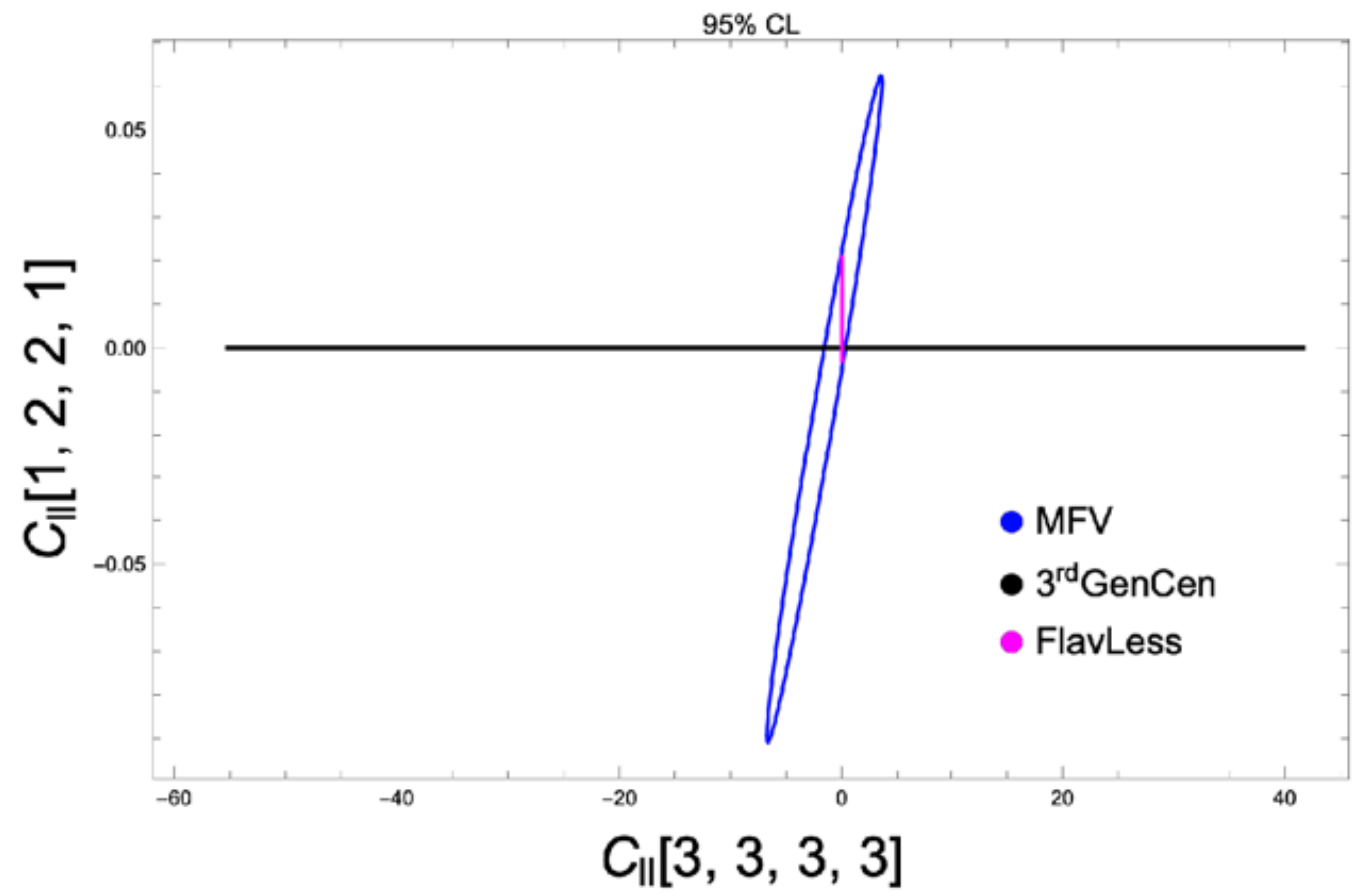
De Blas et al, 2206.08326



Lighter shade: single-parameter fit
Darker shade: marginalised fit

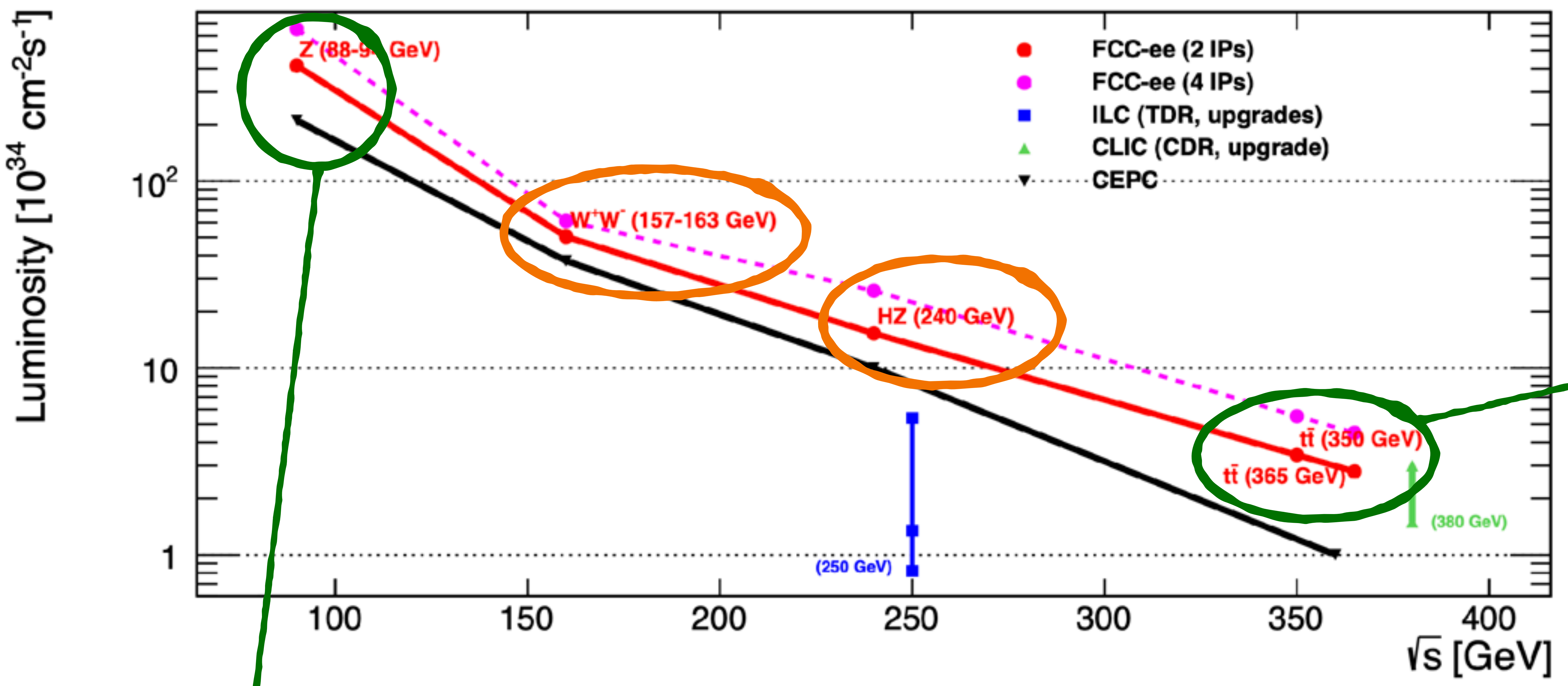
Some operators are only constrained to below 1 TeV, even after HL-LHC

Other types of flavoured operators have not been systematically studied (even using current data)



Bellafronte, Dawson, Giardino 2304.00029

FCC-ee is a flavour factory



FCC Snowmass report, 2203.06520

top production and decay

Numbers for decays of $5 \times 10^{12}\ Z^0$s:

Lenz & Monteil, 2207.11055

Particle species	B^0	B^+	B_s^0	Λ_b	B_c^+	$c\bar{c}$	$\tau^-\tau^+$
Yield ($\times 10^9$)	310	310	75	65	1.5	600	170

$O(10^{11})$ B mesons

About 15 times larger than Belle II dataset

Combines the advantages of B factories and LHCb: highly boosted particles in a clean environment

Precise measurements of the third generation (both quarks and leptons)

Also Yukawa & CKM sector

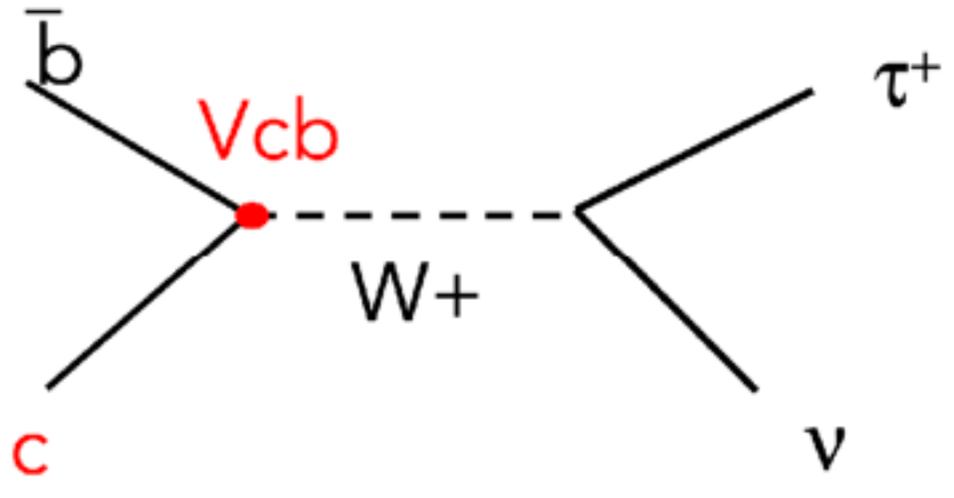
V_{cb} at FCC-ee

?

$$|V_{cb}|^{\text{incl.,2022}} = (42.16 \pm 0.51) \cdot 10^{-3}$$
$$|V_{cb}|^{\text{excl.,PDG}} = (39.5 \pm 0.9) \cdot 10^{-3}$$

Discrepancy between inclusive and exclusive determinations of V_{cb}

With $B_c \to \tau^+ \nu$ decays

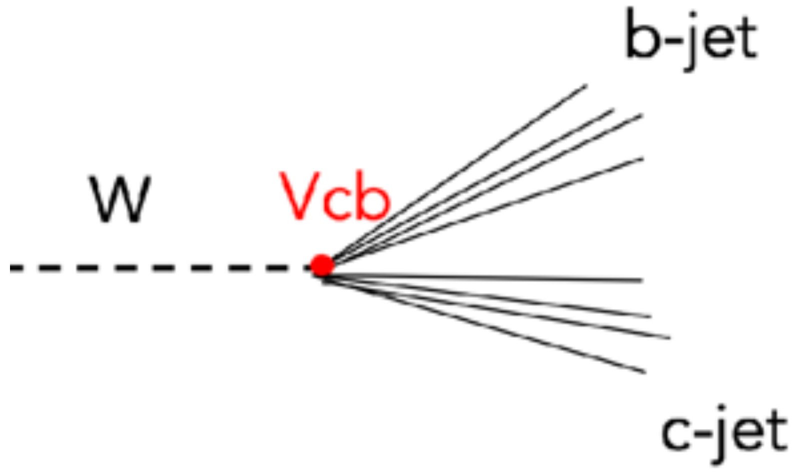


Amhis, Hartmann, Helsens, Hill, Sumensari 2105.13330
Zheng et al, 2007.08234 (CEPC study)

No form factors, just a decay constant

But need to know B_c fraction

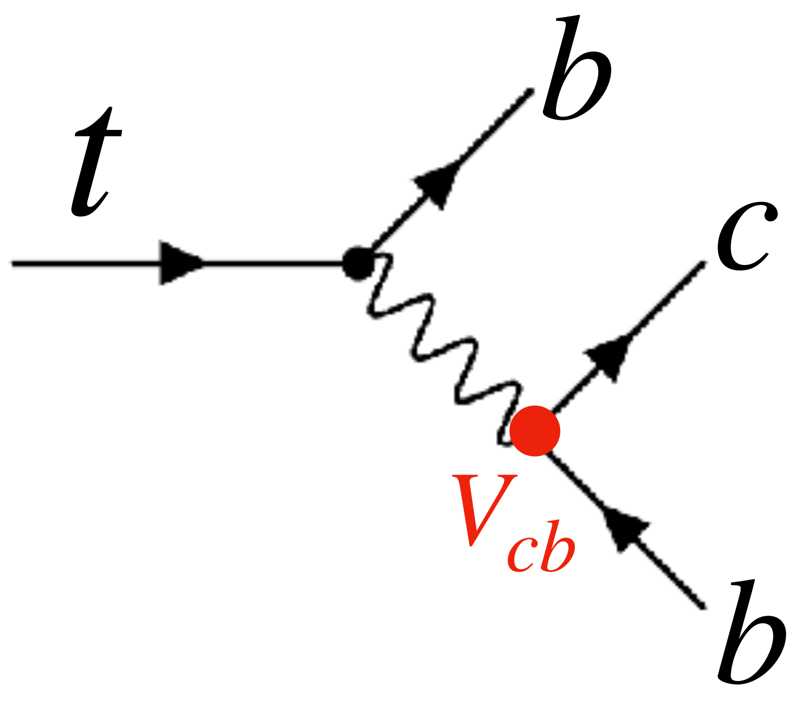
With W decays



Precision depends on tagging of b and c jets

Estimated achievable precision 0.4% Marie-Helene Schune, FCC-ee workshop 2020

With top decays



Harrison & Vladimirov, 1810.09424

More direct measurements of e.g. V_{ts}

Similar story for Vub

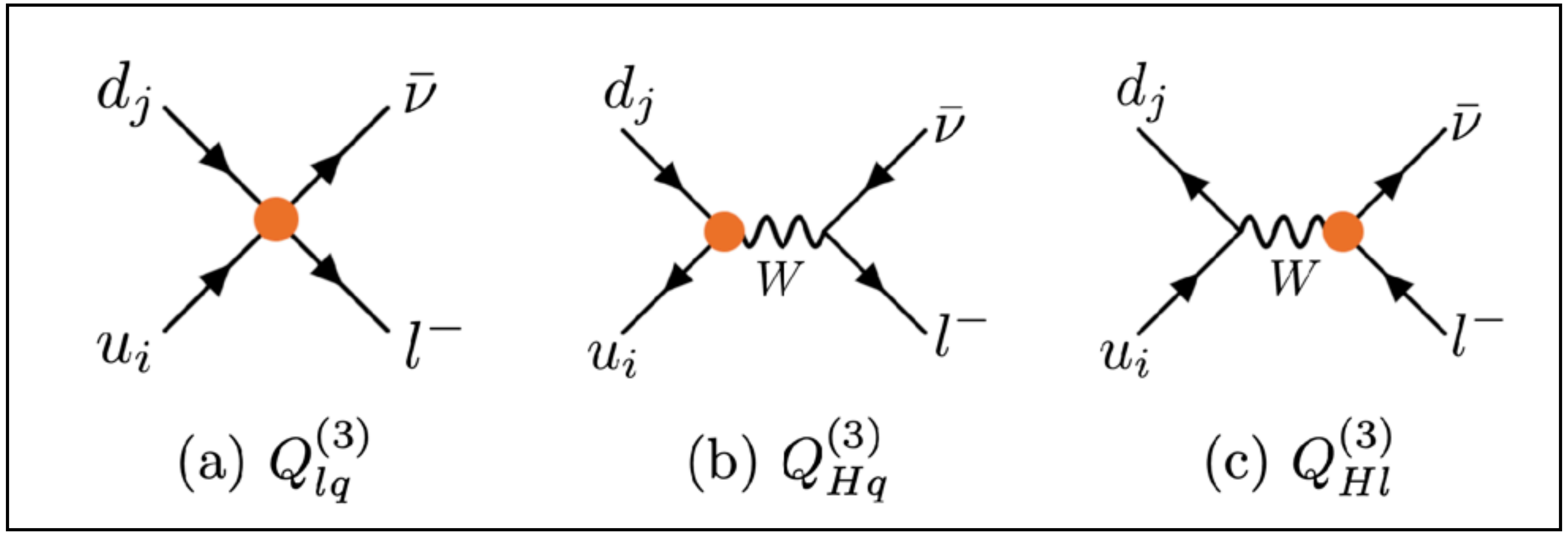
‘CKM’ in the SMEFT

In the absence of some symmetry forbidding it (e.g. R-parity), new physics can enter at tree level in observables from which the CKM is extracted

Possible SMEFT effects in CKM fits must be carefully propagated through Descotes-Genon et al., 1812.08163

Or do a bespoke CKM fit in which SMEFT effects cancel (only possible with flavour assumptions) Aoude, Hurth, SR, Shepherd, 2003.05432

e.g.



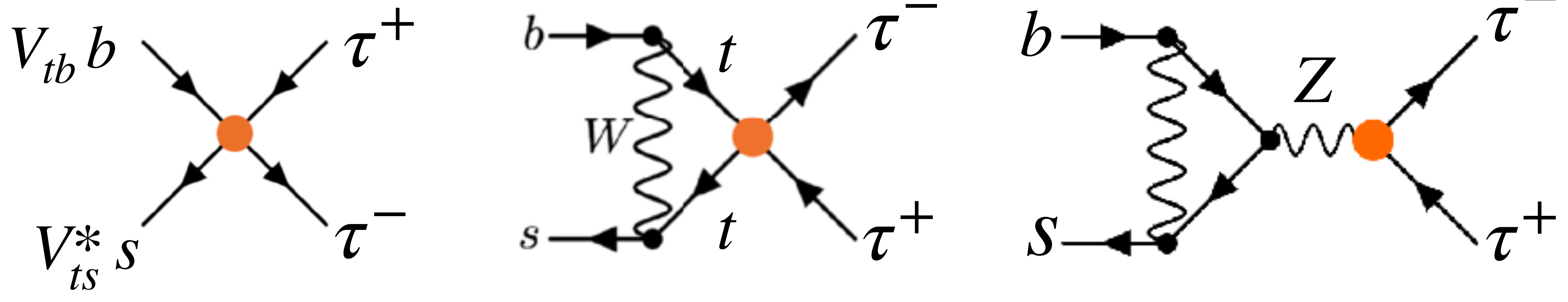
All three of these operators contribute to $b \to c\ell\bar{\nu}$

But only one contributes to $W \to \bar{b}c$

Easier to isolate new physics with more observables
Possibility of combined CKM + SMEFT fits?

B decays into τs

Likely that new physics that speaks only to 3rd gen should show up here:



$B \to K\tau^+\tau^-$

SM branching ratio: $(1.44 \pm 0.15) \times 10^{-7}$ HPQCD, 1306.0434

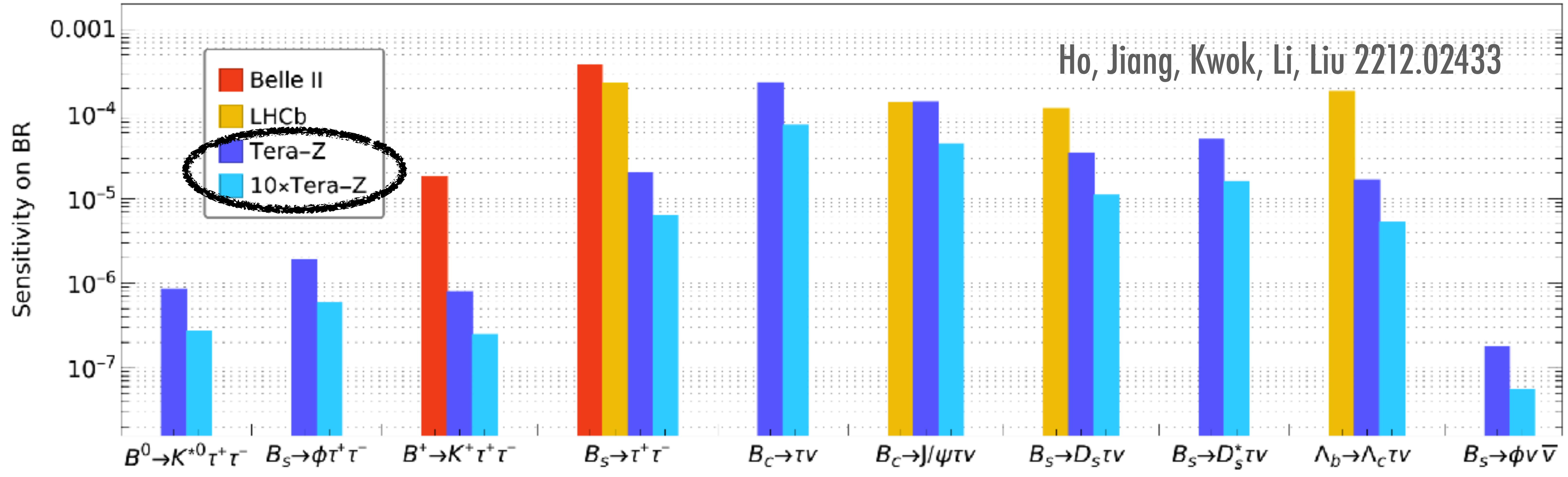
Current limits: 5 orders of magnitude above SM

After Belle II: $BR \leq 10^{-4} - 10^{-5}$

$B_s \to \tau^+\tau^-$

$\mathrm{Br}\left(B_s \to \tau^+\tau^-\right)_{\mathrm{SM}} = (7.73 \pm 0.49) \times 10^{-7}$ Bobeth, 1405.4907

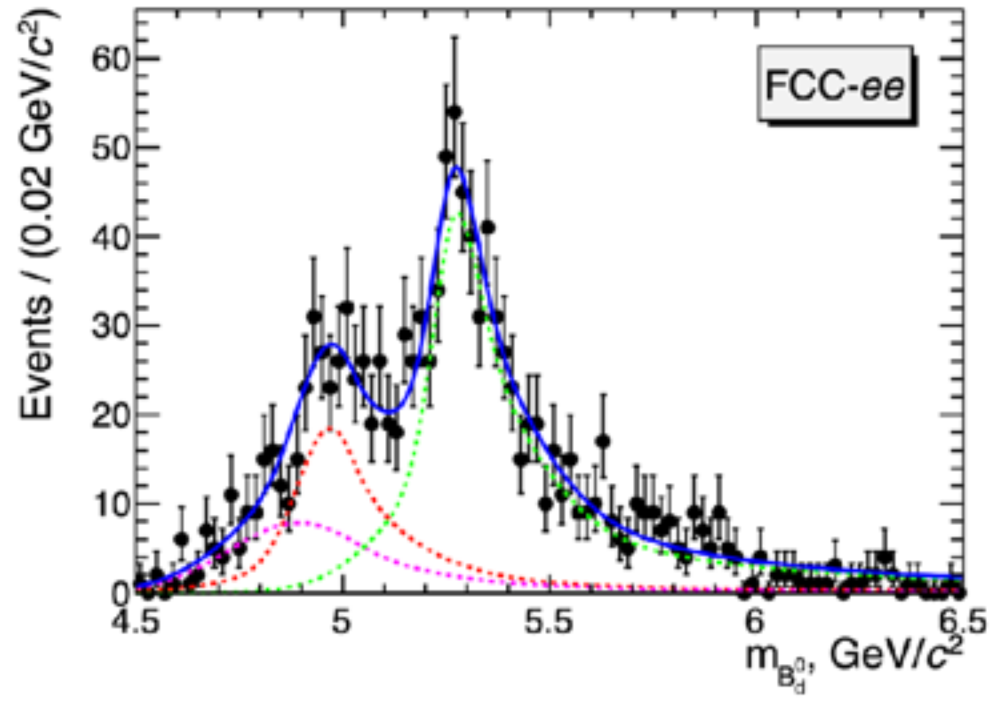
$\mathrm{Br}\left(B_s \to \tau^+\tau^-\right)_{\mathrm{EXP}} \leq 6.8 \times 10^{-3}$ LHCb, 1703.02508



$B \to K^*\tau^+\tau^-$

$\mathcal{O}(10^3)$ reconstructed $B \to K^*\tau^+\tau^-$ events

Can measure τ polarization observables



Kamenik, Monteil, Semkiv, Silva, 1705.11106

$B \to K^{(*)}\tau^+\tau^-$ in the SMEFT

$$O_{lq}^{(1)\,ijkl} = (\bar{L}^i\gamma_\mu L^j)(\bar{Q}^k\gamma^\mu Q^l)$$

$$O_{lq}^{(3)\,ijkl} = (\bar{L}^i\gamma_\mu \tau^I L^j)(\bar{Q}^k\gamma^\mu \tau^I Q^l)$$

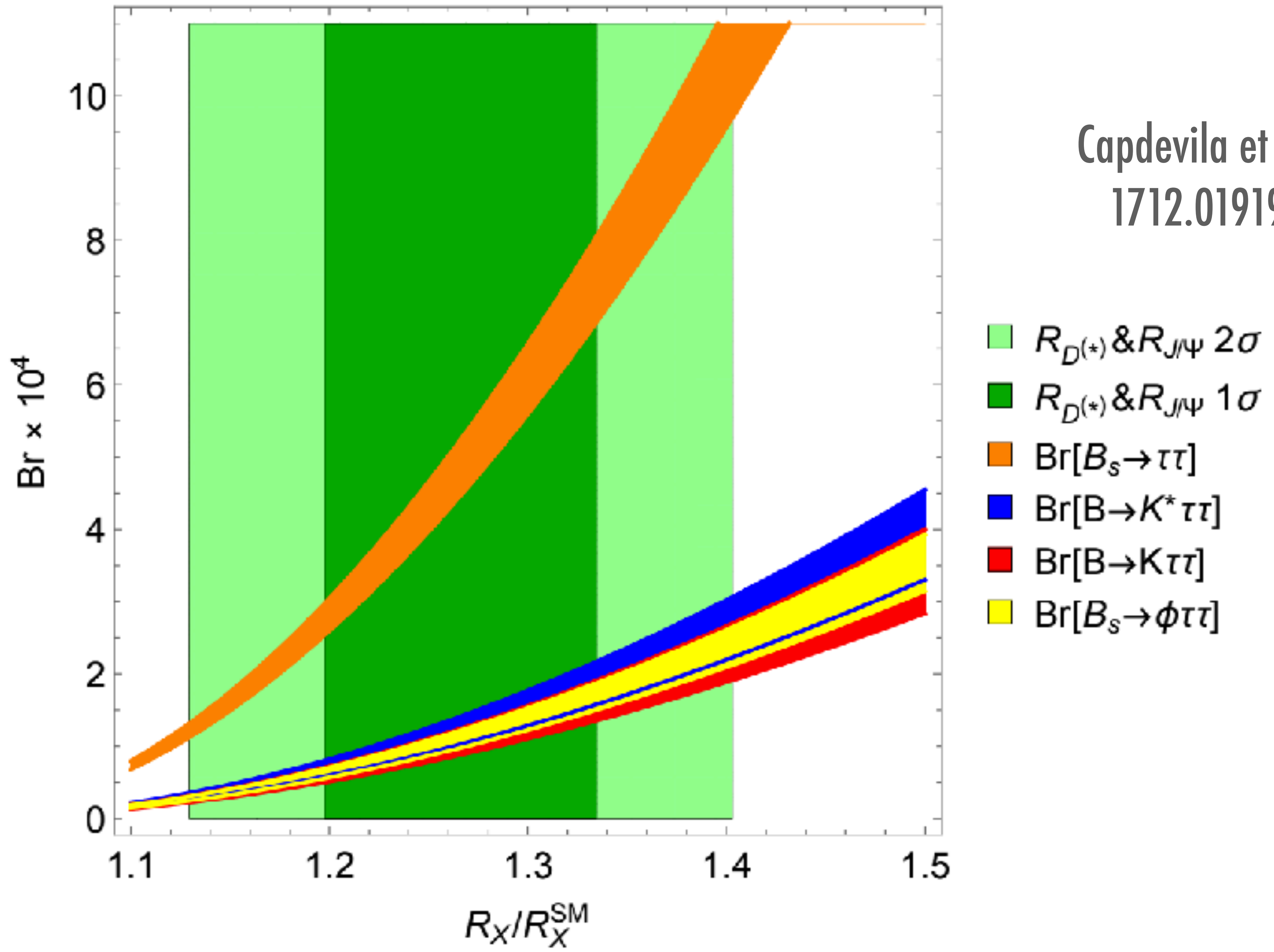
$$O_{qe}^{ijkl} = (\bar{e}^i\gamma_\mu e^j)(\bar{Q}^k\gamma^\mu Q^l)$$

$R_D^{(*)} \propto C_{lq}^{(3)}$

$B \to K^{(*)}\bar{\nu}\nu \propto C_{lq}^{(1)} - C_{lq}^{(3)}$

$B \to K^{(*)}\tau^+\tau^- \propto C_{lq}^{(1)} + C_{lq}^{(3)}$

Can have large $R_D^{(*)}$ without disagreement with $B \to K^{(*)}\bar{\nu}\nu$ if $C_{lq}^{(1)} = C_{lq}^{(3)}$



Capdevila et al, 1712.01919

If the anomalies in $R_D^{(*)}$ persist, expect large deviations in $B \to K^{(*)}\tau^+\tau^-$ and $B_s \to \tau^+\tau^-$

If not, these observables combined will constrain the relevant operators to O(10 TeV)

Ho, Jiang, Kwok, Li, Liu 2212.02433

Tests of lepton flavour universality in tau decays

$\mu - e$ universality

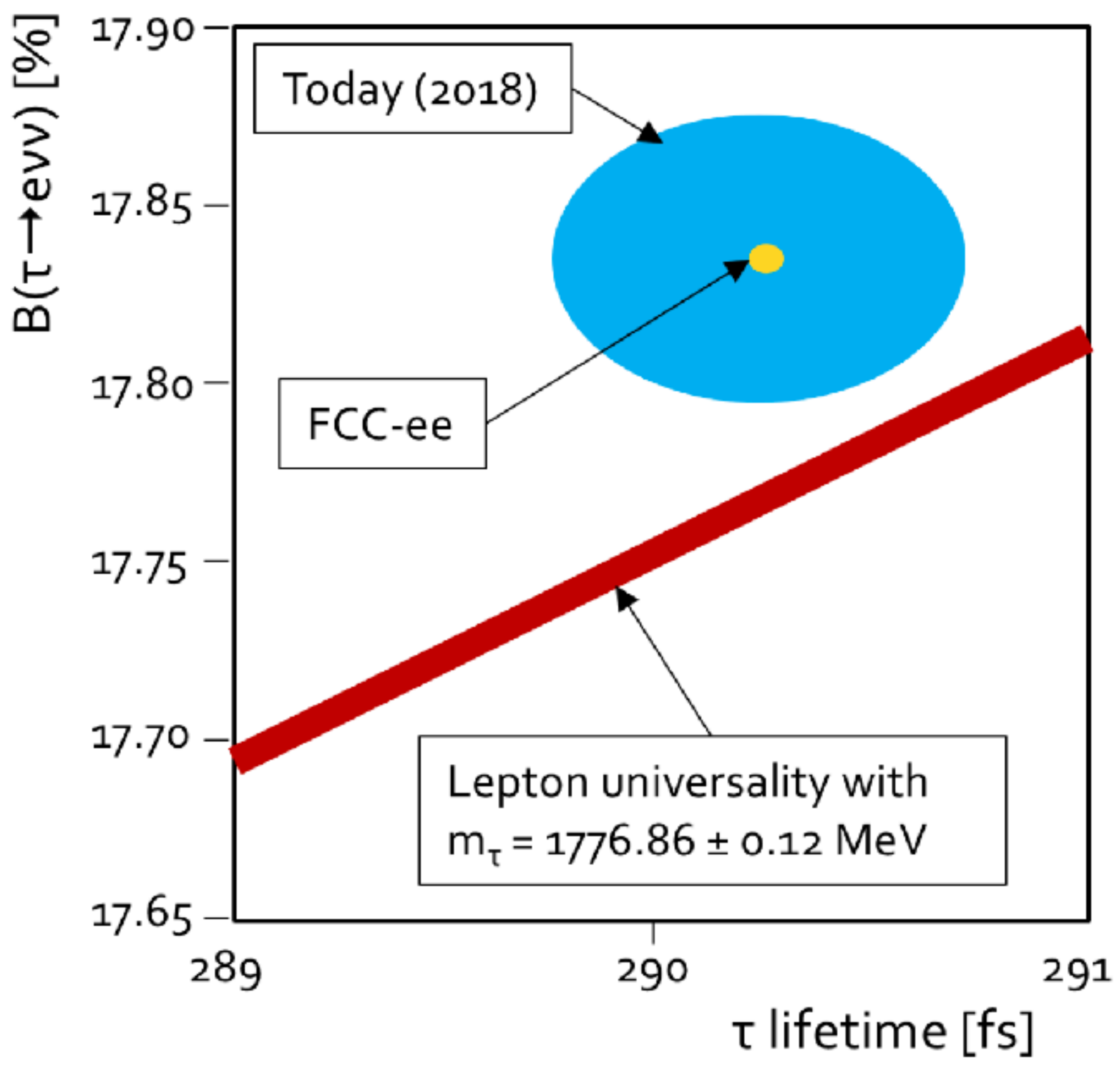
$$\left(\frac{g_\mu}{g_e}\right)^2 = \frac{\mathcal{B}(\tau \to \mu\bar{\nu}\nu)}{\mathcal{B}(\tau \to e\bar{\nu}\nu)} \cdot \frac{f_{\tau e}}{f_{\tau\mu}}$$

$\tau - \mu$ universality

$$\left(\frac{g_\tau}{g_\ell}\right)^2 = \frac{\mathcal{B}(\tau \to \ell\bar{\nu}\nu)}{\mathcal{B}(\mu \to \ell\bar{\nu}\nu)} \cdot \frac{\tau_\mu m_\mu^5}{\tau_\tau m_\tau^5} \cdot \frac{f_{\mu e}}{f_{\tau\ell}} \cdot \frac{R_\gamma^\mu R_W^\mu}{R_\gamma^\tau R_W^\tau}$$

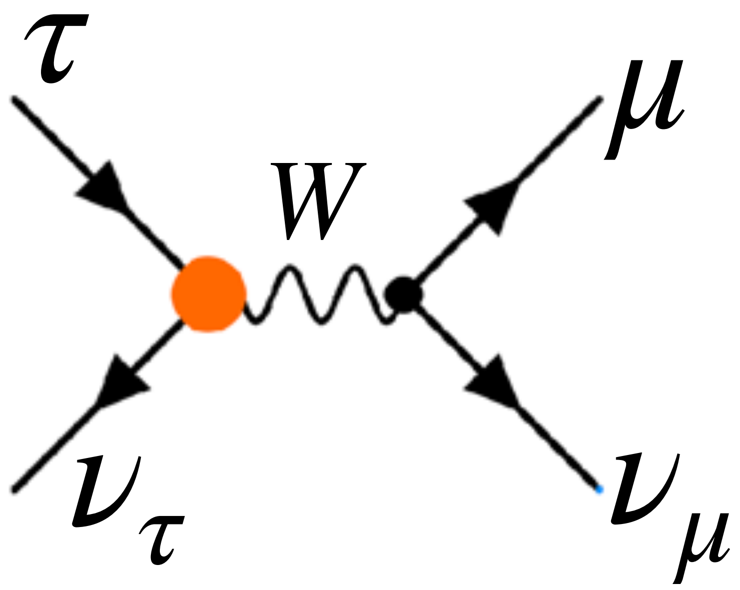
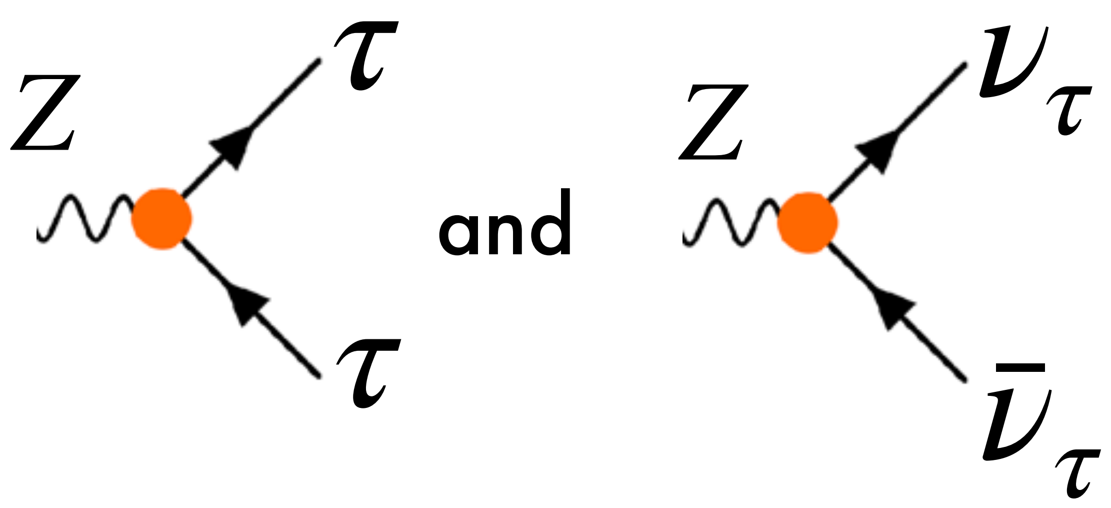
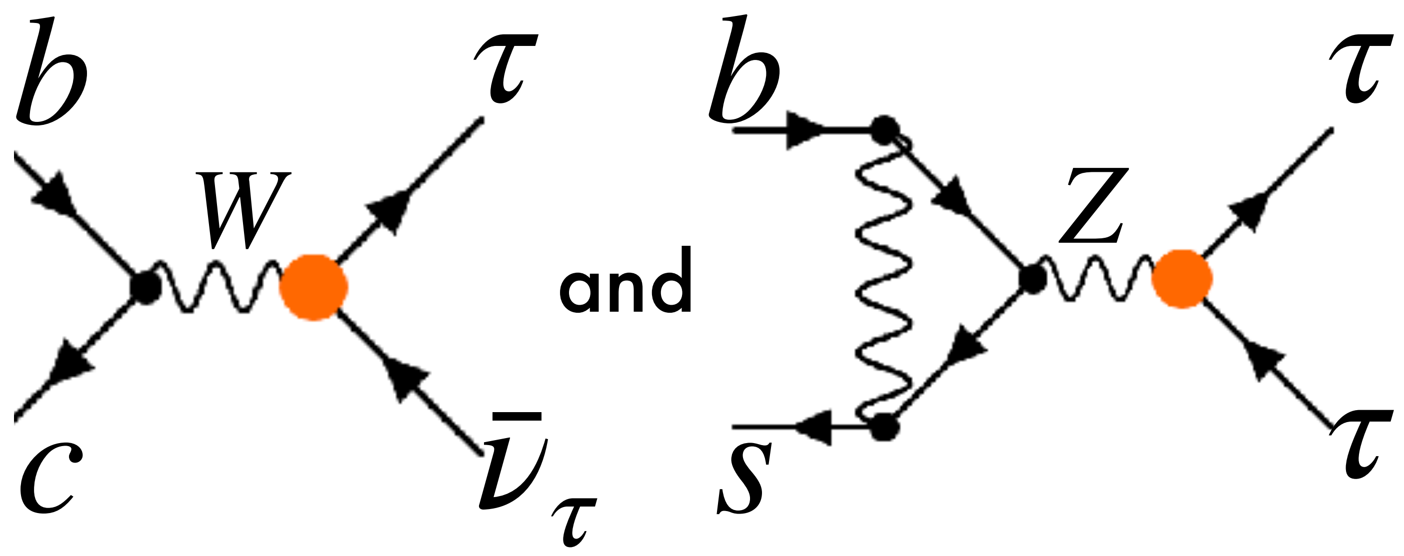
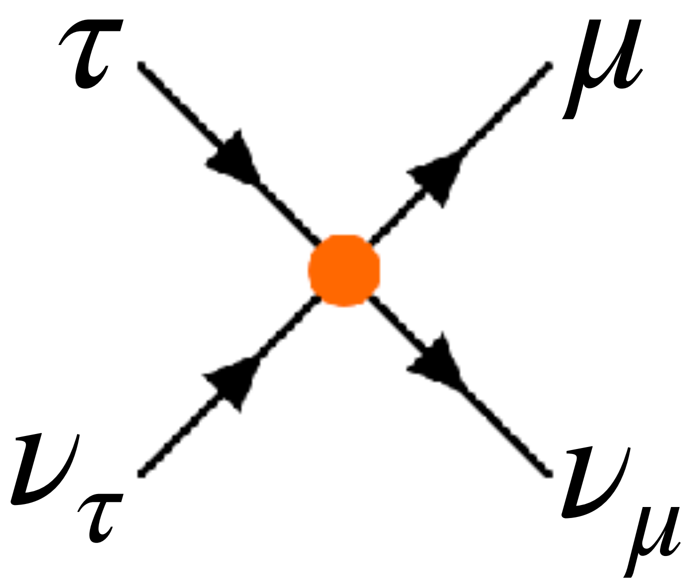
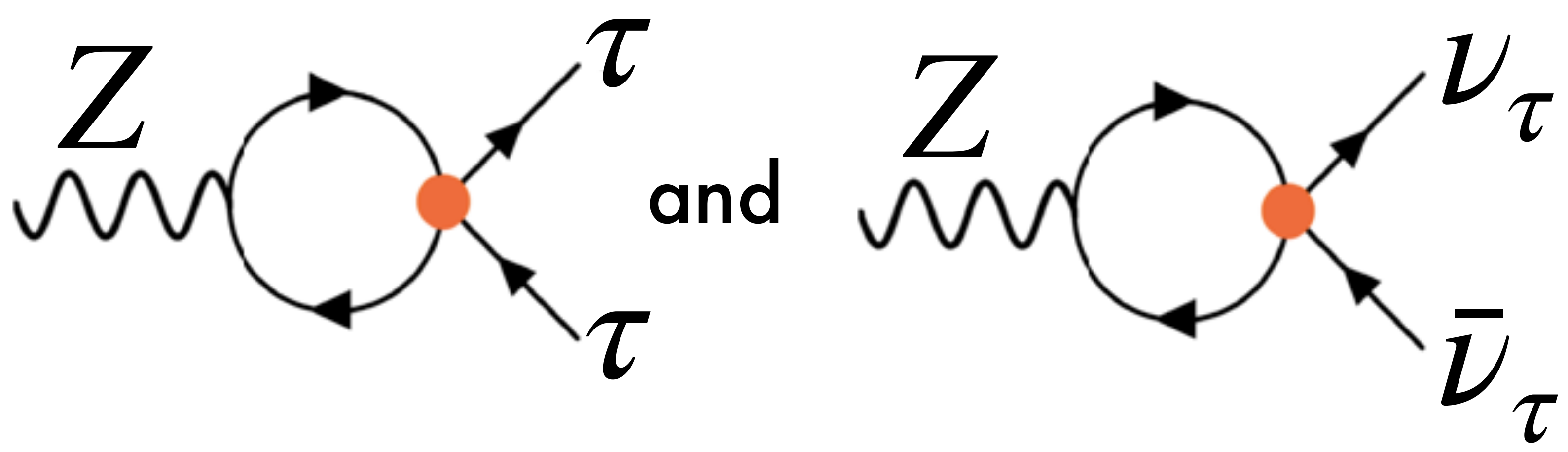
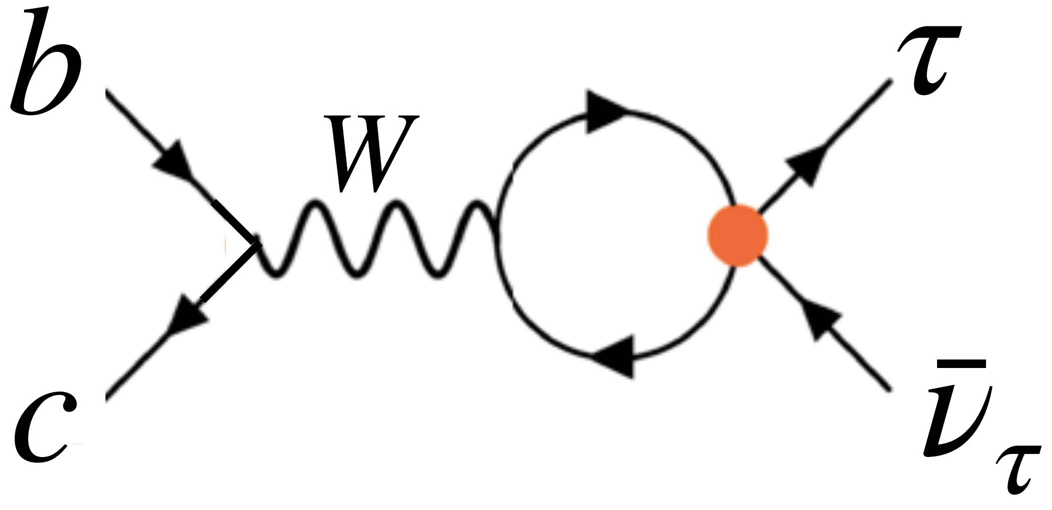
Observable	Present value ± error	FCC-ee stat.	FCC-ee syst.
m_τ (MeV)	1776.86 ± 0.12	0.004	0.1
$\mathcal{B}(\tau \to e\bar{\nu}\nu)$ (%)	17.82 ± 0.05	0.0001	0.003
$\mathcal{B}(\tau \to \mu\bar{\nu}\nu)$ (%)	17.39 ± 0.05	0.0001	0.003
τ_τ (fs)	290.3 ± 0.5	0.001	0.04

Dam, 1811.09408



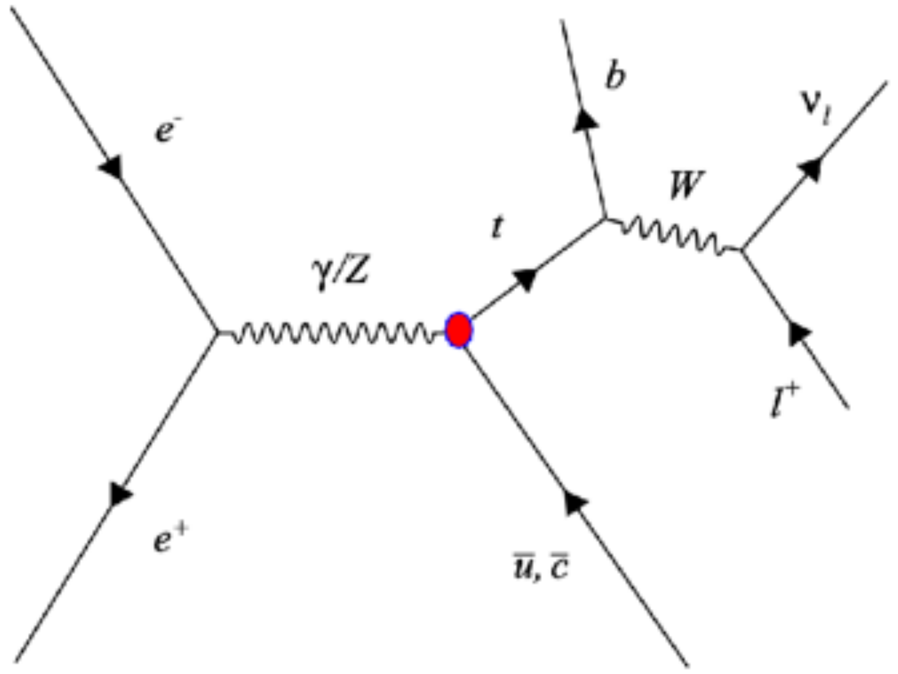
Lepton flavour universality tests

All the tests of LFUV can be tests of the same physics

	Tau decays	Z decays	B decays
$O_{\phi l}^{(1,3)}$ $(\phi^\dagger D_\mu \tau^a \phi)(\bar{L}^3 \gamma^\mu L^3)$			
O_{ll} $(\bar{L}^2 \gamma_\mu L^2)(\bar{L}^3 \gamma^\mu L^3)$			

Top FCNCs

Top FCNCs can be searched for in top decay at $t\bar{t}$ run of FCC-ee

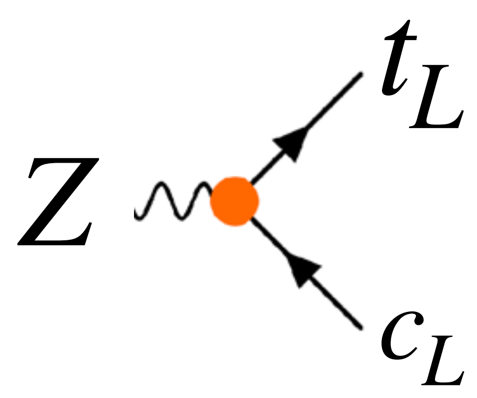


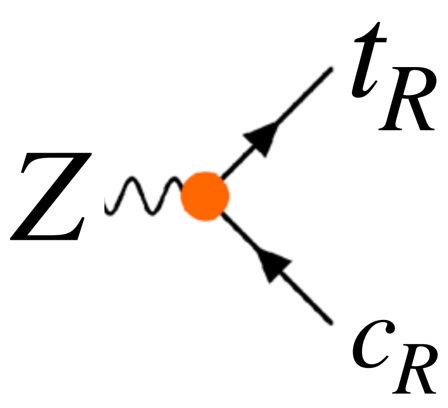
Also in single top production at $\sqrt{s} = 240$ GeV (HZ) run

Khanpour et al, 1408.2090

Effective operators contributing to t-q-Z coupling:

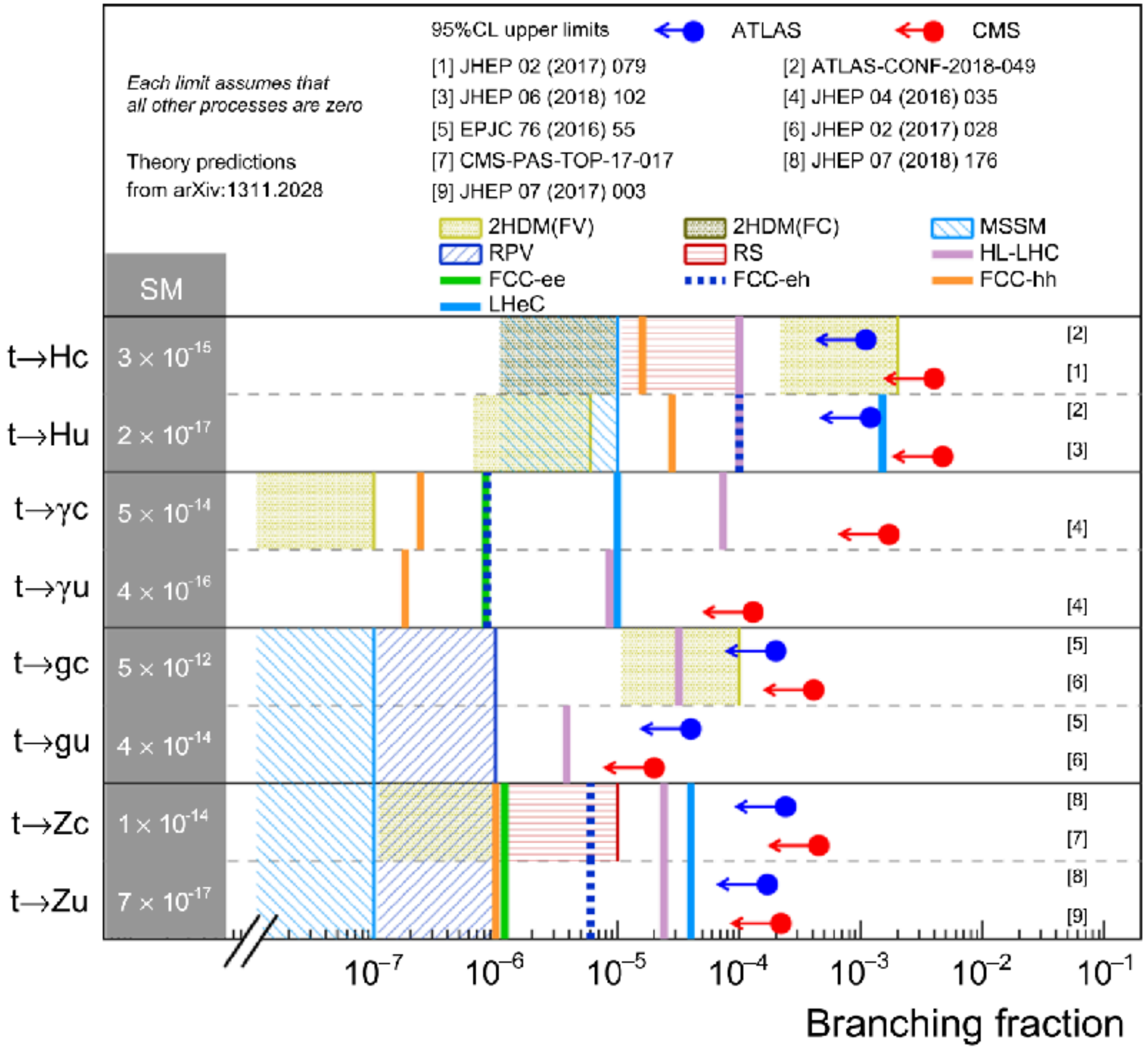
$$O^{(1,3)}_{\phi q} \qquad O_{\phi u}$$



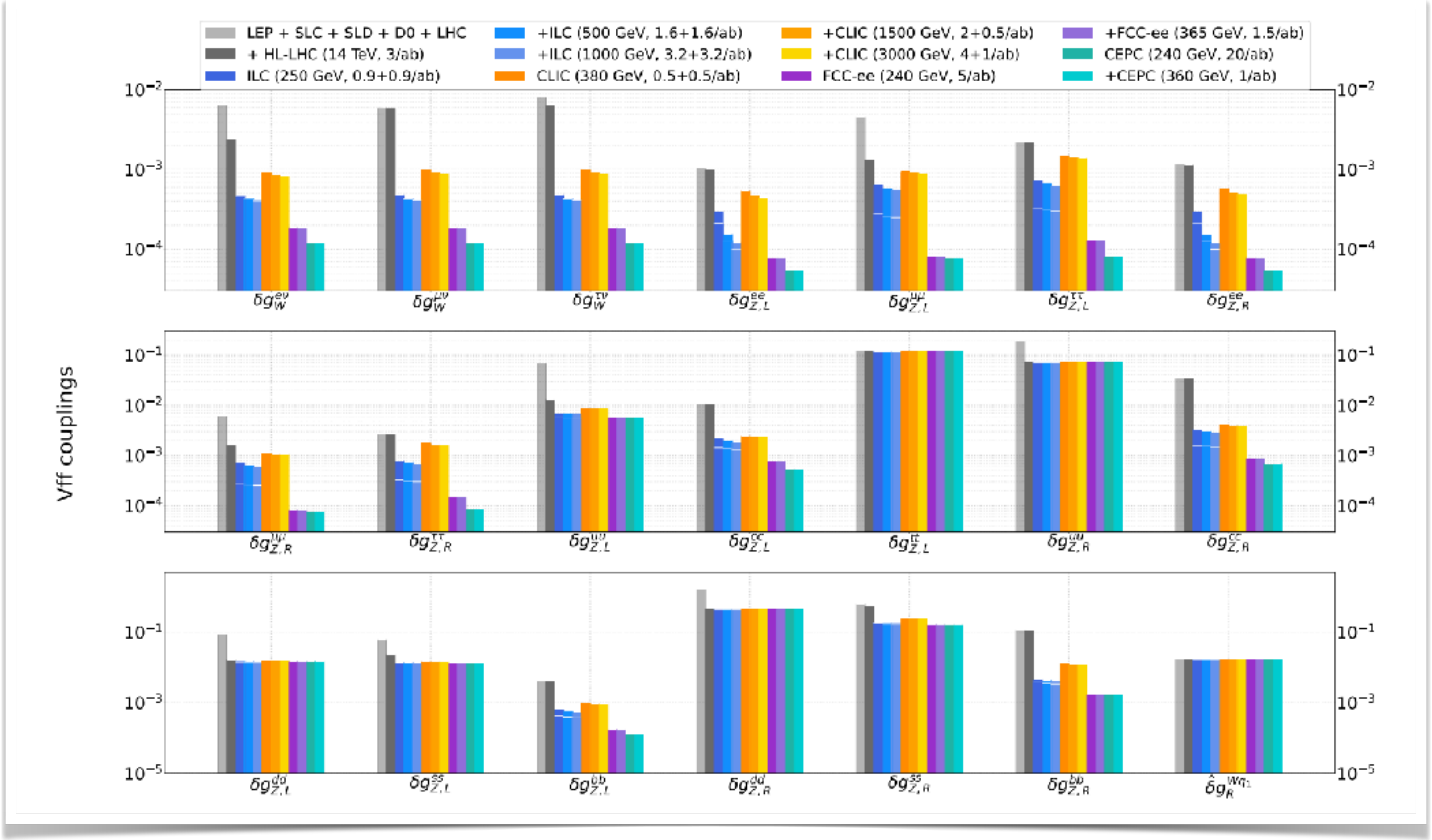


Also gives Z-b-s coupling

Future Circular Collider Conceptual Design Report Volume 1



Z pole at FCC-ee



De Blas et al, 2206.08326

LEP: 17 million Zs

FCC-ee: 5×10^{12} Zs

Bounds at better than per-mille level on most Z coupling deviations

SMEFT on the Z pole

Out of 2499 coefficients in dimension 6 SMEFT, 23 enter Z pole at tree level

Han, Skiba hep-ph/0412166
Berthier, Trott 1502.02570, ...

$\bar{\psi}\psi HD$

$$\{C_{HWB}, C_{HD}, C_{Hl}^{(1)}, C_{Hl}^{(3)}, C_{Hq}^{(1)}, C_{Hq}^{(3)}, C_{Hu}, C_{Hd}, C_{He}, C'_{ll}\}$$

induces muon decay $\Longrightarrow$ shifts G_F

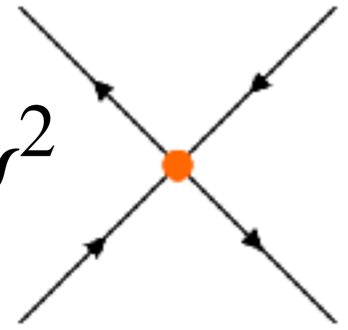
$\propto S$

$\propto T$

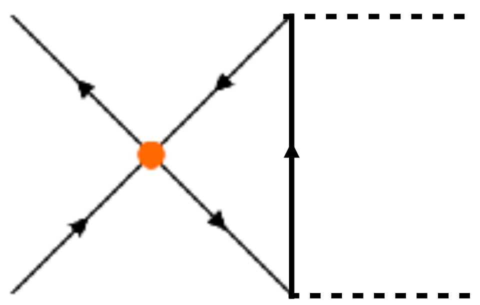
shift Z-fermion couplings

But any particular set of coefficients is not scale invariant in general

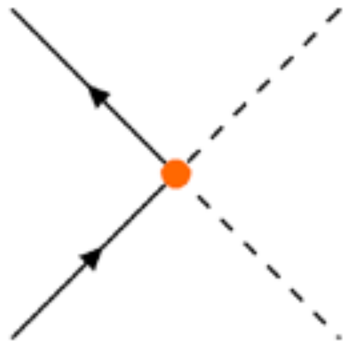
e.g. $\bar{\psi}^2\psi^2$



can be put into a loop:



e.g. $\bar{\psi}\psi HD$



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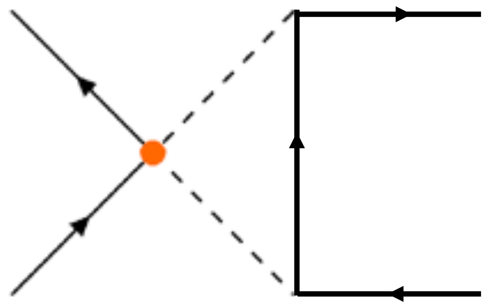
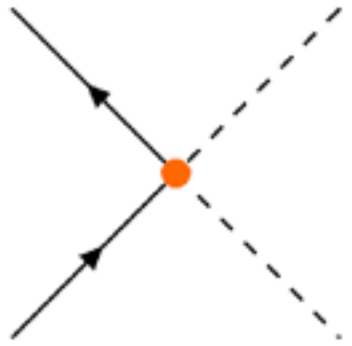


Which gives a divergent contribution to:



$\bar{\psi}\psi HD$

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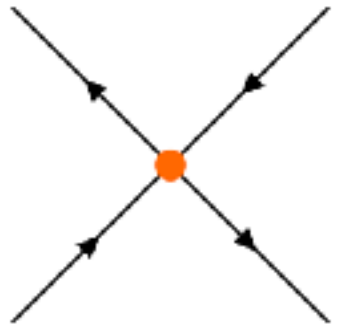


$\bar{\psi}^2\psi^2$

4-fermion operators can generate Z-pole

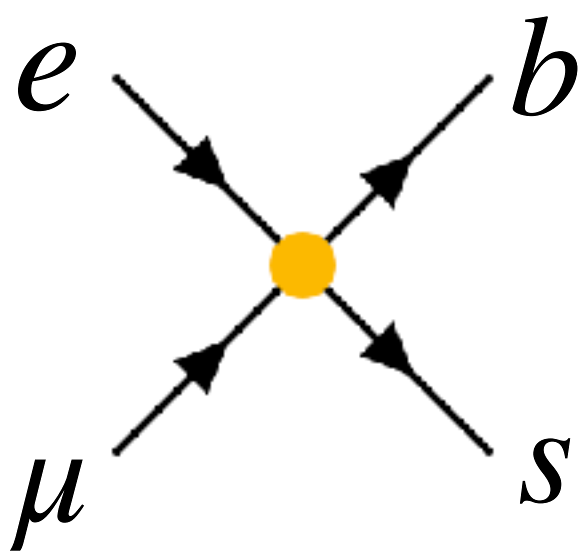
...and vice versa

Flavour vs Z pole: SMEFT and beyond

Flavour off-diagonal operators are protected by SM flavour symmetries from running into Z-pole observables

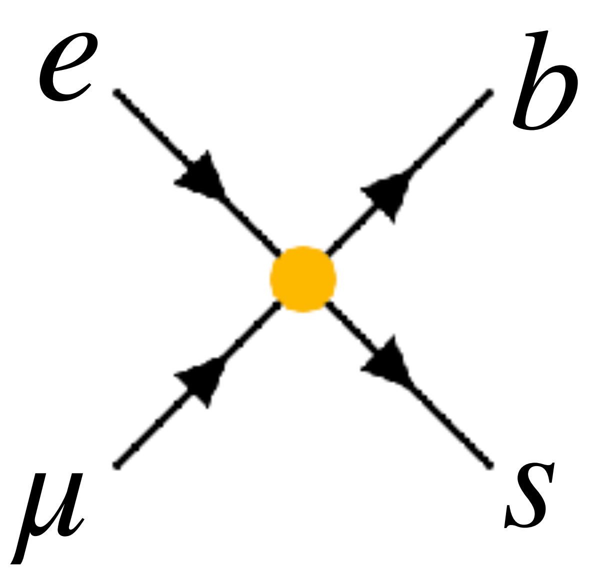
[Machado, SR, Sutherland, JHEP 03 (2023) 226]

e.g.

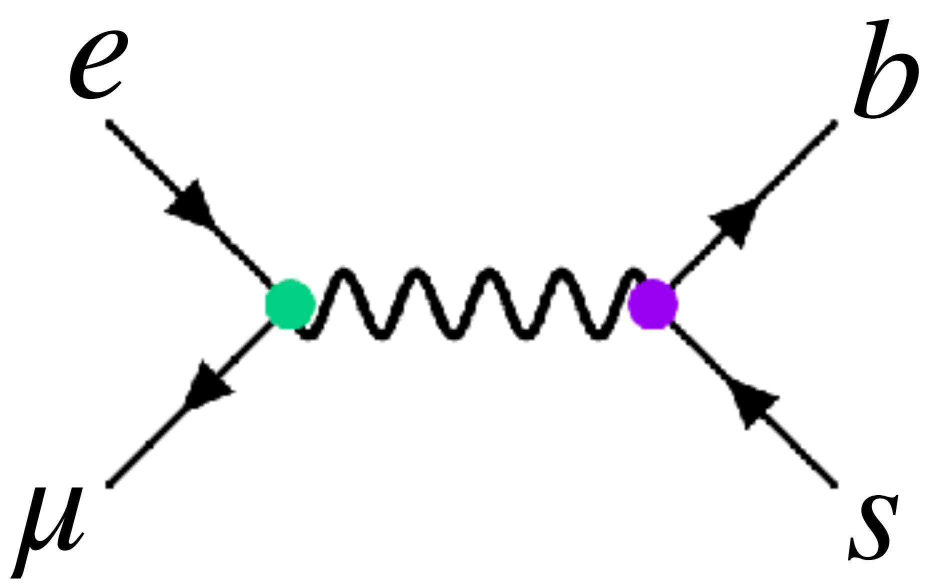


But in (tree level) UV completions, not generally possible to create flavourful operators on their own

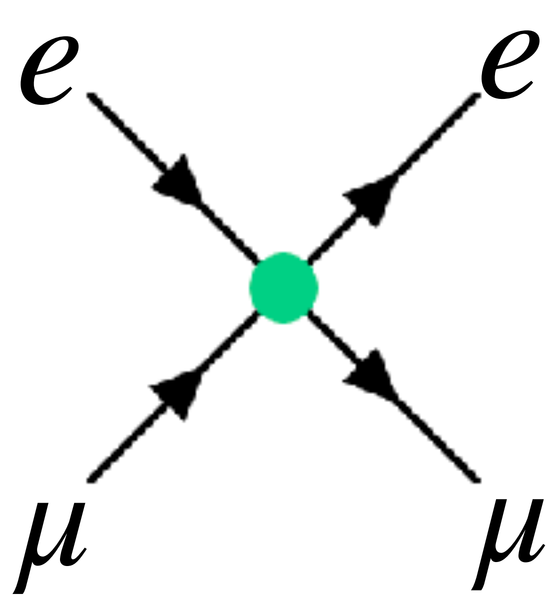
e.g.

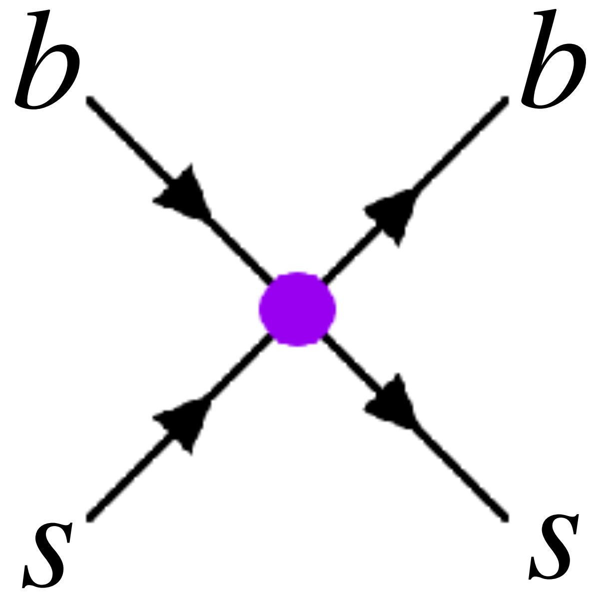


could be UV completed by:



which would inevitably also generate:



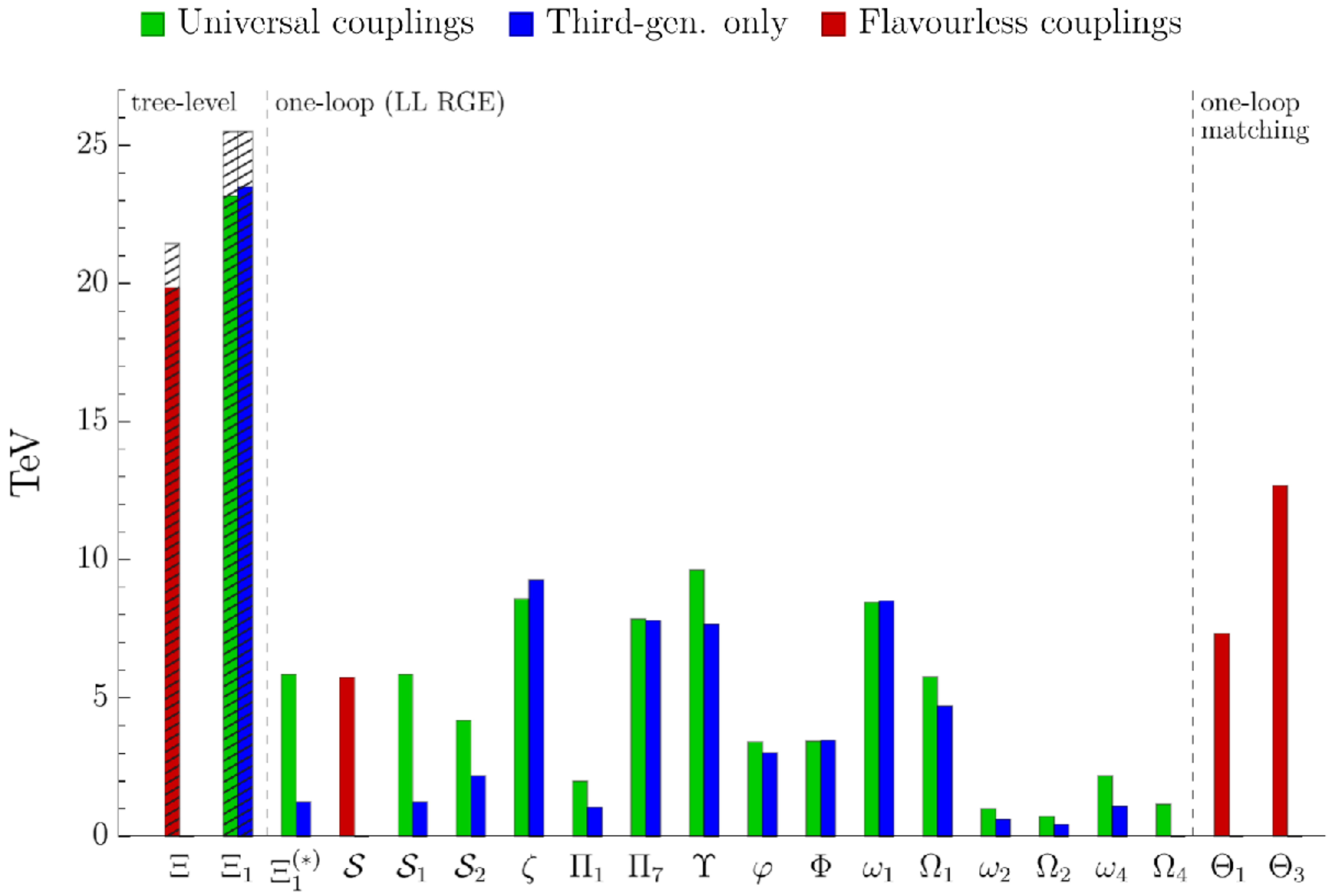


More general arguments can be made from sum rules, e.g. Remmen & Rodd 2010.04723

Investigated all tree-level UV completions: apart from a couple of (weird!) exceptions, not possible to find a flavour structure that avoids Z pole @ 1 loop!

Allwicher, McCullough, SR, 2408.03992

FCC-ee projections: scalars



All scalar states which match at tree level to SMEFT at dim 6

"Granada Dictionary": Criado et al., 1711.10391

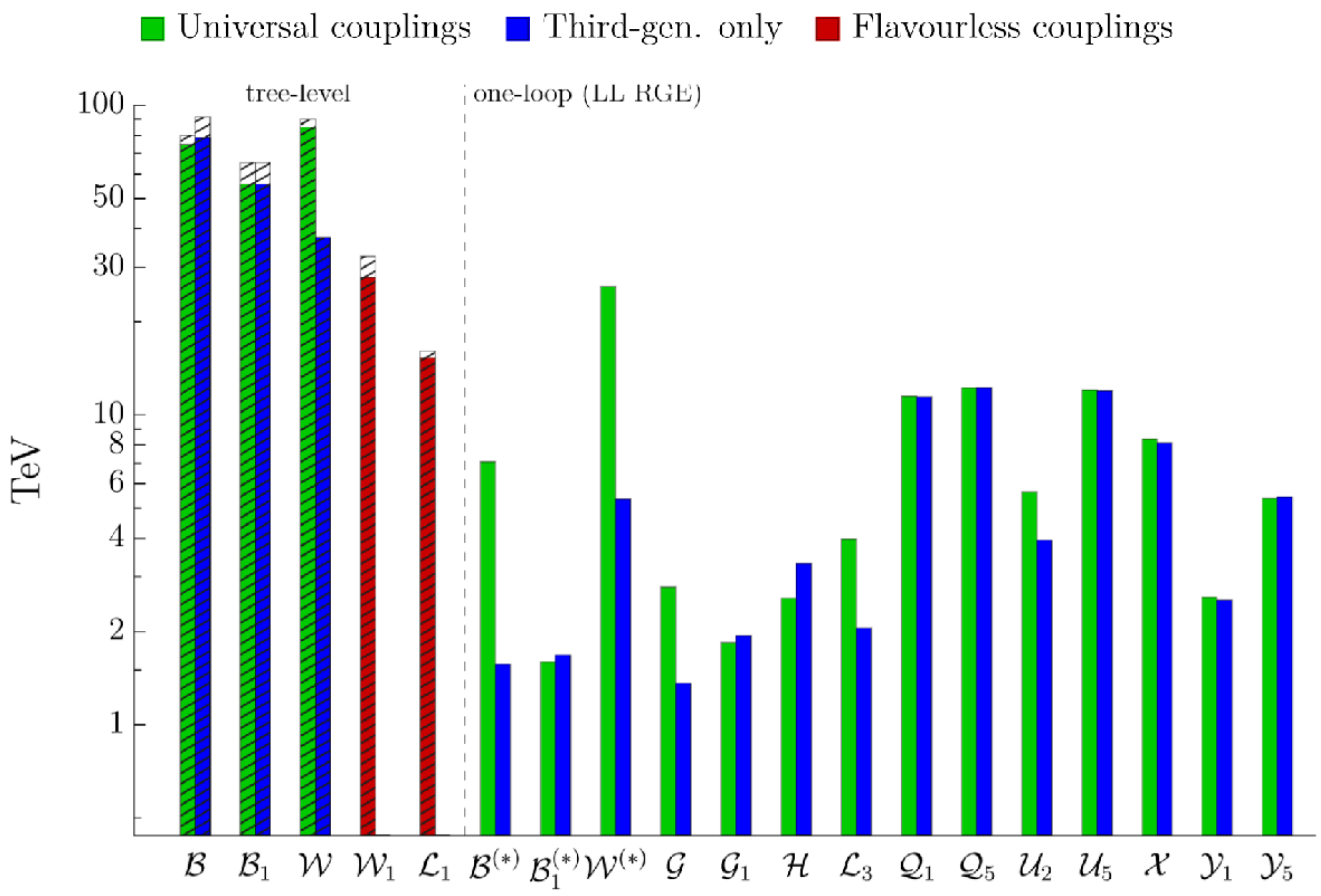
Weakest constraints on states which couple only to quarks

(*): turning off a coupling to Higgs

hatched = tree level limits, without RG running

Allwicher, McCullough, SR, 2408.03992

FCC-ee projections: vectors



All vector states which match at tree level to SMEFT at dim 6

"Granada Dictionary": Criado et al., 1711.10391

Weakest constraints on states which couple only to quarks

($*$): turning off a coupling to Higgs

hatched = tree level limits, without RG running

Allwicher, McCullough, SR, 2408.03992

FCC-ee physics overview

After the LHC, questions will still remain about TeV-scale NP

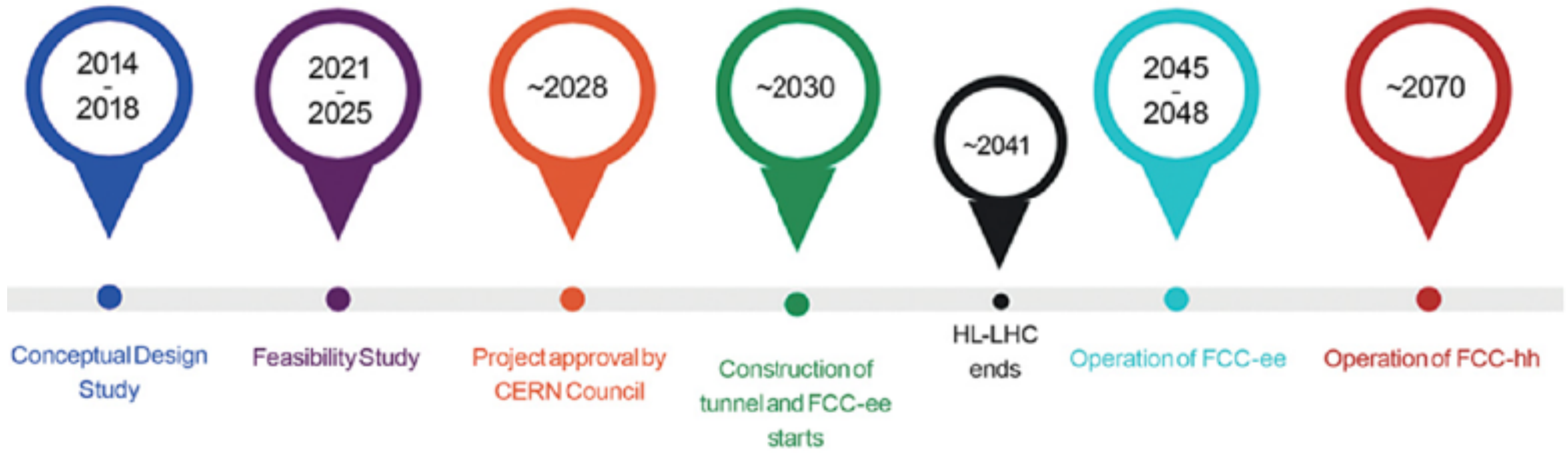
FCC-ee provides multiple lines of attack to close in on these, including:

- *Flavour factory* via copious b, c mesons and τs produced at the Z pole
- Measurements of *Higgs couplings to fermions*
- *Precision Z pole and W pole* measurements
- *Top precision*

Can close many loopholes!

No particle physics on a dead planet

FCC timeline



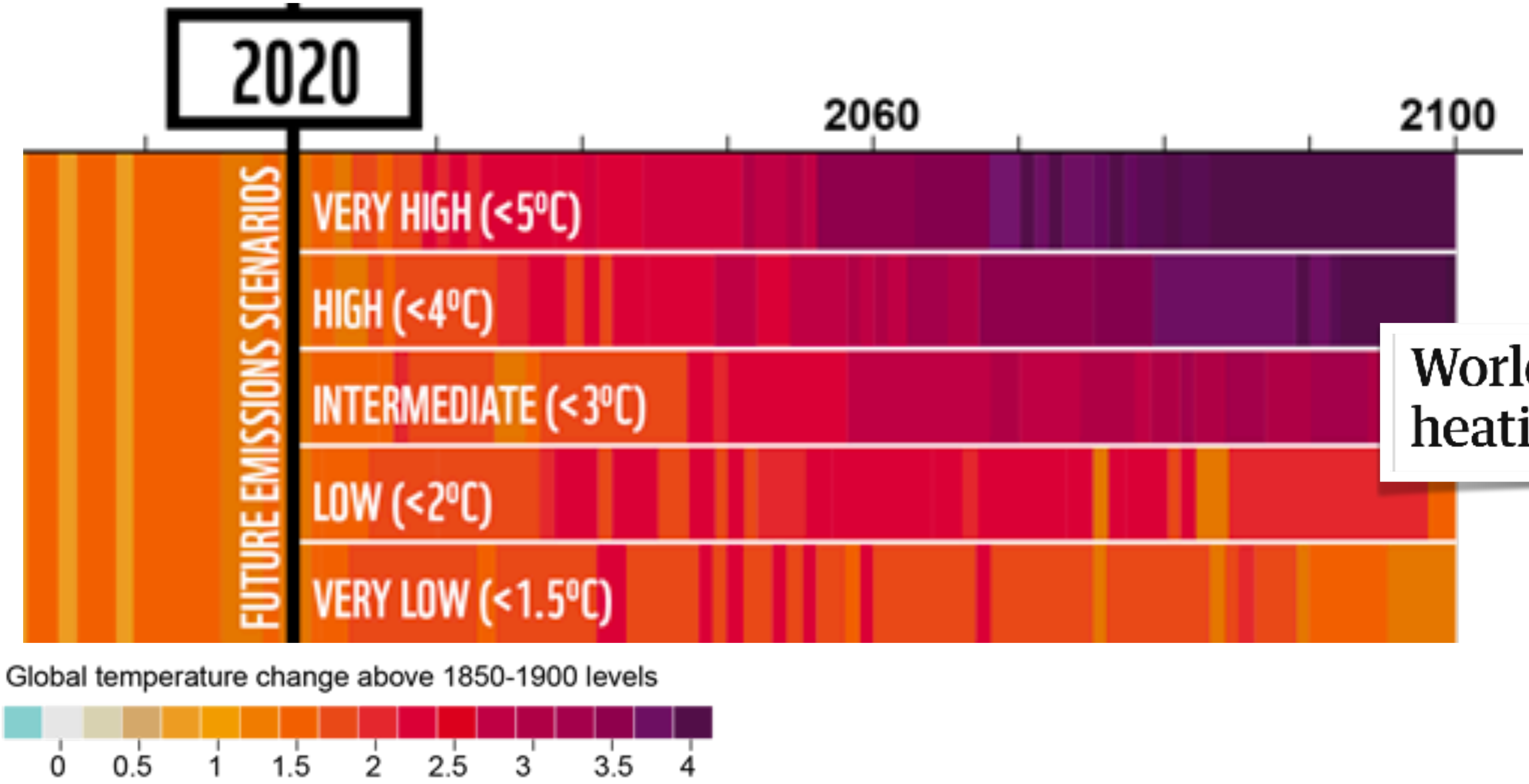
CERN Courier:

ACCELERATORS | MEETING REPORT

Towards a century of trailblazing physics

1 September 2023

IPCC timeline

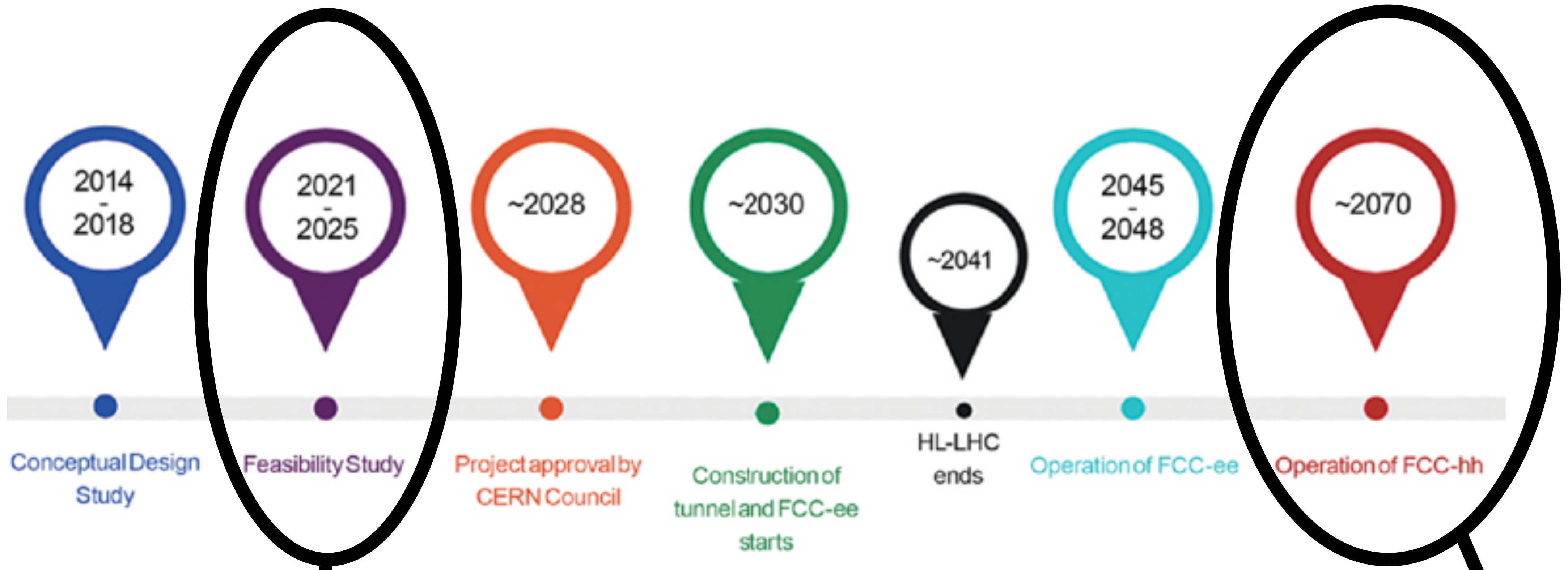


Guardian:

World facing 'hellish' 3C of climate heating, UN warns before Cop28

No particle physics on a dead planet

FCC timeline



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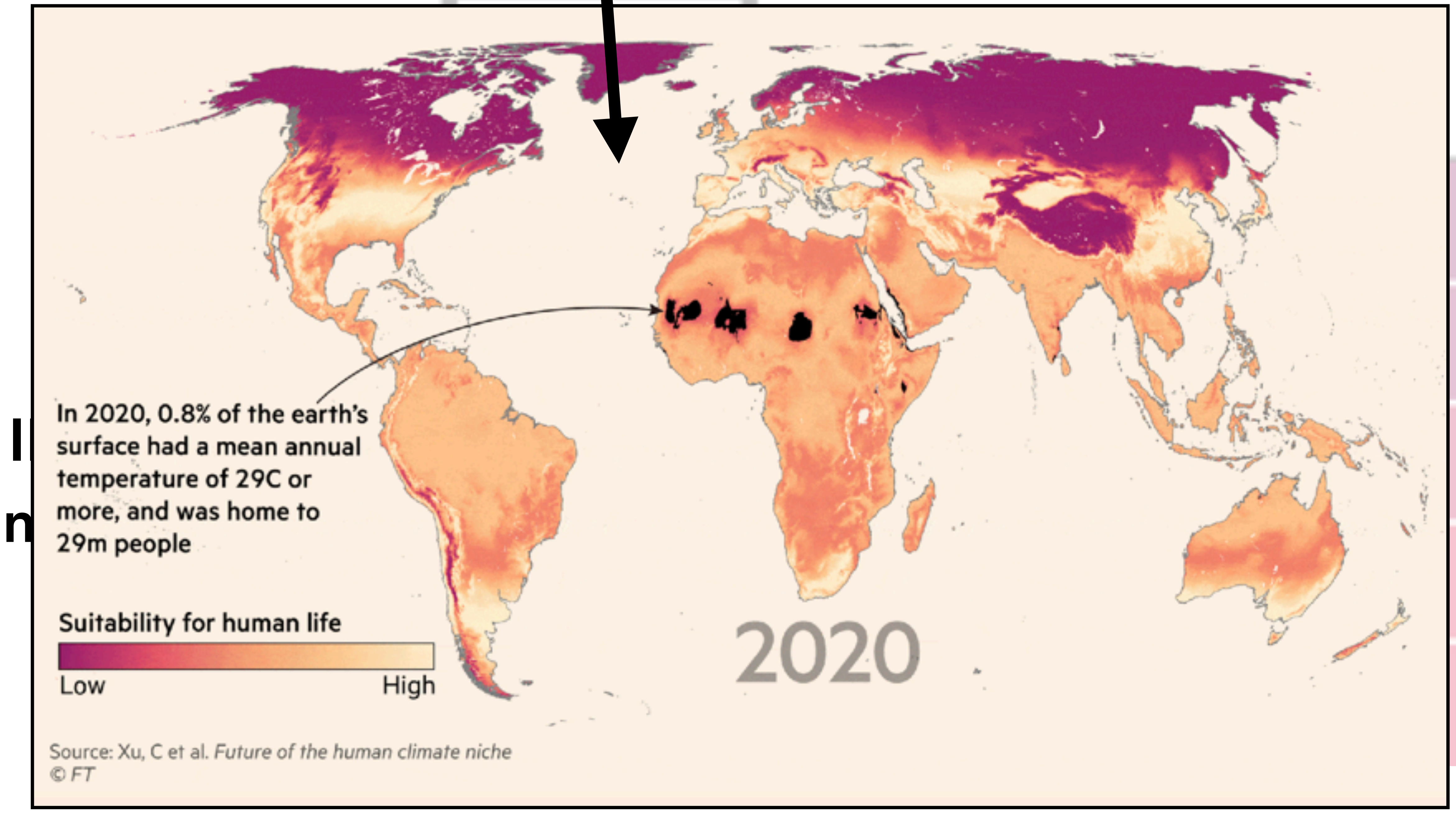

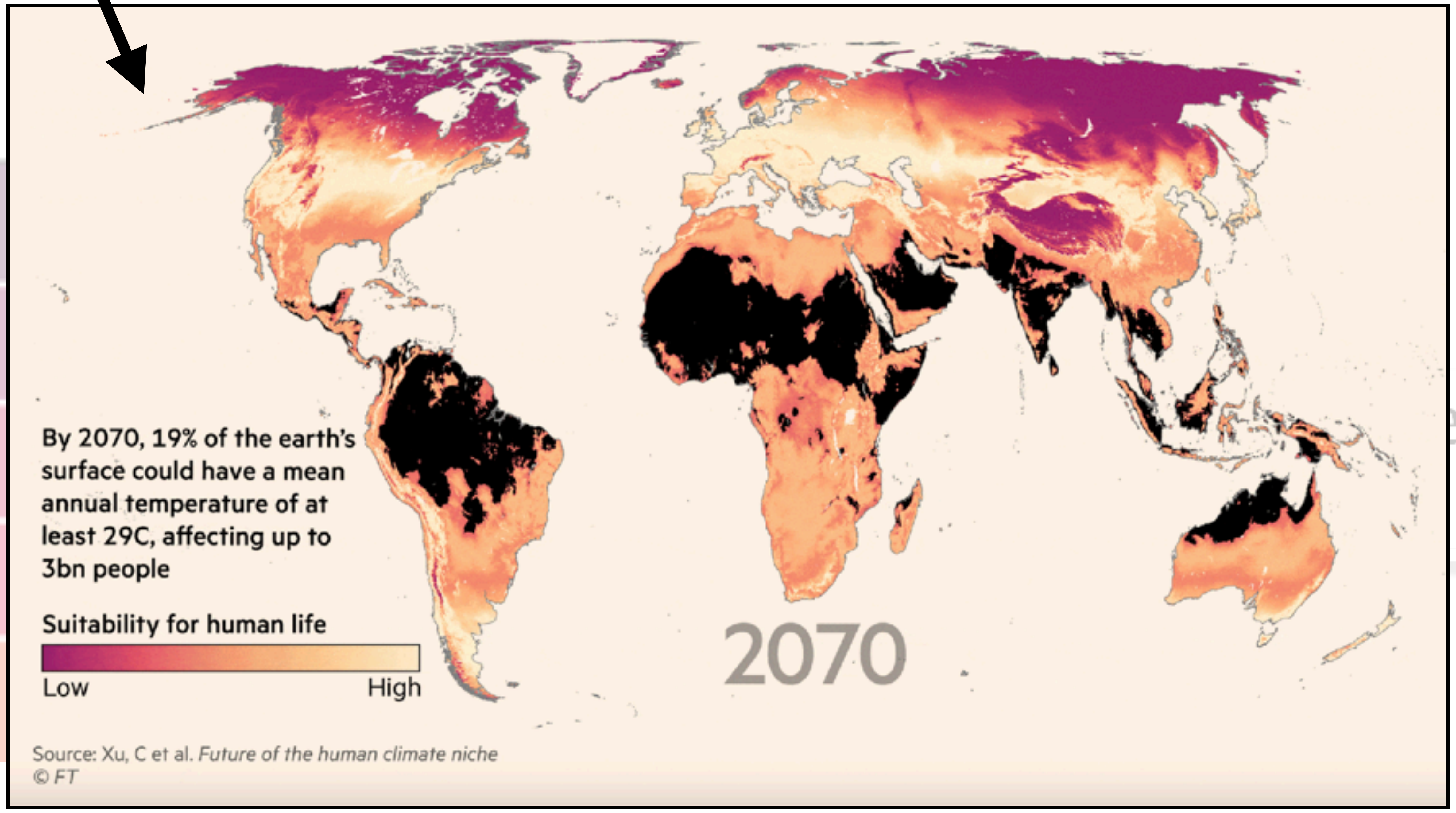

FT article: https://www.ft.com/content/072b5c87-7330-459b-a947-be6767a1099d

Based on this paper: https://www.pnas.org/doi/10.1073/pnas.1910114117

The climate movement & scientists as activists

"'Anything else you're interested in is not going to happen if you can't breathe the air and drink the water. Don't sit this one out. Do something. You are by accident of fate alive at an absolutely critical moment in the history of our planet.' - Carl Sagan"

Perspective

Actions speak louder than words: the case for responsible scientific activism in an era of planetary emergency

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Get involved!

SCIENTISTS FOR EXTINCTION REBELLION

scientistsforxr.earth **(UK)**

scientist rebellion_

scientistrebellion.org **(international)**

London's Science Museum forced to cut ties with oil giant – and faces pressure over other sponsors

Campaigners welcome 'seismic shift' and urge museum bosses to review links with other fossil fuel sponsors

20TH JUNE 2024 BY WEALD ACTION GROUP

Horse Hill: Historic win as Supreme Court upholds landmark climate case

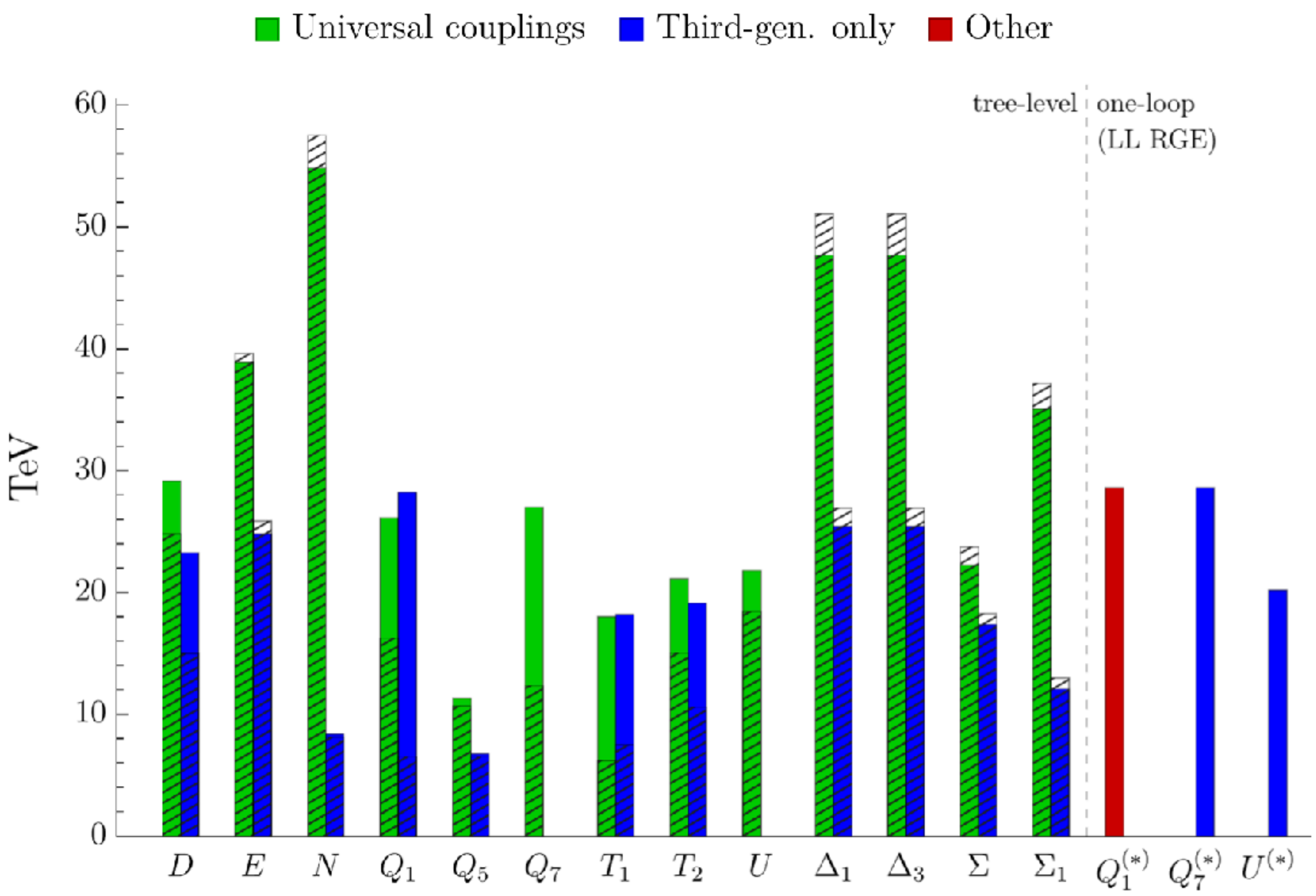
- Groundbreaking judgment could have profound implications for new fossil fuel projects, including Cumbrian coal mine and North Sea oil and gas fields

Coal mine plan quashed by High Court

Legal challenge to Rosebank oil field given go-ahead

Backup

FCC-ee projections: fermions

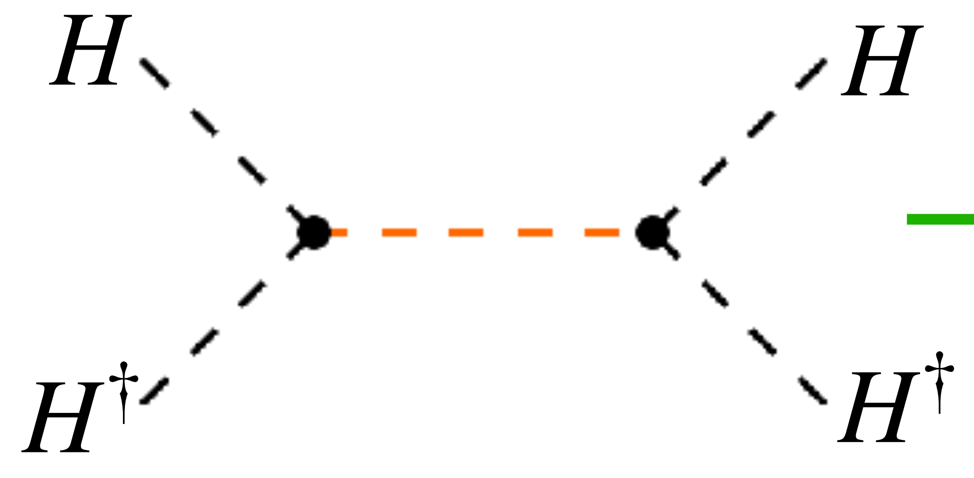


Explicit mediators

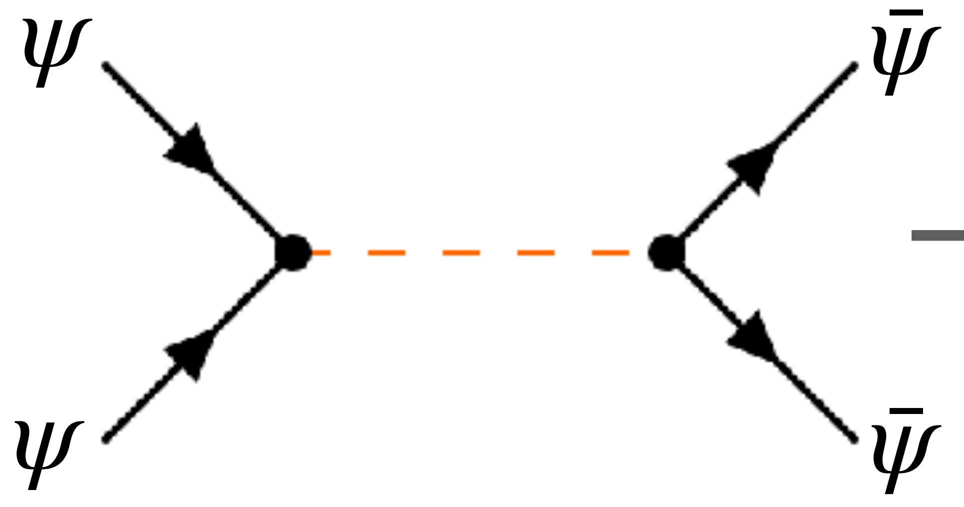
Criado et al., 1711.10391

Can study the full space of tree-level mediators using the “Granada dictionary”

Scalars



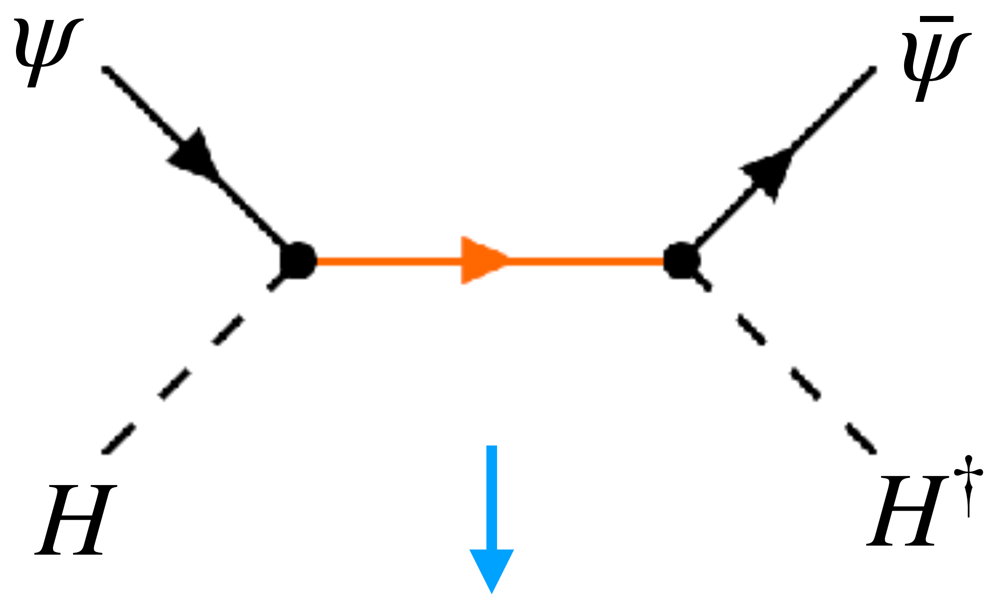
→ C_{HD} (T parameter)



→ $C_{\psi\bar{\psi}}$

Many do not generate Z pole operators at tree level

Fermions



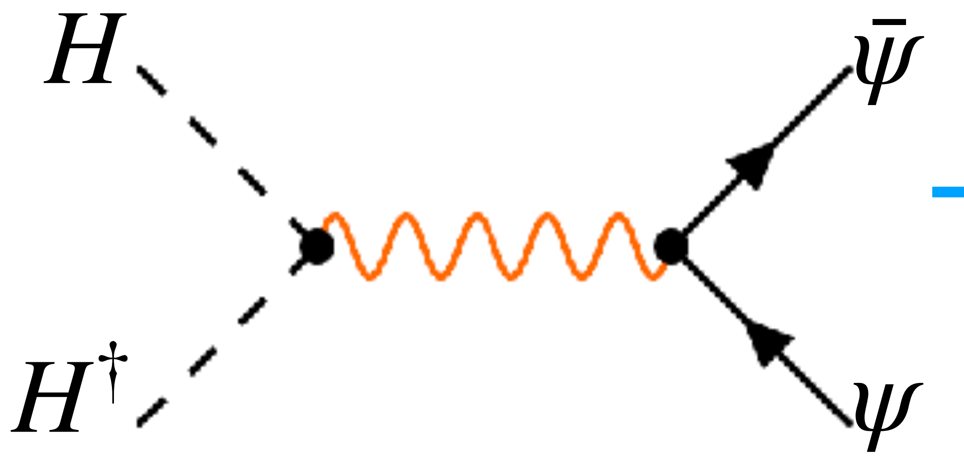
↓ $C_{H\psi}$

(shifts Z couplings to SM fermions)

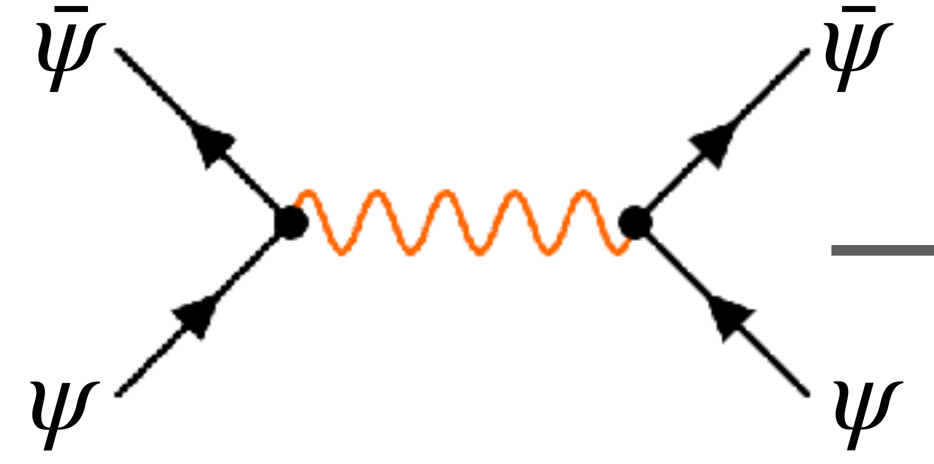
Always generate Z pole operators at tree level (unless couple only to tops)

Vectors

→ C_{HD} (T parameter)



→ $C_{H\psi}$ (shifts Z couplings to SM fermions)



→ $C_{\psi\bar{\psi}}$

Many do not generate Z pole operators at tree level

Z pole RGEs

$$\dot{C}_{HD} = -8N_c y_t^2 C_{Hu}^{33},$$
$$\dot{C}_{Hf_1}^{(1)jj} = 2N_c y_t^2 \left(-S_{f_1 u} C_{uf_1}^{33jj} + S_{f_1 q} C_{qf_1}^{33jj}\right),$$
$$\dot{C}_{Hl}^{(3)jj} = -2N_c y_t^2 C_{lq}^{(3)jj33},$$
$$\dot{C}_{Hq}^{(3)jj} = -2y_t^2 \left(2N_c C_{qq}^{(3)jj33} + C_{qq}^{(1)j33j} - C_{qq}^{(3)j33j}\right),$$

$\propto y_t^2$

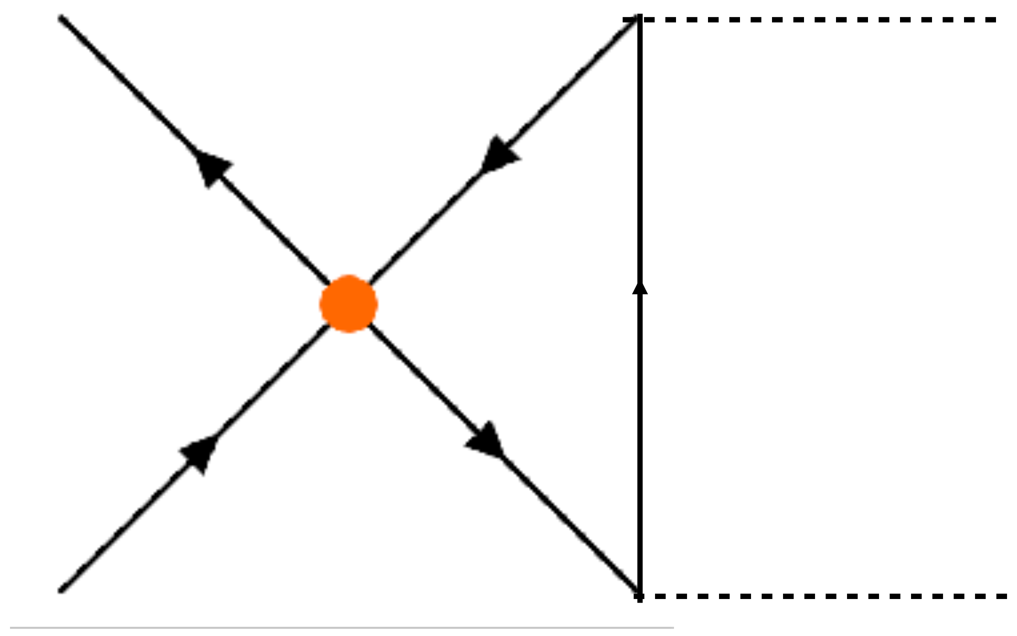
$$\dot{C}_{Hf_1}^{(1)jj} = \frac{4}{3} g_1^2 Y_h \sum_k \left[Y_e S_{f_1 e} C_{f_1 e}^{jjkk} + 2Y_l S_{f_1 l} C_{f_1 l}^{jjkk} + N_c \left(Y_u S_{f_1 u} C_{f_1 u}^{jjkk} + Y_d S_{f_1 d} C_{f_1 d}^{jjkk} + 2Y_q S_{f_1 q} C_{f_1 q}^{jjkk} \right) \right],$$

$\propto g_1^2$

$$\dot{C}_{Hl}^{(3)jj} = \frac{2}{3} g_2^2 \sum_k \left(C_{ll}^{jkkj} + N_c C_{lq}^{(3)jjkk} \right),$$
$$\dot{C}_{Hq}^{(3)jj} = \frac{2}{3} g_2^2 \sum_k \left(C_{lq}^{(3)kkjj} + 2N_c C_{qq}^{(3)kkjj} + C_{qq}^{(1)jkkj} - C_{qq}^{(3)jkkj} \right),$$
$$\dot{C}_{ll}^{1221} = \frac{2}{3} g_2^2 \left[C_{ll}^{2222} + C_{ll}^{2332} + C_{ll}^{1111} + C_{ll}^{1331} + N_c \sum_k \left(C_{lq}^{(3)22kk} + C_{lq}^{(3)11kk} \right) \right]$$

$\propto g_2^2$

Given expected precision at FCC-ee, how many models run into Z pole operators?



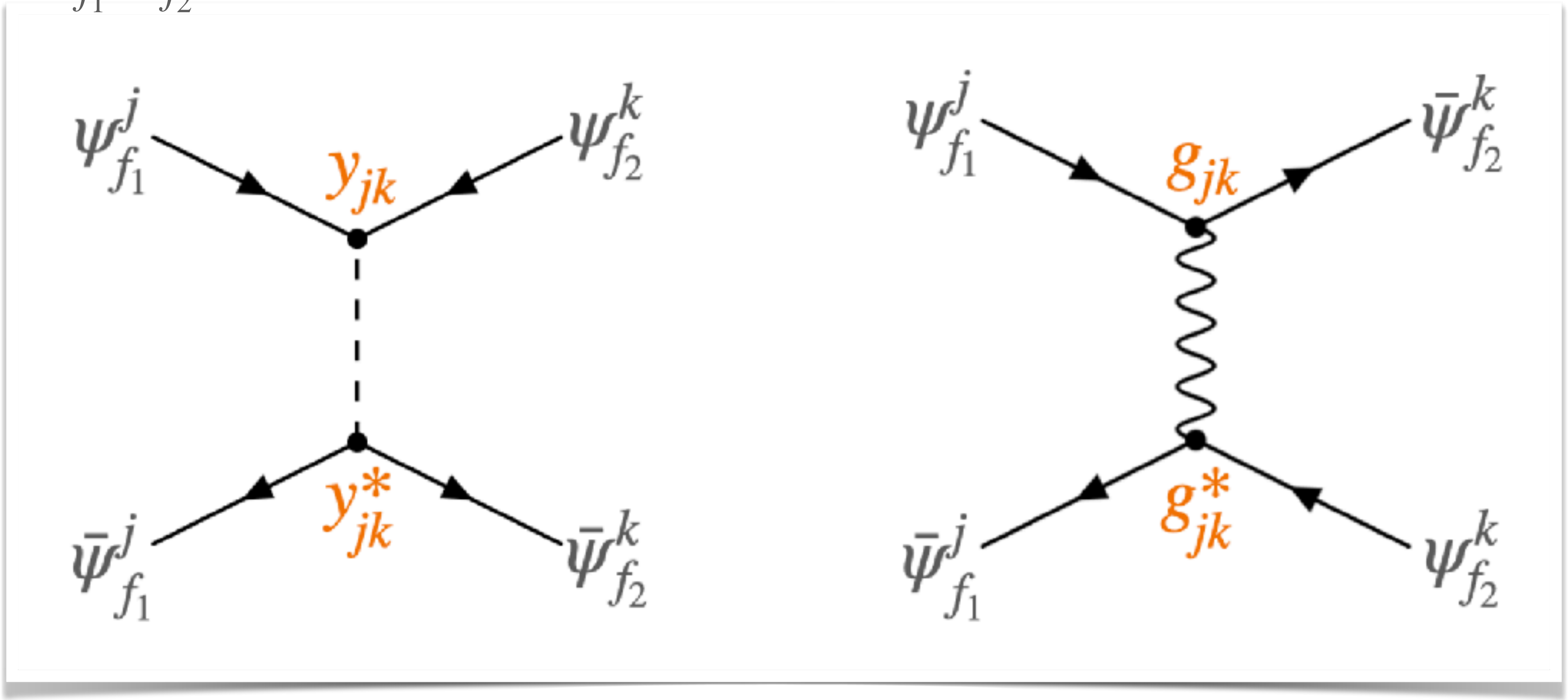
All states(*) produce 4 fermion operators

(*) a few scalar exceptions which couple to Higgs

In order to avoid producing effects at 1 loop, need to additionally produce zeroes in each of these equations…

Cancellations within the RGEs?

$\psi_{f_1}, \psi_{f_2} \in \{Q, u, d, L, e\}$



If a scalar or vector UV completion carries hypercharge:

$$C^{jjkk}_{\psi_{f_1}\psi_{f_2}} \propto |y_{jk}|^2 \quad \text{or} \quad \propto |g_{jk}|^2$$

Then the gauge-dependent RGEs become of the form:

$$\dot{C}^{jj}_{H f_1} \propto \sum_k |y_{jk}|^2$$

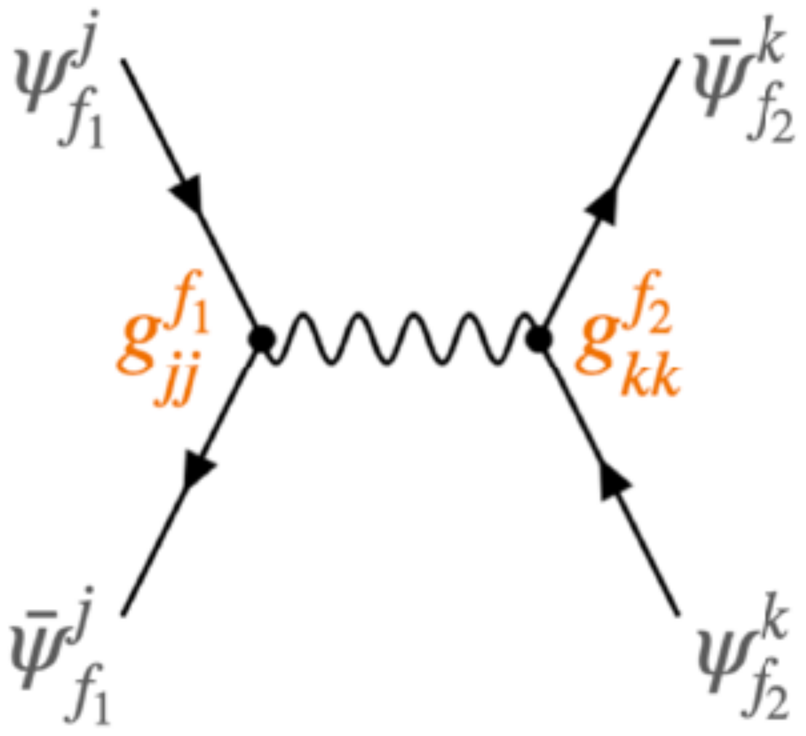
i.e. no zero solution unless all couplings are zero

Cancellations within the RGEs

What about zero hypercharge states?

Zero hypercharge scalars don’t produce 4-fermion operators: their effects depend on their coupling to Higgs

Vectors:



Now $C^{jjkk}_{\psi_{f_1}\psi_{f_2}} \propto g^{f_1}_{jj}\, g^{f_2}_{kk}$ no definite sign

$\mathcal{B} \sim (1,0,0)$ $\quad -\sum_{k=1}^{3}\left((g^e_{\mathcal{B}})_{kk} + (g^d_{\mathcal{B}})_{kk}\right) + 2\sum_{k=1}^{2}(g^u_{\mathcal{B}})_{kk} \stackrel{!}{=} 0, \quad (g^q_{\mathcal{B}})_{ij} \stackrel{!}{=} 0, \quad (g^l_{\mathcal{B}})_{ij} \stackrel{!}{=} 0, \quad (g^u_{\mathcal{B}})_{33} \stackrel{!}{=} 0$

Works for some anomaly-free $U(1)$ Z' models

$\mathcal{W} \sim (1,3,0)$ $\quad (g^l_{\mathcal{W}})_{ij} \stackrel{!}{=} 0, \quad (g^q_{\mathcal{W}})_{3j} \stackrel{!}{=} 0, \quad (g^q_{\mathcal{W}})_{22} \stackrel{!}{=} \pm(g^q_{\mathcal{W}})_{11}, \quad |(g^q_{\mathcal{W}})_{12}| \stackrel{!}{=} (g^q_{\mathcal{W}})_{11}\sqrt{4N_c - 1}$

Strong complementary constraints from kaon mixing

$\mathcal{G} \sim (8,1,0)$ No cancellations, but zero at 1 loop if couples only to RH tops

$\mathcal{H} \sim (8,3,0)$ No solutions

Flat directions

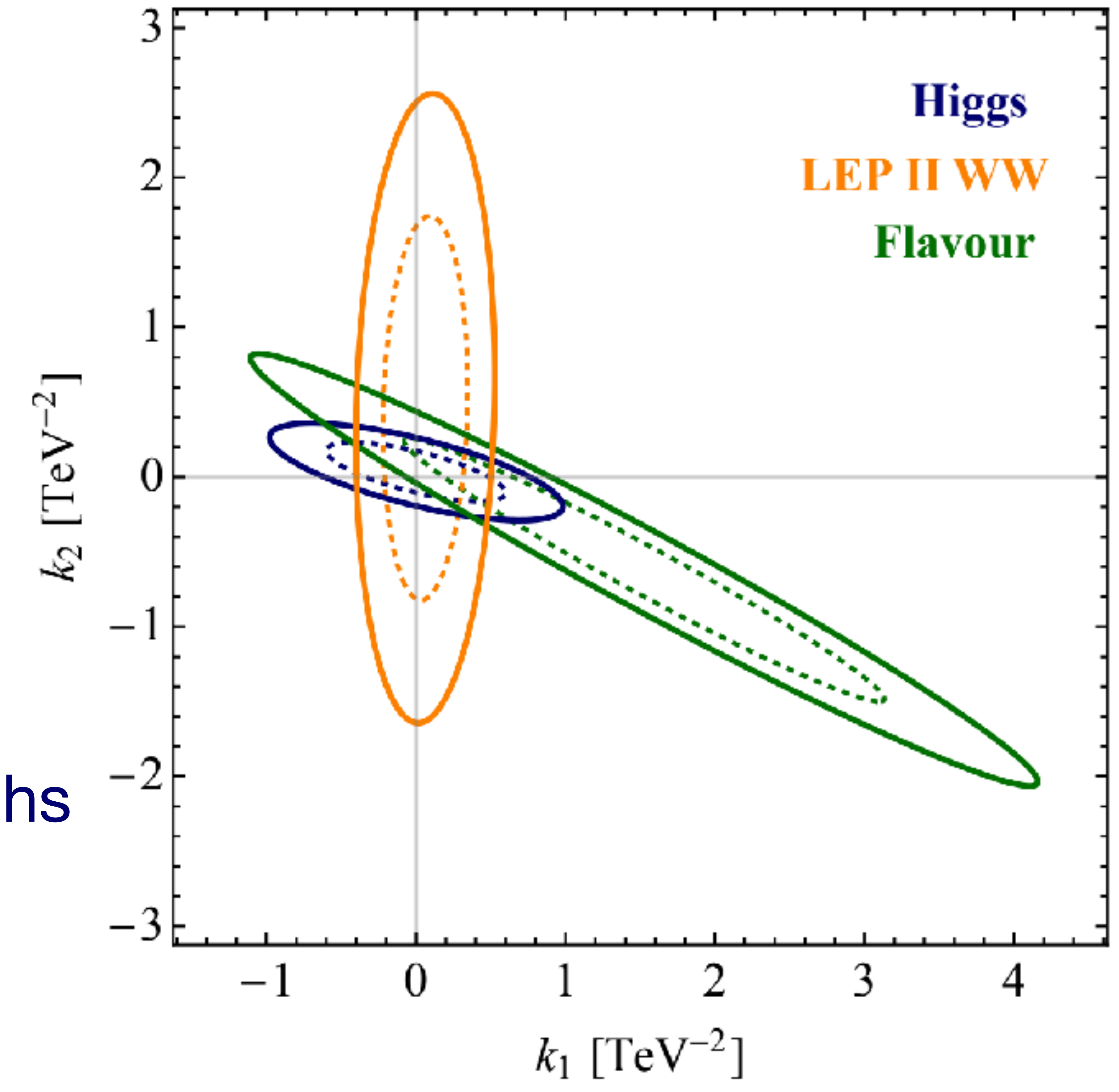
From the 23 Z-pole coefficients there are 3 flat directions

$$\mathcal{C}_0^{(1)} \propto [\mathcal{C}_{Hq}^{(1)}]_{33} - [\mathcal{C}_{Hq}^{(3)}]_{33},$$

$$\mathcal{C}_0^{(2)} \propto -\frac{g_Y}{g_L}\mathcal{C}_{HWB} + \sum_{i=1}^{3}\left([\mathcal{C}_{H\ell}^{(3)}]_{ii} + [\mathcal{C}_{Hq}^{(3)}]_{ii}\right),$$

$$\mathcal{C}_0^{(3)} \propto 2\,\mathcal{C}_{HD} - \frac{1}{2}\frac{g_L}{g_Y}\mathcal{C}_{HWB} + \sum_{\psi}\sum_{i} Y_\psi \mathcal{C}_{H\psi},$$

Aoude, Hurth, SR, Shepherd., 2003.05432



Tree level: Run I Higgs signal strengths

Tree level: LEP II $e^+e^- \to W^+W^-$

Loop level: meson decays/mixing

Origin of flat directions can be understood in terms of : EOM relations on TGC operators [Grojean, Skiba, Terning hep-ph/0602154]
or a reparameterisation invariance in $\psi\psi \to \psi\psi$ processes [Brivio, Trott 1701.06424]