BSM in Tera-Z

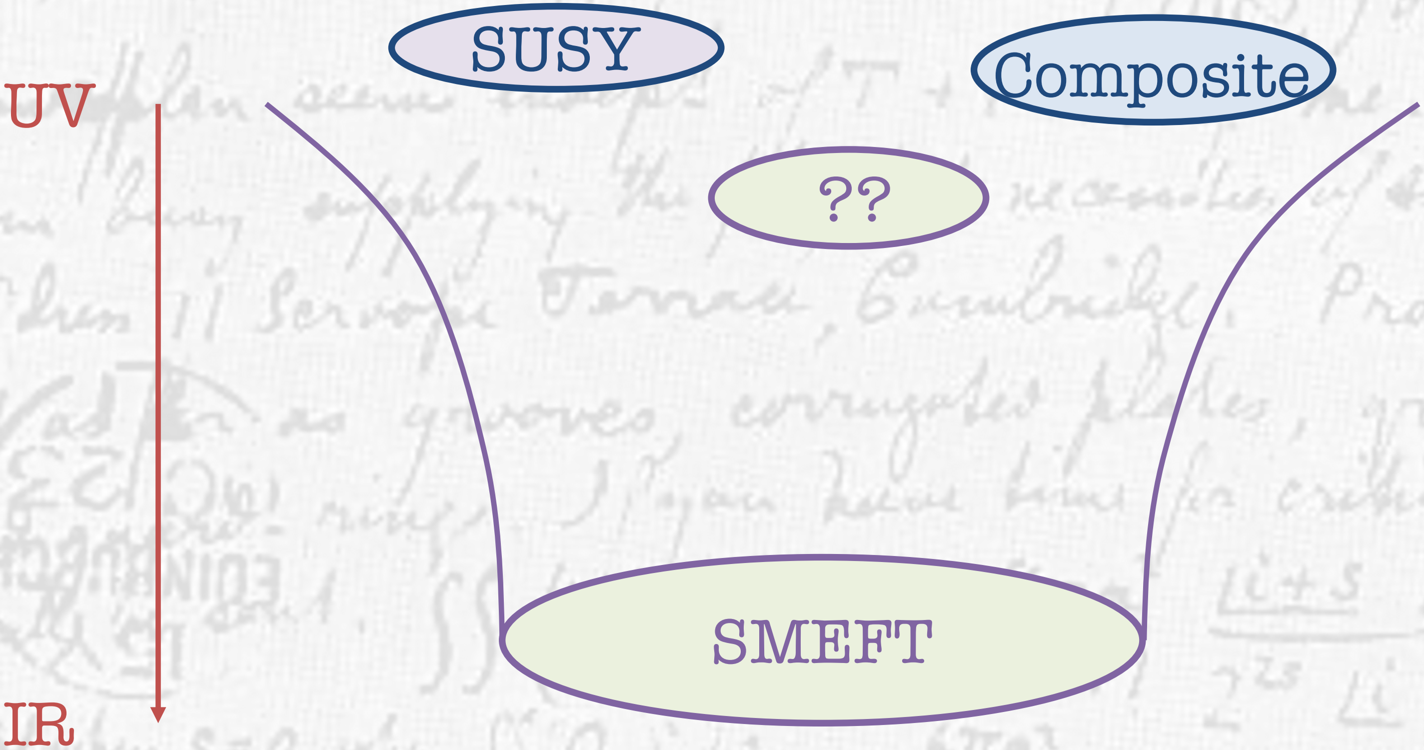
ILC IDT WG3

23.30, Thursday 14th Nov, 2024

Matthew McCullough

Effective Field Theory

What's the point of SMEFT?



SUSY

Composite

??

UV

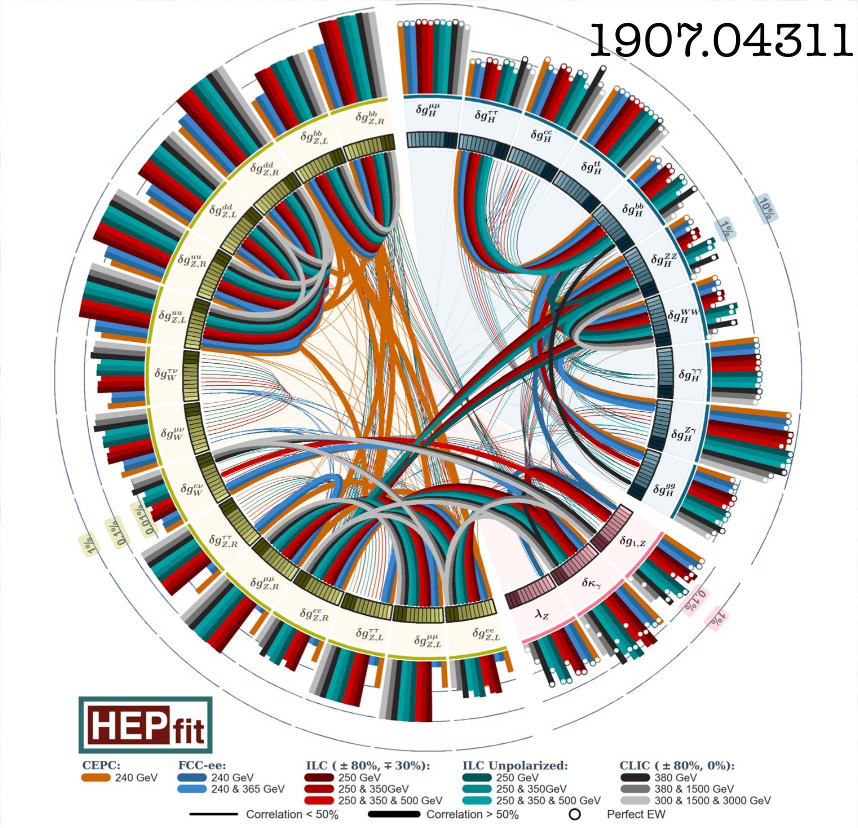
IR

SMEFT

It captures the leading effects of any heavy new states on Standard Model processes at low energy.

Effective Field Theory

What's the value in a SMEFT-only view of future collider reach?



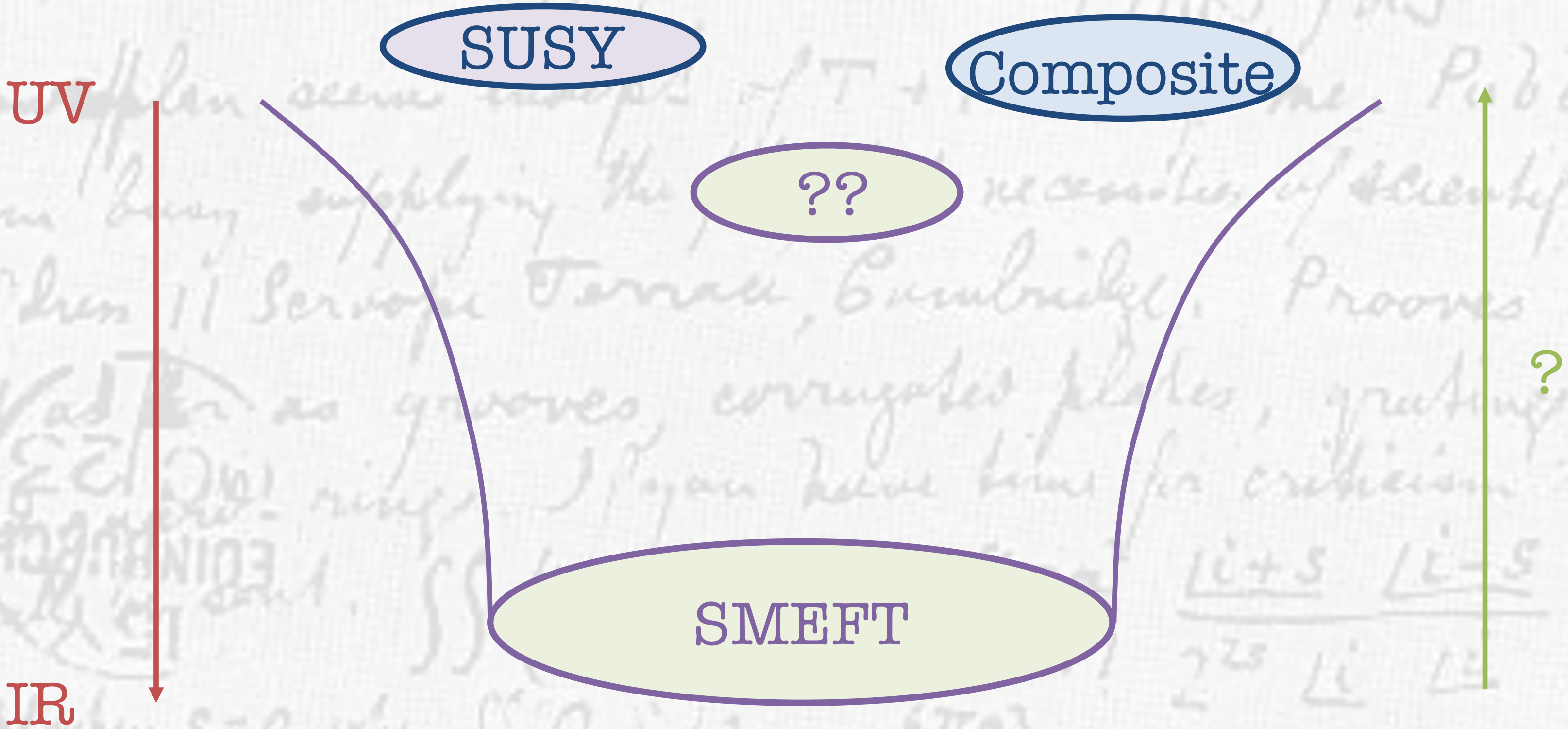
1907.04311

Figure 5: *A scheme-ball illustration of the correlations between Higgs and EW sector couplings. The Z-pole runs are included for both FCC-ee and CEPC. Projections from HL-LHC and measurements from LEP and SLD are included in all scenarios. The outer bars give the one-sigma precision on the individual coupling (see tables 1 and 2).*

It can powerfully illustrate correlations.

Effective Field Theory

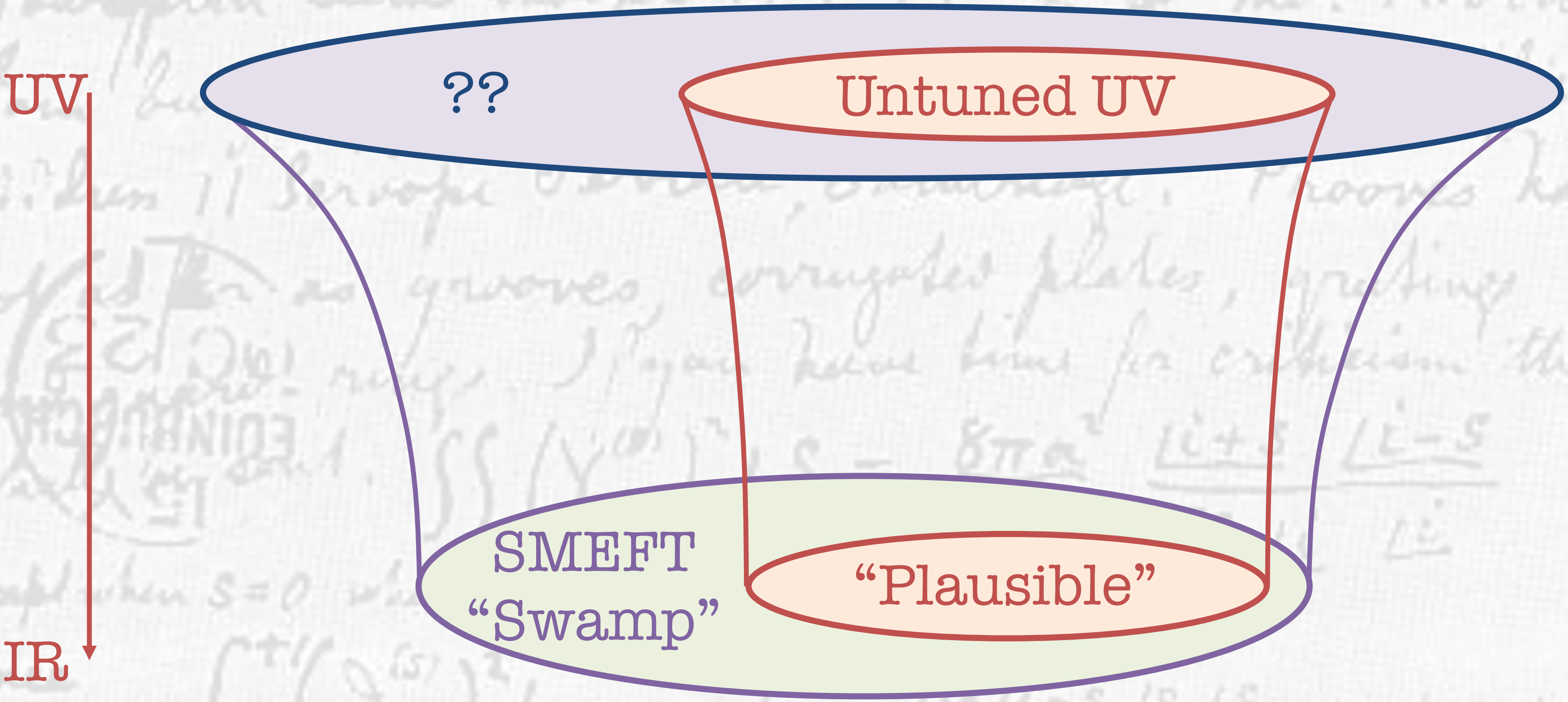
Is SMEFT reversible? Any decoupling UV clearly captured by SMEFT…



But that does not mean that any SMEFT point will correspond to a sensible UV.

Effective Field Theory

In other words, be wary of informing future collider discussions based on SMEFT alone. All operators/combinations are not created equal!



Thanks to Giudice for the “Swamp” term…

Effective Field Theory

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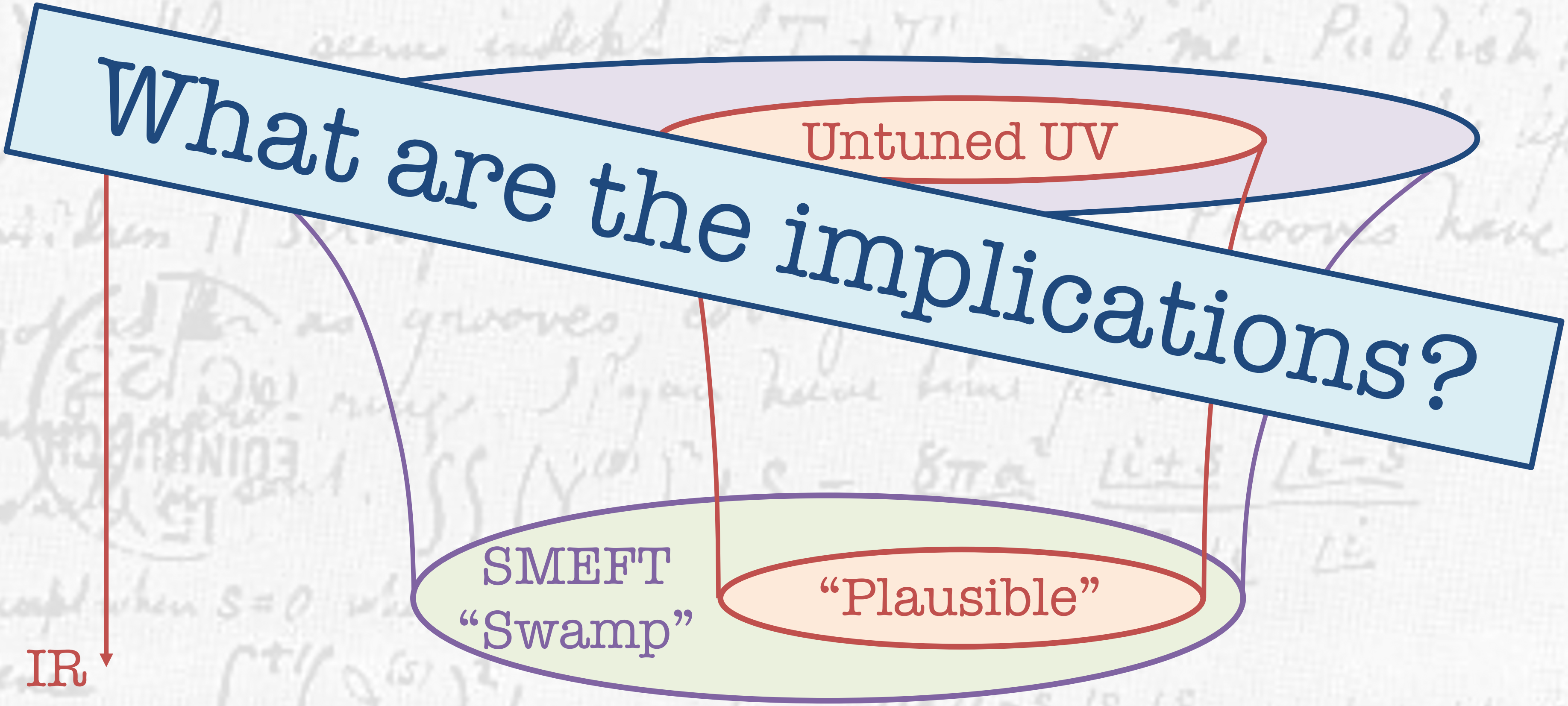


What are the implications?

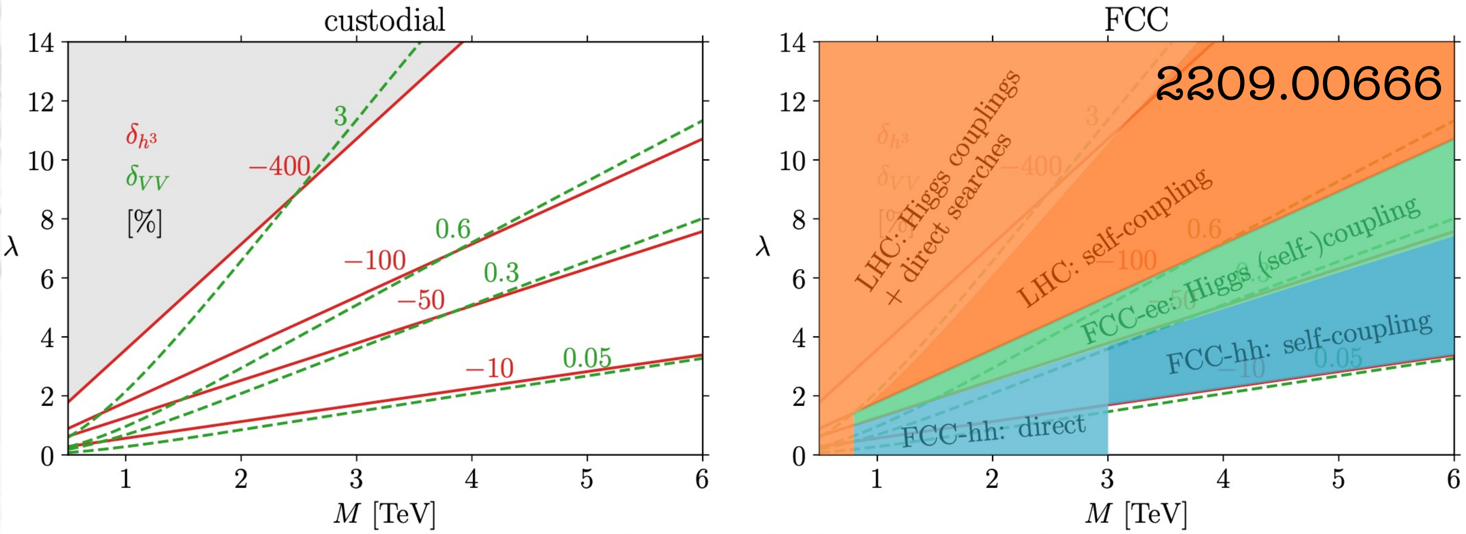
Thanks to Giudice for the “Swamp” term…

Effective Field Theory

In considering the opportunities presented by a future collider, insufficient to demonstrate EFT operator sensitivity alone: Must demonstrate measurement is not in the SMEFT Swampland!

Example: “Indirect” Higgs Self-Coupling.

- Custodial quadruplet model.

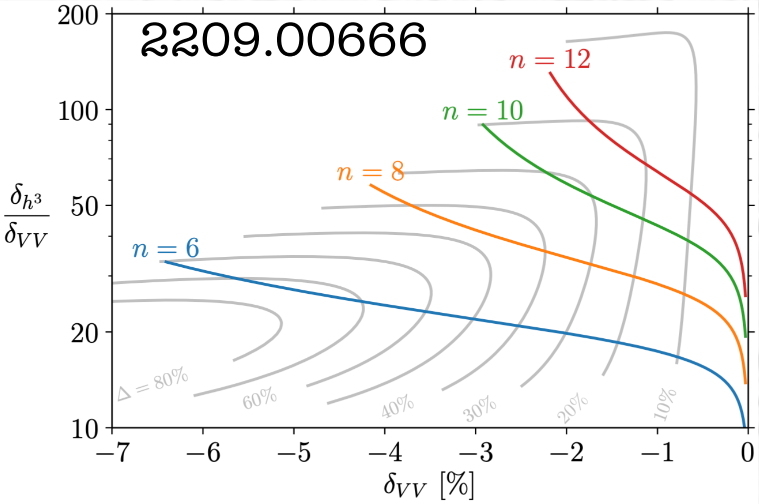


Effective Field Theory

In considering the opportunities presented by a future collider, insufficient to demonstrate EFT operator sensitivity alone: Must demonstrate measurement is not in the SMEFT Swampland!

Example: “Indirect” Higgs Self-Coupling.

- “Gegenbauer” Higgs models.



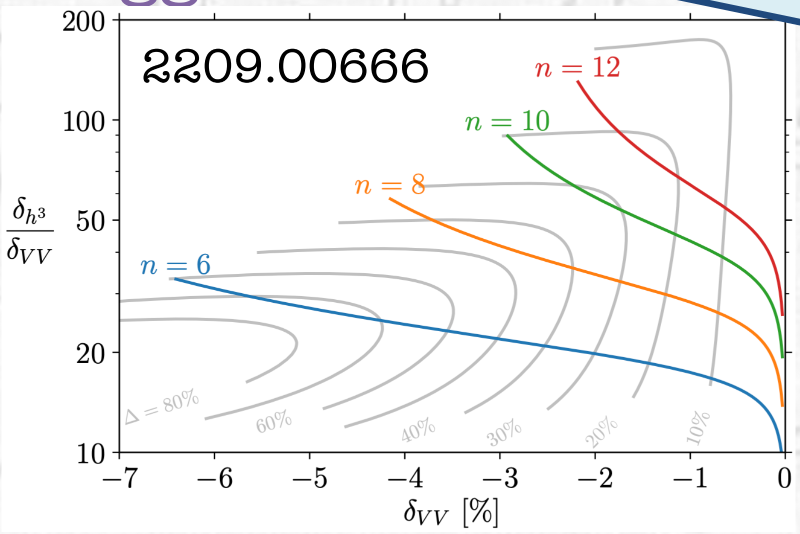
Effective Field Theory

In considering the opportunities presented by a future collider, insufficient to demonstrate EFT operator sensitivity alone: **Must demonstrate m[illegible]ent is not in the SMEFT Swampland!**

Context is key!

Example: “Indir[illegible]

- “Gegenbauer” Higgs models:



Effective Field Theory

In considering potential weaknesses of a future collider, insufficient to demonstrate EFT flat direction alone: Must demonstrate EFT flat direction is not in the SMEFT Swampland!

Example: Ztt vertex modification in Precision Electroweak.

$$\left[\mathcal{O}_{Hq}^{(1)}\right]_{33} - \left[\mathcal{O}_{Hq}^{(3)}\right]_{33}$$

One model at tree-level that this corresponds to: A vector-like right-handed top quark. Nonetheless constrained at one-loop...

Effective Field Theory

In other words, be wary of informing future collider dis… …ased on SMEFT alone. All op… …e not created equal!

So, what is the alternative?

Can we capture all generic SMEFT "patterns" that come from reasonable UV?

Thanks to Giudice for the "Swamp" term…

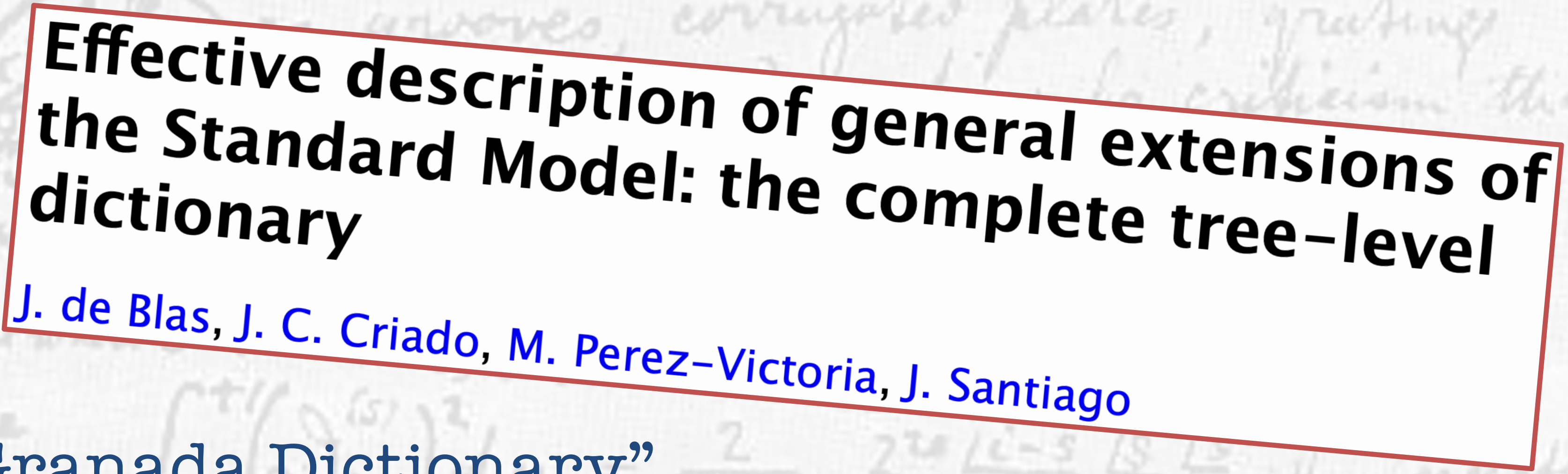
Informed Agnosticism

Organising the UV

Suppose dim-6 SMEFT operators arise at tree-level:

$$\mathcal{O}_1(SM) \underset{\chi_{\text{BSM}}}{\text{―――――}} \mathcal{O}_2(SM) \quad \Longrightarrow \quad \mathcal{O}_{\text{SMEFT}}$$

Is it possible to categorise all possible states? Yes!



Effective description of general extensions of the Standard Model: the complete tree-level dictionary

J. de Blas, J. C. Criado, M. Perez-Victoria, J. Santiago

“Granada Dictionary”.

Organising the UV

Suppose dim-6 SMEFT

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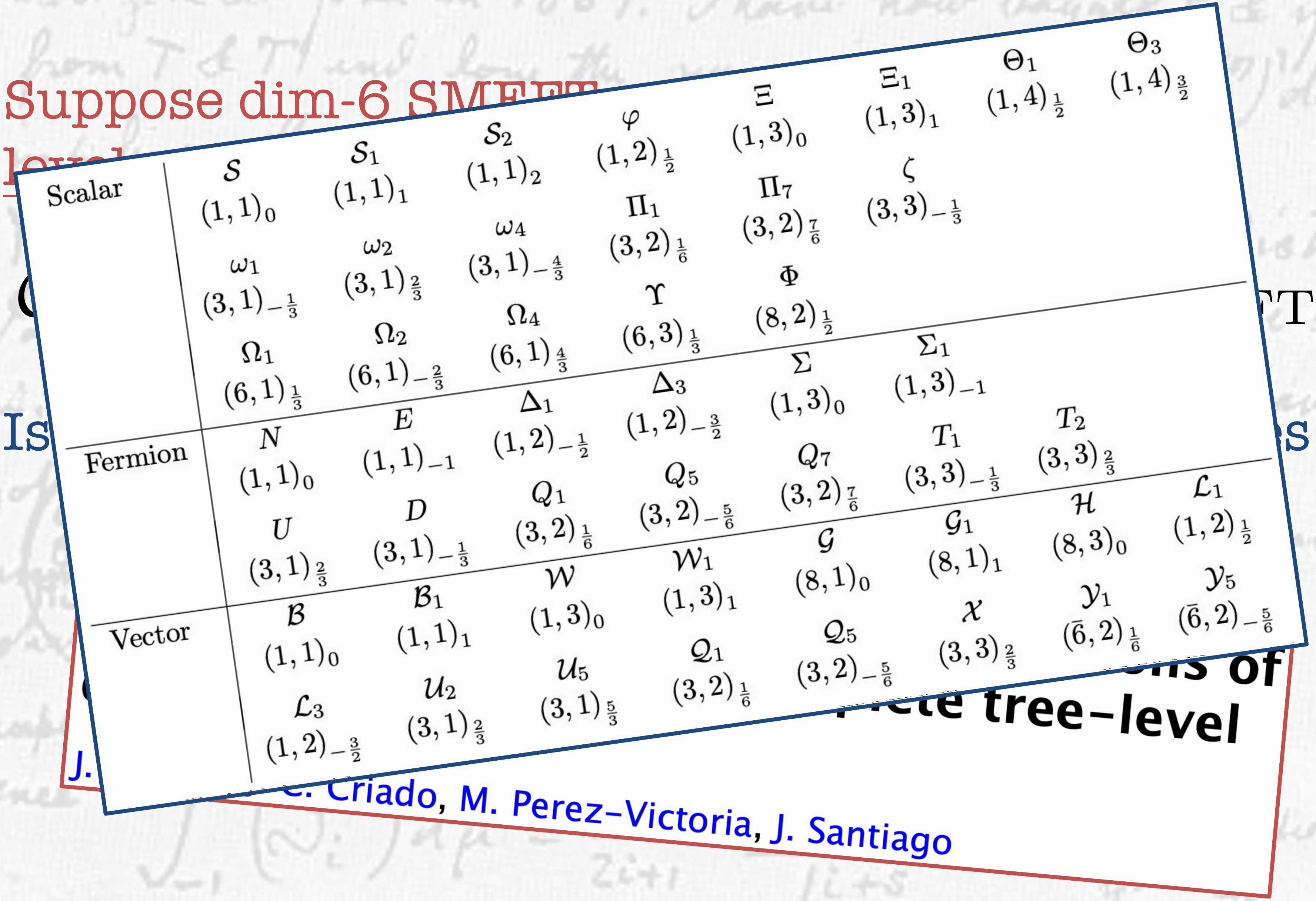

Scalar	$\mathcal{S}$ $(1,1)_0$	$\mathcal{S}_1$ $(1,1)_1$	$\mathcal{S}_2$ $(1,1)_2$	φ $(1,2)_{\frac{1}{2}}$	Ξ $(1,3)_0$	Ξ_1 $(1,3)_1$	Θ_1 $(1,4)_{\frac{1}{2}}$	Θ_3 $(1,4)_{\frac{3}{2}}$
	ω_1 $(3,1)_{-\frac{1}{3}}$	ω_2 $(3,1)_{\frac{2}{3}}$	ω_4 $(3,1)_{-\frac{4}{3}}$	Π_1 $(3,2)_{\frac{1}{6}}$	Π_7 $(3,2)_{\frac{7}{6}}$	ζ $(3,3)_{-\frac{1}{3}}$		
	Ω_1 $(6,1)_{\frac{1}{3}}$	Ω_2 $(6,1)_{-\frac{2}{3}}$	Ω_4 $(6,1)_{\frac{4}{3}}$	Υ $(6,3)_{\frac{1}{3}}$	Φ $(8,2)_{\frac{1}{2}}$			
Fermion	N $(1,1)_0$	E $(1,1)_{-1}$	Δ_1 $(1,2)_{-\frac{1}{2}}$	Δ_3 $(1,2)_{-\frac{3}{2}}$	Σ $(1,3)_0$	Σ_1 $(1,3)_{-1}$		
	U $(3,1)_{\frac{2}{3}}$	D $(3,1)_{-\frac{1}{3}}$	Q_1 $(3,2)_{\frac{1}{6}}$	Q_5 $(3,2)_{-\frac{5}{6}}$	Q_7 $(3,2)_{\frac{7}{6}}$	T_1 $(3,3)_{-\frac{1}{3}}$	T_2 $(3,3)_{\frac{2}{3}}$	
Vector	$\mathcal{B}$ $(1,1)_0$	$\mathcal{B}_1$ $(1,1)_1$	$\mathcal{W}$ $(1,3)_0$	$\mathcal{W}_1$ $(1,3)_1$	$\mathcal{G}$ $(8,1)_0$	$\mathcal{G}_1$ $(8,1)_1$	$\mathcal{H}$ $(8,3)_0$	$\mathcal{L}_1$ $(1,2)_{\frac{1}{2}}$
	$\mathcal{L}_3$ $(1,2)_{-\frac{3}{2}}$	$\mathcal{U}_2$ $(3,1)_{\frac{2}{3}}$	$\mathcal{U}_5$ $(3,1)_{\frac{5}{3}}$	$\mathcal{Q}_1$ $(3,2)_{\frac{1}{6}}$	$\mathcal{Q}_5$ $(3,2)_{-\frac{5}{6}}$	$\mathcal{X}$ $(3,3)_{\frac{2}{3}}$	$\mathcal{Y}_1$ $(\bar{6},2)_{\frac{1}{6}}$	$\mathcal{Y}_5$ $(\bar{6},2)_{-\frac{5}{6}}$

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ete tree-level

J.

C. Criado, M. Perez-Victoria, J. Santiago

Organising the UV

Suppose dim-6 SMEFT operators arise at tree-level:

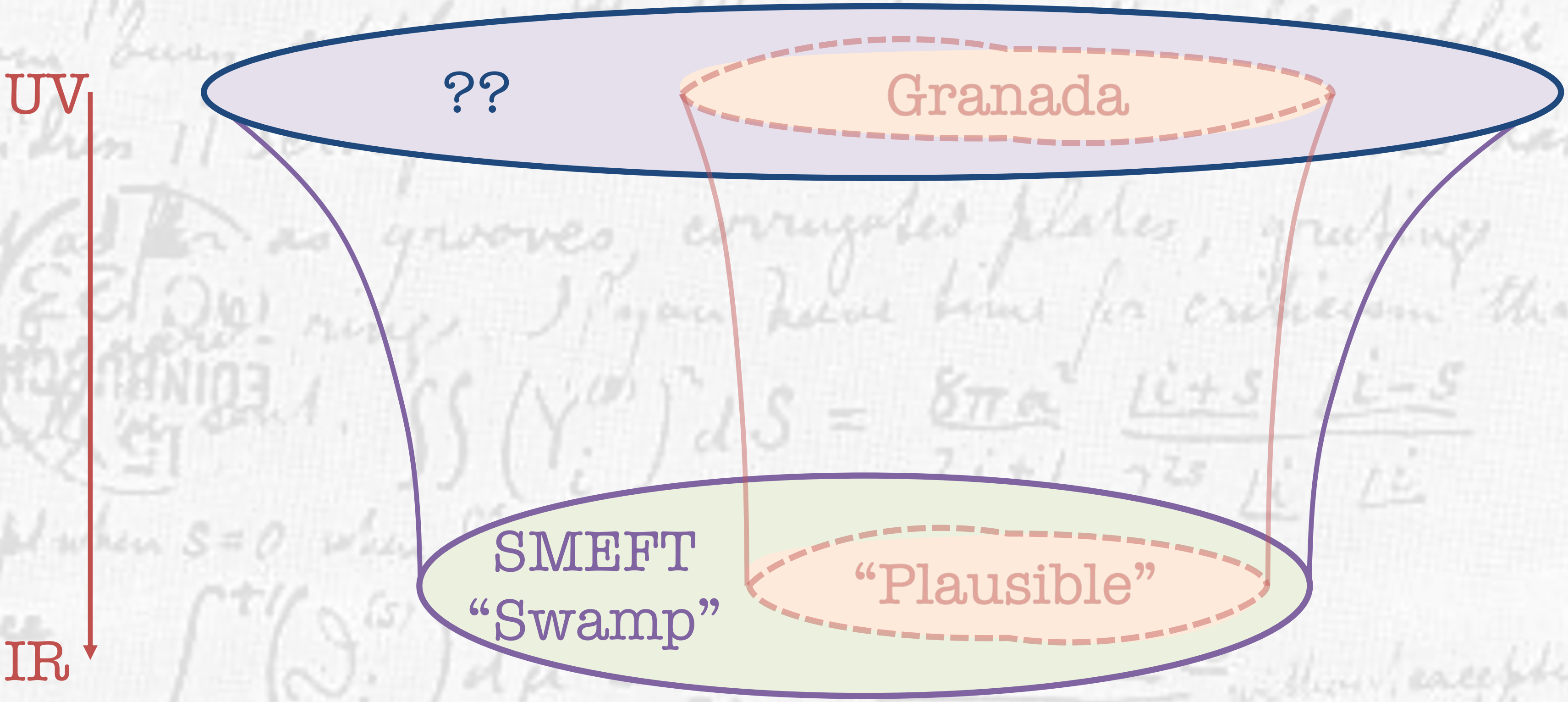
$$\mathcal{O}_1(SM) \underset{\chi_{\mathrm{BSM}}}{\rule{4cm}{0.4pt}} \mathcal{O}_2(SM) \quad \Rightarrow \quad \mathcal{O}_{\mathrm{SMEFT}}$$

Is it possible to categorise all possible states? Yes!

Loop-level will generically give rise to more operators, so studying tree-level is a conservative estimate of “generic” possibilities.

Organising the UV

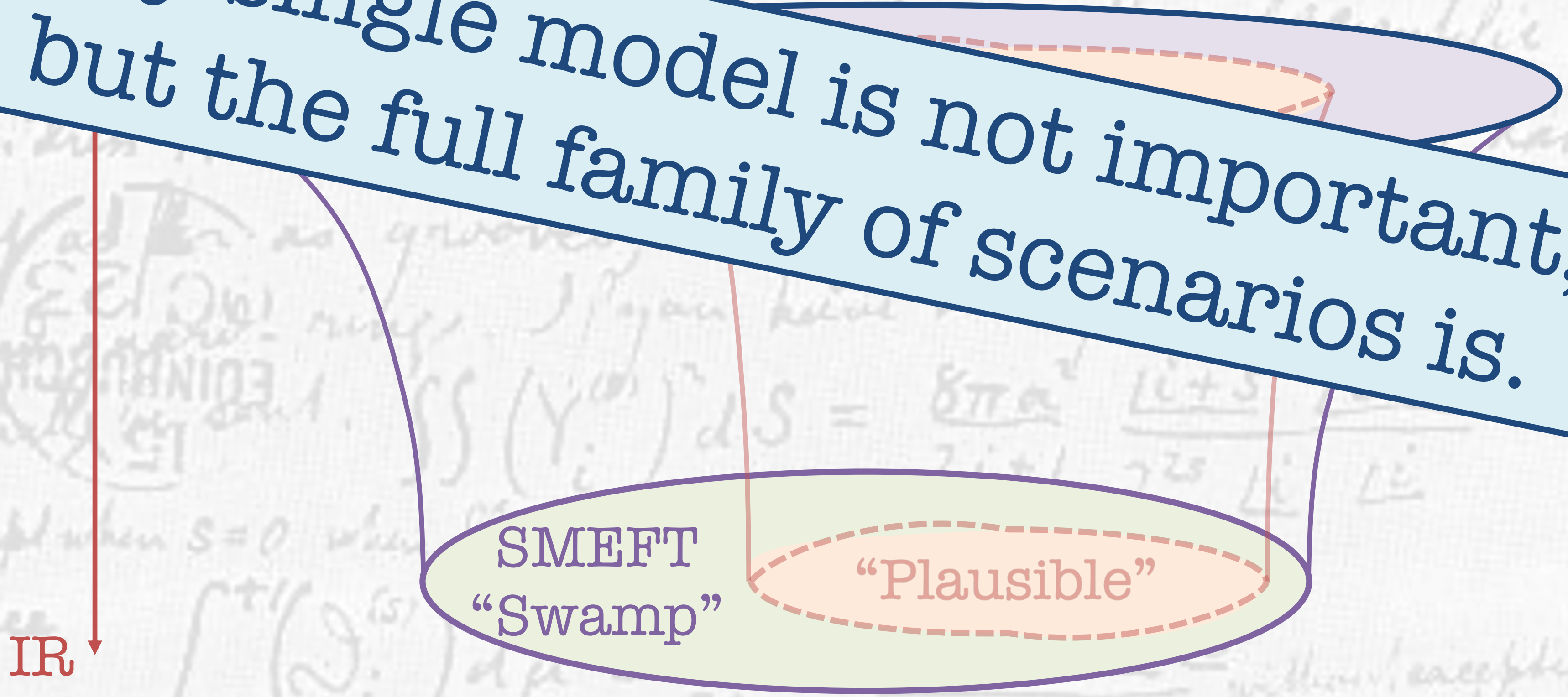
Proposal: Take the families of operators generically arising from these models as representative of the space of SMEFT generated in all non-tuned UV possibilities.



Organising the UV

Proposal: Take the families of operators generically arising from these models as representative of the space of SMEFT generated in all non-tuned UV p

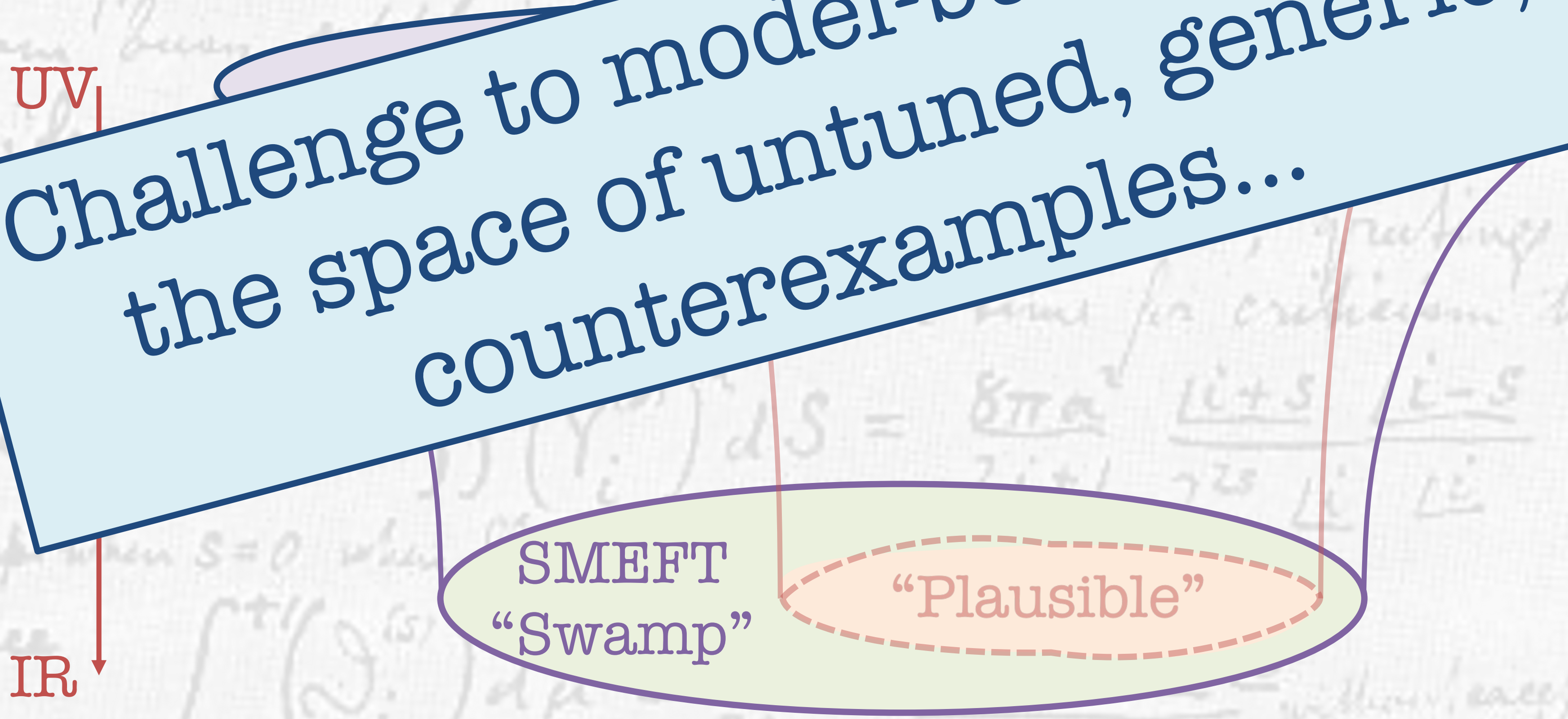
Any single model is not important, but the full family of scenarios is.



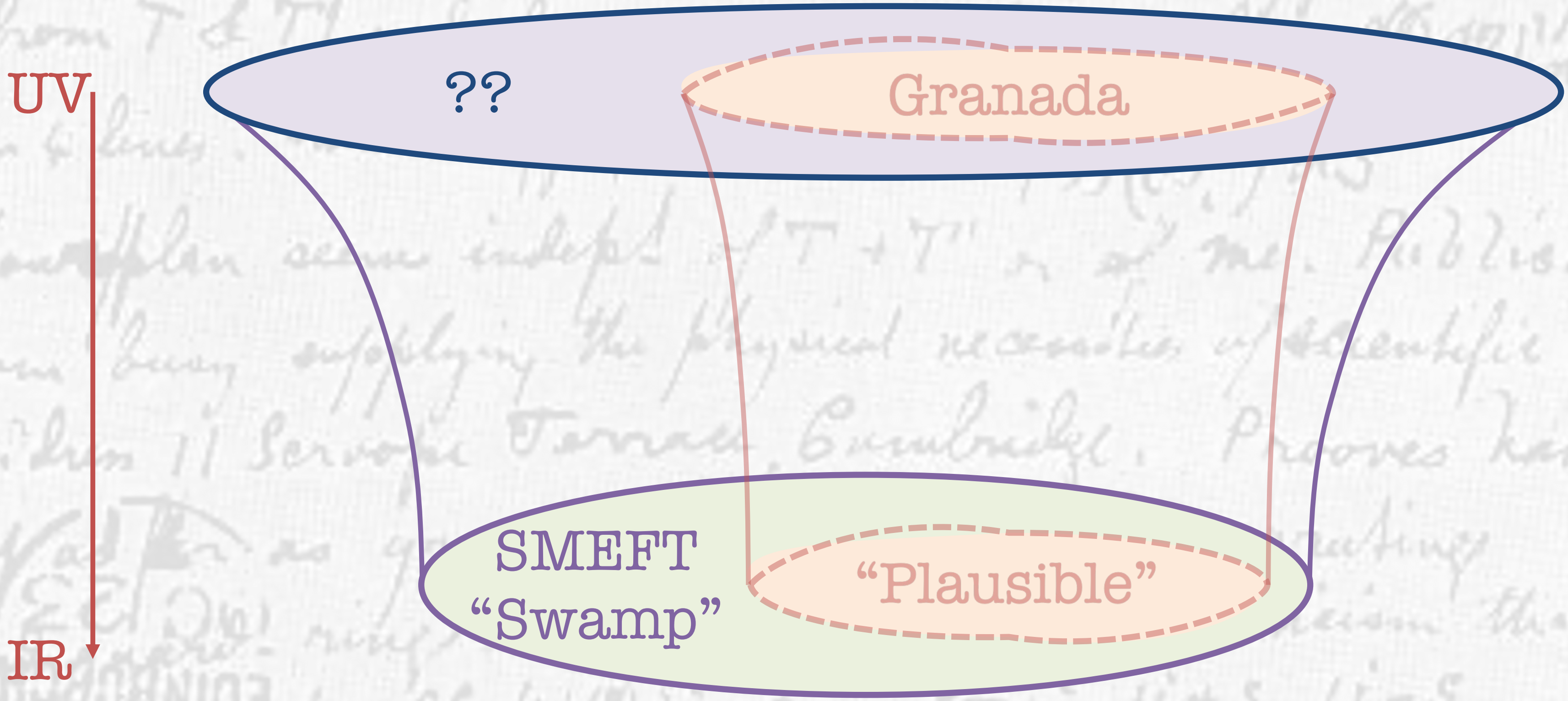
Organising the UV

Proposal: Take the families of operators generically arising from these models as representative of t space of SMEFT generated in all non possibilities.

Challenge to model-builders: Map the space of untuned, generic, counterexamples…



Organising the UV



The intention is to employ this family of models to attempt to map the realistic reach of future precision programmes.

Tera-Z Comments

Extreme precision offered by Tera-Z means quantum effects become highly important.

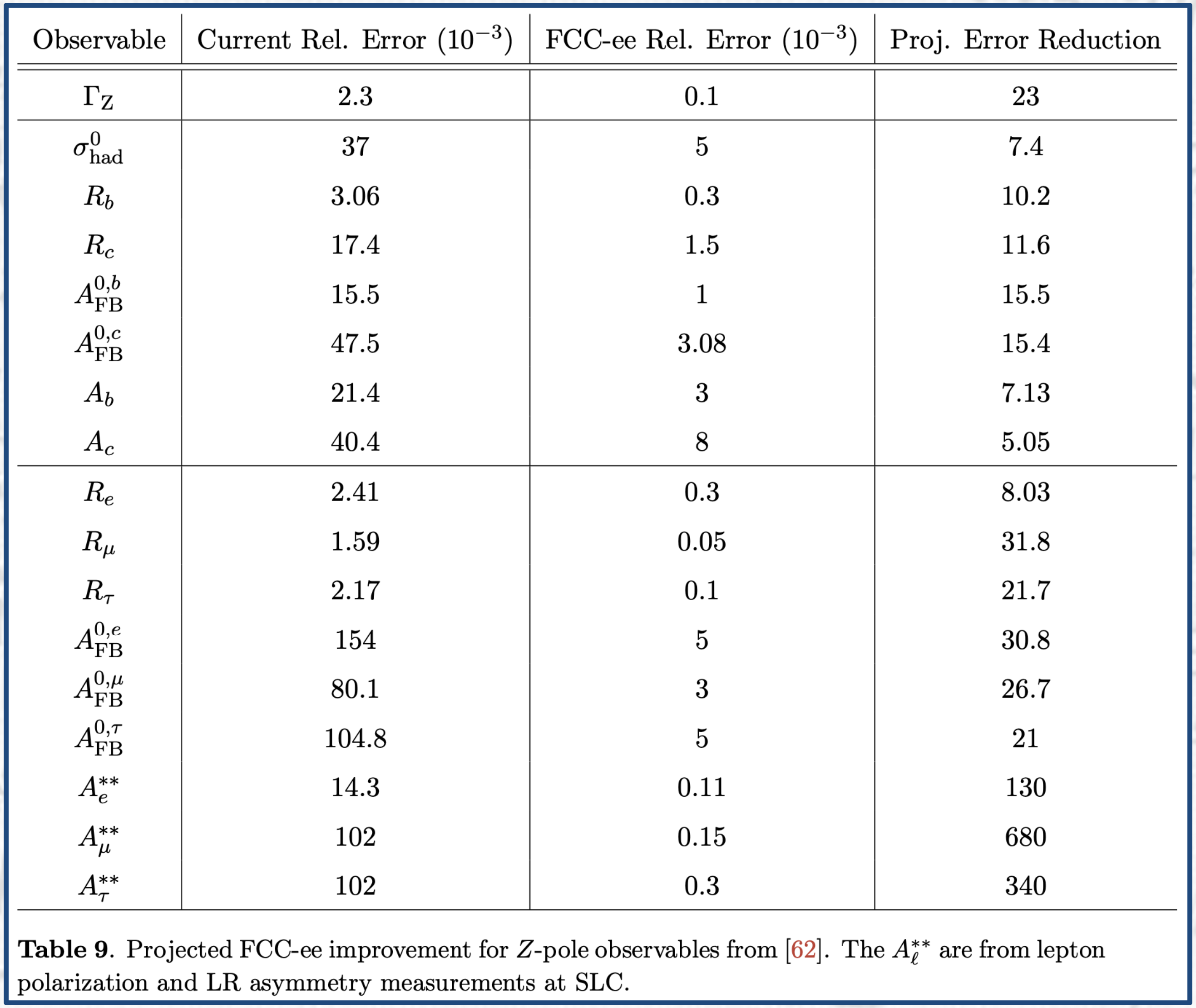
We include one-loop RGE, within SMEFT, from matching scale (assume 2 TeV) to EW scale.

Finite one-loop matching terms not included, typically.

Assume all couplings are unity, in Granada conventions. For simplicity.

Tera-Z Comments

Observable projections from 2311.00020:

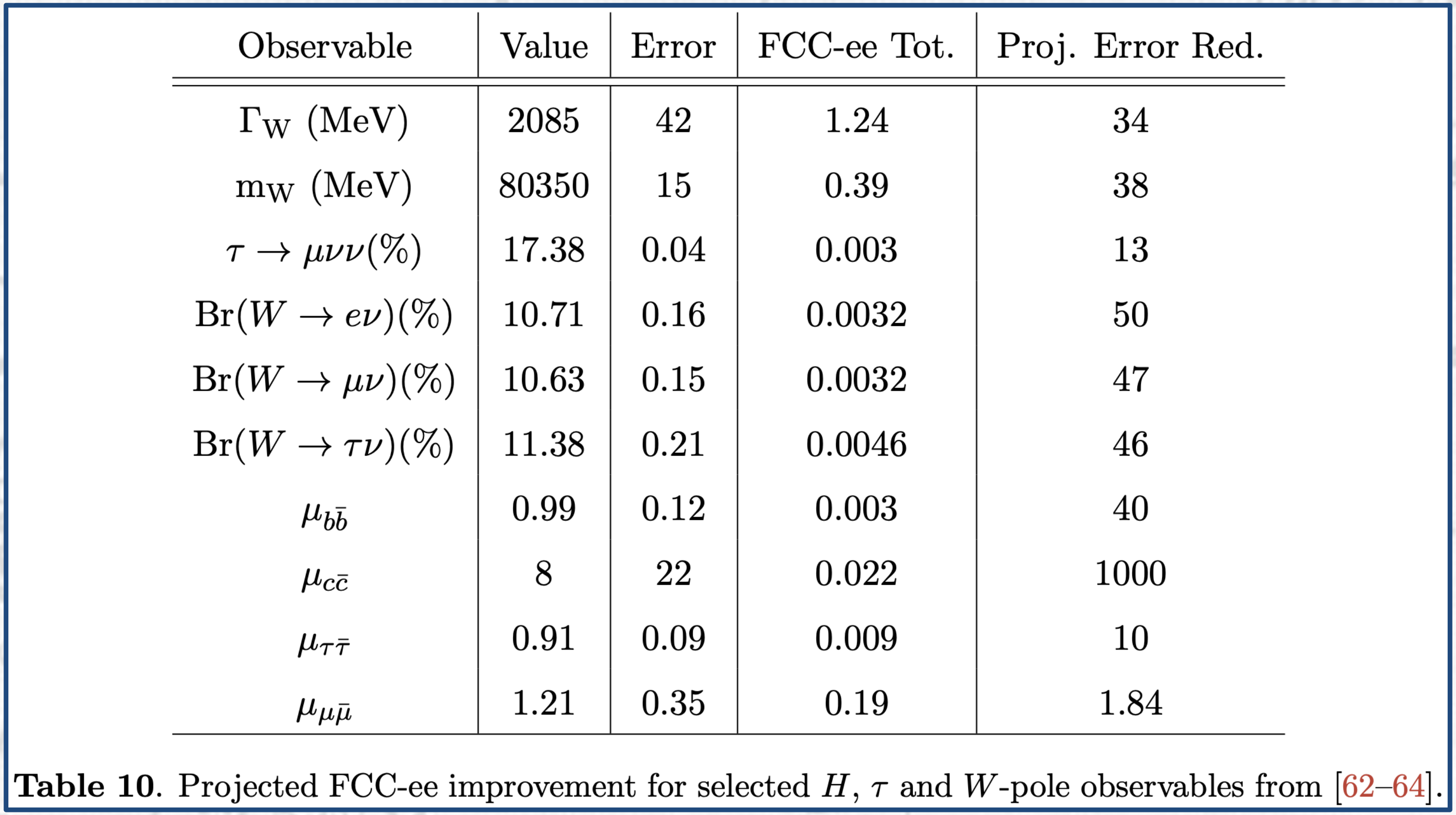


Observable	Current Rel. Error (10^{-3})	FCC-ee Rel. Error (10^{-3})	Proj. Error Reduction
Γ_Z	2.3	0.1	23
σ^0_{had}	37	5	7.4
R_b	3.06	0.3	10.2
R_c	17.4	1.5	11.6
$A^{0,b}_{\text{FB}}$	15.5	1	15.5
$A^{0,c}_{\text{FB}}$	47.5	3.08	15.4
A_b	21.4	3	7.13
A_c	40.4	8	5.05
R_e	2.41	0.3	8.03
R_μ	1.59	0.05	31.8
R_τ	2.17	0.1	21.7
$A^{0,e}_{\text{FB}}$	154	5	30.8
$A^{0,\mu}_{\text{FB}}$	80.1	3	26.7
$A^{0,\tau}_{\text{FB}}$	104.8	5	21
A^{**}_e	14.3	0.11	130
A^{**}_μ	102	0.15	680
A^{**}_τ	102	0.3	340

Table 9. Projected FCC-ee improvement for Z-pole observables from [62]. The A^{**}_ℓ are from lepton polarization and LR asymmetry measurements at SLC.

Tera-Z Comments

Observable projections from 2311.00020:



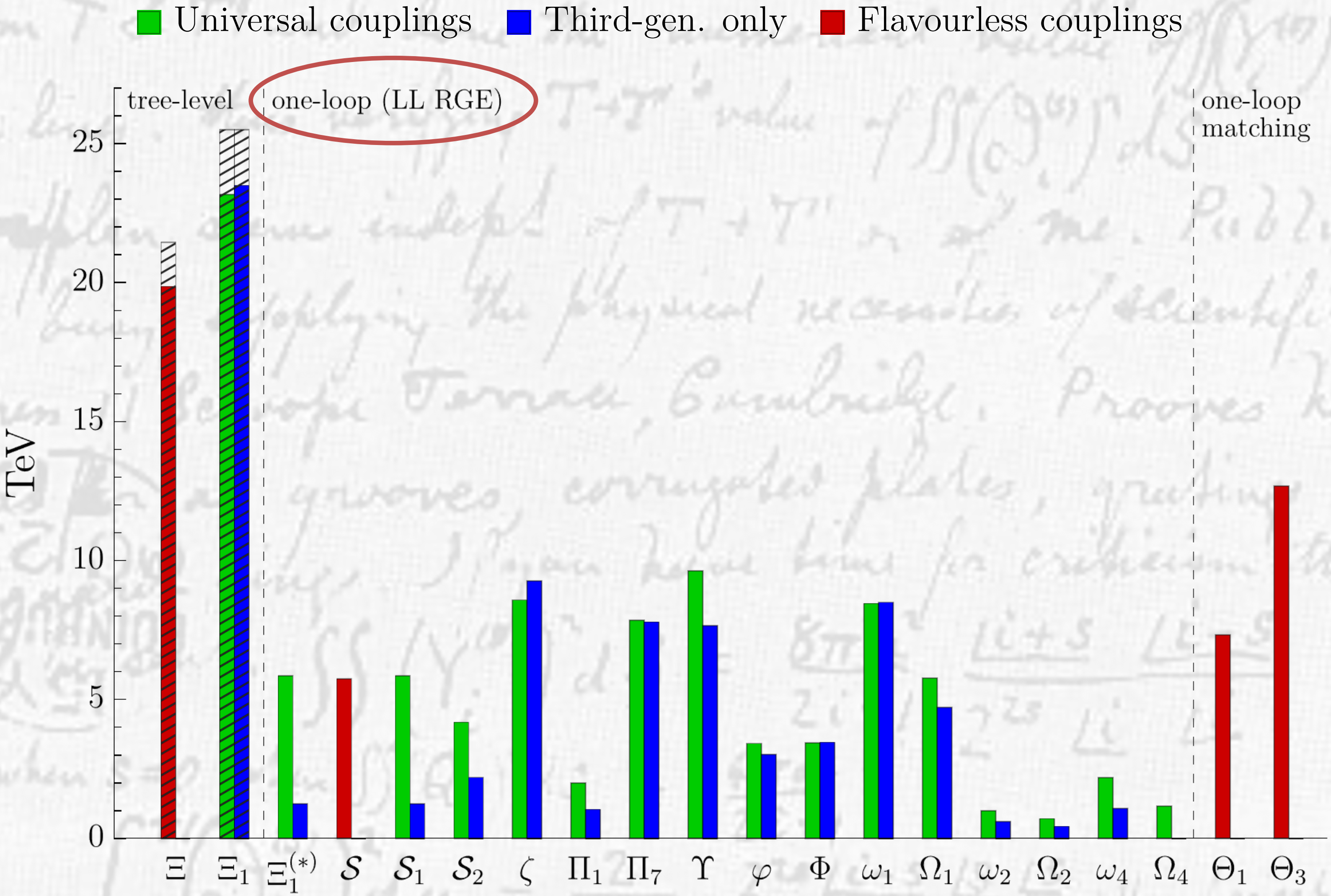
Observable	Value	Error	FCC-ee Tot.	Proj. Error Red.
Γ_W (MeV)	2085	42	1.24	34
m_W (MeV)	80350	15	0.39	38
$\tau \to \mu\nu\nu(\%)$	17.38	0.04	0.003	13
$\mathrm{Br}(W \to e\nu)(\%)$	10.71	0.16	0.0032	50
$\mathrm{Br}(W \to \mu\nu)(\%)$	10.63	0.15	0.0032	47
$\mathrm{Br}(W \to \tau\nu)(\%)$	11.38	0.21	0.0046	46
$\mu_{b\bar{b}}$	0.99	0.12	0.003	40
$\mu_{c\bar{c}}$	8	22	0.022	1000
$\mu_{\tau\bar{\tau}}$	0.91	0.09	0.009	10
$\mu_{\mu\bar{\mu}}$	1.21	0.35	0.19	1.84

Table 10. Projected FCC-ee improvement for selected H, τ and W-pole observables from [62–64].

Three inputs of “LEP” scheme.

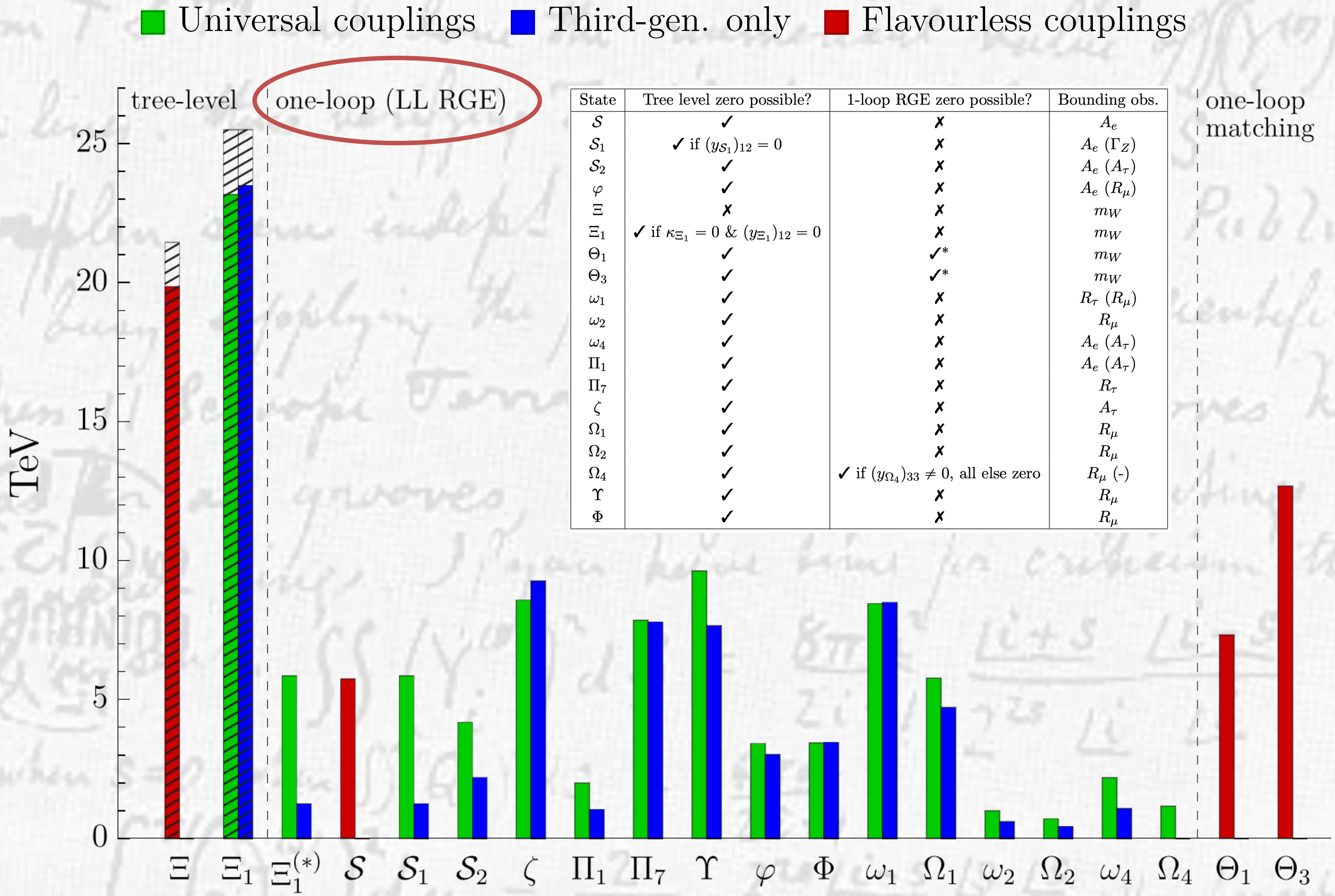
Results

Power of Tera-Z: Scalars



Allwicher, MM, Renner: 2408.03992

Power of Tera-Z: Scalars



State	Tree level zero possible?	1-loop RGE zero possible?	Bounding obs.
$\mathcal{S}$	✓	✗	A_e
$\mathcal{S}_1$	✓ if $(y_{\mathcal{S}_1})_{12} = 0$	✗	A_e (Γ_Z)
$\mathcal{S}_2$	✓	✗	A_e (A_τ)
φ	✓	✗	A_e (R_μ)
Ξ	✗	✗	m_W
Ξ_1	✓ if $\kappa_{\Xi_1} = 0$ & $(y_{\Xi_1})_{12} = 0$	✗	m_W
Θ_1	✓	✓*	m_W
Θ_3	✓	✓*	m_W
ω_1	✓	✗	R_τ (R_μ)
ω_2	✓	✗	R_μ
ω_4	✓	✗	A_e (A_τ)
Π_1	✓	✗	A_e (A_τ)
Π_7	✓	✗	R_τ
ζ	✓	✗	A_τ
Ω_1	✓	✗	R_μ
Ω_2	✓	✗	R_μ
Ω_4	✓	✓ if $(y_{\Omega_4})_{33} \neq 0$, all else zero	R_μ (-)
Υ	✓	✗	R_μ
Φ	✓	✗	R_μ

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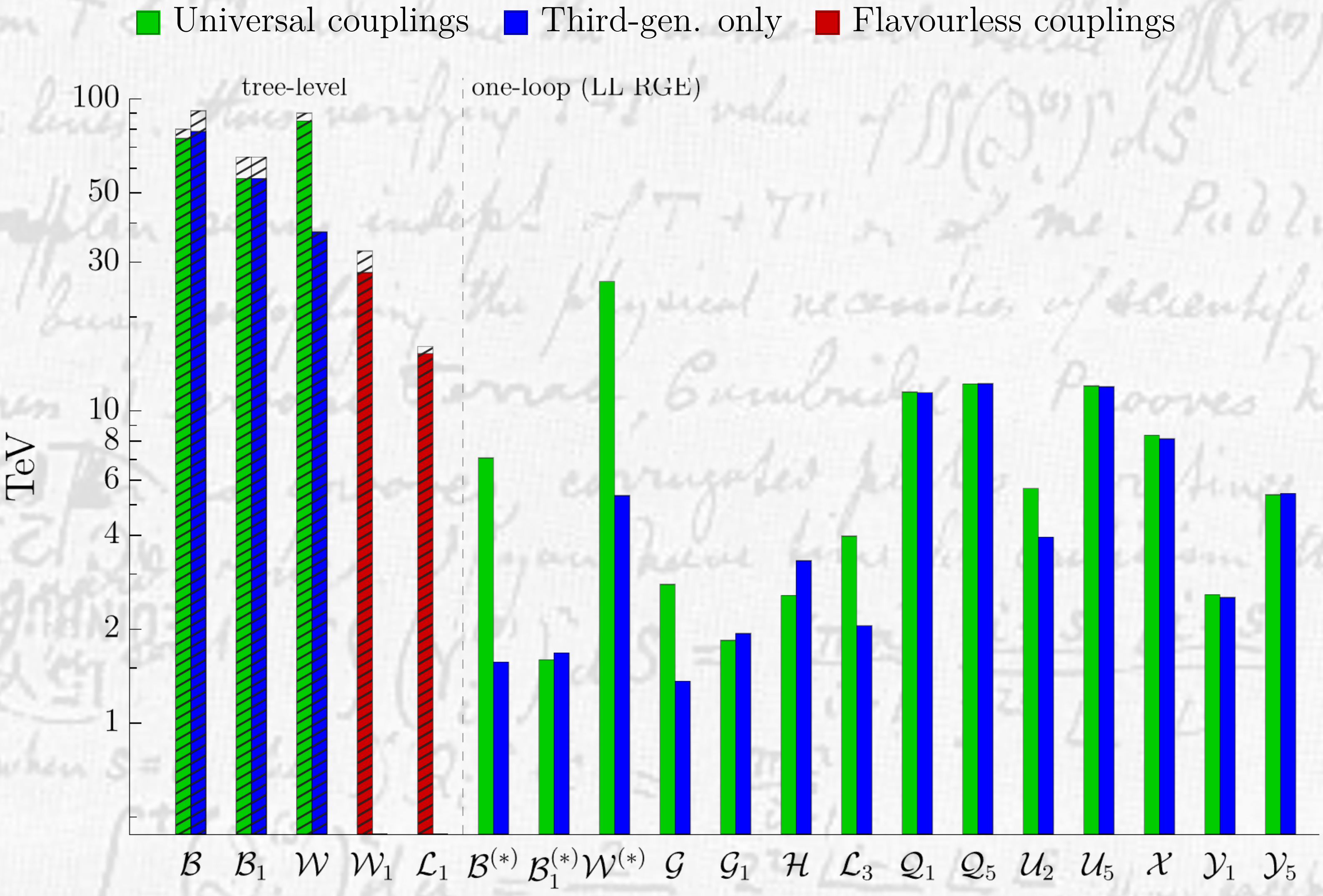
Power of Tera-Z: Vectors



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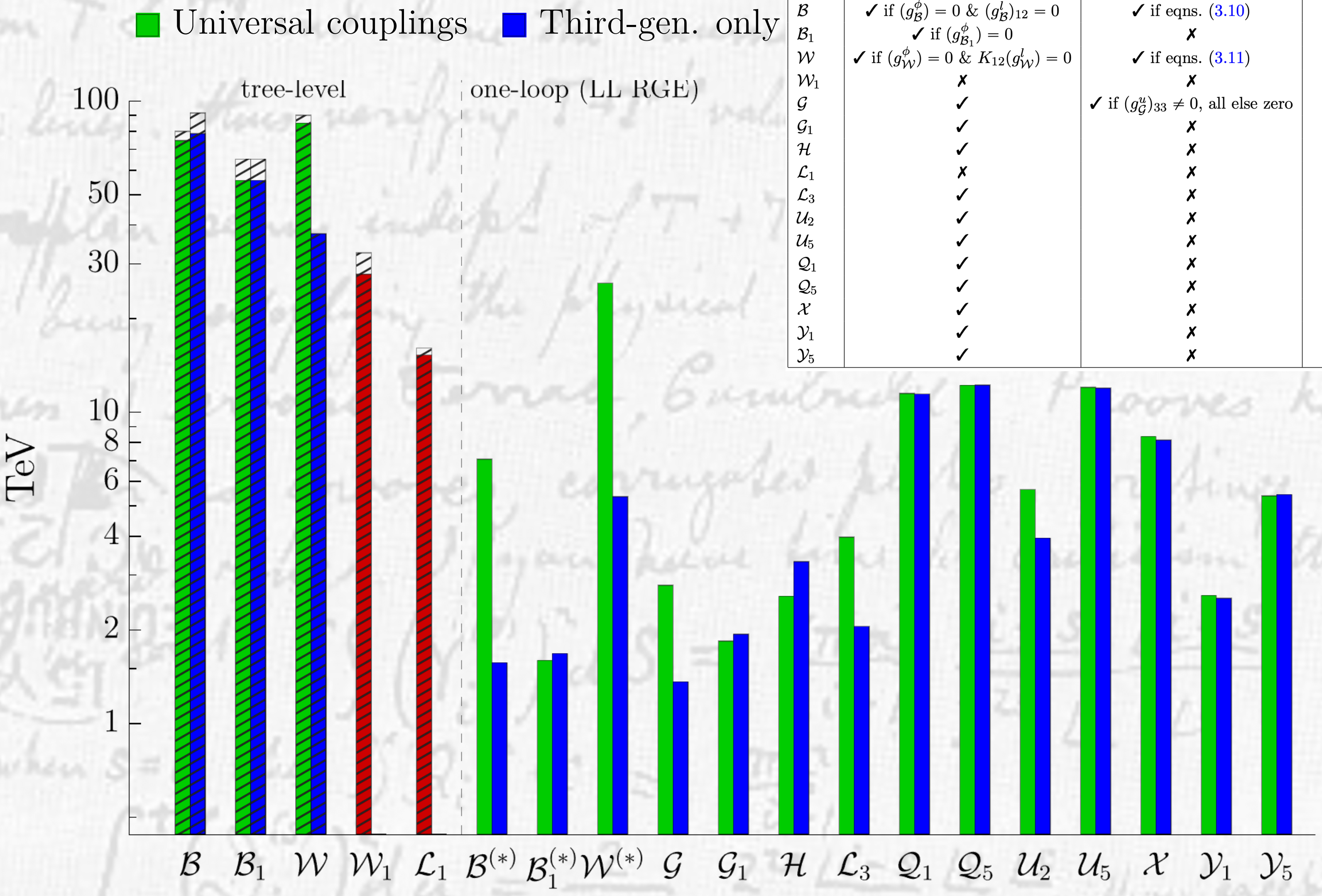

State	Tree level zero possible?	1-loop RGE zero possible?	Bounding obs.
$\mathcal{B}$	✓ if $(g^{\phi}_{\mathcal{B}}) = 0$ & $(g^{l}_{\mathcal{B}})_{12} = 0$	✓ if eqns. (3.10)	m_W
$\mathcal{B}_1$	✓ if $(g^{\phi}_{\mathcal{B}_1}) = 0$	✗	m_W
$\mathcal{W}$	✓ if $(g^{\phi}_{\mathcal{W}}) = 0$ & $K_{12}(g^{l}_{\mathcal{W}}) = 0$	✓ if eqns. (3.11)	A_e (A_τ)
$\mathcal{W}_1$	✗	✗	m_W
$\mathcal{G}$	✓	✓ if $(g^{u}_{\mathcal{G}})_{33} \neq 0$, all else zero	R_μ
$\mathcal{G}_1$	✓	✗	R_μ
$\mathcal{H}$	✓	✗	R_b (R_μ)
$\mathcal{L}_1$	✗	✗	m_W
$\mathcal{L}_3$	✓	✗	A_e (A_τ)
$\mathcal{U}_2$	✓	✗	A_e (Γ_Z)
$\mathcal{U}_5$	✓	✗	A_τ
$\mathcal{Q}_1$	✓	✗	A_τ
$\mathcal{Q}_5$	✓	✗	A_τ
$\mathcal{X}$	✓	✗	A_τ
$\mathcal{Y}_1$	✓	✗	R_μ
$\mathcal{Y}_5$	✓	✗	R_μ

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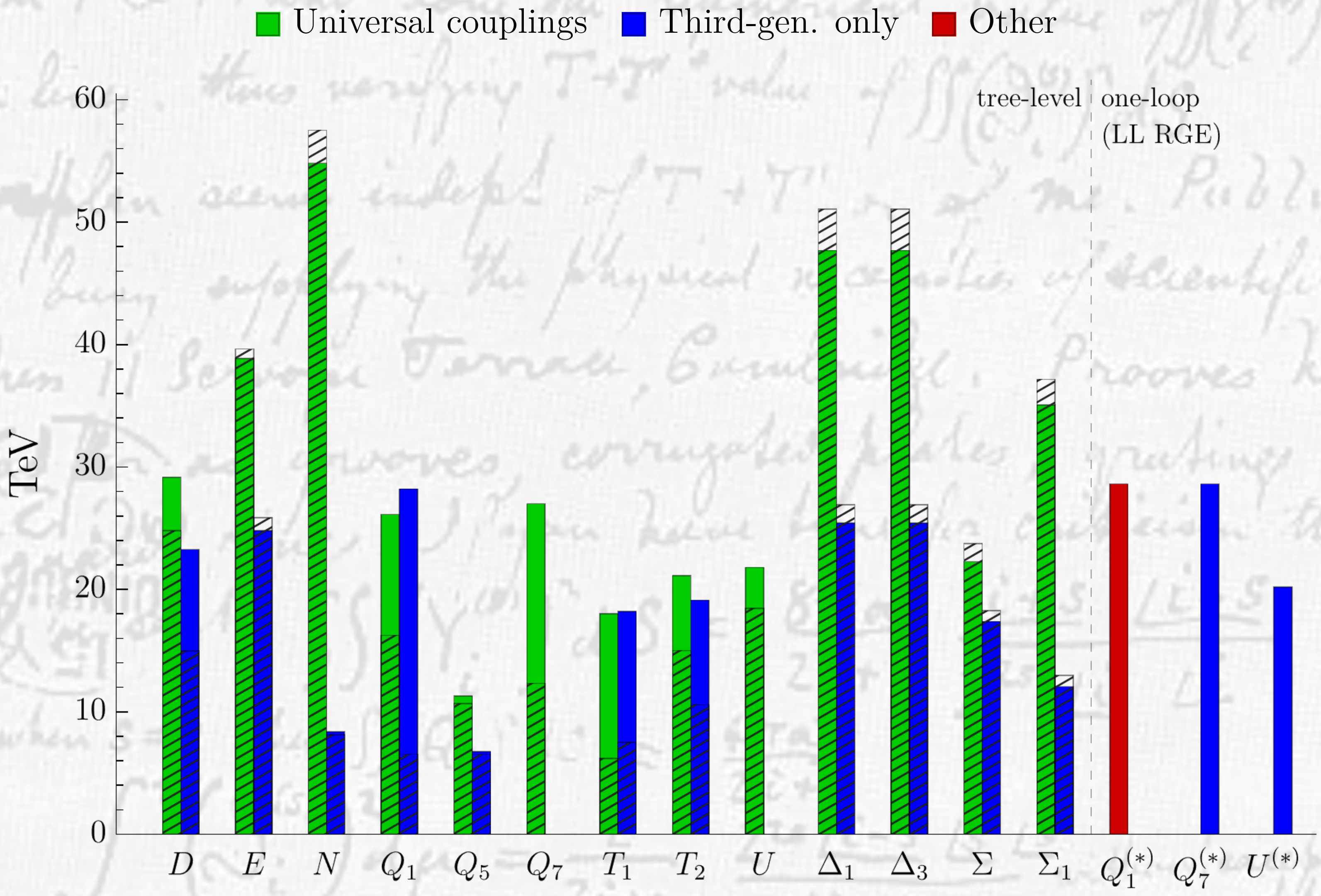
Power of Tera-Z: Fermions



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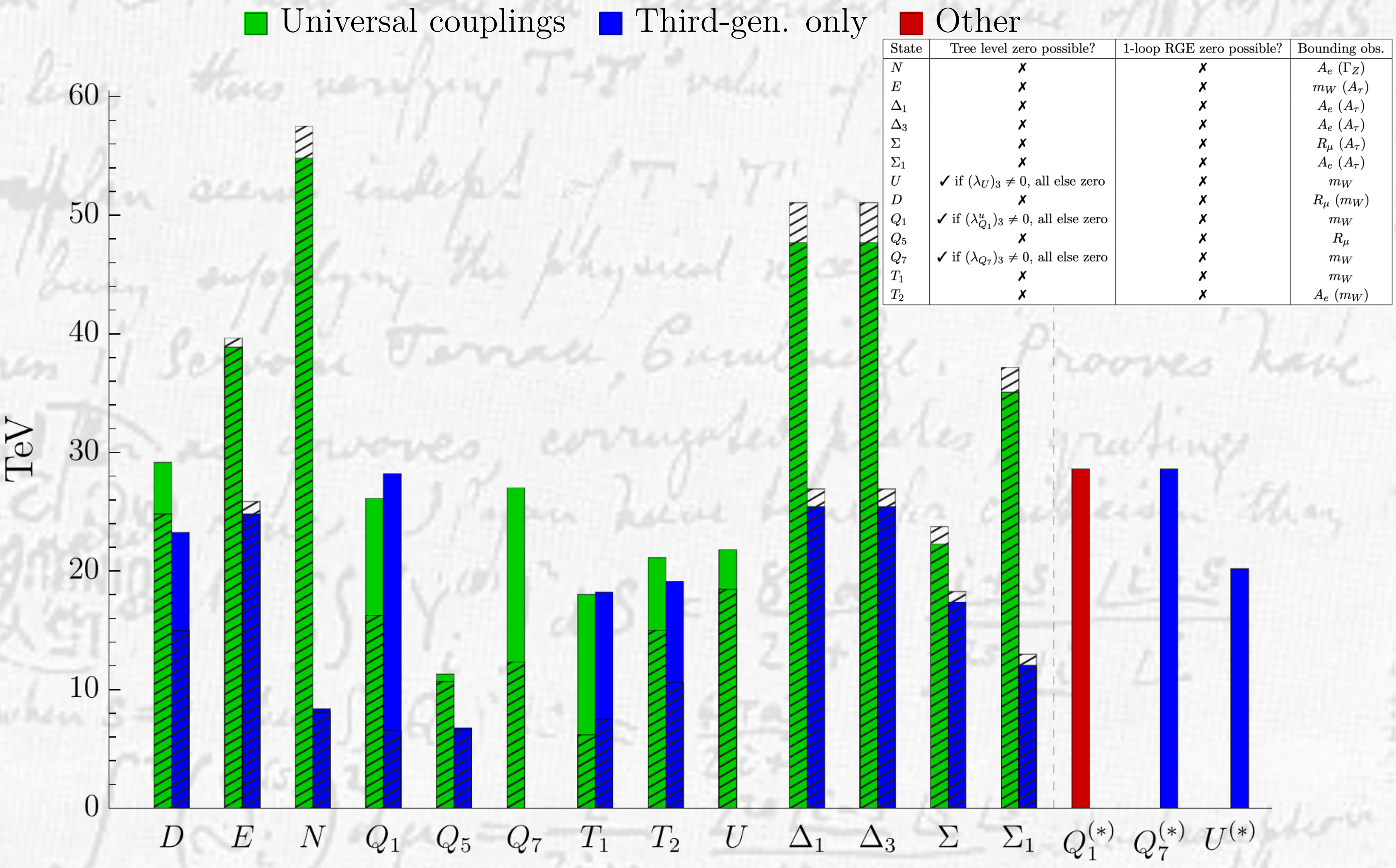
Power of Tera-Z: Fermions



State	Tree level zero possible?	1-loop RGE zero possible?	Bounding obs.
N	✗	✗	A_e (Γ_Z)
E	✗	✗	m_W (A_τ)
Δ_1	✗	✗	A_e (A_τ)
Δ_3	✗	✗	A_e (A_τ)
Σ	✗	✗	R_μ (A_τ)
Σ_1	✗	✗	A_e (A_τ)
U	✓ if $(\lambda_U)_3 \neq 0$, all else zero	✗	m_W
D	✗	✗	R_μ (m_W)
Q_1	✓ if $(\lambda^u_{Q_1})_3 \neq 0$, all else zero	✗	m_W
Q_5	✗	✗	R_μ
Q_7	✓ if $(\lambda_{Q_7})_3 \neq 0$, all else zero	✗	m_W
T_1	✗	✗	m_W
T_2	✗	✗	A_e (m_W)

Allwicher, MM, Renner: 2408.03992

Power of Tera-Z: Punchline

Save for a few exceptions, the **Tera-Z programme gives comprehensive coverage of new UV physics**.

Power of Tera-Z: Punchline

Save for a few exceptions, the **Tera-Z programme gives comprehensive coverage of new UV physics**.

If a signature shows up elsewhere, it will show up at Tera-Z. Quantum RG effects play a crucial role.

Exceptions: $\mathcal{G}$, Ω_4 .

Allwicher, MM, Renner: 2408.03992

Power of Tera-Z: Punchline

Save for a few exceptions, the **Tera-Z programme g** … **rehensive coverage of new UV**

But there’s an awful lot more to Tera-Z than precision EW…

If a signature shows up o … at Tera-Z. Quantum RG effects play a

Exceptions: $\mathcal{G}$, Ω_4 .

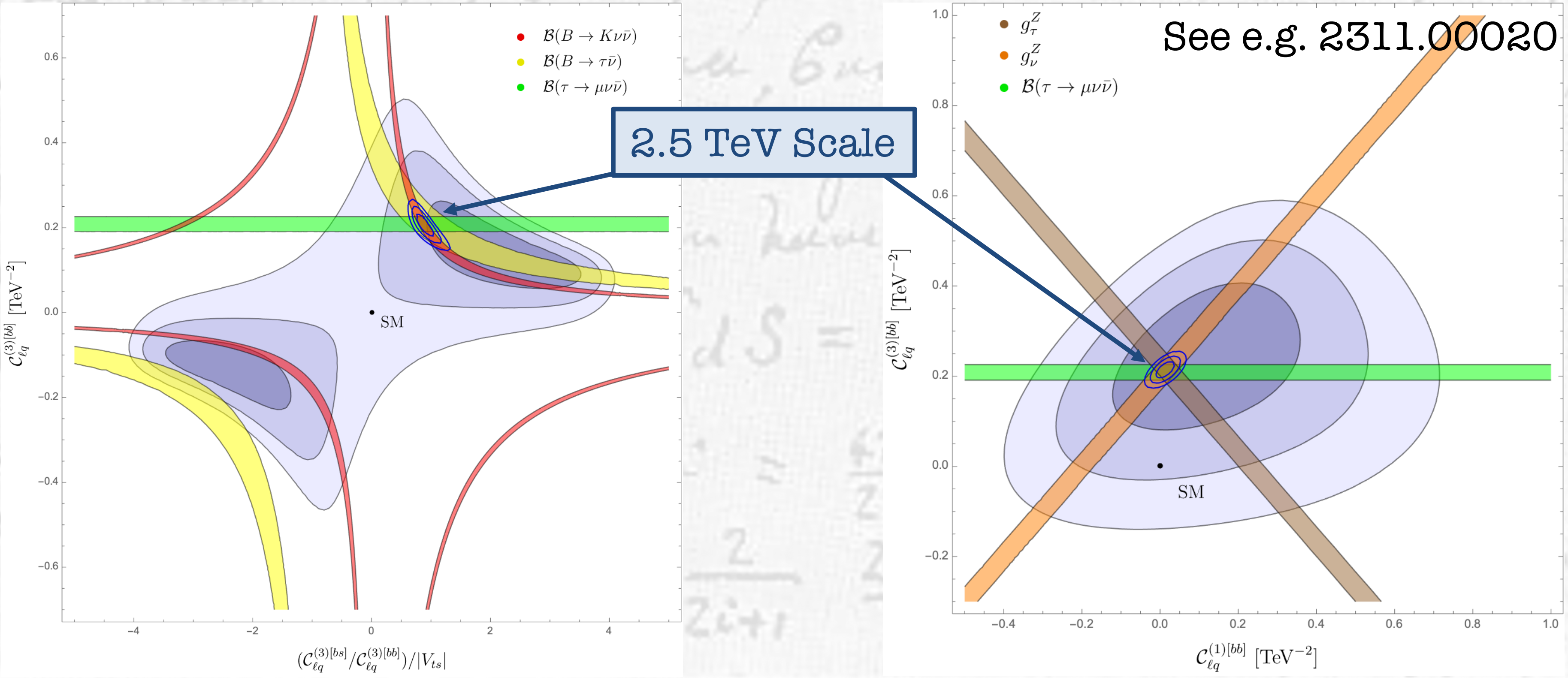
Allwicher, MM, Renner: 2408.03992

The Flavour of Discovery

Rich interplay at FCC-ee between flavour programme…

Particle species	B^0	B^+	B_s^0	Λ_b	B_c^+	$c\bar{c}$	$\tau^-\tau^+$
Yield ($\times 10^9$)	370	370	90	80	2	720	200

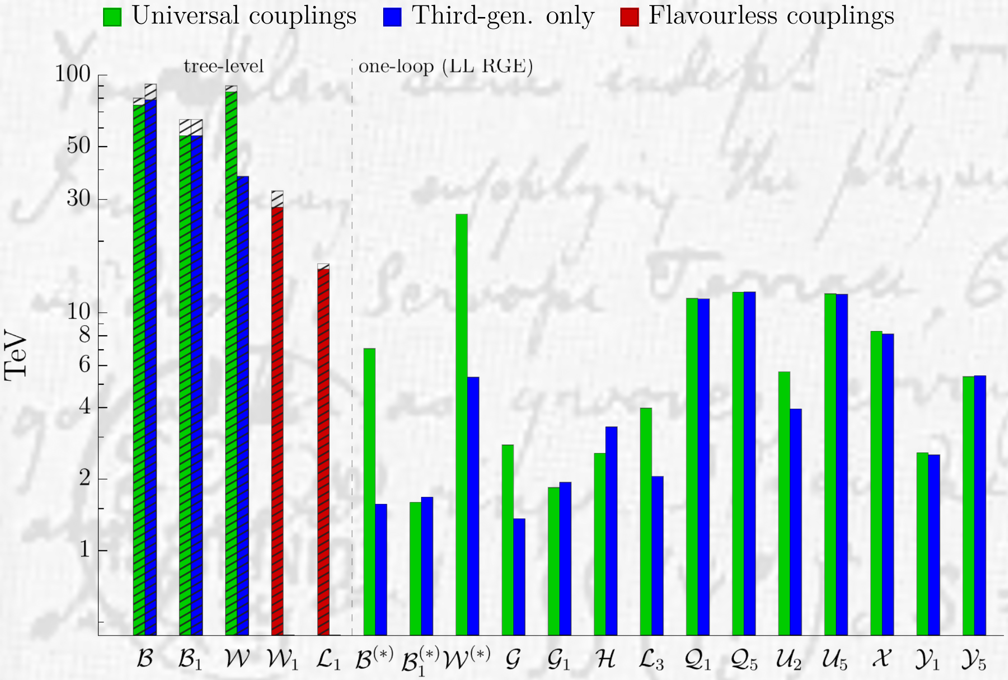
and the precision EW programme.

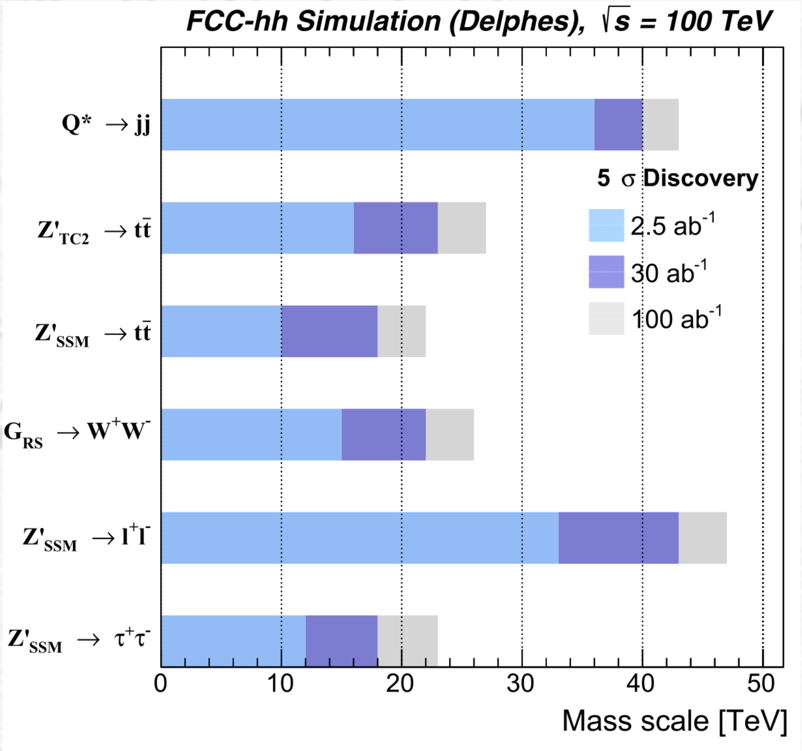


See e.g. 2311.00020

FCC-hh: Seeing the Unseen.

Rich interplay between FCC-ee indirect sensitivity and FCC-hh direct discovery.



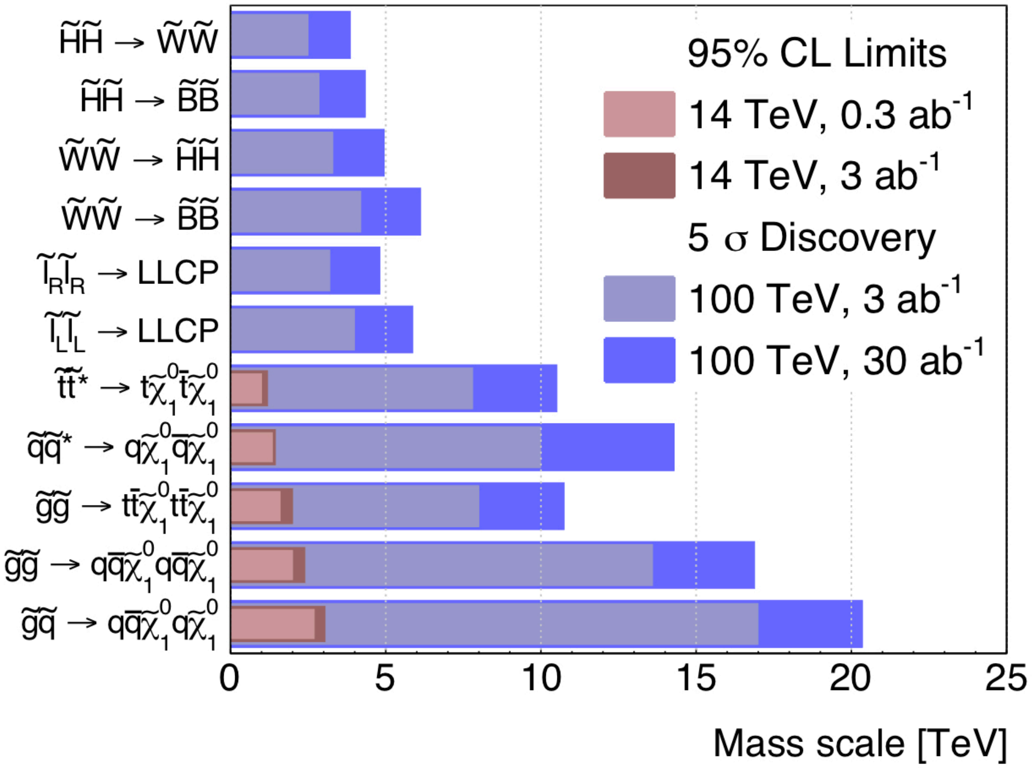


N.B. Direct exploration in a post-FCC-ee era will require a machine with $\sqrt{s} \gg 10$ TeV partonic CM energy.

FCC-hh: Seeing the Unseen.

For new states respecting a Z_2 symmetry, such that they only appear in pairs, have no tree-level.

Generically, as compared to tree-level, expect indirect FCC-ee mass reach to be a factor of 4π less for unit couplings.



FCC-hh, on the other hand, still has significant discovery potential in this scenario!

Summary

Tera-Z offers unprecedented indirect exploration of physics at the shortest distance scales.

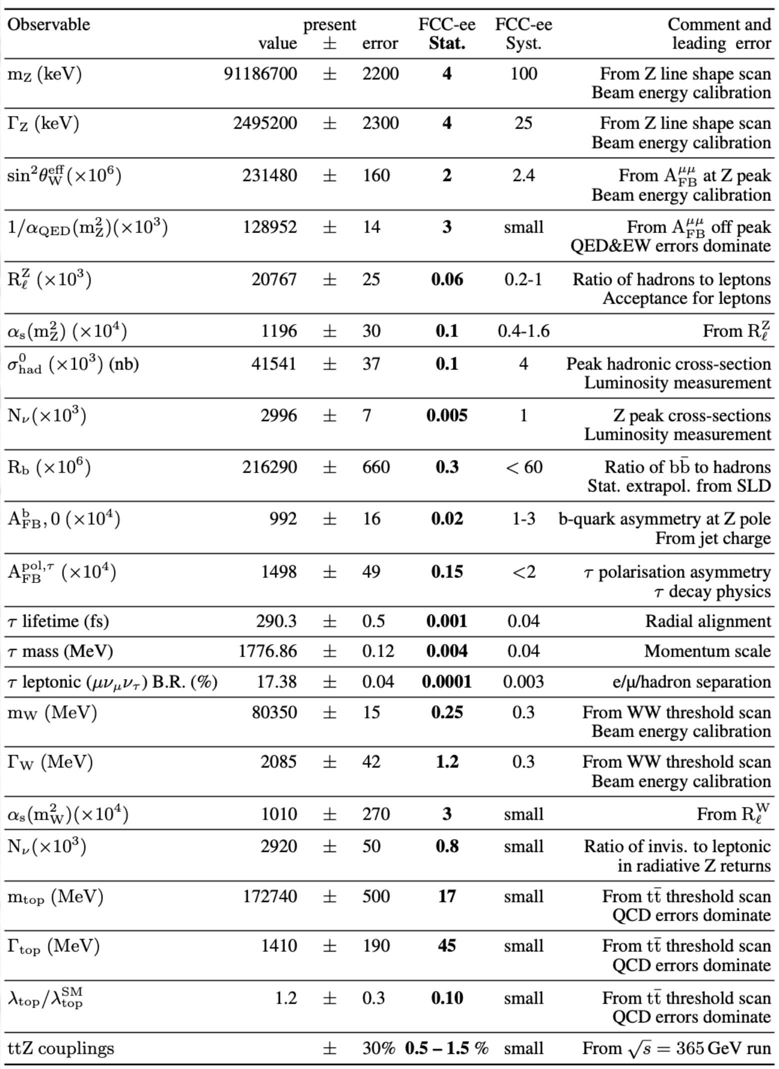
Quantum effects are crucial: Consider as LEP at your peril!

Flavour is a powerful key element of the programme.

FCC-ee offers the springboard to direct exploration at the highest energies, well beyond 10 TeV.

Backup

FCC-ee stat vs syst.



Observable	present			FCC-ee	FCC-ee	Comment and
	value	±	error	**Stat.**	Syst.	leading error
m_Z (keV)	91186700	±	2200	**4**	100	From Z line shape scan Beam energy calibration
Γ_Z (keV)	2495200	±	2300	**4**	25	From Z line shape scan Beam energy calibration
$\sin^2\theta_W^{\rm eff}(\times 10^6)$	231480	±	160	**2**	2.4	From $A_{FB}^{\mu\mu}$ at Z peak Beam energy calibration
$1/\alpha_{QED}(m_Z^2)(\times 10^3)$	128952	±	14	**3**	small	From $A_{FB}^{\mu\mu}$ off peak QED&EW errors dominate
R_ℓ^Z $(\times 10^3)$	20767	±	25	**0.06**	0.2-1	Ratio of hadrons to leptons Acceptance for leptons
$\alpha_s(m_Z^2)$ $(\times 10^4)$	1196	±	30	**0.1**	0.4-1.6	From R_ℓ^Z
$\sigma_{\rm had}^0$ $(\times 10^3)$ (nb)	41541	±	37	**0.1**	4	Peak hadronic cross-section Luminosity measurement
$N_\nu(\times 10^3)$	2996	±	7	**0.005**	1	Z peak cross-sections Luminosity measurement
R_b $(\times 10^6)$	216290	±	660	**0.3**	< 60	Ratio of $b\bar{b}$ to hadrons Stat. extrapol. from SLD
$A_{FB}^b, 0$ $(\times 10^4)$	992	±	16	**0.02**	1-3	b-quark asymmetry at Z pole From jet charge
$A_{FB}^{{\rm pol},\tau}$ $(\times 10^4)$	1498	±	49	**0.15**	<2	τ polarisation asymmetry τ decay physics
τ lifetime (fs)	290.3	±	0.5	**0.001**	0.04	Radial alignment
τ mass (MeV)	1776.86	±	0.12	**0.004**	0.04	Momentum scale
τ leptonic $(\mu\nu_\mu\nu_\tau)$ B.R. (%)	17.38	±	0.04	**0.0001**	0.003	e/μ/hadron separation
m_W (MeV)	80350	±	15	**0.25**	0.3	From WW threshold scan Beam energy calibration
Γ_W (MeV)	2085	±	42	**1.2**	0.3	From WW threshold scan Beam energy calibration
$\alpha_s(m_W^2)(\times 10^4)$	1010	±	270	**3**	small	From R_ℓ^W
$N_\nu(\times 10^3)$	2920	±	50	**0.8**	small	Ratio of invis. to leptonic in radiative Z returns
$m_{\rm top}$ (MeV)	172740	±	500	**17**	small	From $t\bar{t}$ threshold scan QCD errors dominate
$\Gamma_{\rm top}$ (MeV)	1410	±	190	**45**	small	From $t\bar{t}$ threshold scan QCD errors dominate
$\lambda_{\rm top}/\lambda_{\rm top}^{\rm SM}$	1.2	±	0.3	**0.10**	small	From $t\bar{t}$ threshold scan QCD errors dominate
ttZ couplings		±	30%	**0.5 – 1.5 %**	small	From $\sqrt{s} = 365$ GeV run