Universität Zürich[UZH]

Flavour & BSM Model Building

13.11.2024, Mainz

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Outline

I. BSM: motivation, ideas and hints from exp.

II. Flavour Deconstructing the Composite Higgs[+]

[+]2407.10950 with Sebastiano Covone , Joe Davighi and Gino Isidori

The Standard Model as an Effective Field Theory

$$\mathcal{L}_{\rm SMEFT} = \mathcal{L}_{\rm SM} + \sum_{d\geq 5} \sum_i \frac{c_i^{(d)}}{\Lambda^{d-4}} \mathcal{O}_i^{(d)}$$

Open questions:

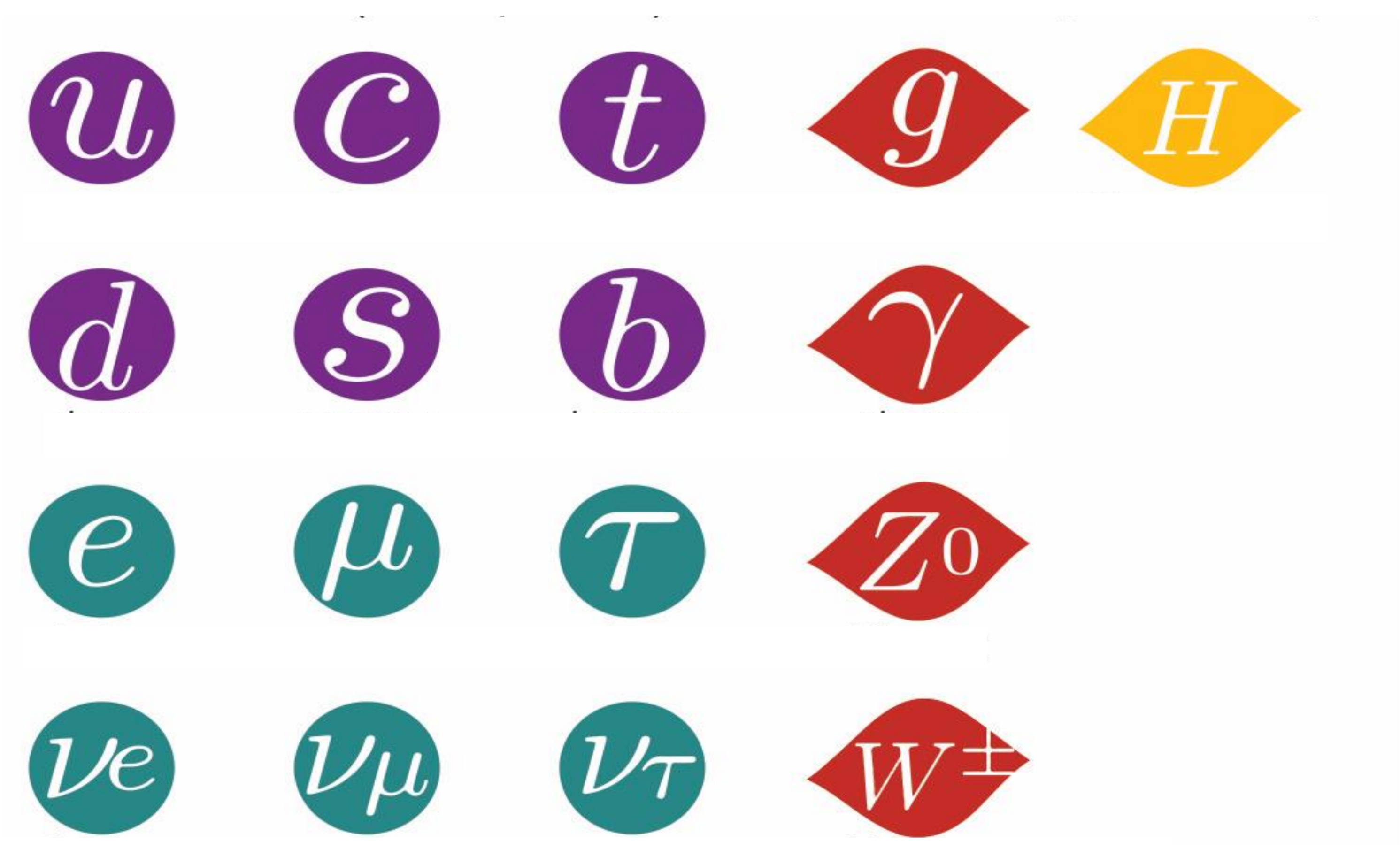
- Origin of neutrinos masses
- Dark Matter
- CP violation in the strong sector
- **Flavour Puzzle**

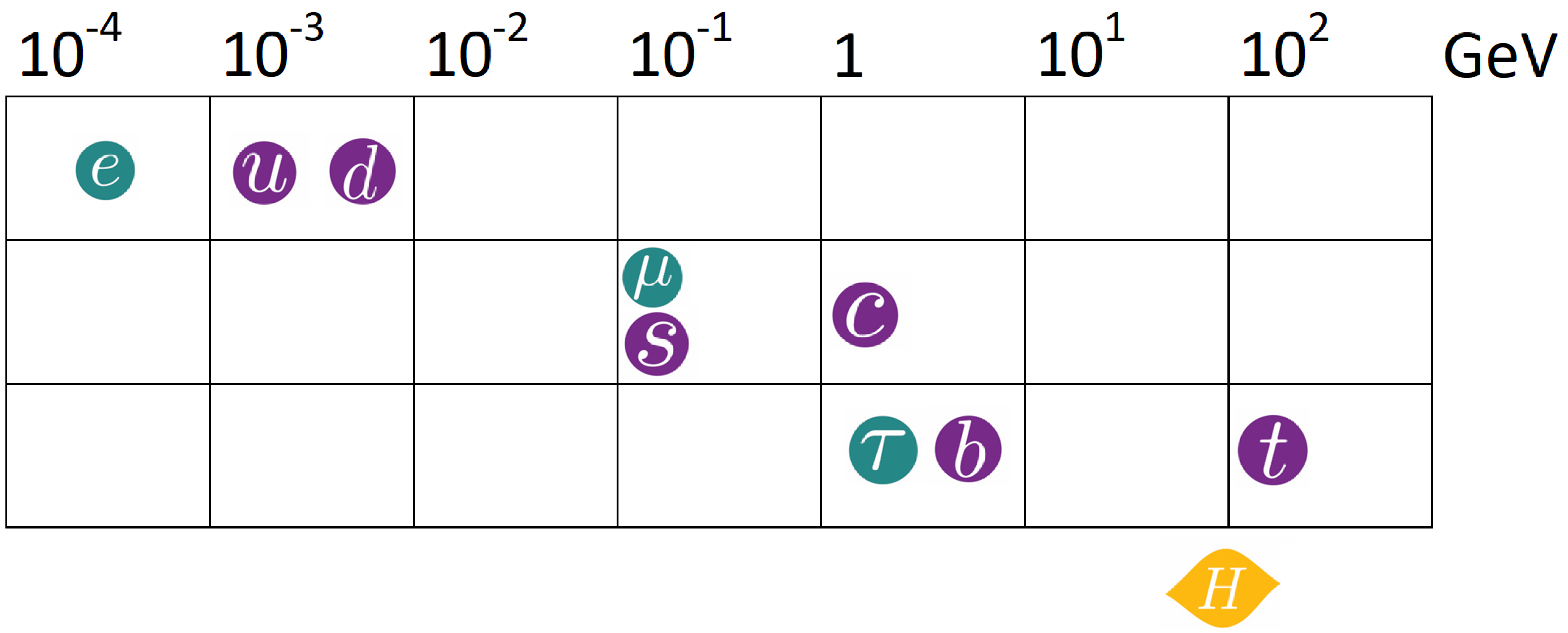
...

Many talks this week: Sophie, Anke, Ajdin, ...

Flavour Puzzle

Hierarchical pattern of fermion masses and mixing angles: **Flavour Puzzle**





Flavour Puzzle

$$\mathcal{L}^{d\leq 4} = \mathcal{L}_{\text{gauge}} + \mathcal{L}_{\text{Higgs}}$$

Flavour-universal — Yukawa hierarchies

➡ Flavour degeneracy in the gauge sector -> broken by Yukawas!

Flavour Puzzle

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Flavour-universal — Yukawa hierarchies

➡ Flavour degeneracy in the gauge sector -> broken by Yukawas!

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

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

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

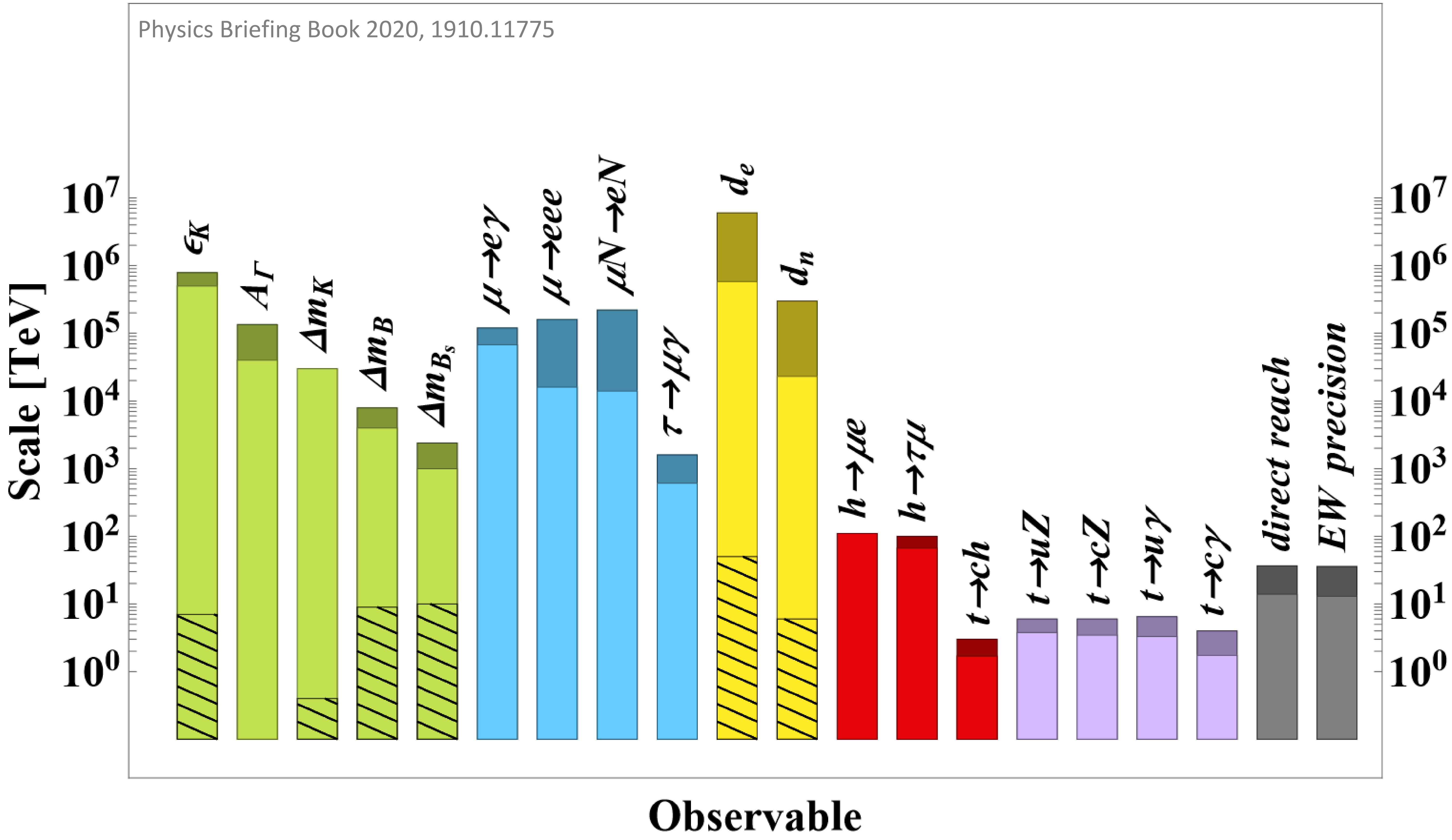
➡ $y_{33} \sim 1$, all the others are $y_{ij} << 1 \Rightarrow U(2)^n$ approx. flavour symmetry

Barbieri et al. 2011, Isidori & Straub 2012, Kagan et al. 2009, Blankenburg et al. 2012
-> Anders's talk last week

➡ Marginal couplings -> no clear NP scale

Experimental Constraints on NP Scale

- No clear direct signals of NP -> Mass gap is a « fact » of life
- Proton decay, neutrino masses, EDMs, … -> NP scale could be very high
- Flavour probes very high scale too!



The Hierarchy Problem

One could imagine that the scale of NP is very high (GUT, Planck)…

- Explain the observed « simplicity » of the SM

- Explain why we haven't seen anything yet + what we've seen is very small

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BUT !

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BUT !

$$m_H^2 \sim c\Lambda^2 \quad \text{vs} \quad m_H = 125\,\text{GeV}$$

$\Lambda \approx 10^{16}\,\text{GeV} \Rightarrow c \approx 10^{-28}$ ➡ Fine-tuning

$\delta m_H^2 \lesssim m_H^2\big|_{\text{EXP}} \Rightarrow \Lambda \approx \mathcal{O}(\text{TeV})$ ➡ What about high scale NP ?

The Hierarchy Problem

$$m_H << \Lambda$$

SM « simplicity »

Naturalness

$$\Lambda \approx \mathcal{O}(\text{TeV})$$

SM « simplicity »

Naturalness

Hierarchy Problem

The Hierarchy Problem

$m_H << \Lambda$

SM « simplicity » 😇

Naturalness 😑

$\Lambda \approx \mathcal{O}(\text{TeV})$

SM « simplicity » 😑

Naturalness 😇

✨ **Hierarchy Problem** ✨

➡ It can be a BSM model building **guide**

Our mission, should we choose to accept it, is to:

Address the SM mysteries in a natural way

The Hierarchy Problem

What possible theoretical frameworks can address the Hierarchy problem ?

The « not accepting the mission » option

Agrawal et al., 1997
Kawai & Okada, 2011
Giudice et al. 2021
Kephart & Päs 2024,
…

↓

Solution: « Elsewhere »

Multiverse / Anthropics
Cosmological evolution
(Failure of EFT)

$$? \longrightarrow m_H$$

SUSY

↓

Elementary scalars are protected by symmetry

$$\Lambda^2 \longrightarrow M_{\tilde{t}}^2 \log \frac{M_{\tilde{t}}}{\Lambda}$$

Higgs Compositeness

Dugan et al. 1985
Agashe et al. 2005,
…

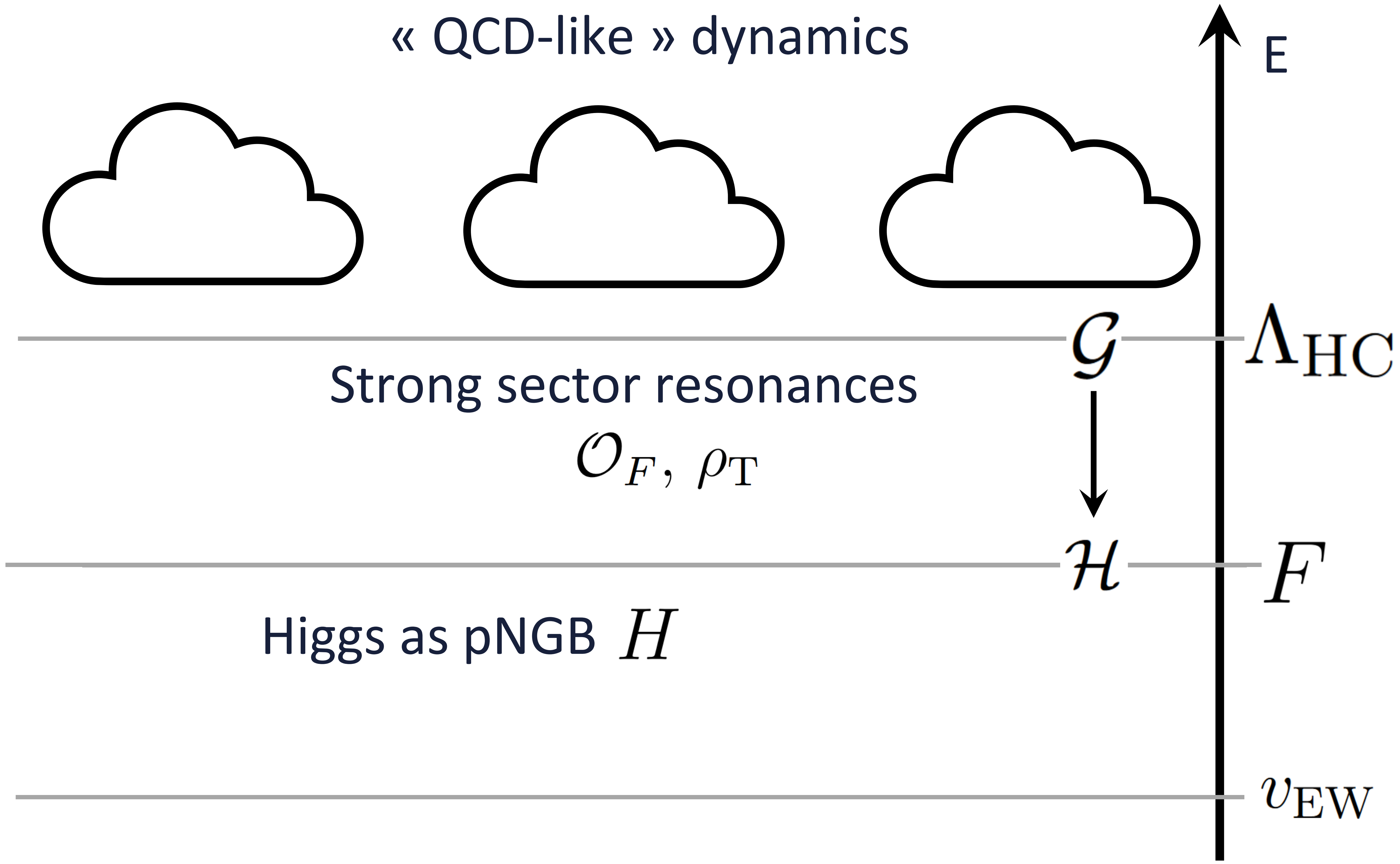
↓

No elementary scalars

Higgs emerges as a composite pseudo-Goldstone boson of S.S.B

$$\Lambda^2 \longrightarrow \frac{F^2}{16\pi^2} \times (\ldots)$$

Higgs Compositeness



➡ Compositeness scale cuts off quantum corrections to the Higgs potential

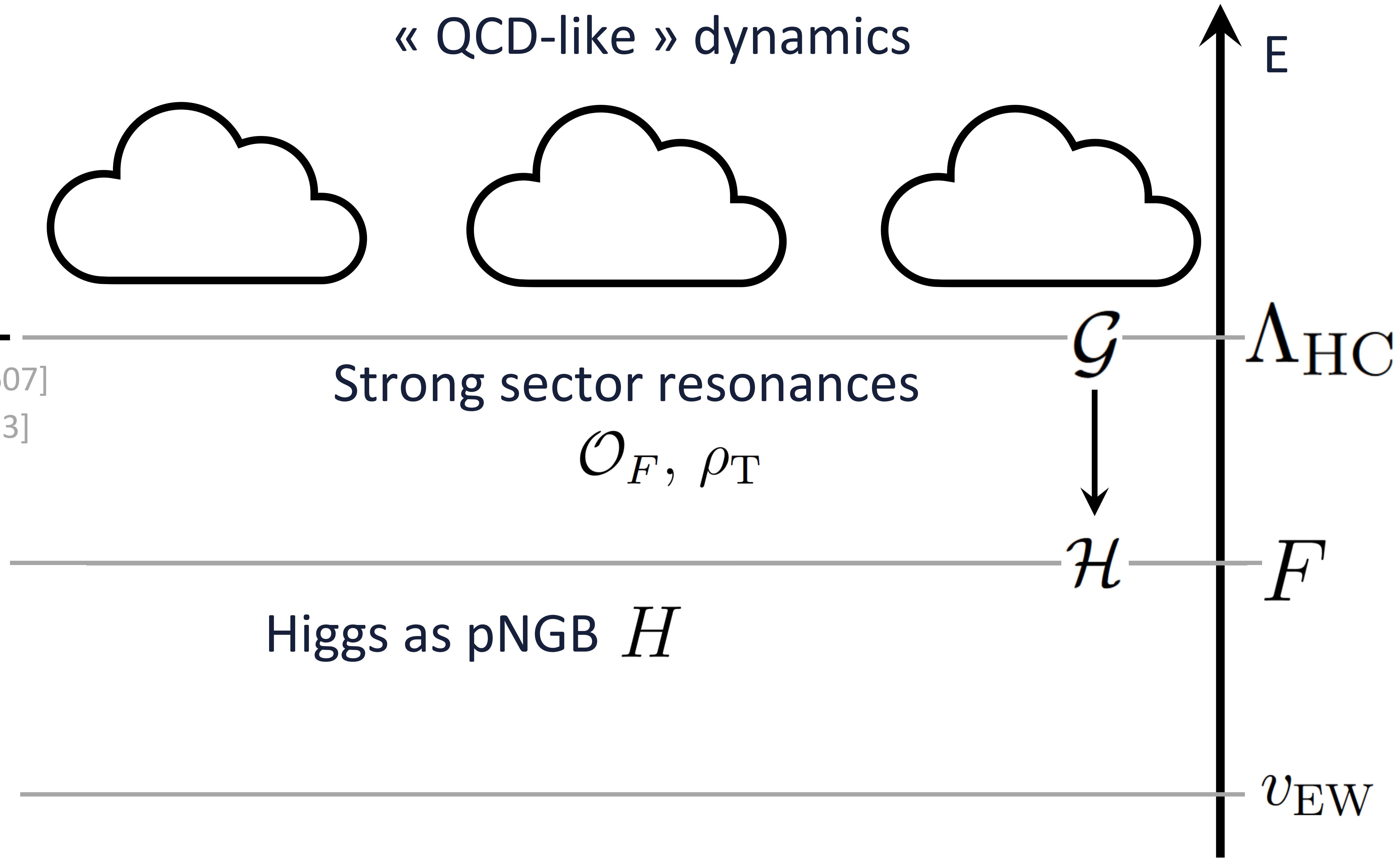
Wulzer & Panico 2015
Agashe et al. 2005,
...

Higgs Compositeness

Compositeness scale cannot be too low!

$M_\rho \gtrsim 5\ \mathrm{TeV}$

ATLAS, [2402.10607]
CMS, [2310.19893]



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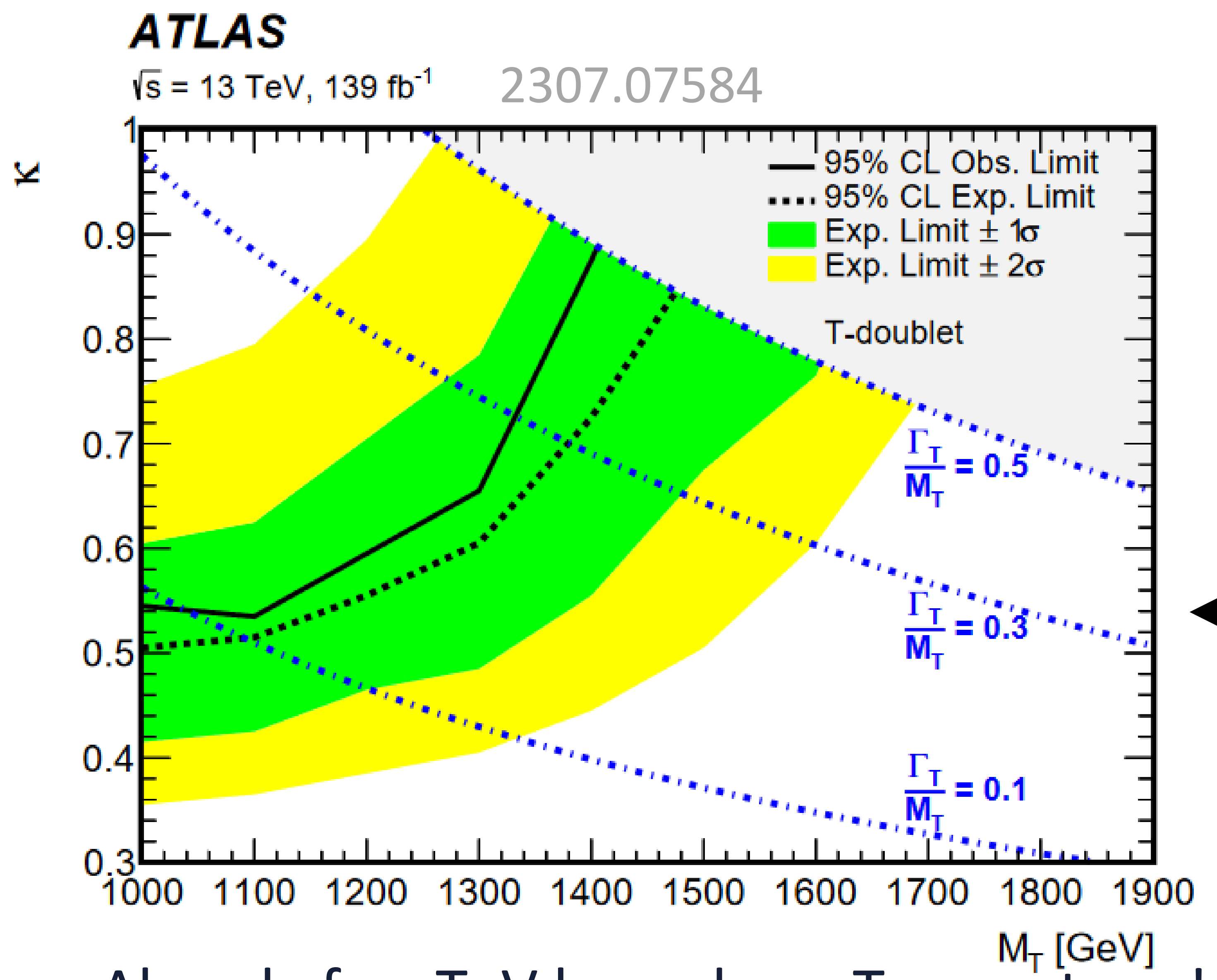
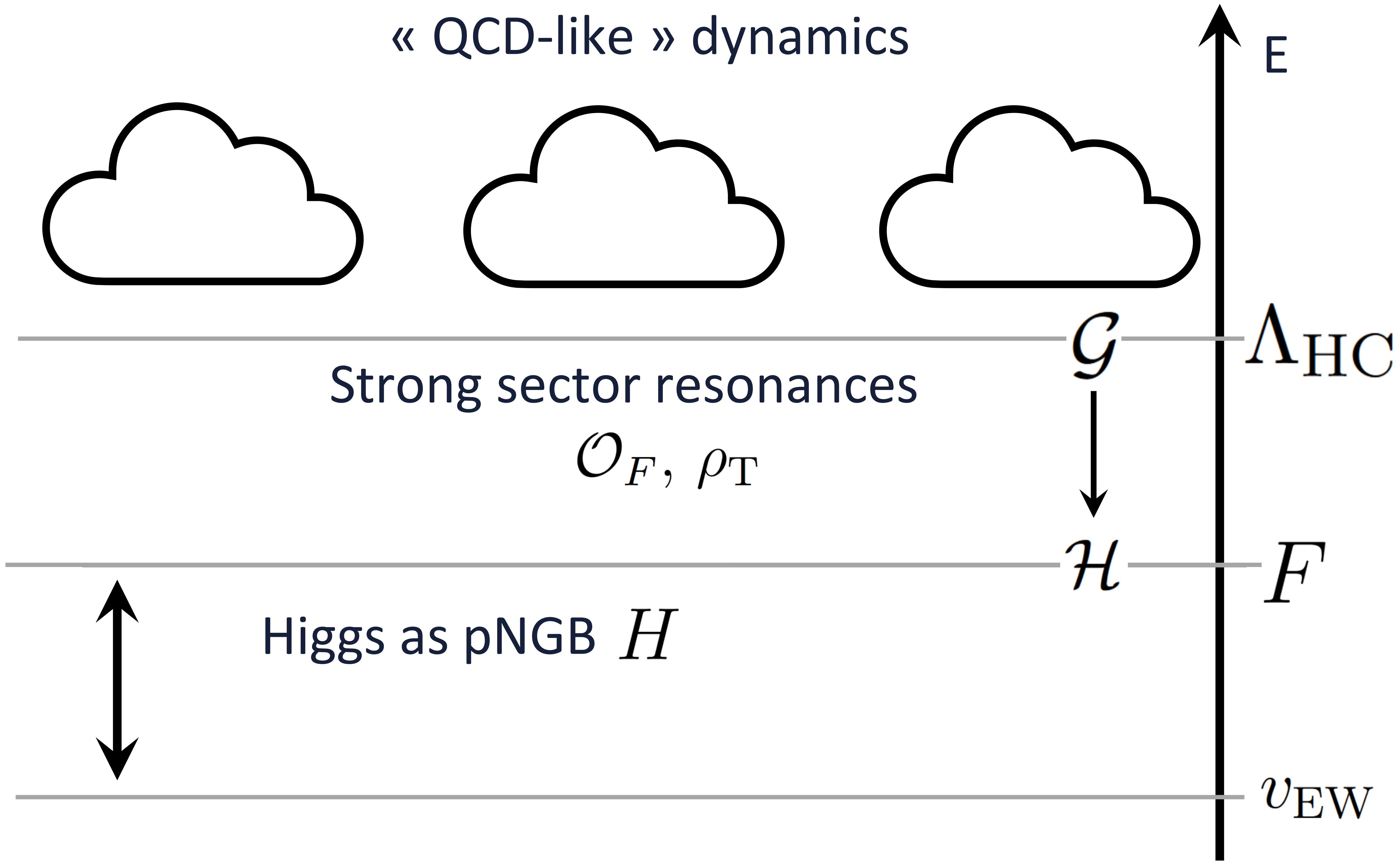


Already few TeV bounds on Top partner !

$$m_T \sim F$$

Mass Gap



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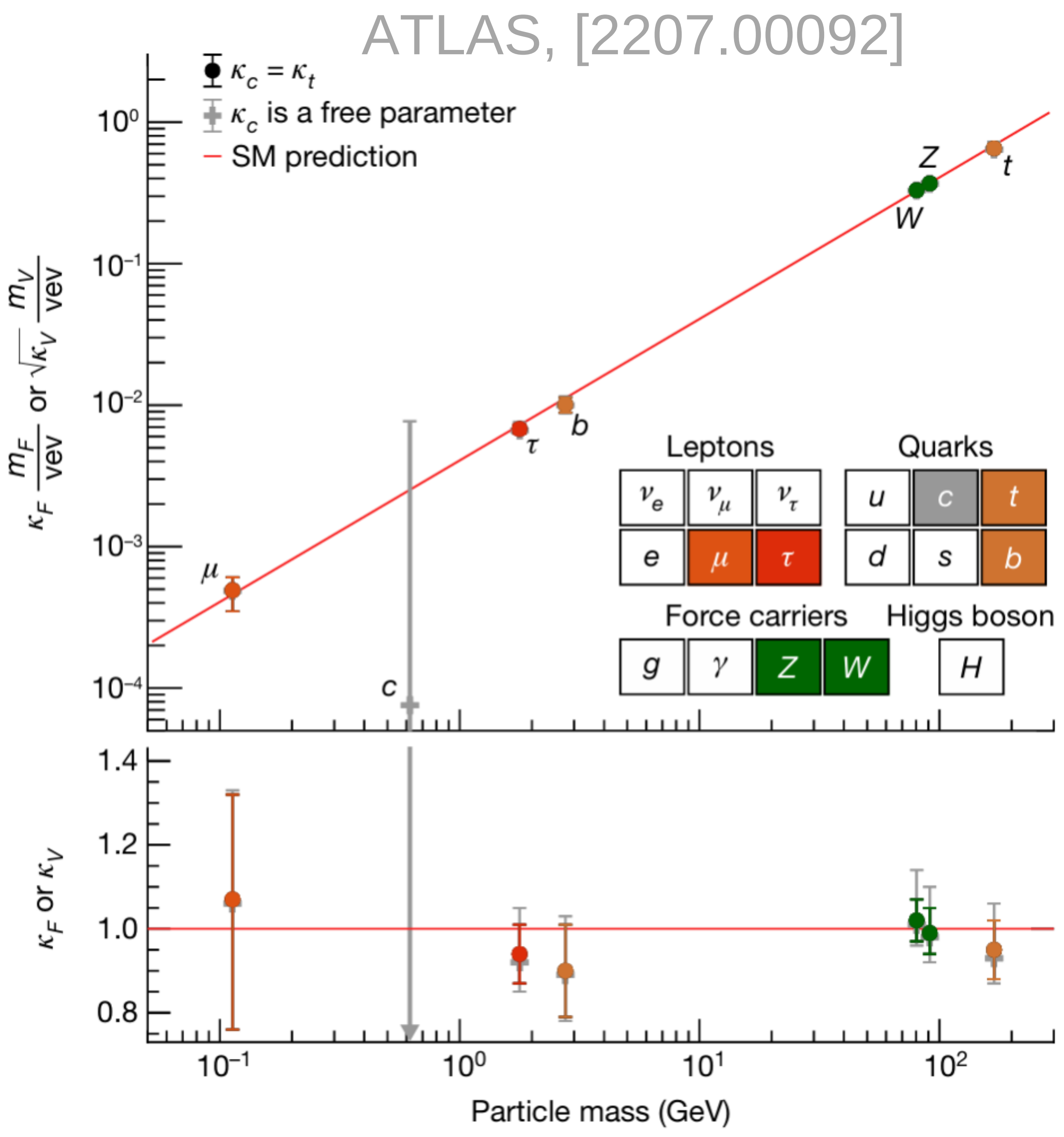
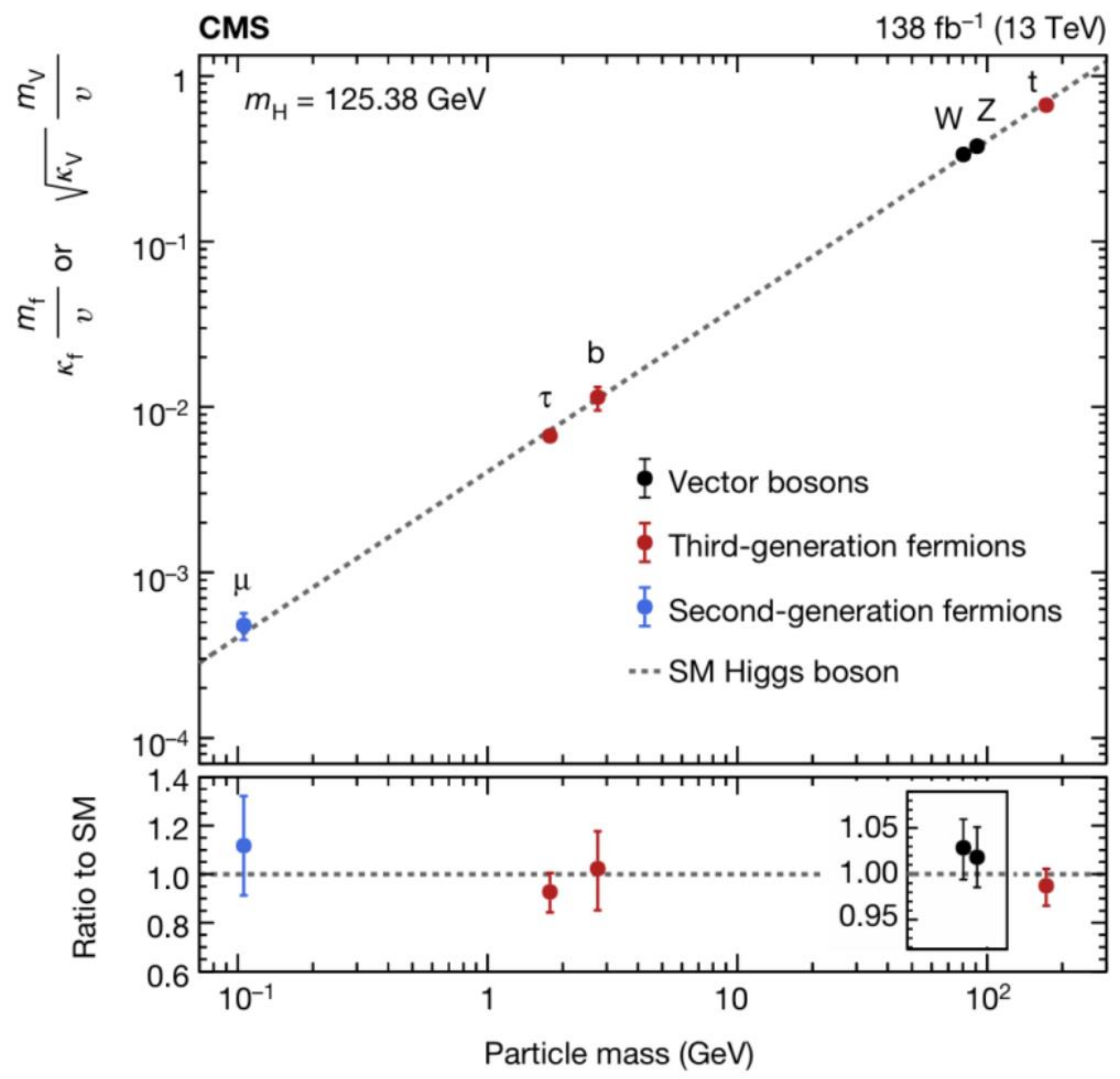
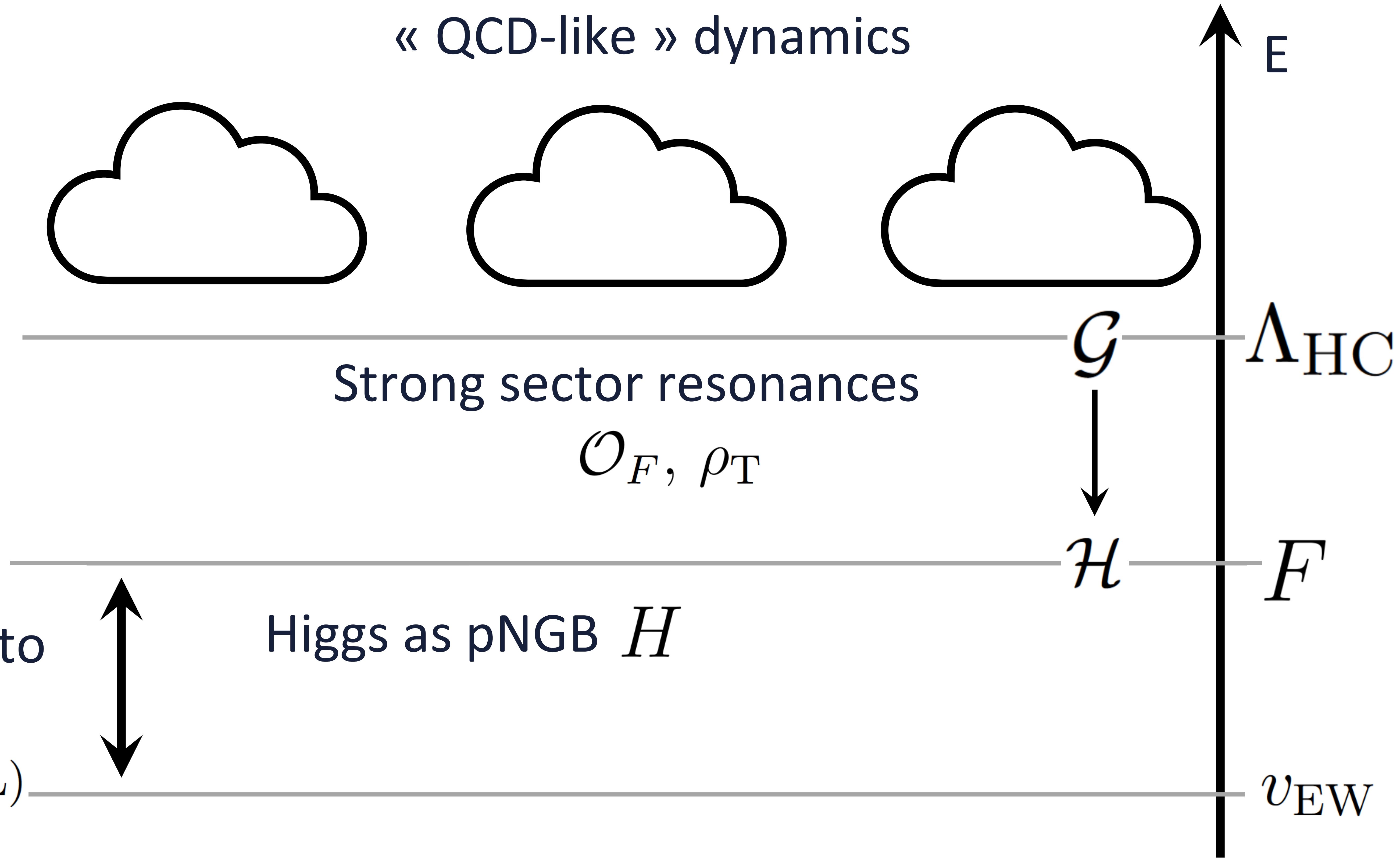
Higgs Compositeness





Higgs is SM-like to good approx.

$\xi < 0.06$ (95% CL)



Compositeness corrects SM predictions

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

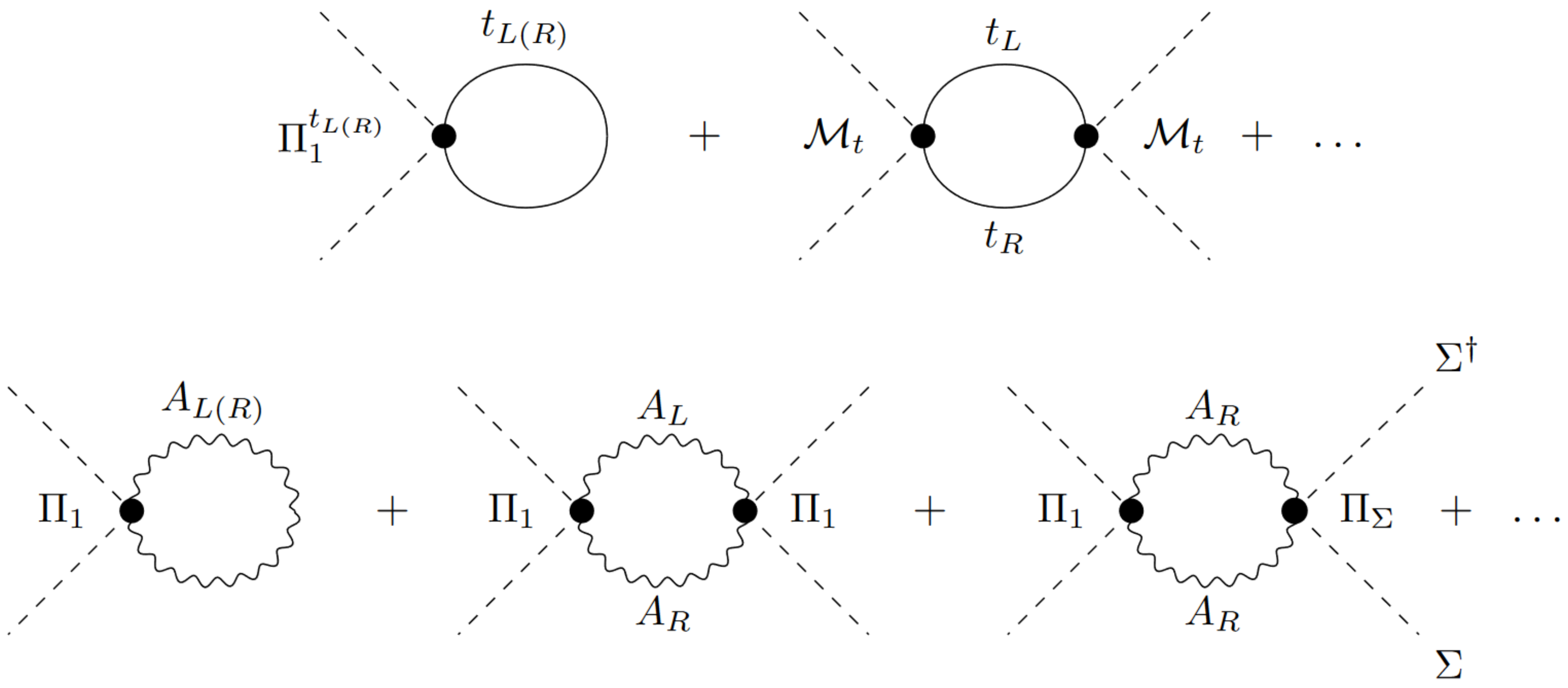
$$g_{VVhh} = g_{VVhh}^{\rm SM}\,(1-2\xi)$$

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

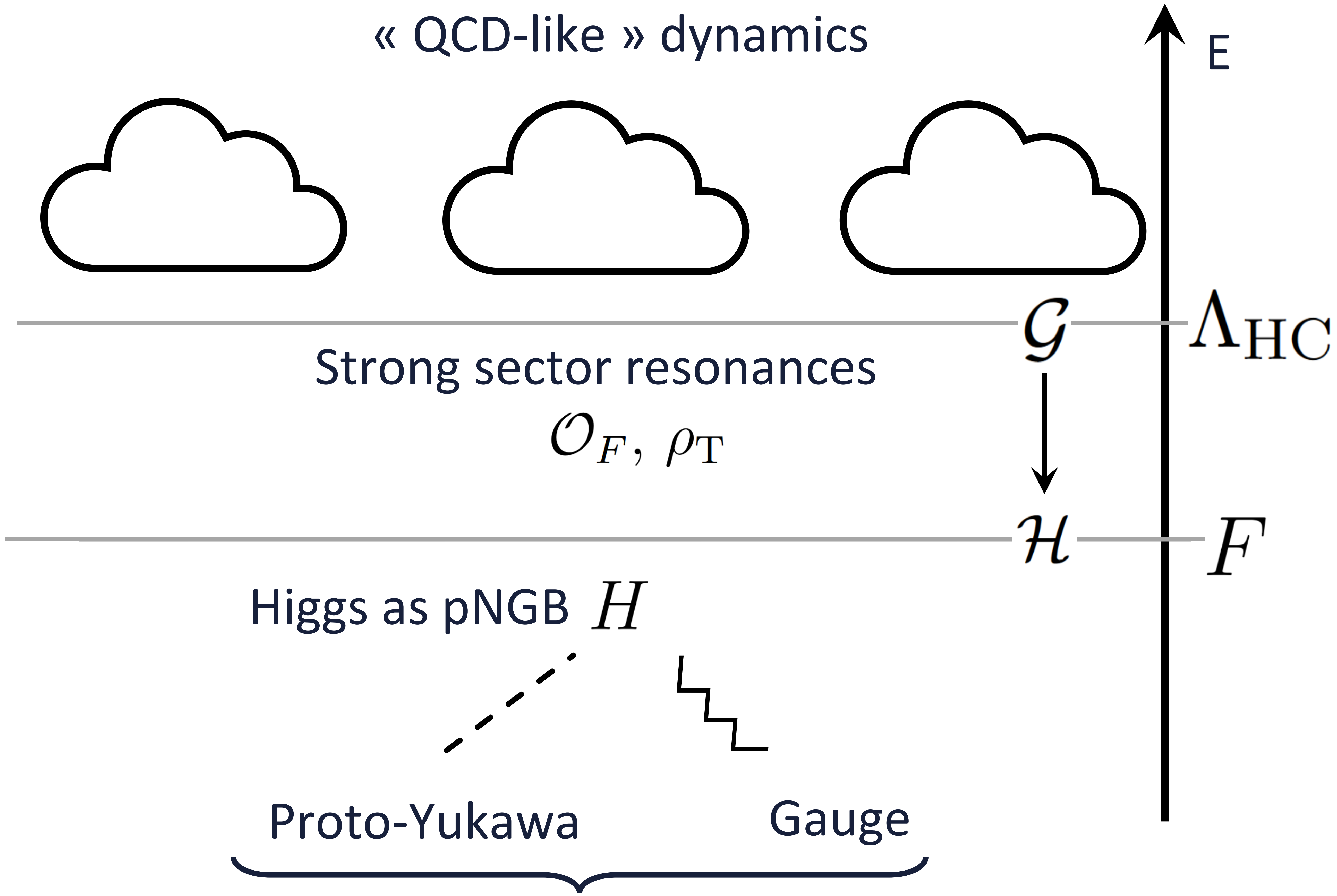
Wulzer & Panico 2015
Agashe et al. 2005,
...

Higgs Compositeness

Potential at 1-loop



(Concrete example later!)



$$\delta m_H^2 \sim \frac{F^2}{16\pi^2}\left(\# N_c y_t^2 M_T^2 - \# g_1^2 M_\rho^2\right)$$

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

Back to Flavour

Natural Higgs -> close-by NP scale
What about Flavour ?

Lessons from EXP:

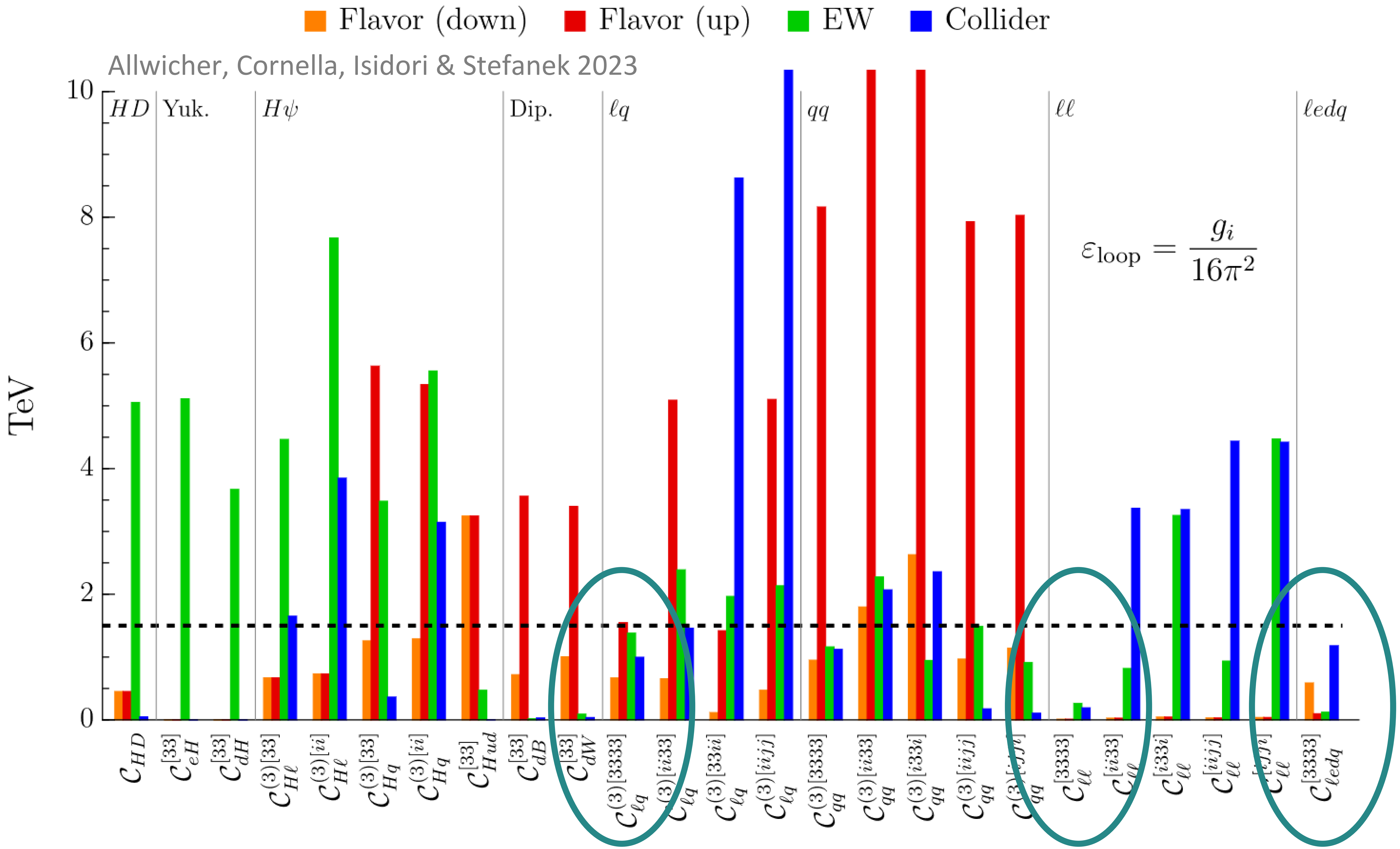
- No large breaking of $U(2)^5$ around the TeV scale
- Any NP at the TeV scale has a highly non-generic flavour structure
- $U(2)^5$ is a good symmetry to understand the Yukawa pattern! $Y_u \sim \begin{pmatrix} & < 0.01 & 0.04 \\ & & 1 \end{pmatrix}$

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

Which NP should we look for ?

Back to Flavour

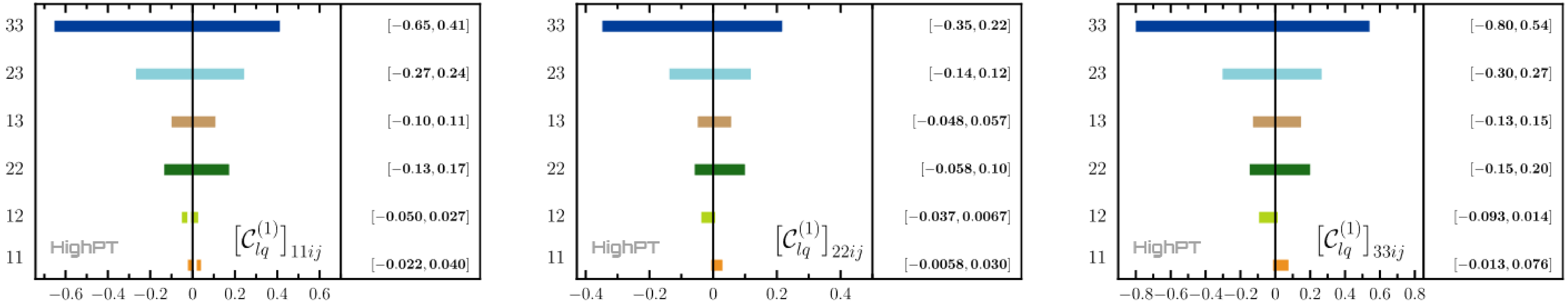
3rd Gen. is the less constrained



Back to Flavour

3rd Gen. is the less constrained

High-pt Drell-Yan tails



Allwicher et al. 2022

Allwicher et al. 2022
D'Ambrosio et al. 2002
Li & Ma 1981

Back to Flavour

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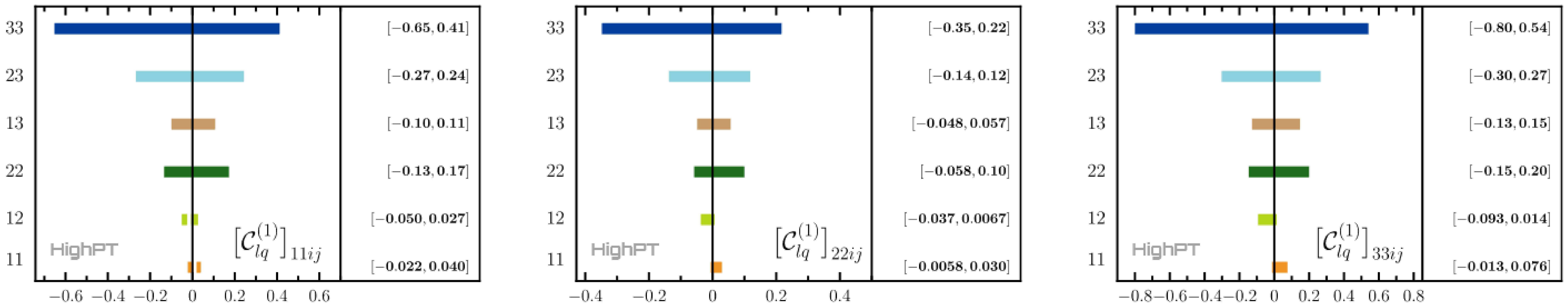

Allwicher et al. 2022

Experiments have imposed strong bounds on flavour universal NP

Frameworks such as MFV are pushed above O(10 TeV)!

(Naturalness 😑)

➡ Flavour **non-universal** NP @TeV-scale, mainly coupled to 3rd gen.

Allwicher et al. 2022
D'Ambrosio et al. 2002
Li & Ma 1981

Flavour Non-Universal UV Completion

Our mission, should we choose to accept it, is to:

Address the SM ***mysteries*** *in a* ***natural*** *way*

Flavour Non-Universal UV Completion

Our mission, should we choose to accept it, is to:
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- ➡ $U(2)^5$ as an accidental symmetry*
- ➡ 3rd gen. NP is the less constrained + $y_{33} \sim 1$

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UV … -> $G_{12} \times G_{3+H}$ ** -> G_{SM}

(Rich pheno from flavoured gauge bosons)
(completely generic breaking)

**Different options to Flavour deconstruct: Davighi & Isidori 2023
… or split the families -> Javi's talk

*Gauge $U(2)^n$: Darmé et al. 2023, Greljo &Thomsen 2023, Greljo et al. 2024

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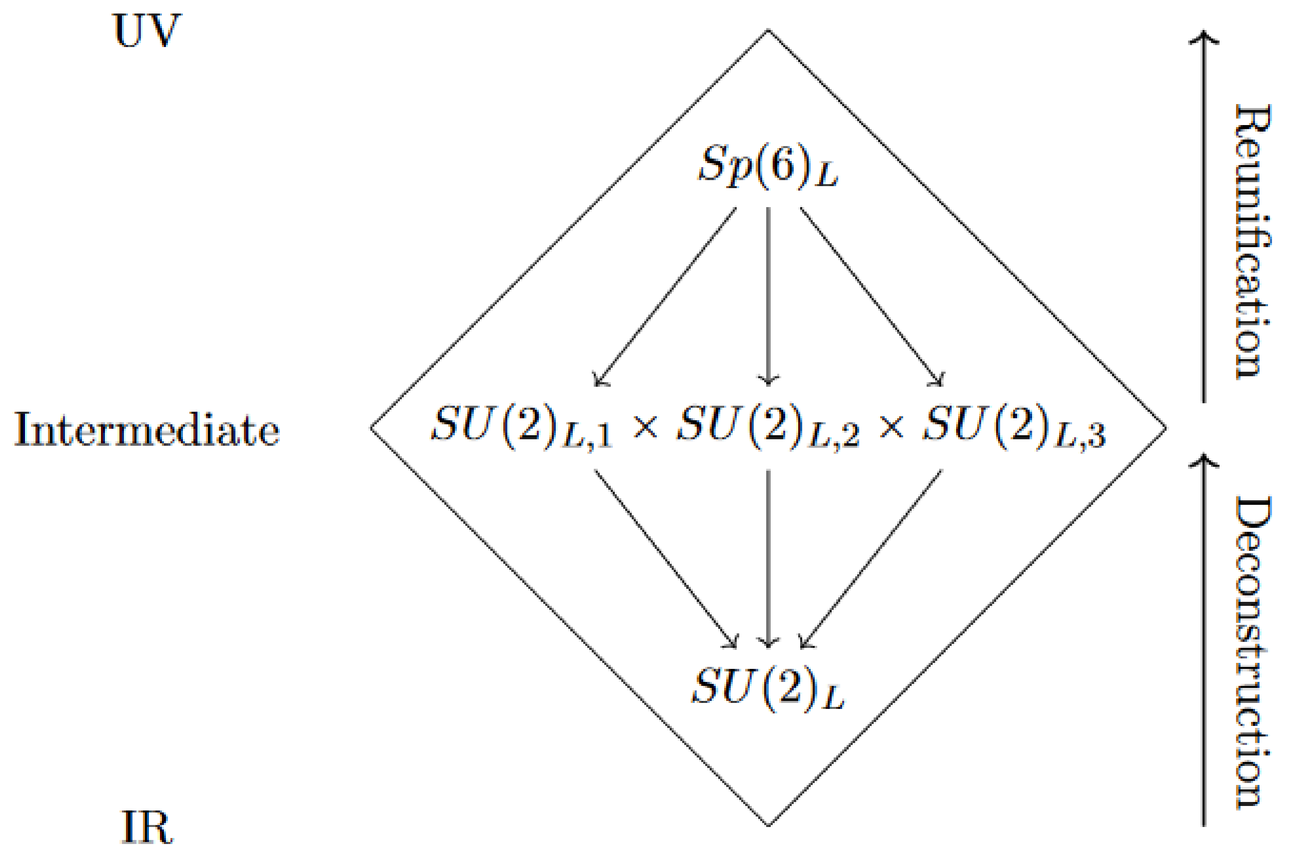
Re-unification in the UV

Electroweak flavour unification (+ quark-lepton unif.): Davighi et al. 2022



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+

- Higgs Compositeness
- Flavour in CHM -> Partial Compositeness

Higgs as pNGB

**Different options to Flavour deconstruct: Davighi & Isidori 2023
… or split the families -> Javi's talk

Exploring the Flavor Symmetry Landscape, Glioti et al. 2024
-> Flavour symmetries options to reduce scale of NP
-> Luca's talk last week

*Gauge $U(2)^n$: Darmé et al. 2023, Greljo &Thomsen 2023, Greljo et al. 2024

Flavour Deconstructing the Composite Higgs[+]

$G_{12} \times G_{3+H} \rightarrow G_{SM}$ &

Composite Higgs

$$Sp(4)^{*} \xrightarrow{H \sim (\mathbf{2},\mathbf{2})} SU(2)_L \times SU(2)_R^{[3]}$$

- Flavour non-universal NP @TeV mainly coupled to 3rd generation
  - $U(2)^5$ protection
  - Lower compositeness scale -> naturalness
  - Explain SM flavour

[+]2407.10950 with Sebastiano Covone , Joe Davighi, Gino Isidori and MP

*: $\mathfrak{sp}(4) \cong \mathfrak{so}(5)$

Flavour Deconstructing the Composite Higgs

$$SU(3)_c \times Sp(4) \times U(1)_{B-L}^{[3]} \times U(1)_Y^{[12]}$$

Non-perturbative Dynamics

$\Lambda_{\mathrm{HC}} \downarrow$ $\quad H \sim (\mathbf{2}, \mathbf{2})$

$$SU(3)_c \times SU(2)_L \times SU(2)_R^{[3]} \times U(1)_{B-L}^{[3]} \times U(1)_Y^{[12]}$$

Flavour Deconstructing the Composite Higgs

$$SU(3)_c \times Sp(4) \times U(1)^{[3]}_{B-L} \times U(1)^{[12]}_Y$$

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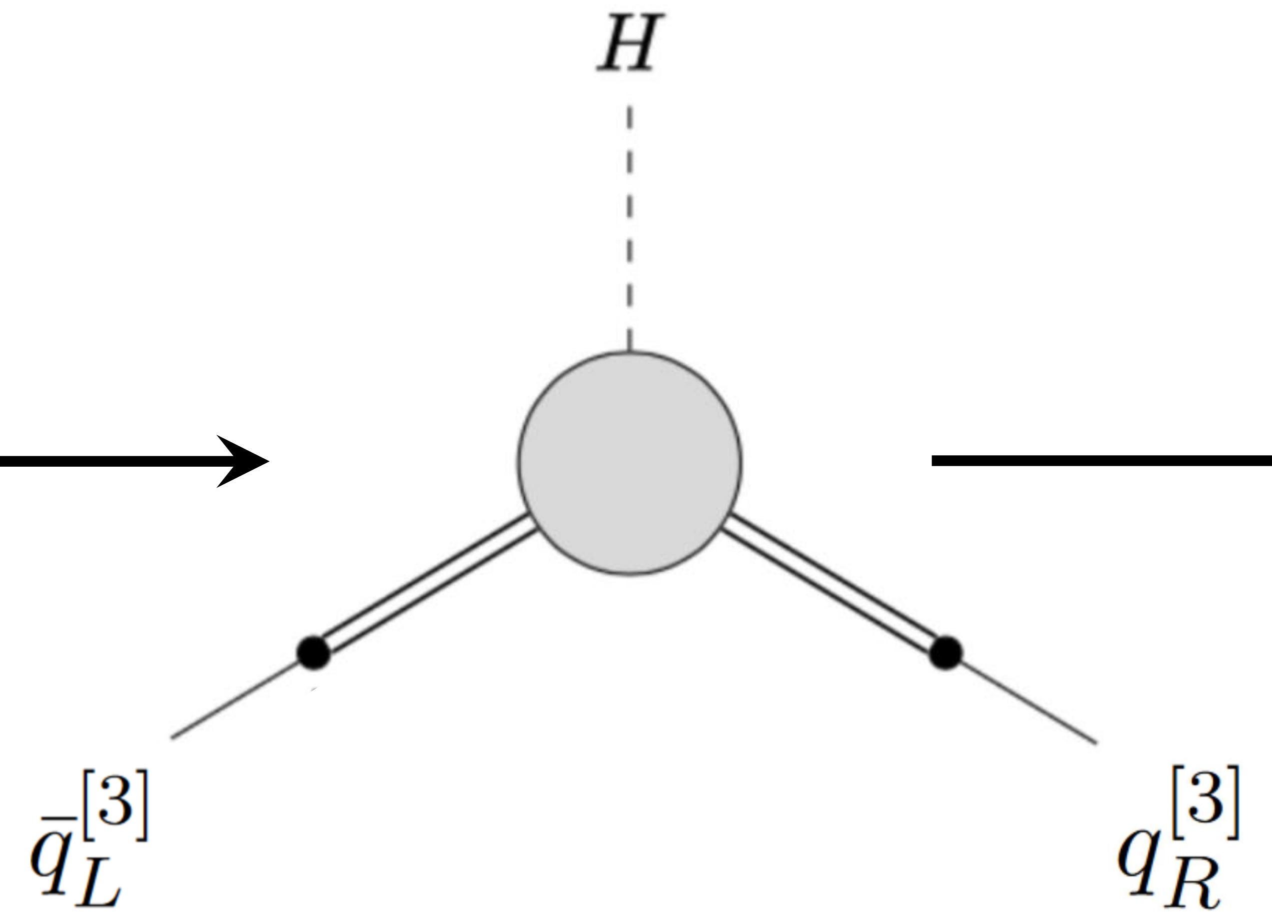
Λ_{HC} $\downarrow$ $H \sim (\mathbf{2},\mathbf{2})$

$$SU(3)_c \times SU(2)_L \times SU(2)^{[3]}_R \times U(1)^{[3]}_{B-L} \times U(1)^{[12]}_Y$$

Third-family Partial Compositeness:

(Light fields are elementary)

$$\mathcal{L} \supset \lambda_L \bar{q}^{[3]}_L \mathcal{O}_R \longrightarrow$$



$$\longrightarrow \quad |y_q| = \lambda^q_L \lambda^{q*}_R \kappa^q_{LR} \frac{F}{\sqrt{2} M_q}$$

Flavour Deconstructing the Composite Higgs

$$SU(3)_c \times Sp(4) \times U(1)^{[3]}_{B-L} \times U(1)^{[12]}_{Y}$$

Non-perturbative Dynamics

Λ_{HC} $\downarrow$ $H \sim (\mathbf{2}, \mathbf{2})$

$$SU(3)_c \times SU(2)_L \times SU(2)^{[3]}_R \times U(1)^{[3]}_{B-L} \times U(1)^{[12]}_{Y}$$

Horizontal Breaking

$\langle \Sigma_R \rangle$ $\langle \Omega \rangle$ $\longrightarrow$ Two Z′ and a pair of $W_R^{\pm}$

$$SU(3)_c \times SU(2)_L \times U(1)_Y$$

Flavour Deconstructing the Composite Higgs

$$SU(3)_c \times Sp(4) \times U(1)_{B-L}^{[3]} \times U(1)_Y^{[12]}$$

Non-perturbative Dynamics

$\Lambda_{\rm HC}$ $\downarrow$ $H \sim (\mathbf{2},\mathbf{2})$

$$SU(3)_c \times SU(2)_L \times SU(2)_R^{[3]} \times U(1)_{B-L}^{[3]} \times U(1)_Y^{[12]}$$

Horizontal Breaking

$\langle \Sigma_R \rangle$ $\downarrow$ $\langle \Omega \rangle$

$$SU(3)_c \times SU(2)_L \times U(1)_Y$$

Deconstructing hypercharge to explain the Yukawa pattern

Flavour Non-Universal Gauge Interactions, J.Davighi @ “Flavour Path to New Physics”

Flavour Deconstructing the Composite Higgs

$$SU(3)_c \times SU(2)_L \times SU(2)_R^{[3]} \times U(1)_{B-L}^{[3]} \times U(1)_Y^{[12]}$$

Horizontal Breaking $\langle \Sigma_R \rangle$ $\langle \Omega \rangle$

$$\downarrow$$

$$SU(3)_c \times SU(2)_L \times U(1)_Y$$

Flavour Deconstructing the Composite Higgs

$$SU(3)_c \times SU(2)_L \times SU(2)_R^{[3]} \times U(1)_{B-L}^{[3]} \times U(1)_Y^{[12]}$$

Horizontal Breaking

$$\langle \Sigma_R \rangle \quad \langle \Omega \rangle$$

$$SU(3)_c \times SU(2)_L \times U(1)_Y$$

$$\epsilon_R = \frac{\langle \Sigma \rangle}{M_F}$$

$$\epsilon_\Omega = \frac{\langle \Omega \rangle}{M_F}$$

$$Y_{u,d,e} \sim \begin{pmatrix} \epsilon_R & \epsilon_\Omega \\ \epsilon_R \epsilon_\Omega & 1 \end{pmatrix}$$

Flavour Deconstructing the Composite Higgs

$$SU(3)_c \times SU(2)_L \times SU(2)_R^{[3]} \times U(1)_{B-L}^{[3]} \times U(1)_Y^{[12]}$$

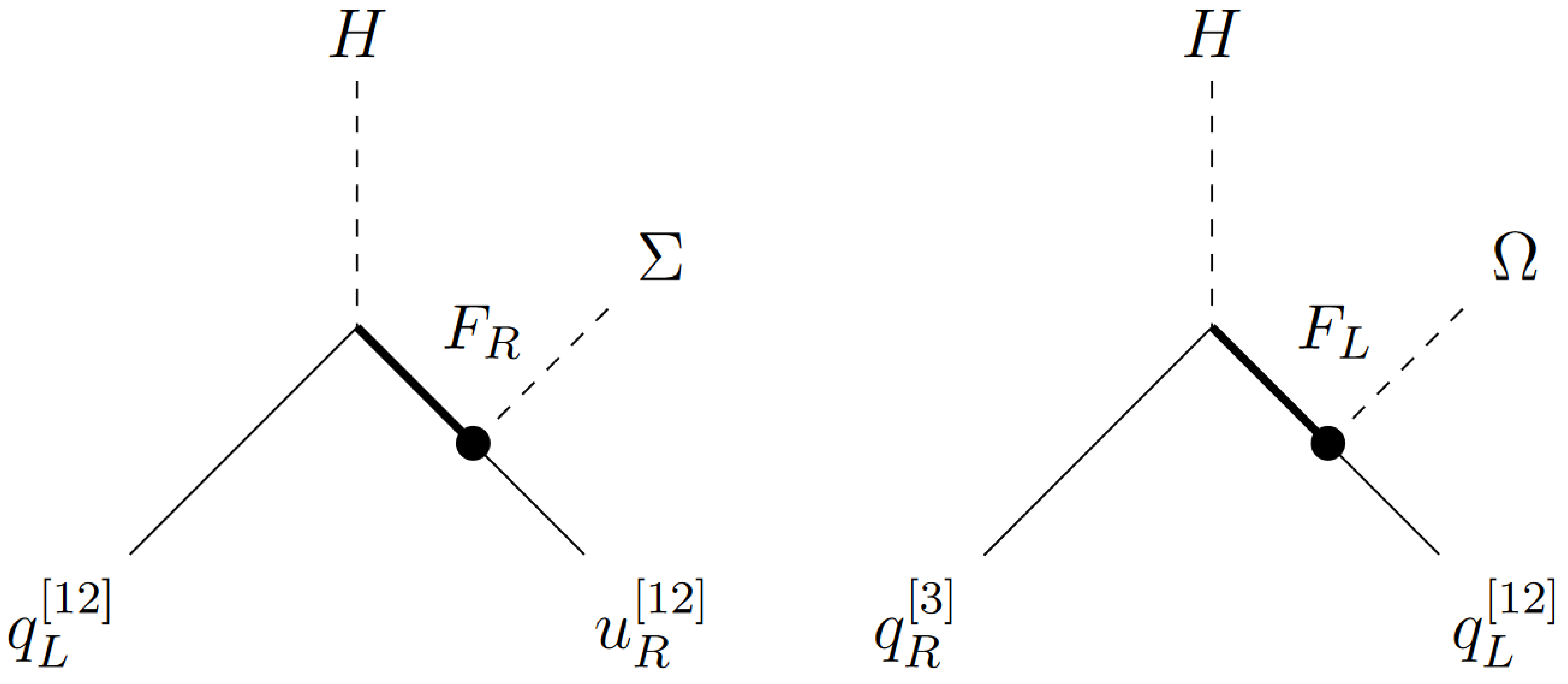
Horizontal Breaking $\langle \Sigma_R \rangle$ $\langle \Omega \rangle$

$$\downarrow$$

$$SU(3)_c \times SU(2)_L \times U(1)_Y$$

$$Y_{u,d,e} \sim \begin{pmatrix} \epsilon_R & \epsilon_\Omega \\ \epsilon_R \epsilon_\Omega & 1 \end{pmatrix}$$

$$\epsilon_\Omega = \frac{\langle \Omega \rangle}{M_F} \qquad \epsilon_R = \frac{\langle \Sigma \rangle}{M_F}$$



Flavour Deconstructing the Composite Higgs

$$SU(3)_c \times SU(2)_L \times SU(2)_R^{[3]} \times U(1)_{B-L}^{[3]} \times U(1)_Y^{[12]}$$

Horizontal Breaking $\langle \Sigma_R \rangle$ $\langle \Omega \rangle$

$$SU(3)_c \times SU(2)_L \times U(1)_Y$$

$$Y_{u,d,e} \sim \begin{pmatrix} \epsilon_R & \epsilon_\Omega \\ \epsilon_R \epsilon_\Omega & 1 \end{pmatrix}$$

$$\epsilon_\Omega = \frac{\langle \Omega \rangle}{M_F} \qquad \epsilon_R = \frac{\langle \Sigma \rangle}{M_F}$$

$$\epsilon_\Omega = O\left(|V_{cb}|\right) = O\left(10^{-1}\right)$$

$$\epsilon_R = O\left(m_c/m_t\right) = O\left(10^{-2}\right)$$

Flavour Deconstructing the Composite Higgs

$$SU(3)_c \times SU(2)_L \times SU(2)_R^{[3]} \times U(1)_{B-L}^{[3]} \times U(1)_Y^{[12]}$$

Horizontal Breaking $\quad \langle \Sigma_R \rangle \quad \langle \Omega \rangle$

$$\downarrow$$

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$$\epsilon_\Omega = O\left(|V_{cb}|\right) = O\left(10^{-1}\right)$$

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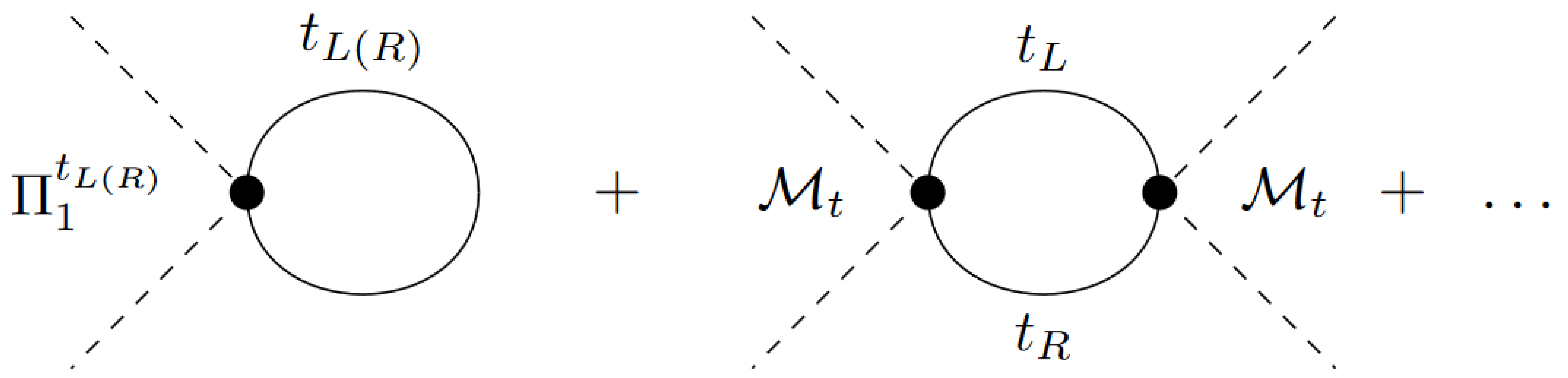
⟶ The deconstruction scale is ***anchored*** by its impact on the Higgs potential

Higgs Potential

➡ Higgs potential induced at 1-loop

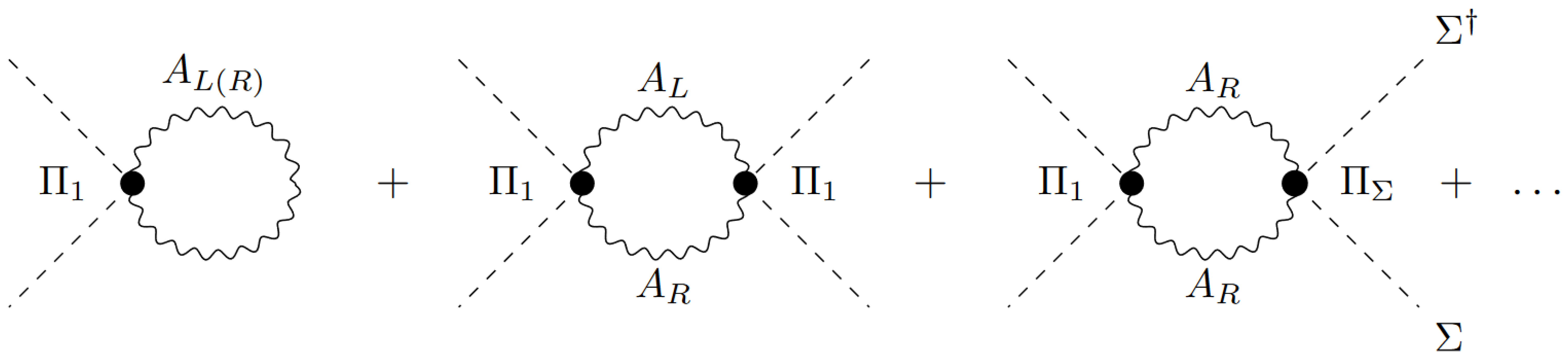
Fermion contribution

$\Delta V(h)_f$



Gauge contribution

$\Delta V(h)_A$



Higgs Potential

$$V(h) = \Delta V_f(h) + \Delta V_A(h) \approx c_0 - c_1 \sin^2\left(\frac{h}{2F}\right) + c_2 \sin^4\left(\frac{h}{2F}\right)$$

Naive dimensional analysis

$$c_{1,2} = O(1) \times F^4$$

VS

$$\left.\frac{c_1}{F^4}\right|_{\text{phys.}} = \frac{m_h^2}{F^2}$$ → Tuning ($m_h^2/F^2 \lesssim 0.03$)

$$\left.\frac{c_2}{F^4}\right|_{\text{phys.}} = \frac{2m_h^2}{v^2} \approx \frac{1}{2}$$ Natural

Higgs Potential

$$V(h) = \Delta V_f(h) + \Delta V_A(h) \approx c_0 - c_1 \sin^2\left(\frac{h}{2F}\right) + c_2 \sin^4\left(\frac{h}{2F}\right)$$

$$\frac{c_2}{F^4} = \frac{N_c y_t^2}{4\pi^2} \frac{M_T^2}{F^2} + \text{Gauge contributions (suppressed)}$$

Top partner → $M_T \approx 2.5F$

Higgs Potential

$$V(h) = \Delta V_f(h) + \Delta V_A(h) \approx c_0 - c_1 \sin^2\left(\frac{h}{2F}\right) + c_2 \sin^4\left(\frac{h}{2F}\right)$$

Top partner — Gauge contributions

$$\frac{c_1}{F^4} = \frac{N_c}{8\pi^2}\left[\left(\lambda_R^t\right)^2 \kappa_R^t - \left(\lambda_L^t\right)^2 \kappa_L^t\right]\frac{M_f^2}{F^2} + \boxed{\frac{N_c y_t^2}{4\pi^2}\frac{M_T^2}{F^2}} - \underbrace{\frac{9g_R^2}{32\pi^2}\left(1 - \frac{g_R^2 v_\Sigma^2}{2M_\rho^2}\right)\frac{M_\rho^2}{F^2}} + \mathcal{O}\left(g_L g_R, g_L^2\right)$$

Recall, we need: $\left.\frac{c_1}{F^4}\right|_{\text{phys.}} = \frac{m_h^2}{F^2}$ ⟶ Tuning ($m_h^2/F^2 \lesssim 0.03$)

Higgs Potential

$$V(h) = \Delta V_f(h) + \Delta V_A(h) \approx c_0 - c_1 \sin^2\left(\frac{h}{2F}\right) + c_2 \sin^4\left(\frac{h}{2F}\right)$$

Top partner

Gauge contributions

$$\frac{c_1}{F^4} = \frac{N_c}{8\pi^2}\left[\left(\lambda_R^t\right)^2 \kappa_R^t - \left(\lambda_L^t\right)^2 \kappa_L^t\right]\frac{M_f^2}{F^2} + \boxed{\frac{N_c y_t^2}{4\pi^2}\frac{M_T^2}{F^2}} - \frac{9 g_R^2}{32\pi^2}\left(1 - \frac{g_R^2 v_\Sigma^2}{2M_\rho^2}\right)\frac{M_\rho^2}{F^2} + \mathcal{O}\left(g_L g_R, g_L^2\right)$$

Impose L-R symmetry

Higgs Potential

$$V(h) = \Delta V_f(h) + \Delta V_A(h) \approx c_0 - c_1 \sin^2\left(\frac{h}{2F}\right) + c_2 \sin^4\left(\frac{h}{2F}\right)$$

Top partner — Gauge contributions

$$\frac{c_1}{F^4} = \frac{N_c}{8\pi^2}\underbrace{\left[\left(\lambda_R^t\right)^2 \kappa_R^t - \left(\lambda_L^t\right)^2 \kappa_L^t\right]}_{\text{Impose L-R symmetry}} \frac{M_f^2}{F^2} + \boxed{\frac{N_c y_t^2}{4\pi^2}\frac{M_T^2}{F^2}} \downarrow - \overbrace{\frac{9g_R^2}{32\pi^2}\left(1 - \frac{g_R^2 v_\Sigma^2}{2M_\rho^2}\right)\frac{M_\rho^2}{F^2}}^{\text{Gauge contributions}} + \mathcal{O}\left(g_L g_R, g_L^2\right)$$

- Increase size of gauge contribution ⟶ $g_{R,3} = O(1) \gg g_{R,12} \approx g_Y^{\mathrm{SM}}$

  (Allowed by flavour *non-universality* !)

- Avoid suppression / sign flip ⟶ $M_{W_R}^2 = \frac{1}{4} g_R^2 v_\Sigma^2 < \frac{1}{2} M_\rho^2$

Phenomenological Constraints

- Constraints related to strong dynamics
  - Modification of VVh- and VVhh-couplings

$$F \gtrsim 500\,\mathrm{GeV}$$

  - Top partners and heavy resonances searches

$$M_T \gtrsim 1.5\ \mathrm{TeV} \longrightarrow F \gtrsim 600\,\mathrm{GeV}$$

$$M_\rho \gtrsim 5\ \mathrm{TeV}$$

  - EWPO (S and T parameters)

$$g_{L,R}^2 \frac{v^2}{M_\rho^2} \lesssim 10^{-3}$$

- Constraints related to flavoured gauge bosons
  - $B \to X_s \gamma$
  - Bound on Z-pole obs.

$$\left.\right\} v_\Sigma \gtrsim 3\ \mathrm{TeV}$$

  - Bounds on Z′ masses from FCNC (B_s-mixing)

$$v_\Omega \gtrsim 2.7\ \mathrm{TeV}$$ (up- vs down-alignment)

  - LHC bound from Drell-Yan data

$$v_\Sigma \gtrsim 2.0\ \mathrm{TeV}$$

Phenomenological Constraints

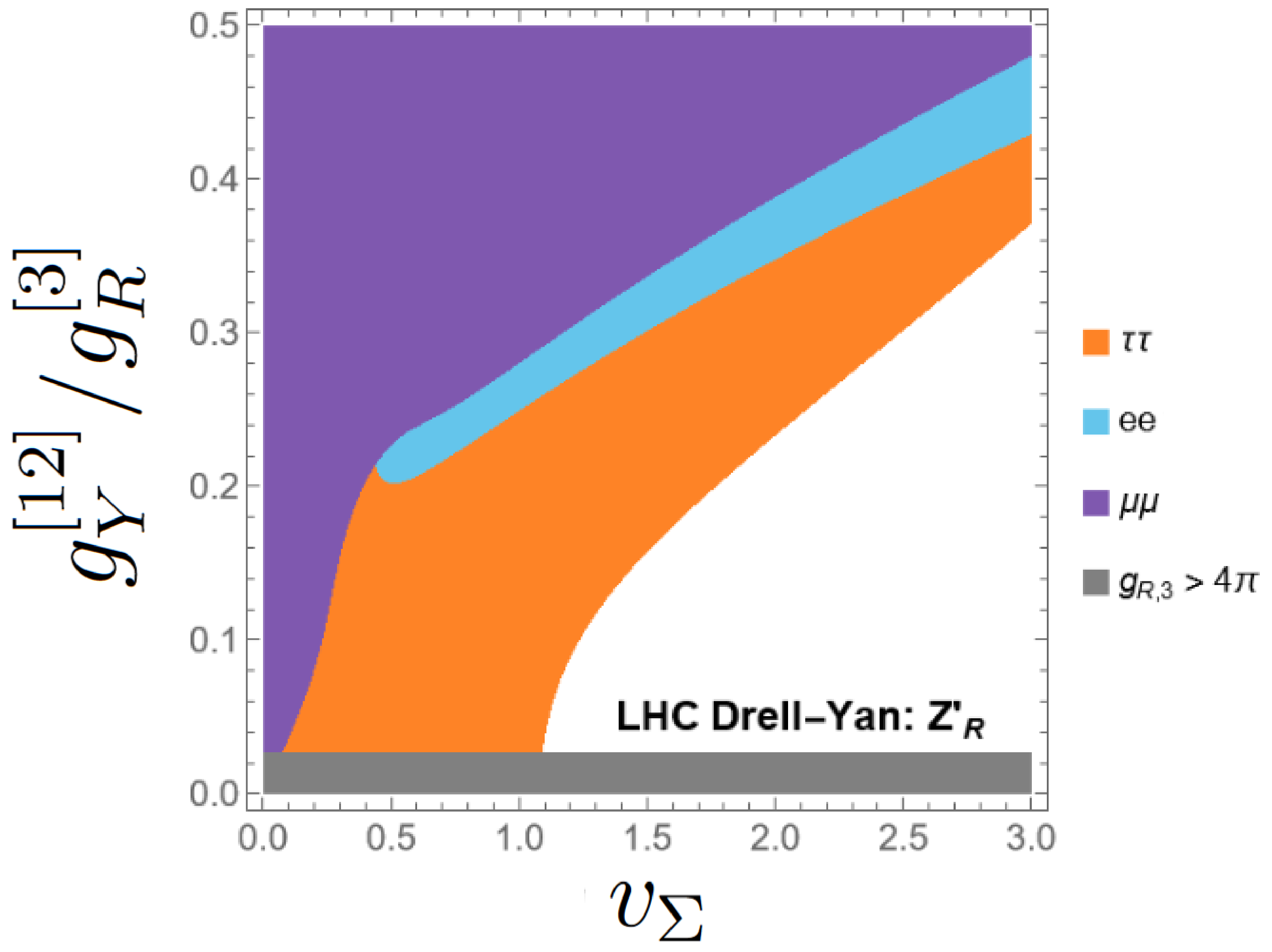
Benchmark scenario

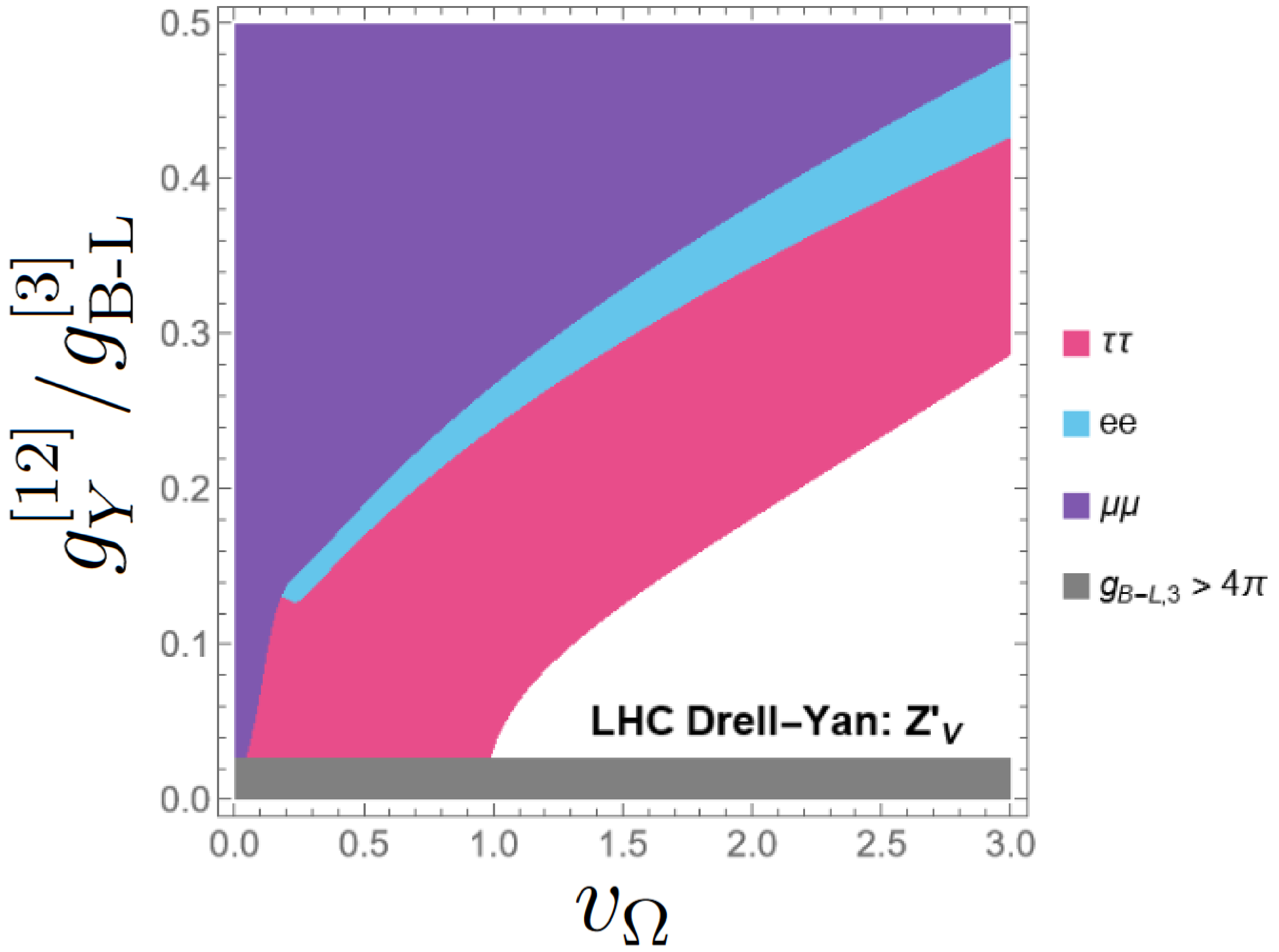
- Large 3rd gen. RH gauge coupling: $g_{R,3} = O(1)$
- Light Top partner $M_T \approx 2$ TeV and $M_\rho \approx 10$ TeV
- Compositeness scale $F \approx 750\,\text{GeV}$ and $v_\Sigma \approx 3$ TeV

All constraints are satisfied and $\delta_{\text{EW}} \lesssim 10^{-3}$

→ 3% tuning in the potential

→ $O(1\%)$ corrections to Higgs couplings



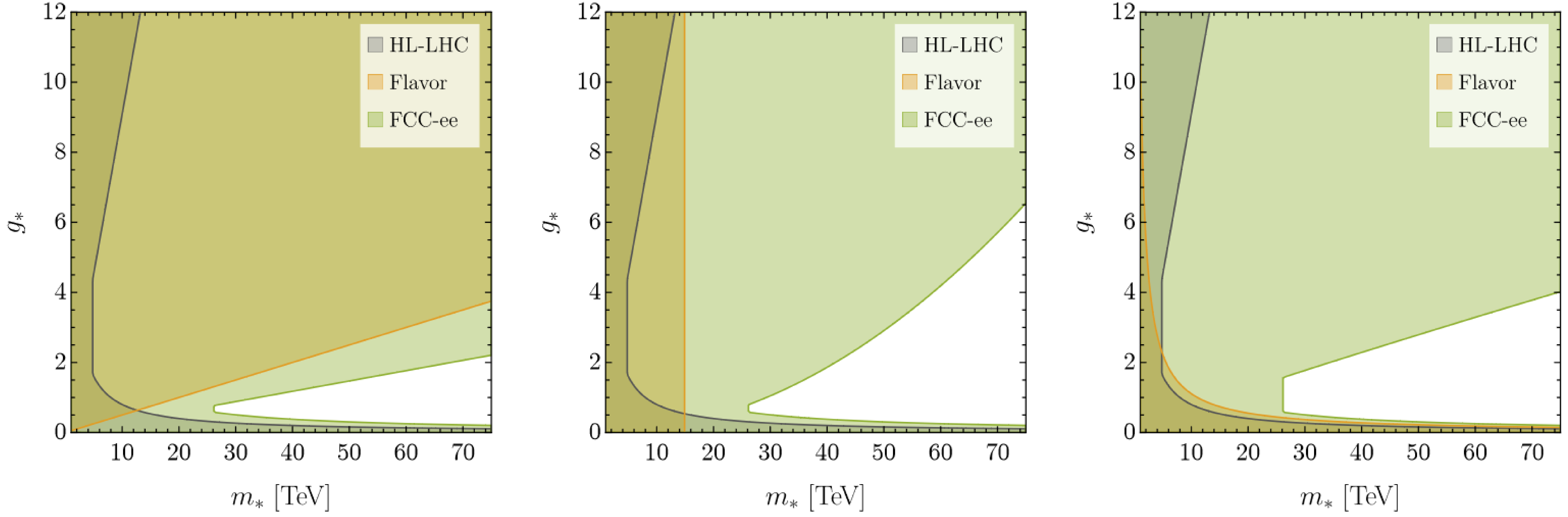


Allwicher et al. 2022

Composite Higgs @ HL-LHC and FCC-ee

Stefanek 2024

$[\ m_* = F g_*\ ]$



(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

- Interesting pheno & possible NP coupled to 3rd gen @ few TeV compatible with current exp. bounds

- Flavour non-universality + Higgs compositeness $\longrightarrow$ interesting interplay for BSM and predictive framework

➡ Future directions: Explore other global symmetries of the strong sector

$$Sp(6)_{\text{global}} \longrightarrow SU(2)_L \times SU(2)_R^{[3]} \times SU(2)_R^{[12]}$$

Conclusion

Flavour and Hierarchy problem = important guides for BSM model building

FCC-ee will probe the Higgs better than ever before

➡ what if we see « nothing » = SM only… ?

Thank you for your attention !