Universität Zürich[UZH]

Where is the future taking us?*

04.02.2025, Bern

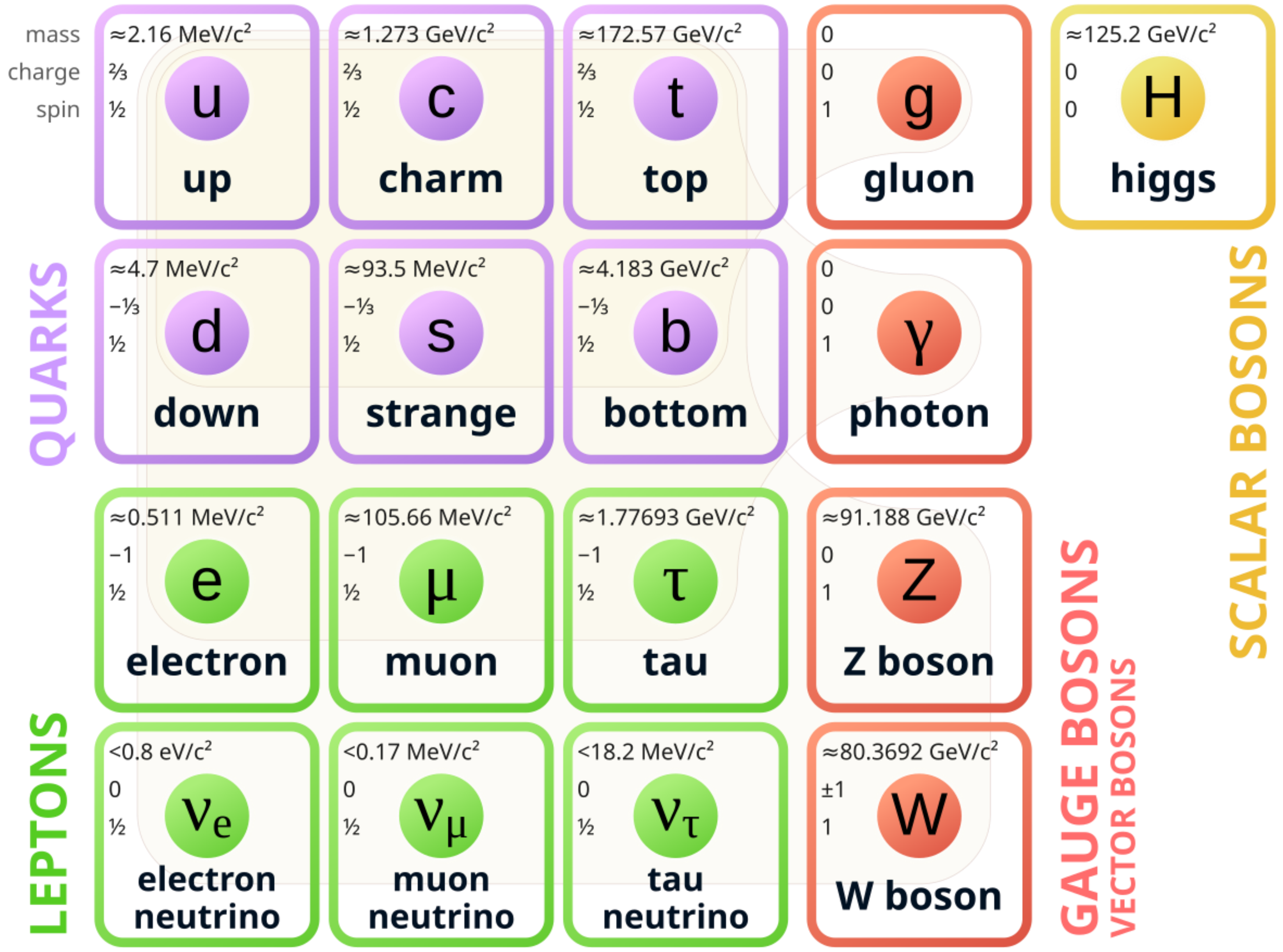
Marko Pesut

University of Zürich

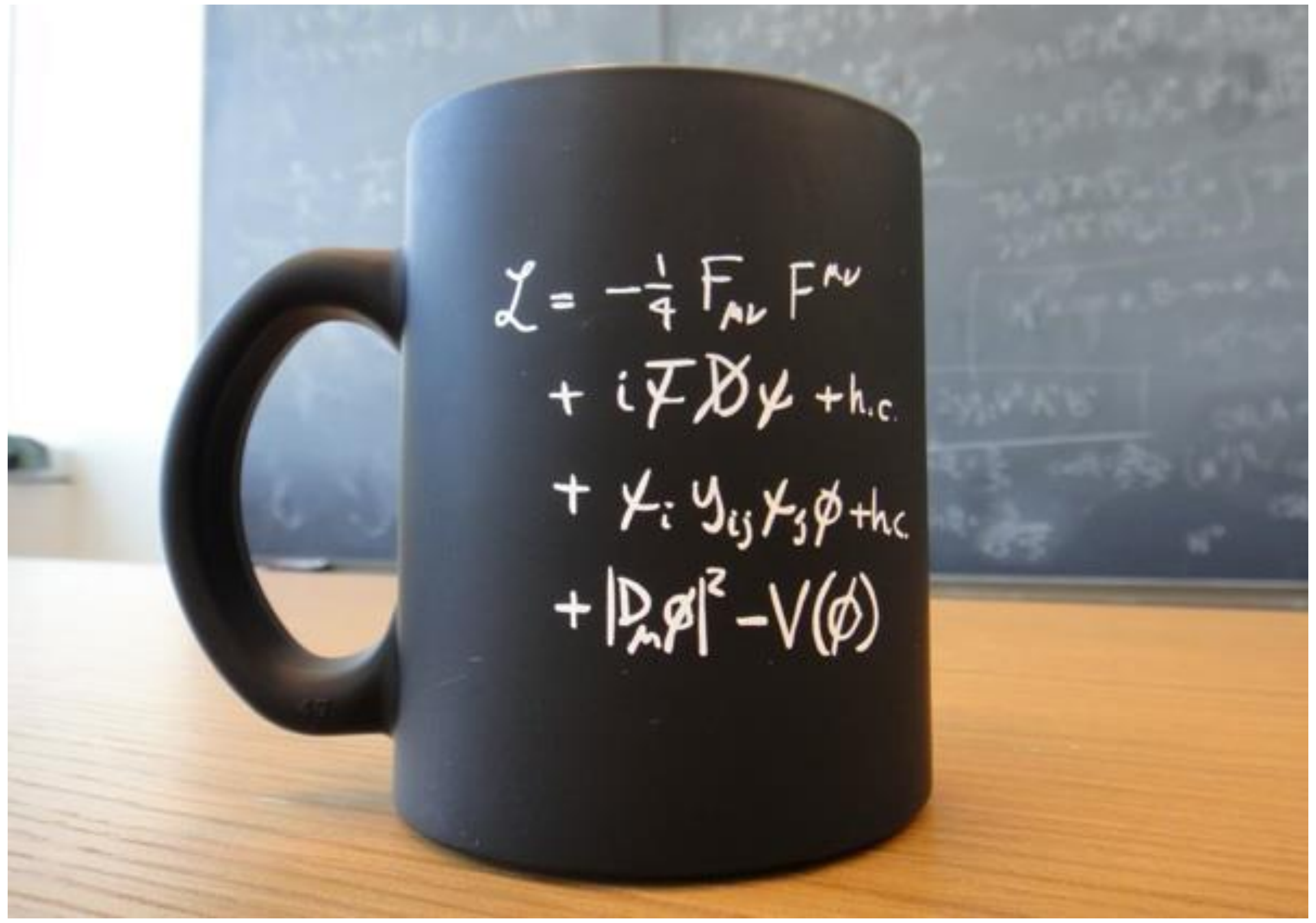
Swiss Institute of Particle Physics

*Biased personal perspectives

Where has the past taken us?



Special
Relativity
+
Quantum
Mechanics



- Understanding of Yang-Mills gauge theories:

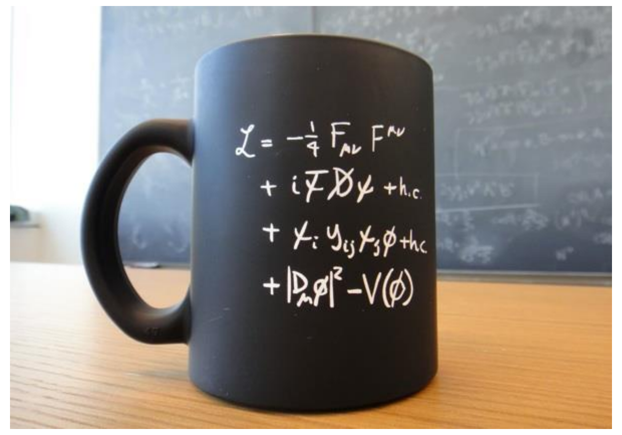
  - SU(2) x U(1) structure

  - QCD: asymptotic freedom, SSB of chiral sym.

- Flavour and CKM: peculiar Yukawa pattern, CP violation
- Consistency conditions (anomaly can.)
- *All QFTs are Effective Field Theories: RGEs, Wilsonian approach to renormalization*

All QFTs are EFTs…

$$\mathcal{L}_{\mathrm{SMEFT}} = \mathcal{L}_{\mathrm{SM}}^{d\leq 4} + \underbrace{\frac{1}{\Lambda_{\mathrm{UV}}}\mathcal{L}^{d=5}}_{m_\nu \neq 0} + \underbrace{\frac{1}{\Lambda_{\mathrm{UV}}^2}\mathcal{L}^{d=6} + \ldots}_{\text{New Physics effects}}$$



New Physics effects:

- (More) Flavour violation / FCNCs ΔM_K
- (More) CP violation ε_k
- (More) EDMs d_e
- Modified EWPO $S,\ T$
- B and L breaking $\mathrm{p}^+ \longrightarrow \mathrm{e}^+ + \pi^0$

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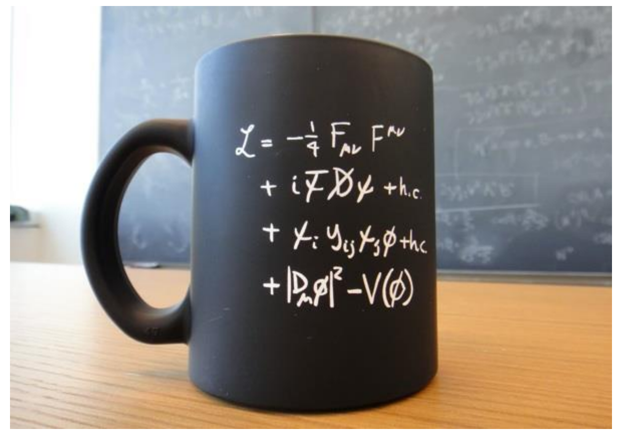

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➡ Nothing seen yet … NP must be **really heavy** !

$$\Lambda_{\text{EW}} \ll \Lambda_{\text{UV}}$$

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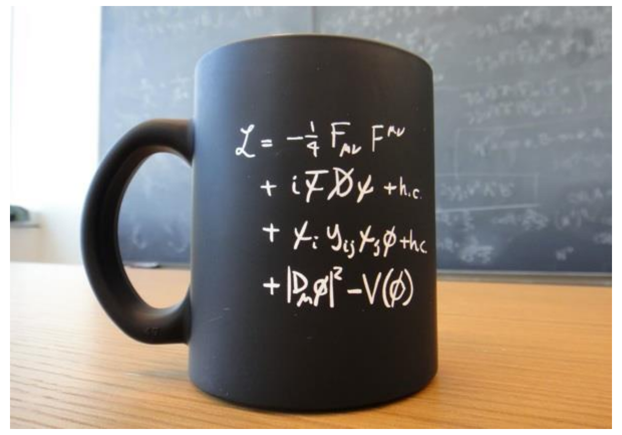

$m_\nu \neq 0$

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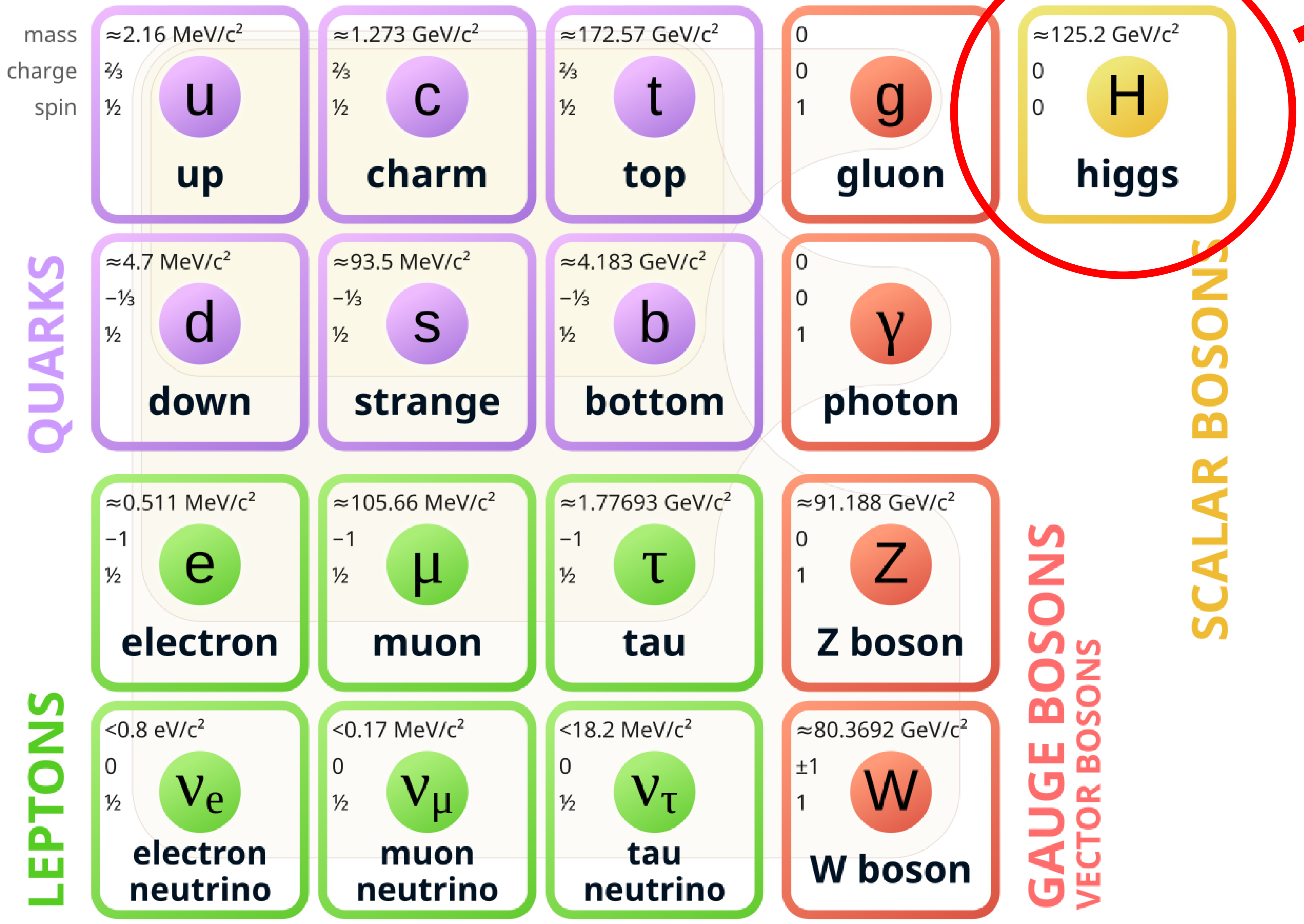
$$\Lambda_{\rm EW} \ll \Lambda_{\rm UV}$$

$m_H^2 \sim c\Lambda_{\rm UV}^2$ vs $m_H = 125\,{\rm GeV}$

Simplicity vs Naturalness

Naturalness wants **close by** New Physics scale $\Lambda_{\rm UV} \lesssim \mathcal{O}({\rm TeV})$

We already have “New” Physics!



An elementary spin 0 particle !?

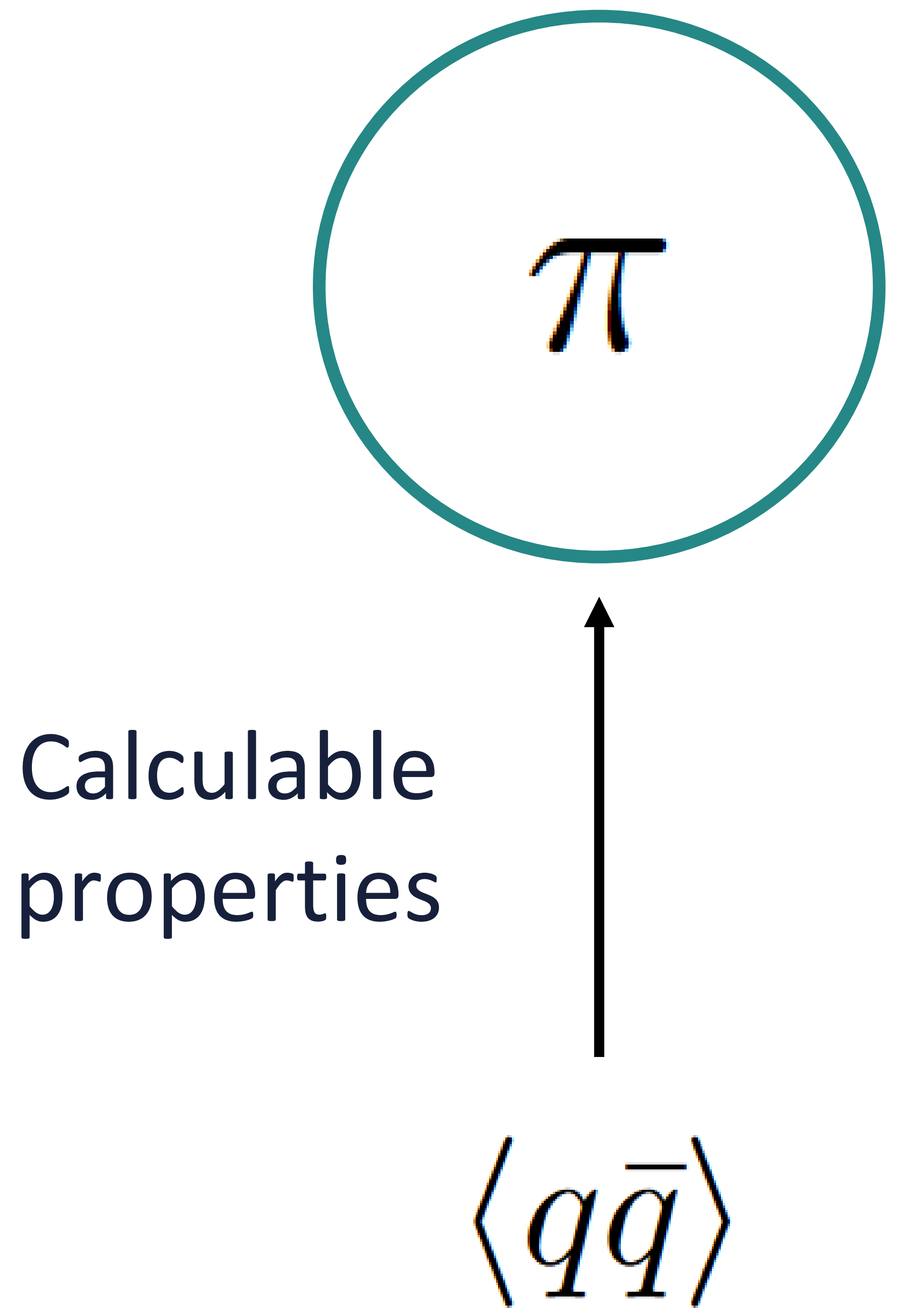
$$\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} + i\bar{\Psi} \not{D} \psi + D_\mu \Phi^\dagger D^\mu \Phi - V(\Phi) + \bar{\Psi}_L \hat{Y} \Phi \Psi_R + h.c.$$

Most of the SM puzzles are related to the Higgs sector …

We already have "New" Physics!

➡ We have *never* observed an elementary scalar before!

e.g. the pions in QCD



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π

Similar Mechanism for the Higgs ?

[More on this idea later]

Calculable properties

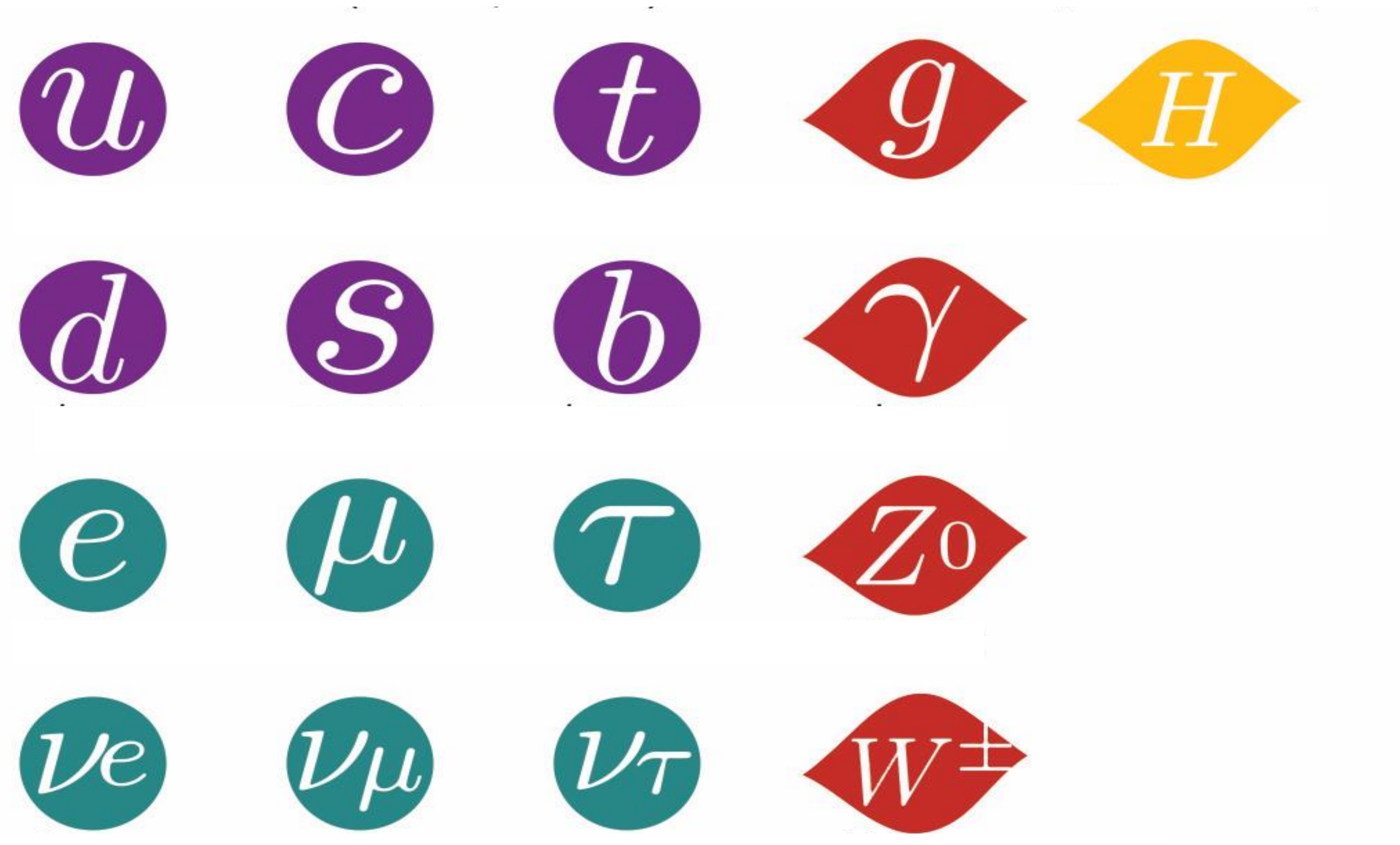
$\langle q\bar{q} \rangle$

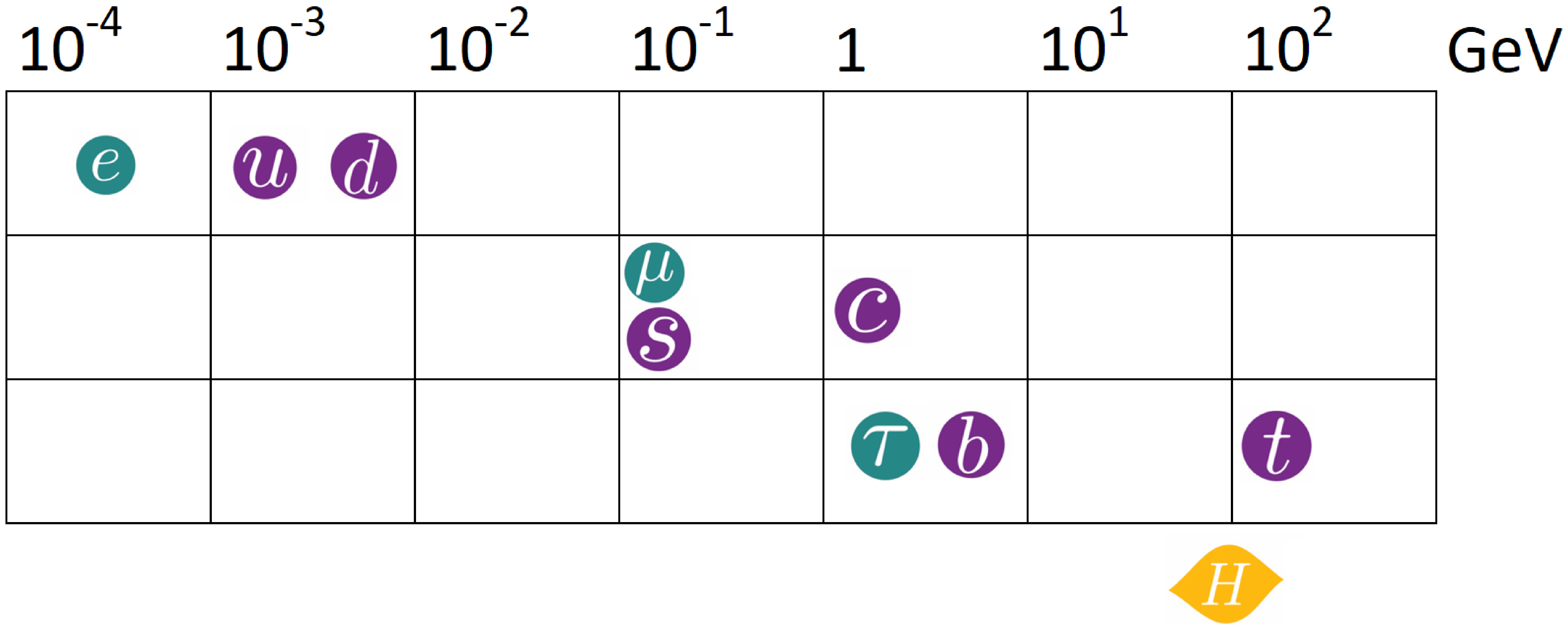
?

Is the Higgs elementary or composite ?

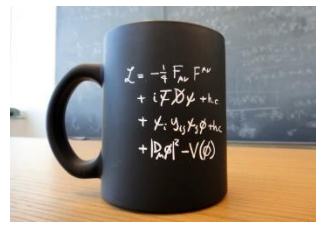
The Flavour Puzzle

Hierarchical pattern of fermion masses





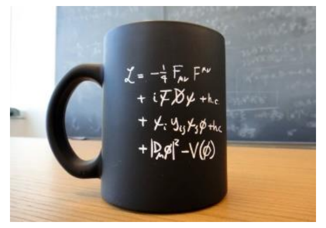
The Flavour Puzzle



$$= -\frac{1}{4}F_{\mu\nu}F^{\mu\nu}$$
$$+ i\bar{\Psi}\not{D}\psi$$
$$+ D_\mu\Phi^\dagger D^\mu\Phi - V(\Phi)$$
$$+ \bar{\Psi}_L\hat{Y}\Phi\Psi_R + h.c.$$

Exact $U(3)^5$ flavour symmetries

The Flavour Puzzle

 $= -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + i\bar{\Psi}\not{D}\psi$ → Exact $U(3)^5$ flavour symmetries

$$+ D_\mu\Phi^\dagger D^\mu\Phi - V(\Phi)$$

$$+ \bar{\Psi}_L\hat{Y}\Phi\Psi_R + h.c.$$

➡ $y_{33} \sim 1$, all the others are $y_{ij} << 1$

$$Y_u \sim \begin{pmatrix} & & \\ & < 0.01 & 0.04 \\ & & 1 \end{pmatrix}$$

$$V_{CKM} \approx \begin{pmatrix} 1 & 0.2 & 0.004 \\ 0.2 & 1 & 0.04 \\ 0.009 & 0.04 & 1 \end{pmatrix}$$

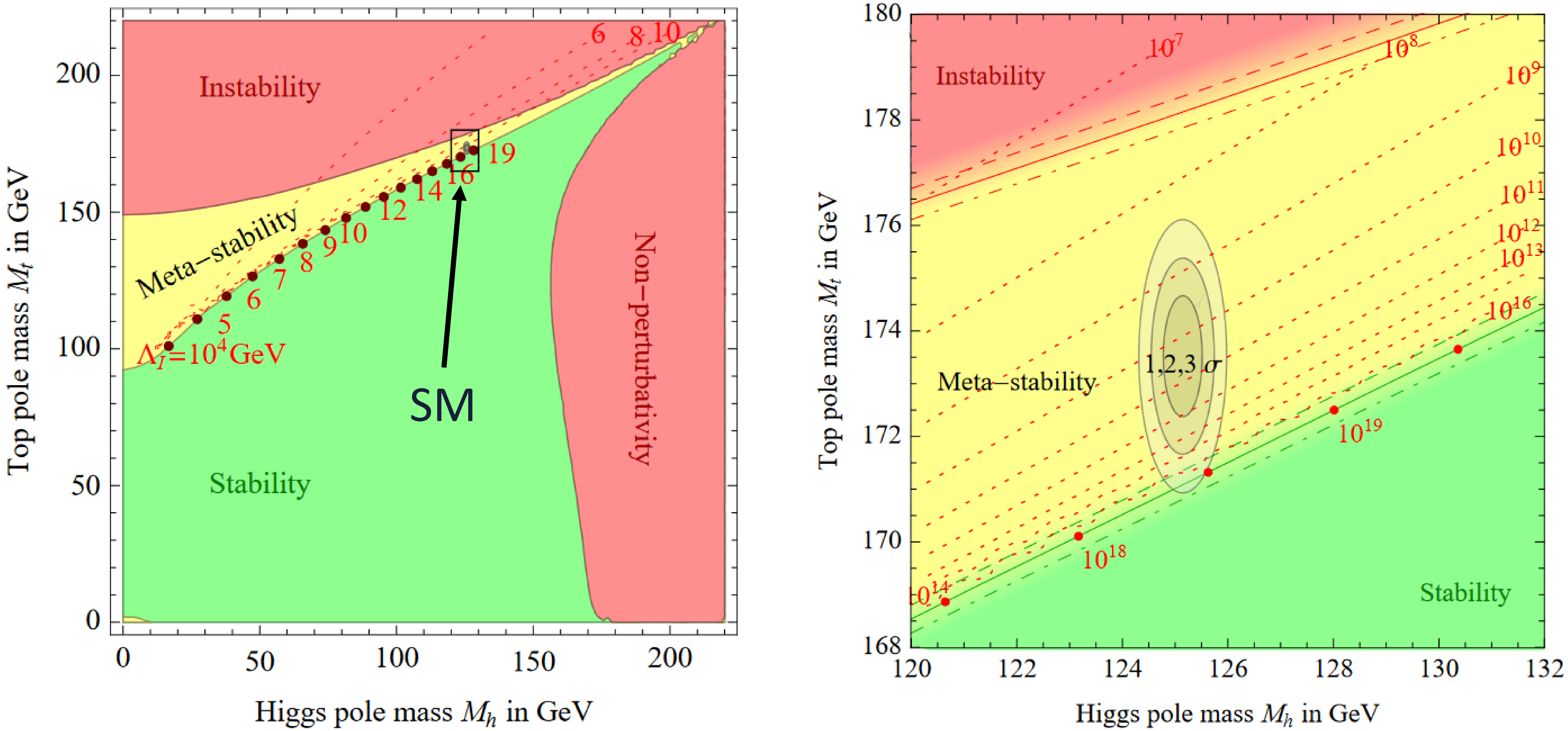
$$\Rightarrow V_{11} \gg V_{21} \gg V_{31}$$

$\Rightarrow U(2)^n$ approx. flavour symmetry

Vacuum Stability

- The value of the Higgs mass suggests that the EW vacuum is *meta-stable*

➡ RGE of the Higgs self coupling

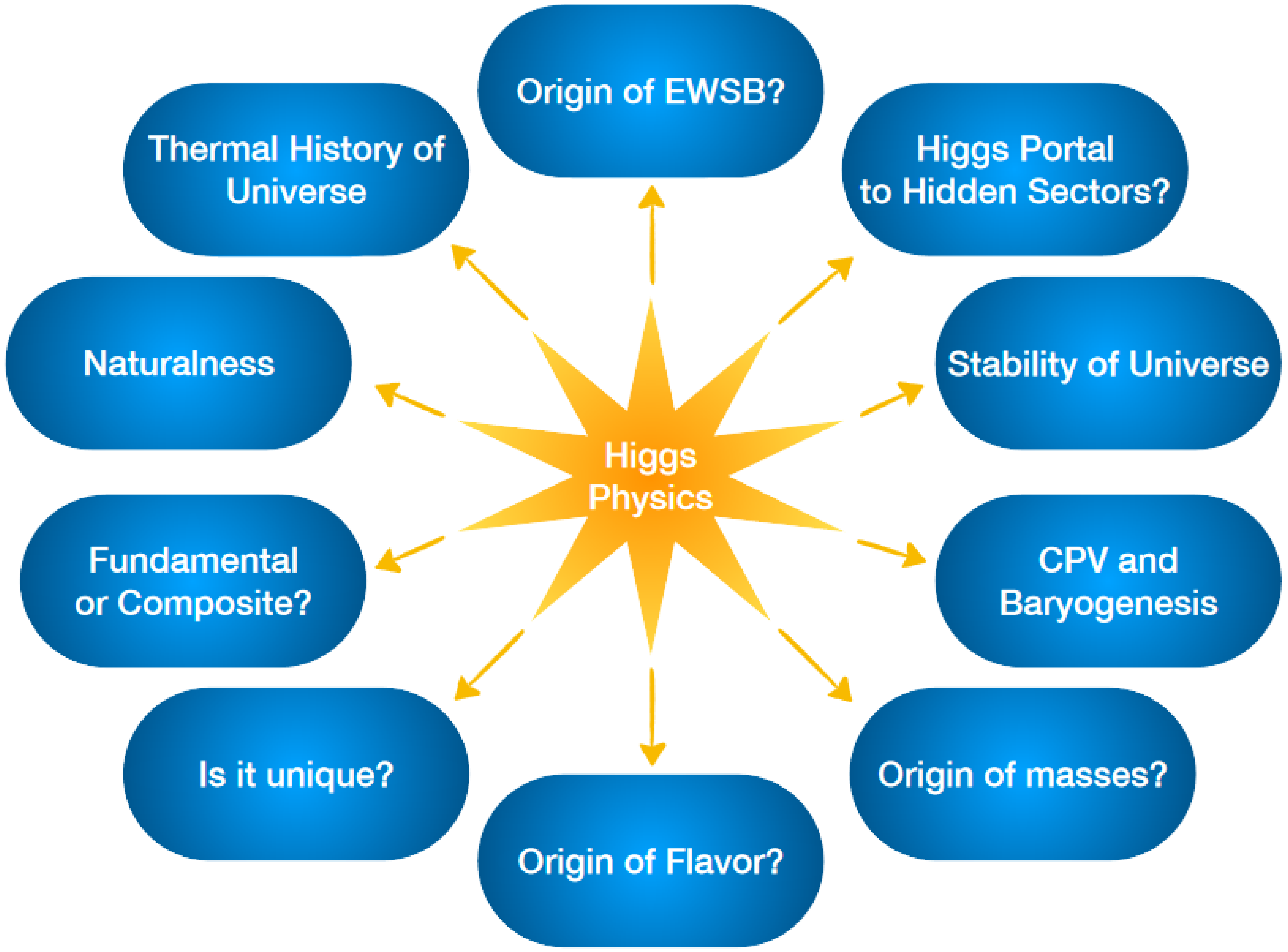


[1307.3536]

Standard Model Puzzles & Mysteries

- The Higgs is at the *heart* of many of SM puzzles: naturalness, flavour, vacuum stability,…

- We also face many challenges / mysteries: Dark Matter, charge quantization, Strong CP problem, matter-antimatter asymmetry, cosmological constant, early universe, quantum gravity…



[2209.07510]

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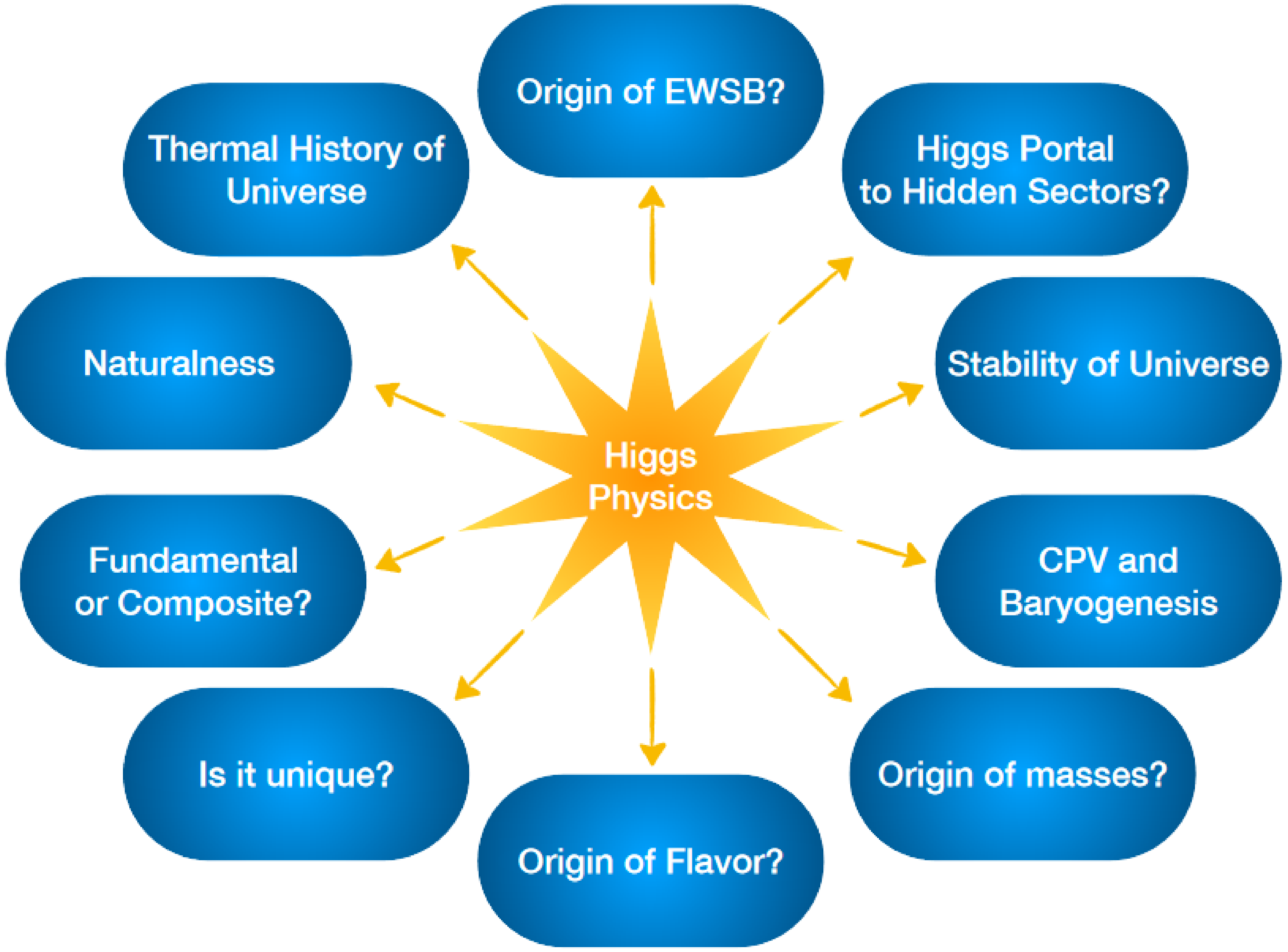

[2209.07510]

What are we looking for ?

1. SM Parameters *(CKM, Higgs self couplings, light Yukawa…)*
2. SM puzzles & mysteries + Higgs
3. Missing pieces *(DM, matter-antimatter, cosmo. const…)*

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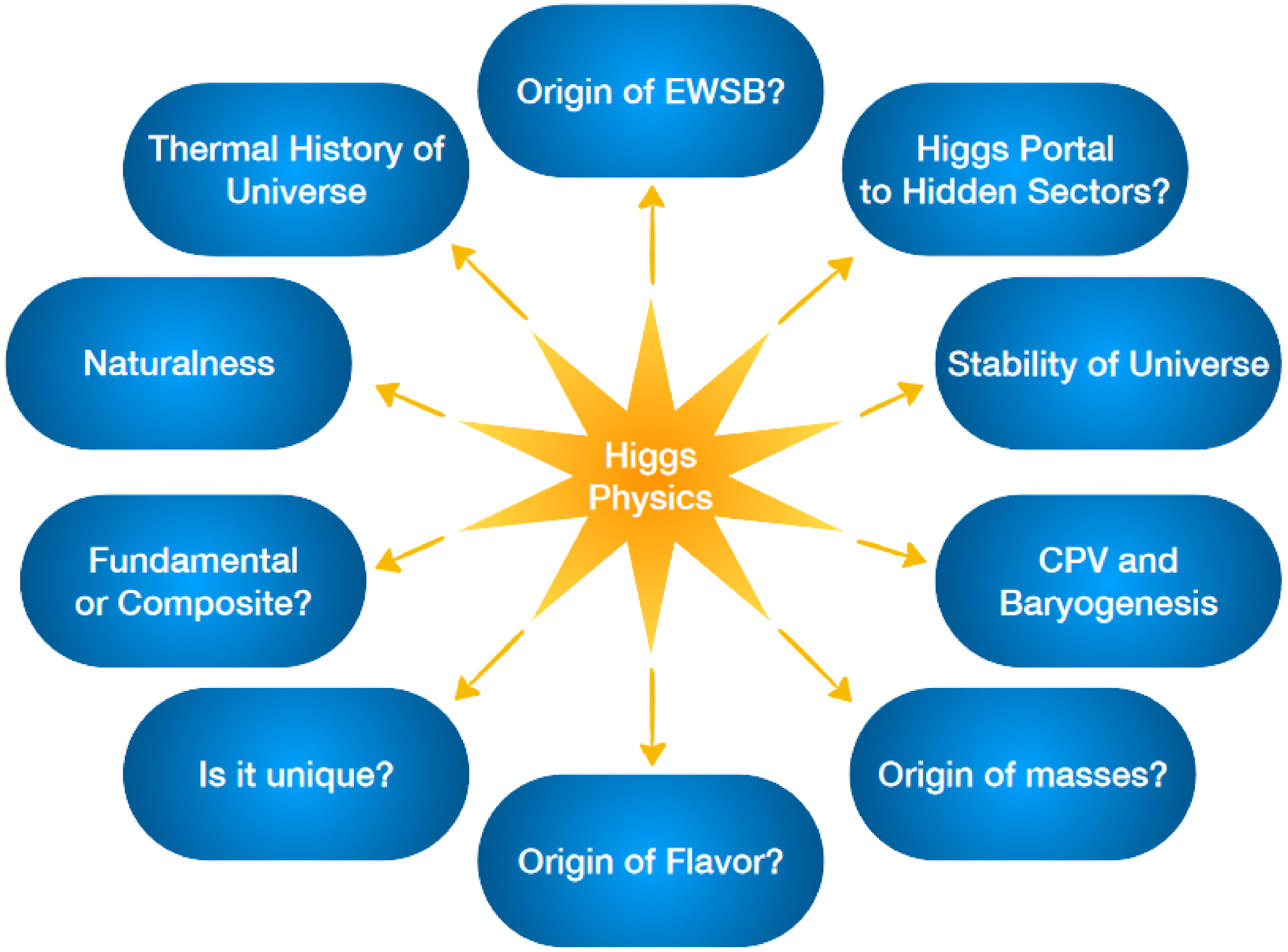

[2209.07510]

What are we looking for ?

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What are our guiding principles ?

➡ Learn more about the Higgs (+EW)

➡ Unbiased exploration of other possibilities

$$\mathcal{L}_{\rm SMEFT} = \mathcal{L}_{\rm SM}^{d\leq 4} + \frac{1}{\Lambda_{\rm UV}}\mathcal{L}^{d=5} + \frac{1}{\Lambda_{\rm UV}^2}\mathcal{L}^{d=6} + \ldots$$

Case Study I: Flavour and EW @FCC-ee

Why Flavour ?

The low-energy flavour prospects at FCC-ee come largely from the tera-$\boldsymbol{Z}$ run:

Of the 10^{12} Z-bosons produced at tera-Z:

- 15% decay to b
- 12% decay to c
- 3% decay to τ

FCC-ee combines advantages of B factories and LHC + open new frontiers

➡ Clean environment + huge statistics + full range of (boosted) B mesons

} Complementarity with LHC & Belle II

[2106.01259]

[More on this in Armin's and Pantelis's talk]

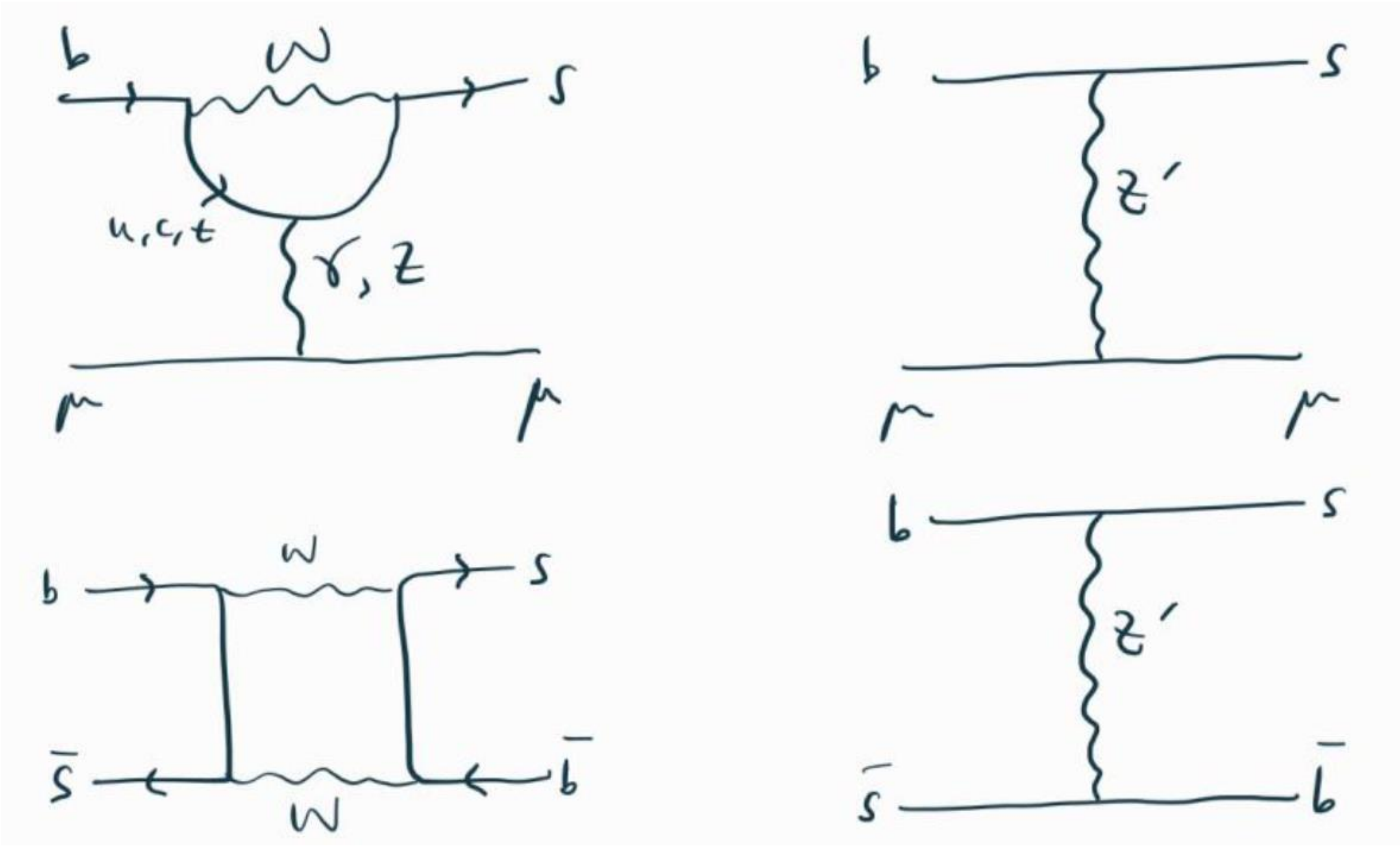
Credits: Joe Davighi's and Lukas Allwicher's talks @ FCC workshop 2025

Case Study I: Flavour and EW @FCC-ee

Why Flavour ?

➡ Flavour-Changing processes are *rare* (e.g. FCNC: GIM + loops + CKM suppressions)

BSM might not respect these features…



E.g. a flavour non-universal Z'

Credits: Joe Davighi's and Lukas Allwicher's talks @ FCC workshop 2025

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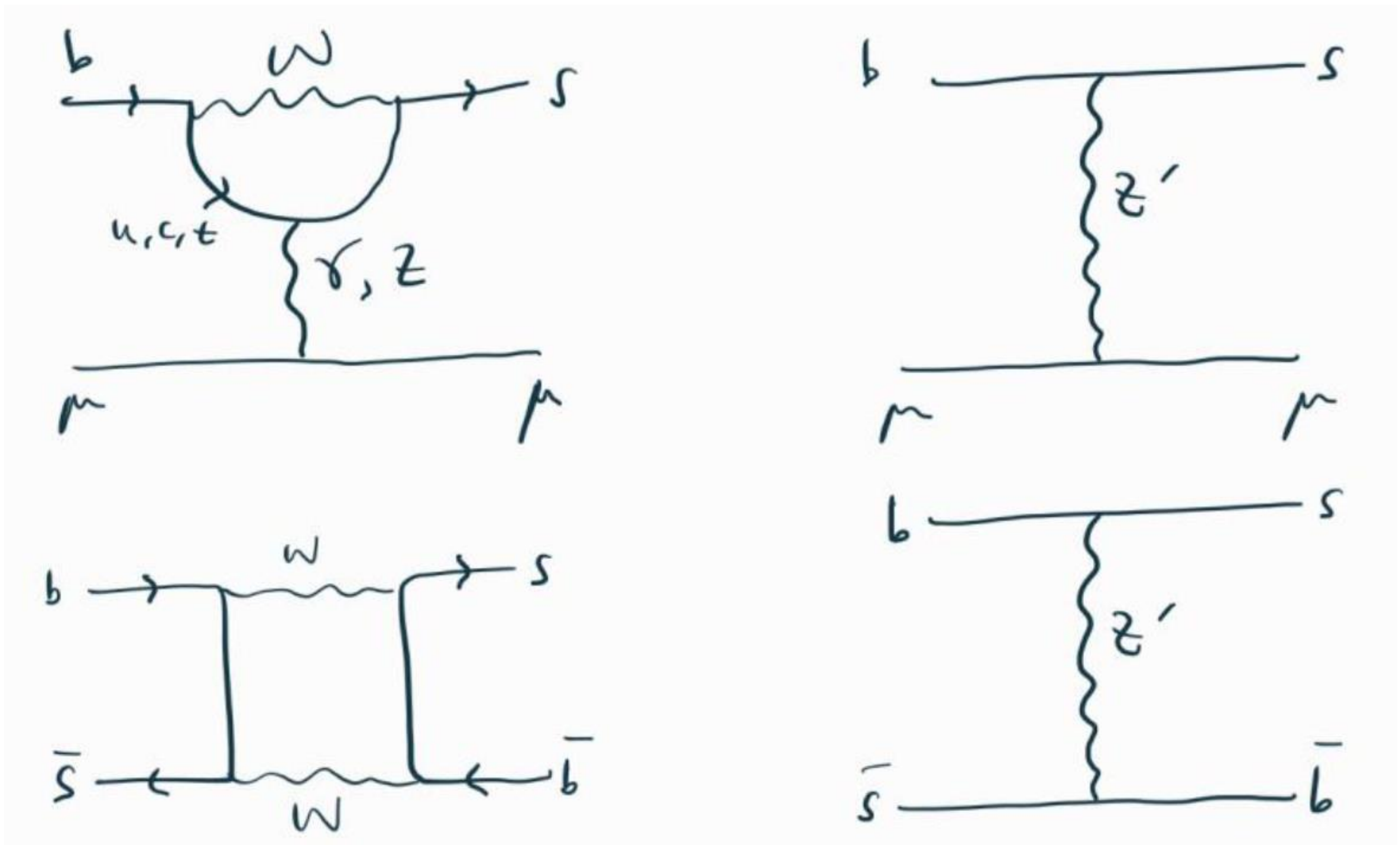

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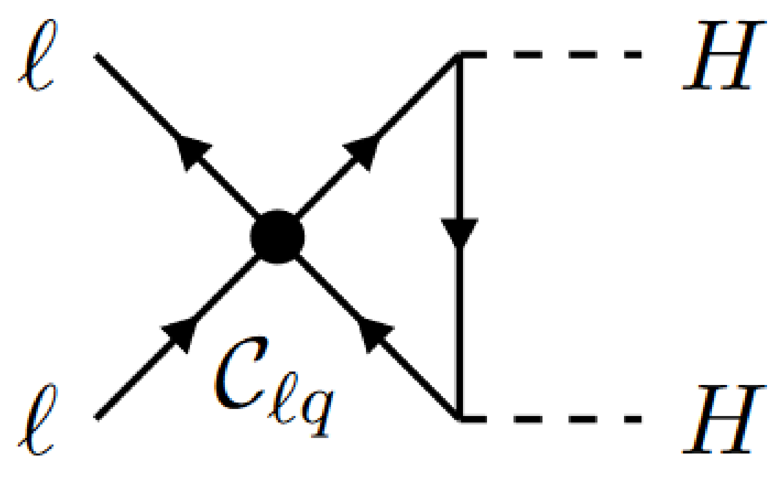
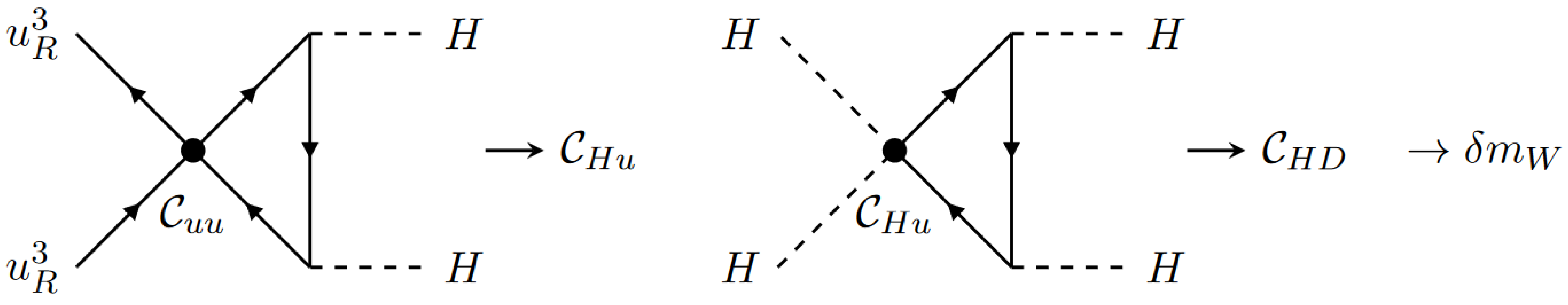
RGE effects become *crucial* @FCC-ee!



- Particularly relevant if y_t is involved
- Effects e.g. in $Z \to \tau\,\tau$



[See Case Study II]

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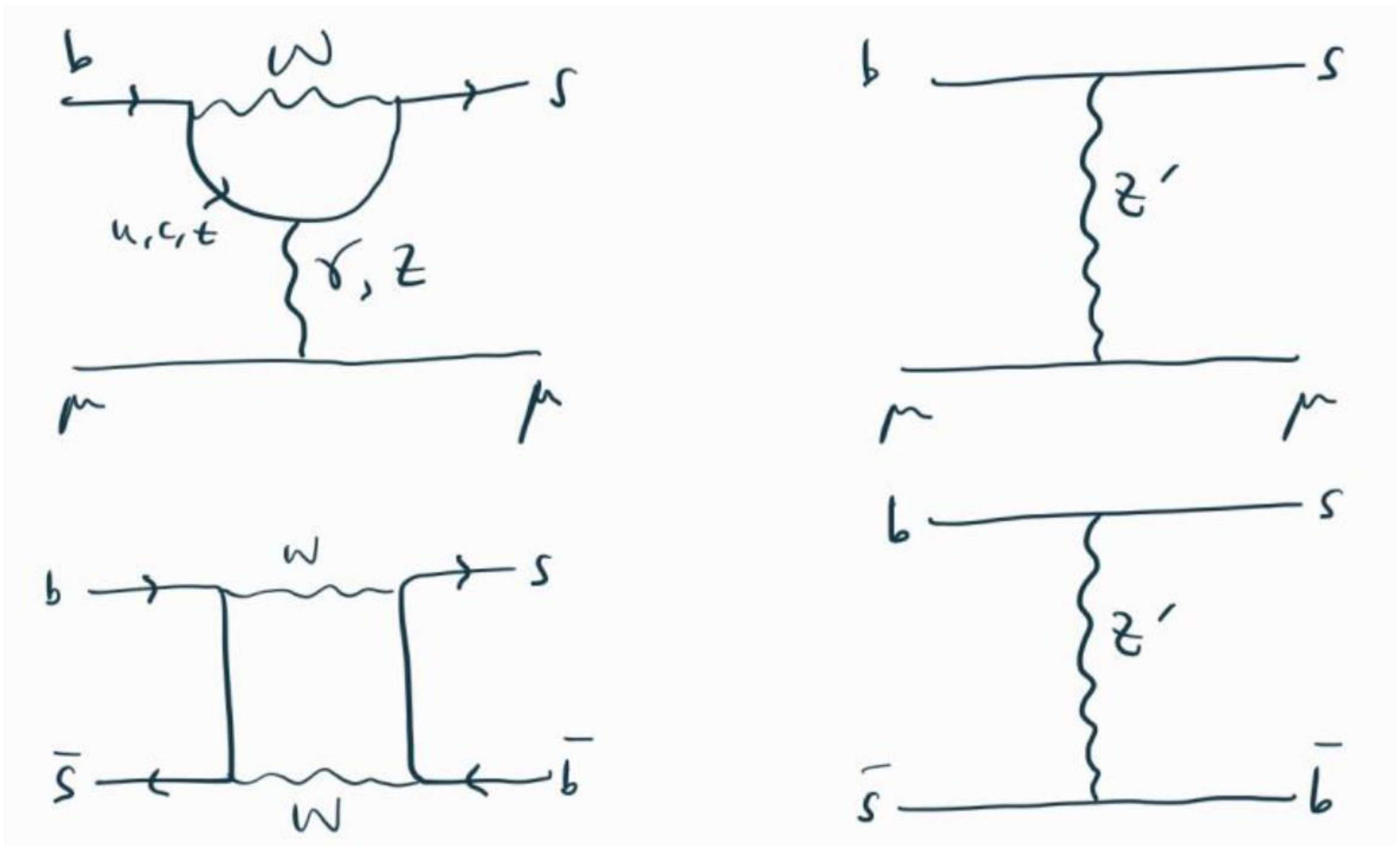

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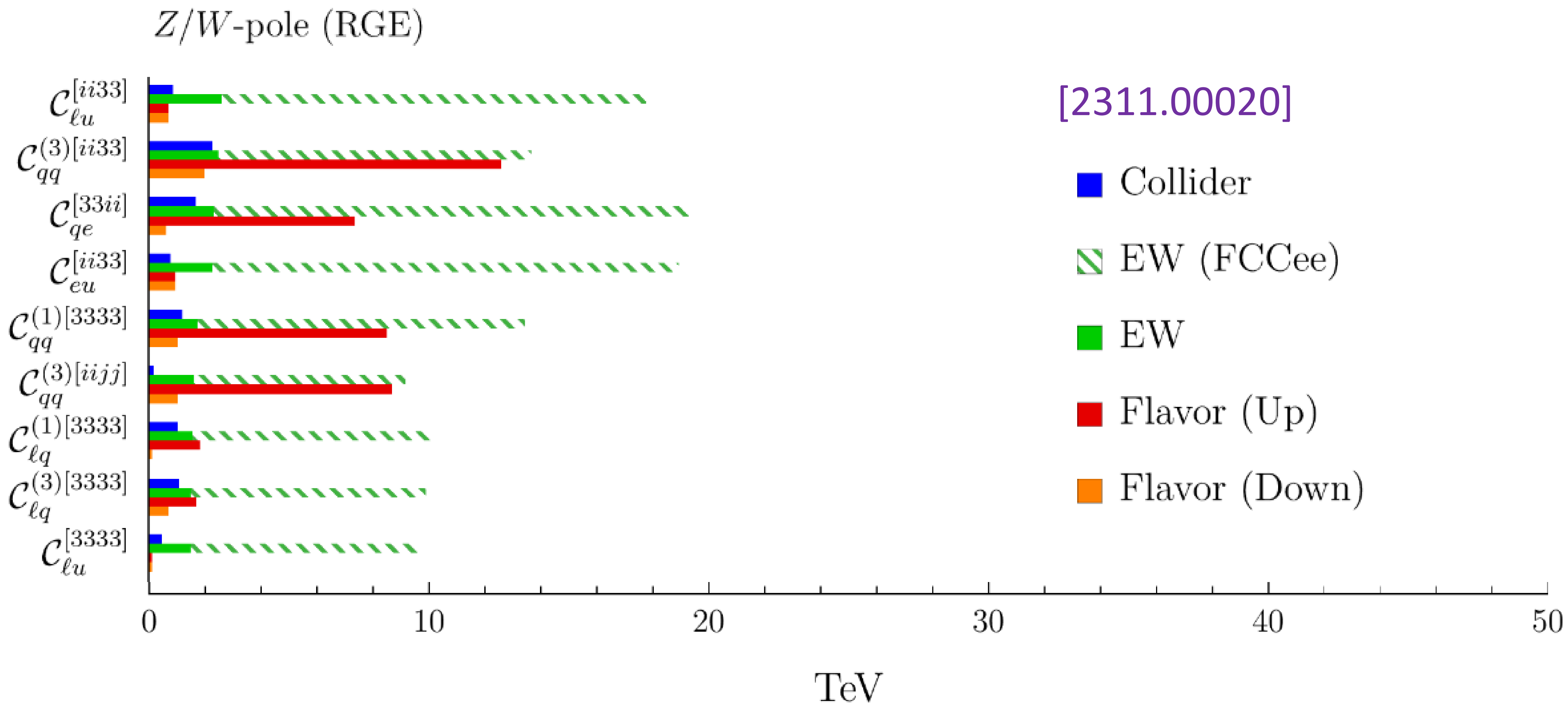
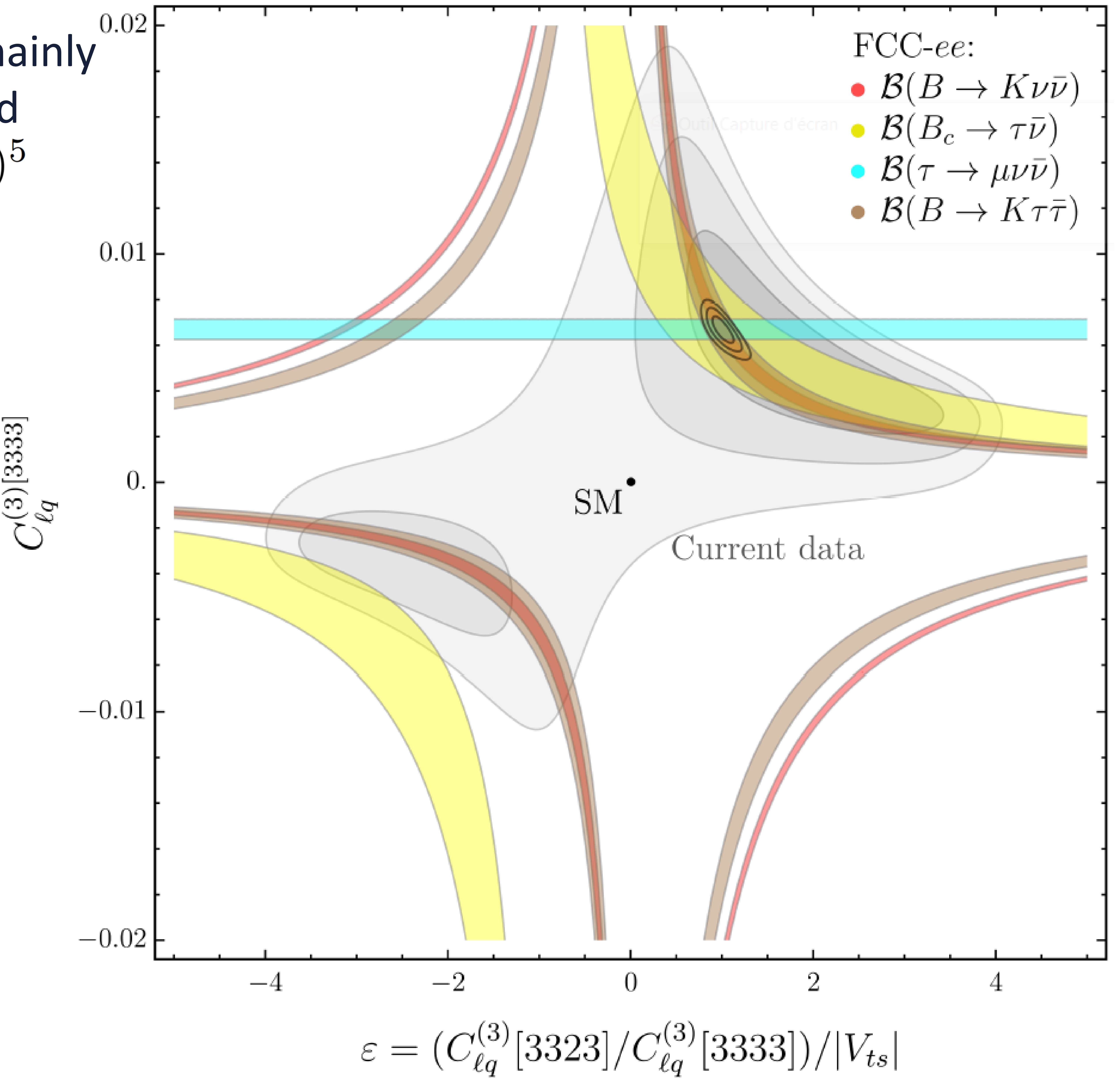


Credits: Joe Davighi's and Lukas Allwicher's talks @ FCC workshop 2025

Case Study I: Flavour and EW @FCC-ee

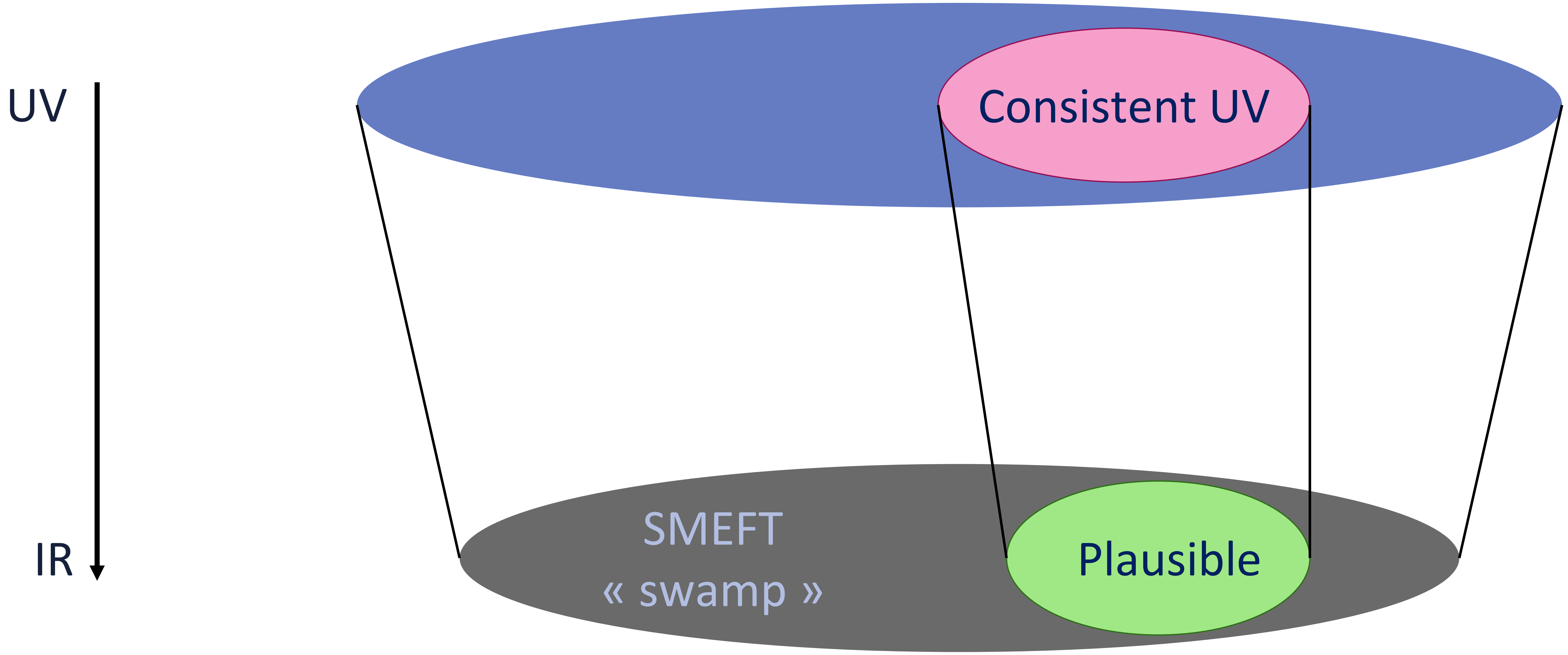
Flavour non-universal NP, mainly coupled to 3rd family and minimally-broken $U(2)^5$

[Allwicher, Isidori, Pesut w.i.p]



Case Study I: Flavour and EW @FCC-ee

Not all SMEFT parameter space can be spanned by UV models



$$\mathcal{L}_{\rm SMEFT} = \mathcal{L}_{\rm SM}^{d\leq 4} + \frac{1}{\Lambda_{\rm UV}}\mathcal{L}^{d=5} + \frac{1}{\Lambda_{\rm UV}^2}\mathcal{L}^{d=6} + \ldots$$

Fits are not enough … need to have a concrete UV picture in mind a.k.a a model !

Credits: Matthew McCullough's talk @ FCC workshop 2025

Case Study I: Flavour and EW @FCC-ee

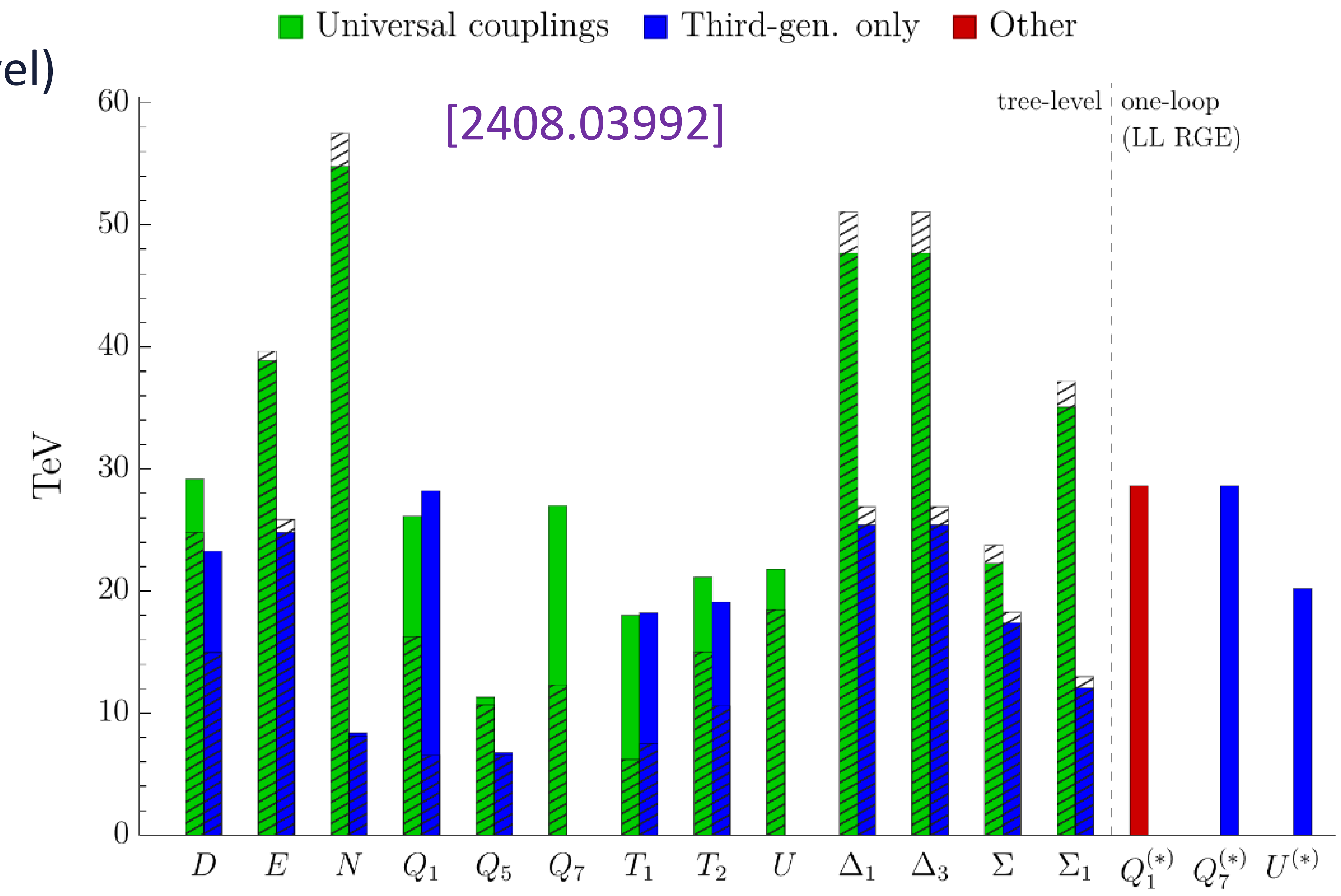
Lets suppose BSM affect dim-6 operators at tree-level…what are all the possible states ?

BSM states that match to dim-6 SMEFT (@ tree-level)

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	$\mathcal{B}$ $(1,1)_0$	$\mathcal{B}_1$ $(1,1)_1$	$\mathcal{W}$ $(1,3)_0$	$\mathcal{W}_1$ $(1,3)_1$	$\mathcal{G}$ $(8,1)_0$	$\mathcal{G}_1$ $(8,1)_1$	$\mathcal{H}$ $(8,3)_0$	$\mathcal{L}_1$ $(1,2)_{\frac{1}{2}}$
	$\mathcal{L}_3$ $(1,2)_{-\frac{3}{2}}$	$\mathcal{U}_2$ $(3,1)_{\frac{2}{3}}$	$\mathcal{U}_5$ $(3,1)_{\frac{5}{3}}$	$\mathcal{Q}_1$ $(3,2)_{\frac{1}{6}}$	$\mathcal{Q}_5$ $(3,2)_{-\frac{5}{6}}$	$\mathcal{X}$ $(3,3)_{\frac{2}{3}}$	$\mathcal{Y}_1$ $(\bar{6},2)_{\frac{1}{6}}$	$\mathcal{Y}_5$ $(\bar{6},2)_{-\frac{5}{6}}$

"Granada Dictionary" [1711.10391]

(Almost) all these new states are probed by EWPOs at one-loop



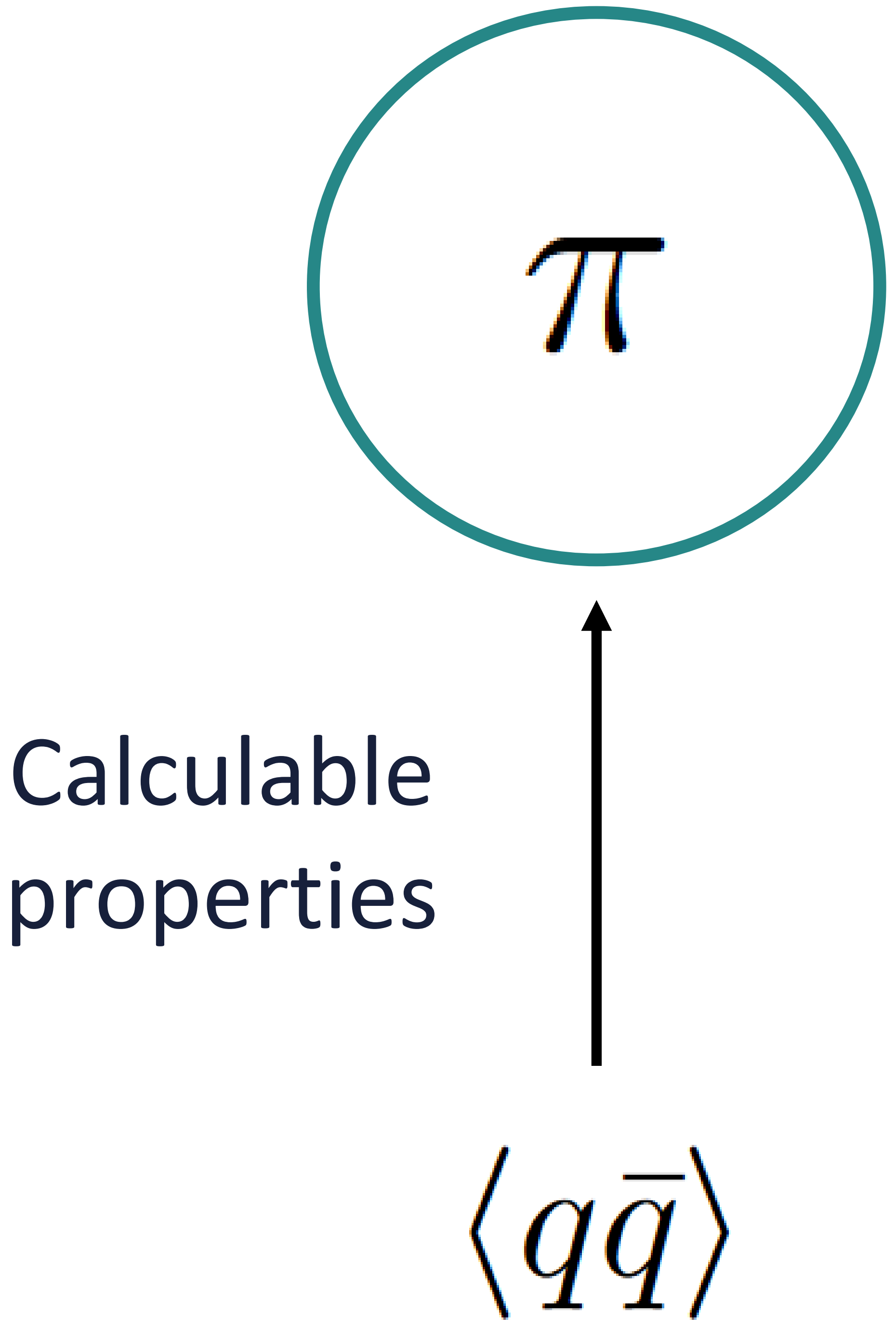
Nothing can hide from FCC-ee !

Credits: [Matthew]() McCullough's talk @ FCC workshop 2025

What about the Higgs?

➡ We have *never* observed an elementary scalar before!

e.g. the pions in QCD



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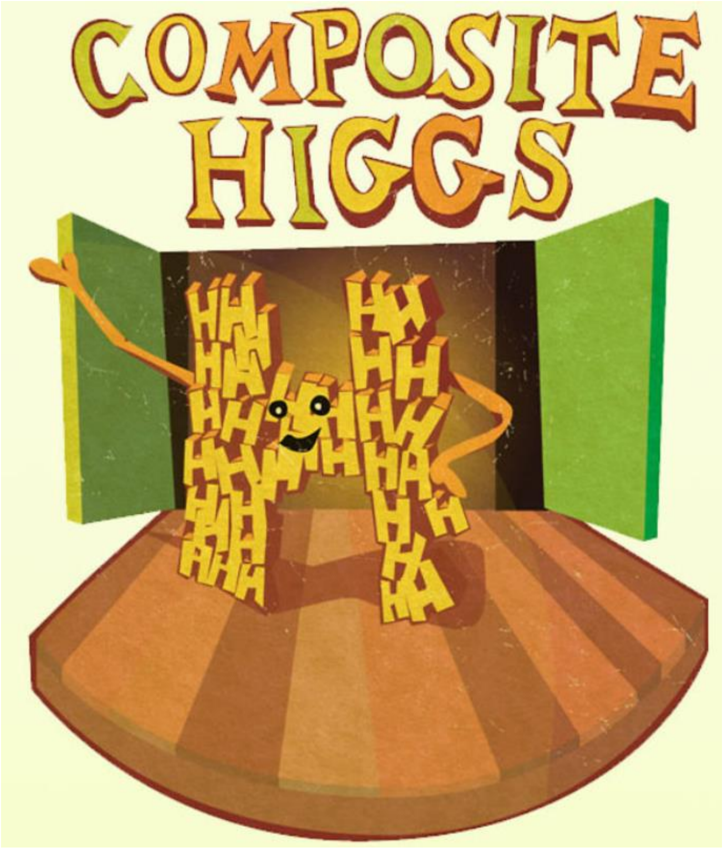
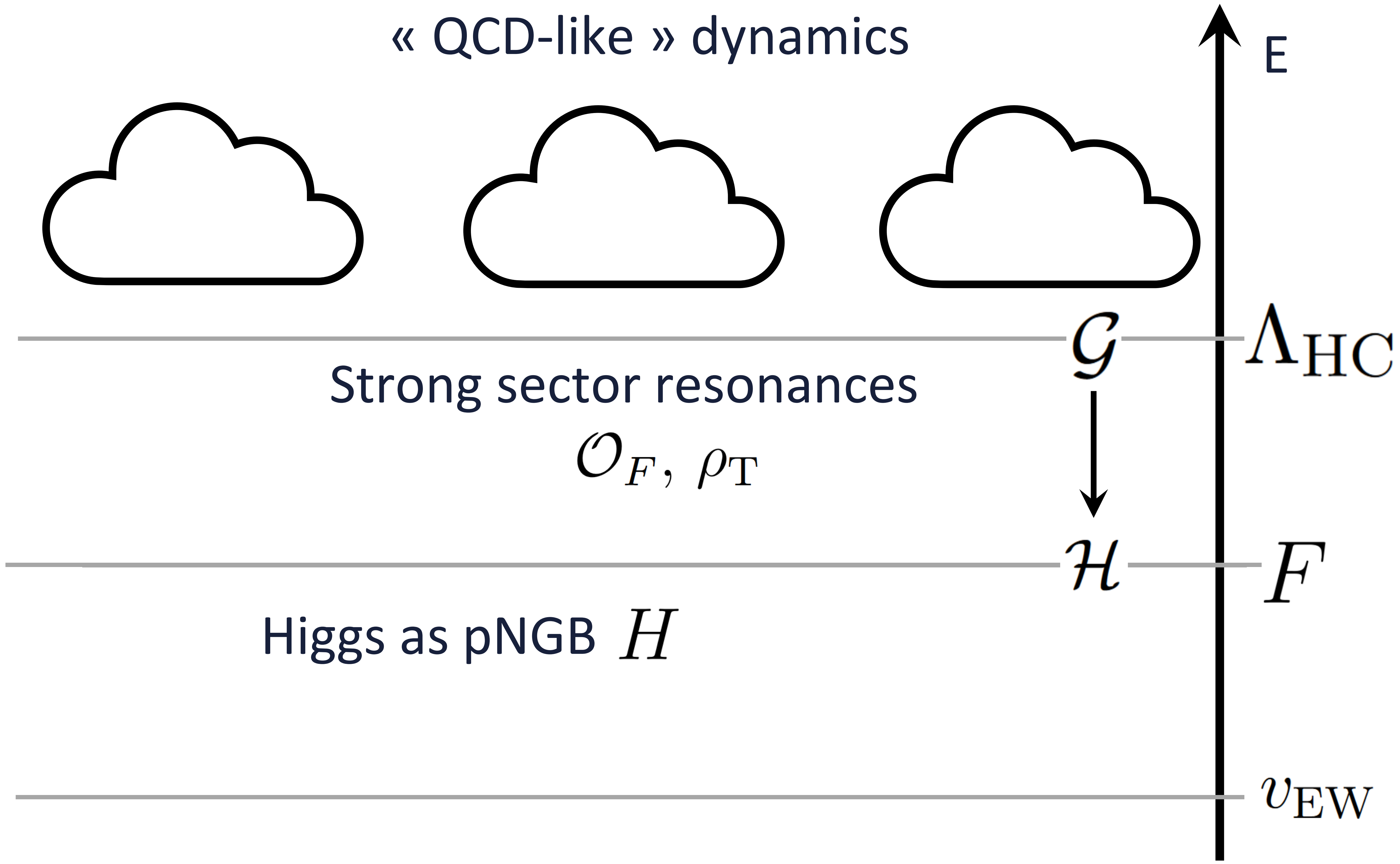
Calculable properties

$\langle q\bar{q} \rangle$

Similar Mechanism for the Higgs ?



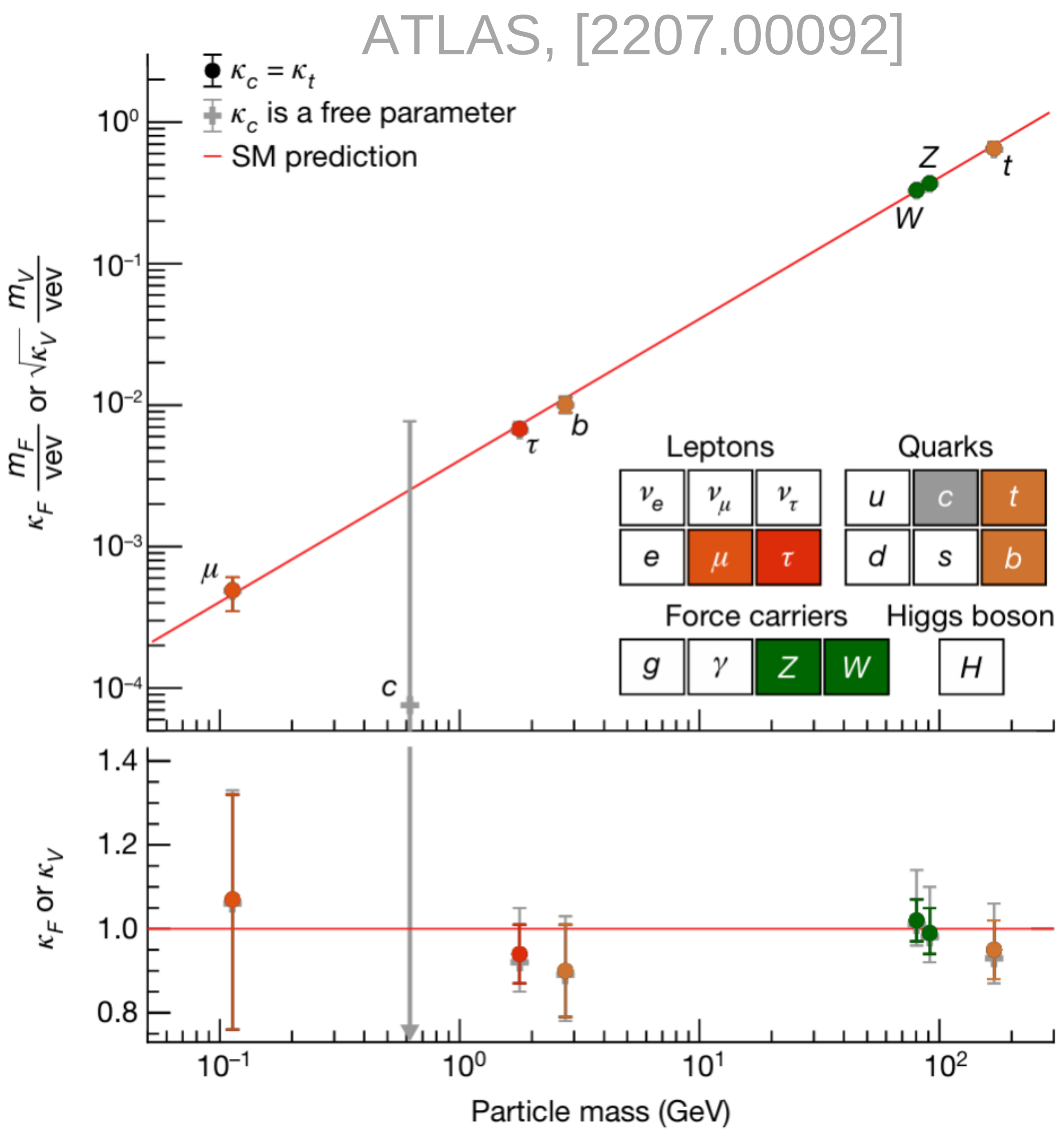
Case Study II: Higgs Compositeness

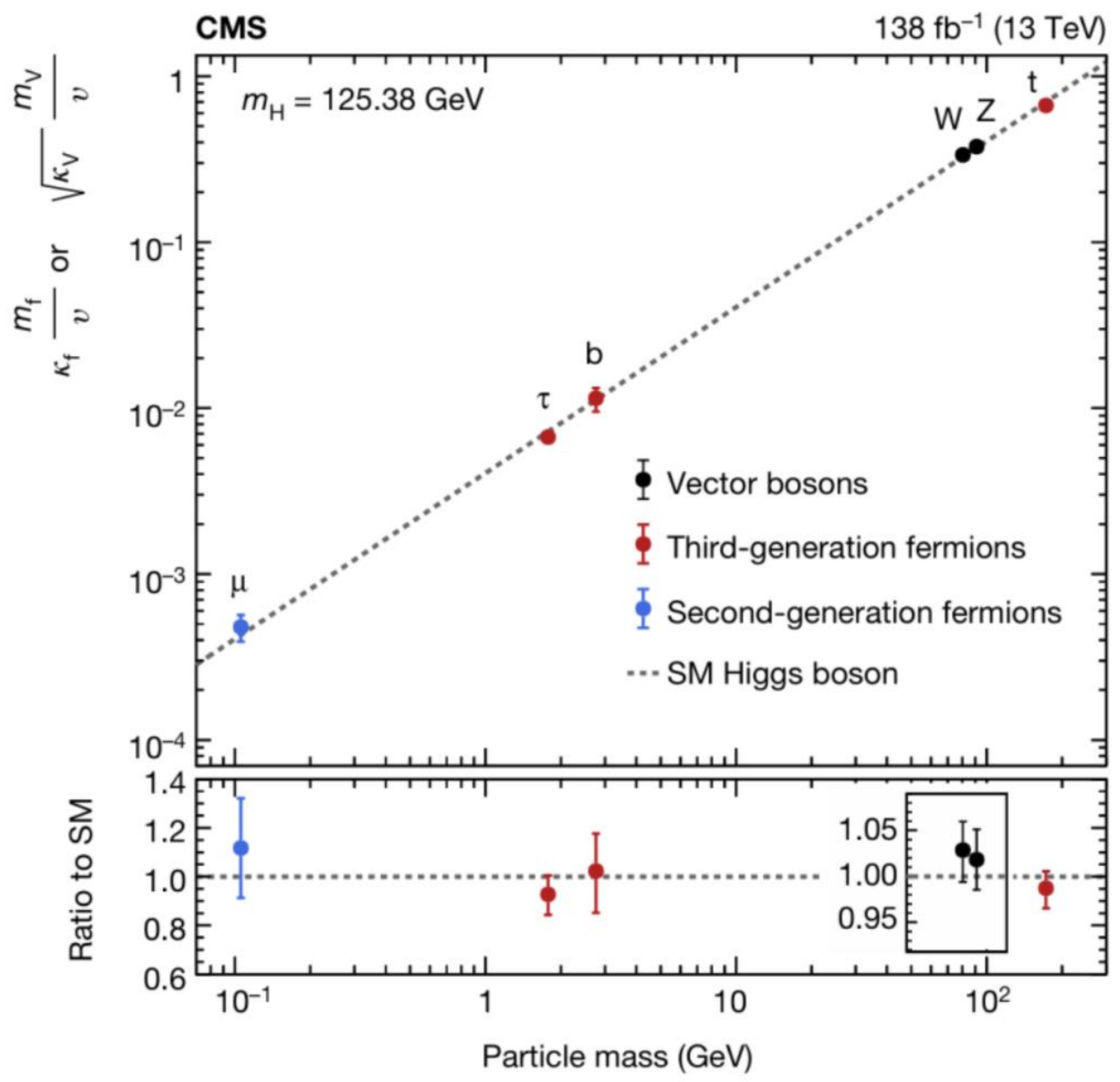


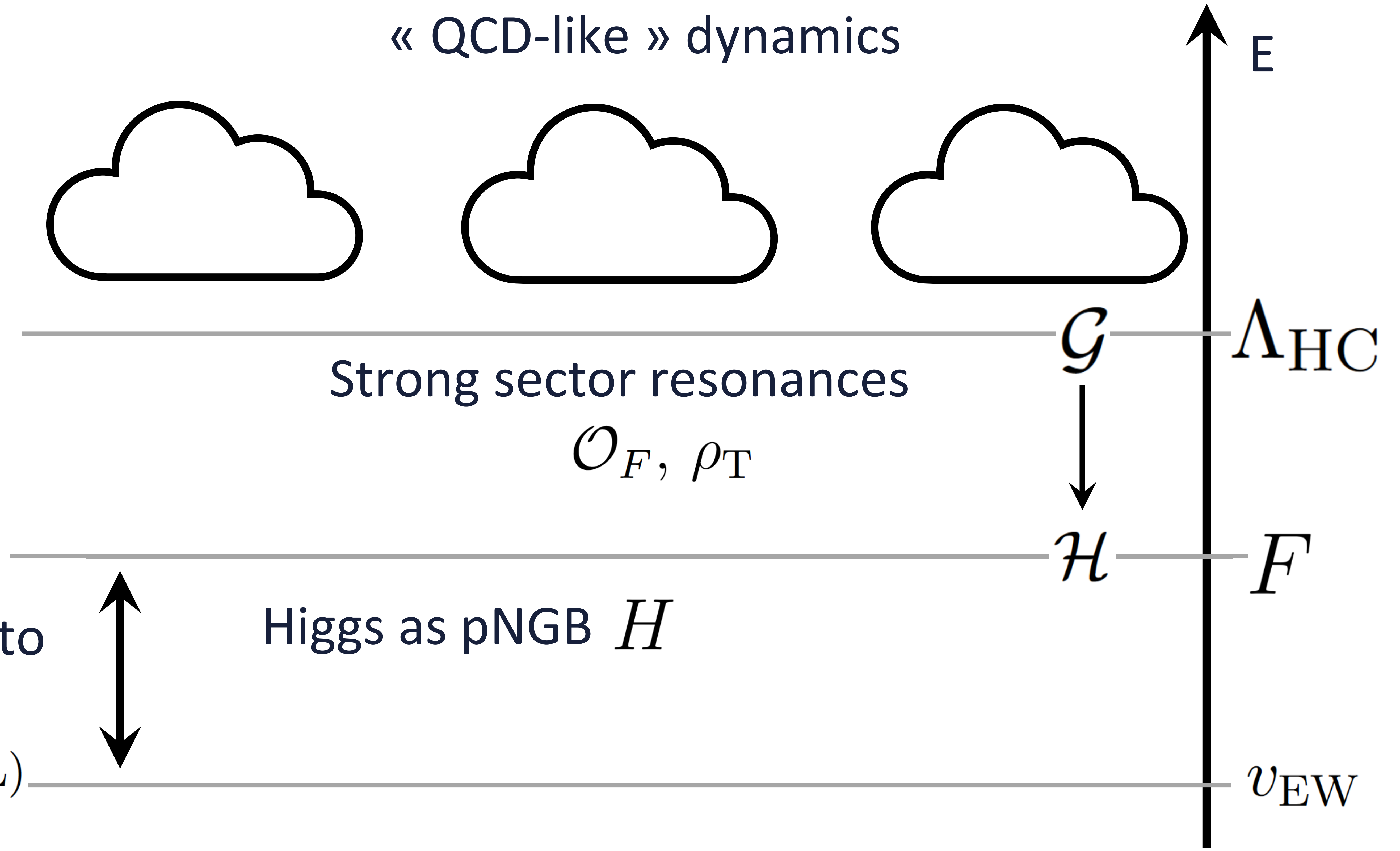
➡ Compositeness scale cuts off quantum corrections to the Higgs potential

Wulzer & Panico 2015
Agashe et al. 2005,
...

Case Study II: Higgs Compositeness







Higgs is SM-like to good approx.
$\xi < 0.06$ (95% CL)

Compositeness corrects SM predictions

$$g_{VVh} = g_{VVh}^{\text{SM}}\sqrt{1-\xi}$$

$$g_{VVhh} = g_{VVhh}^{\text{SM}}(1-2\xi)$$

$$\xi = \frac{v_{\text{EW}}^2}{4F^2}$$

Wulzer & Panico 2015
Agashe et al. 2005,
...

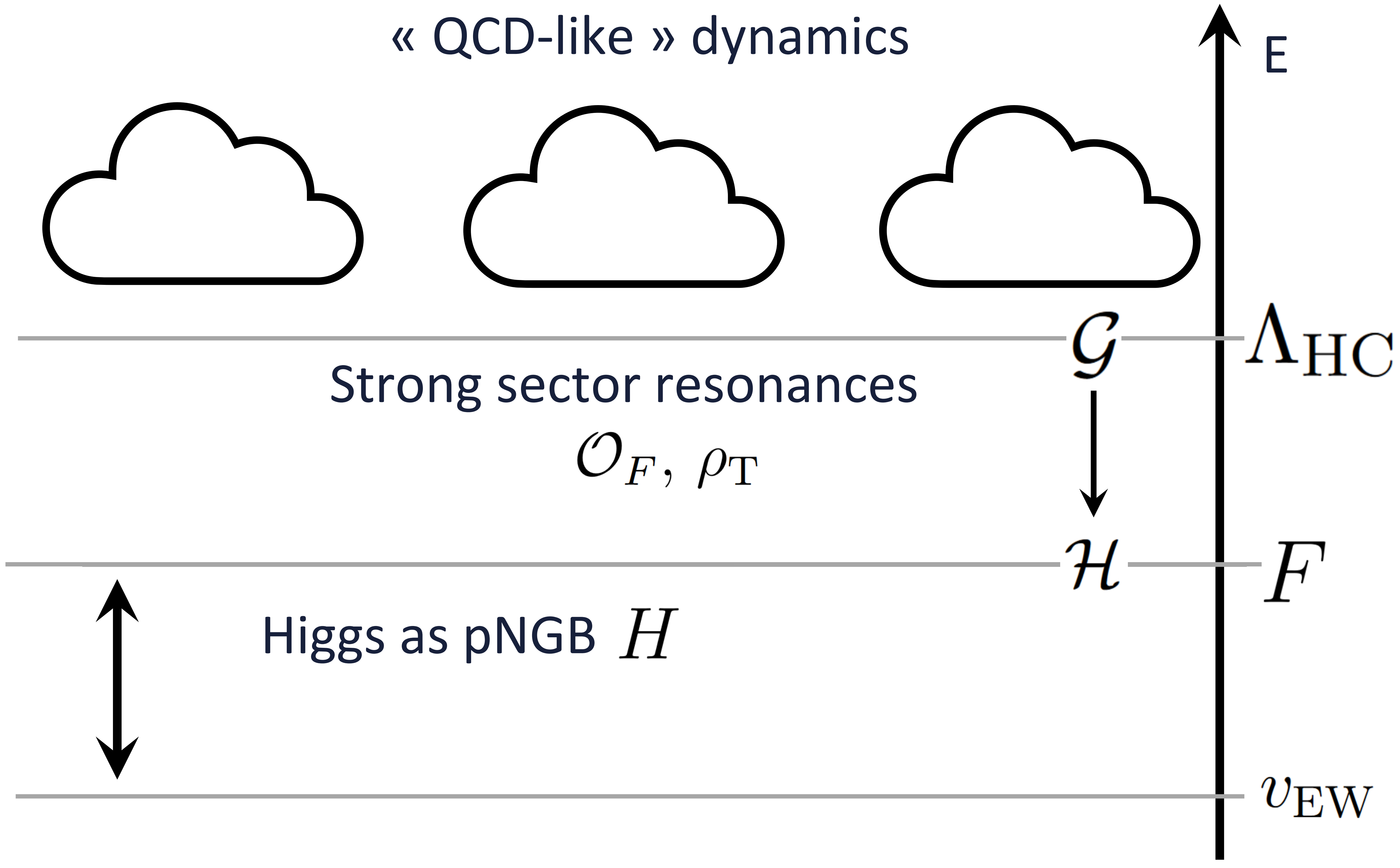
Case Study II: Higgs Compositeness

- Order of magnitude improvement
- HL-LHC interplay with FCC

Collider	HL-LHC	FCC-ee$_{240\to365}$	FCC-INT
Lumi (ab^{-1})	3	5 + 0.2 + 1.5	30
Years	10	3 + 1 + 4	25
g_{HZZ} (%)	1.5	0.18 / 0.17	0.17/0.16
g_{HWW} (%)	1.7	0.44 / 0.41	0.20/0.19
g_{Hbb} (%)	5.1	0.69 / 0.64	0.48/0.48
g_{Hcc} (%)	SM	1.3 / 1.3	0.96/0.96
g_{Hgg} (%)	2.5	1.0 / 0.89	0.52/0.5
$g_{H\tau\tau}$ (%)	1.9	0.74 / 0.66	0.49/0.46
$g_{H\mu\mu}$ (%)	4.4	8.9 / 3.9	0.43/0.43
$g_{H\gamma\gamma}$ (%)	1.8	3.9 / 1.2	0.32/0.32
$g_{HZ\gamma}$ (%)	11.	– / 10.	0.71/0.7
g_{Htt} (%)	3.4	10. / 3.1	1.0/0.95
g_{HHH} (%)	50.	44./33. 27./24.	3-4

[2106.13885]

[More on this in Jason's talk]



$$g_{VVh} = g_{VVh}^{SM}\sqrt{1-\xi}$$

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Wulzer & Panico 2015
Agashe et al. 2005,
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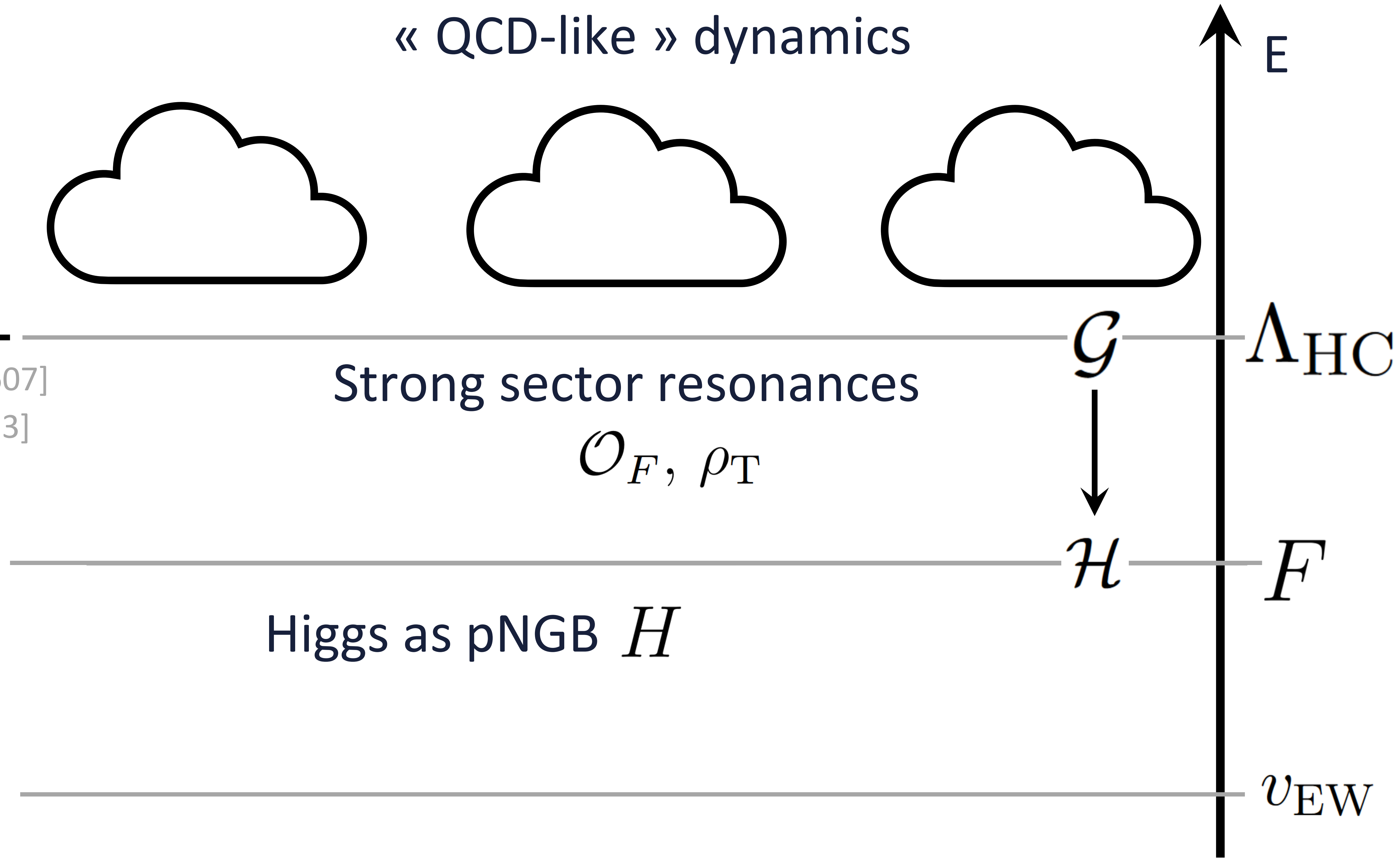
Case Study II: Higgs Compositeness

« QCD-like » dynamics

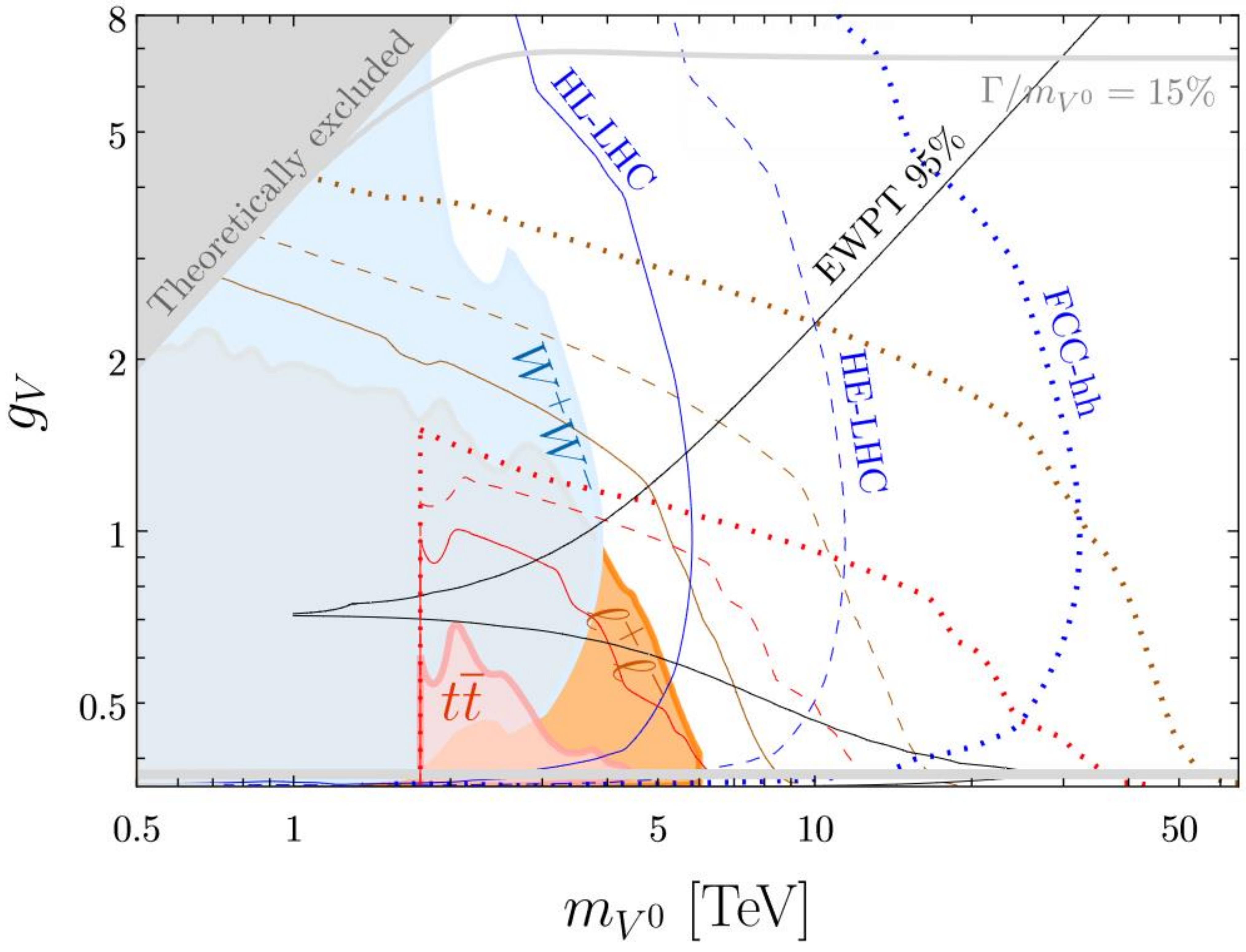


$M_\rho \gtrsim 5$ TeV

ATLAS, [2402.10607]
CMS, [2310.19893]

Strong sector resonances
$\mathcal{O}_F,\ \rho_T$

Higgs as pNGB H



FCC-hh probes spin 1 resonances up to high scales!

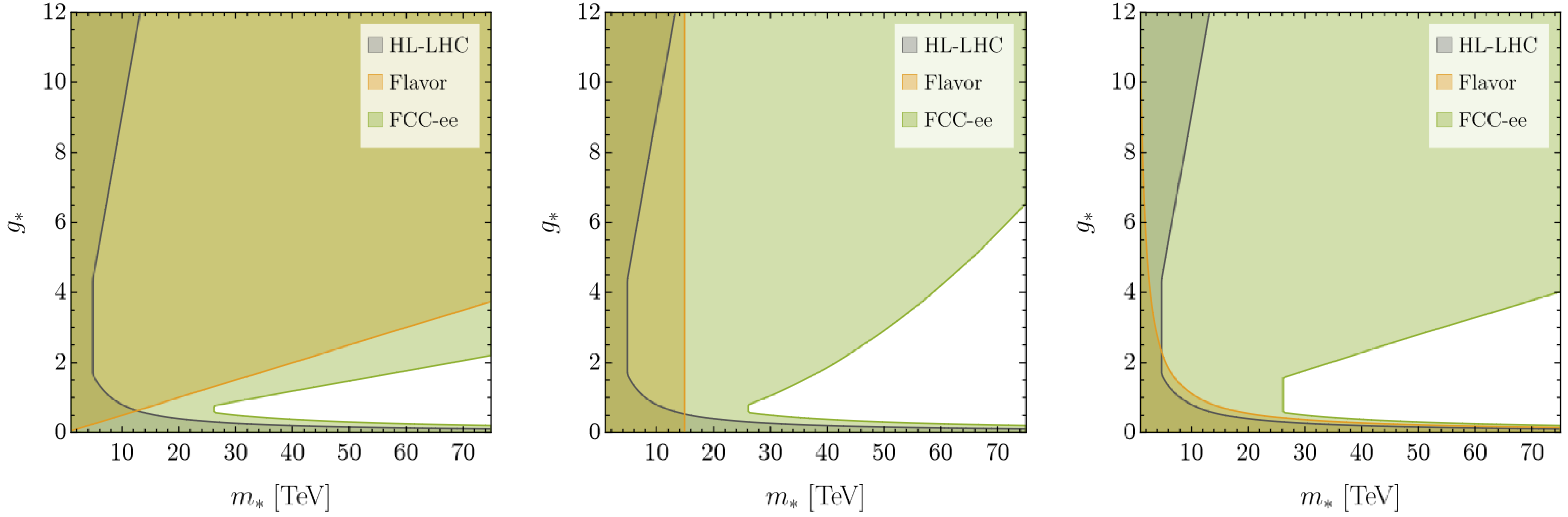
Important *complementarity* between HL-LHc, FCC-ee and FCC-hh

Wulzer & Panico 2015
Agashe et al. 2005,
...

Case Study II: Higgs Compositeness

Stefanek 2024

$$\left(m_* = F g_* \right)$$



(a) Left compositeness (b) Mixed compositeness (c) Right compositeness

➡ With improved precision: RG-running into EWPO become **crucial**

➡ Composite Higgs will be put under a microscope @ FCC-ee!

Conclusion

Fundamental questions need to be answered … and we need a machine ASAP !

- Understand better the Higgs (naturalness, flavour,…)
- Unbiased exploration of whatever Nature may be hiding

➡ FCC-ee, via precision measurements, *indirectly* probes very *broad* and *well-motivated* classes of UV extensions of the SM

Thank you!