Universität Zürich UZH

Flavour Deconstructing the Composite Higgs*

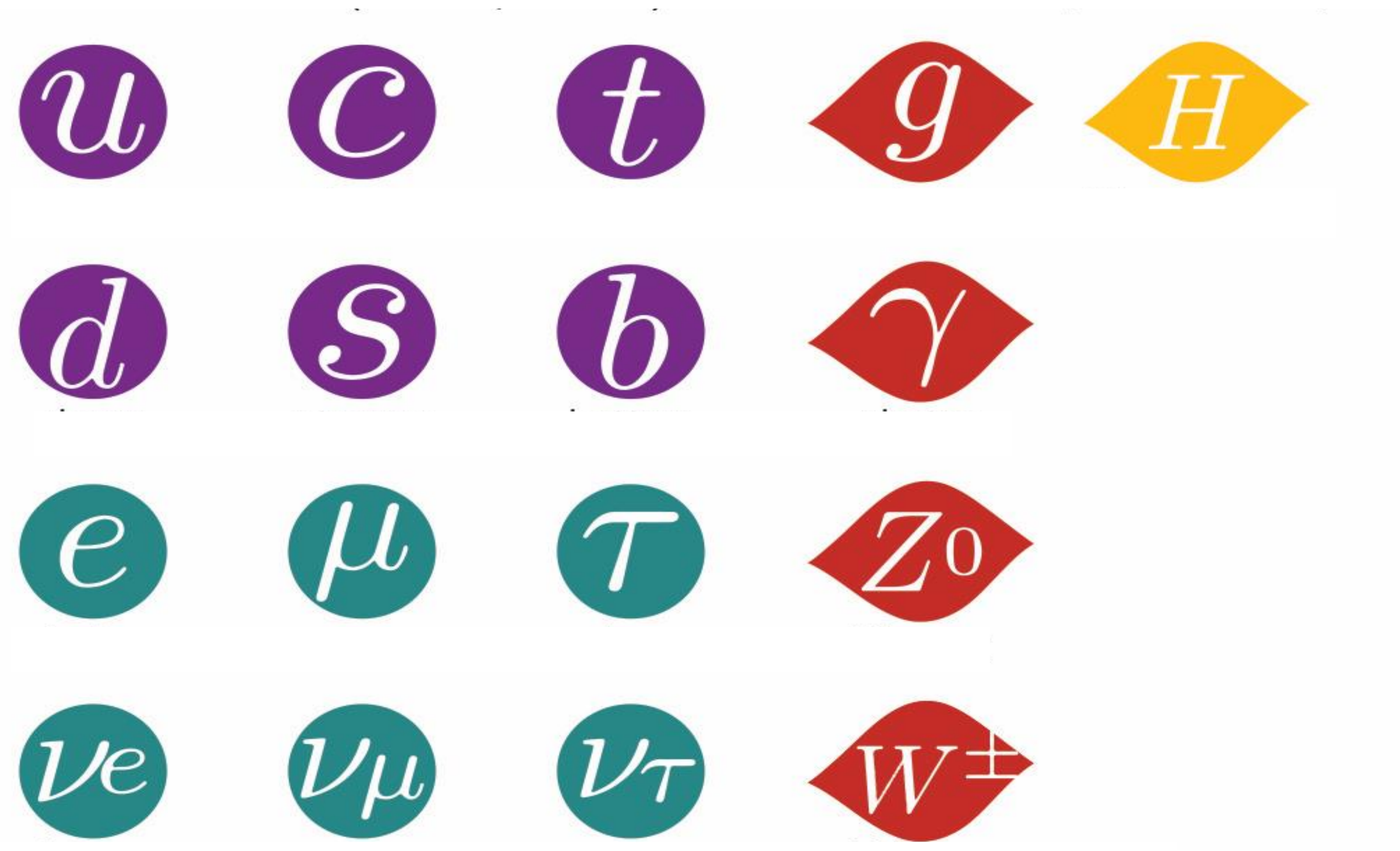
29.05.2025, Padova

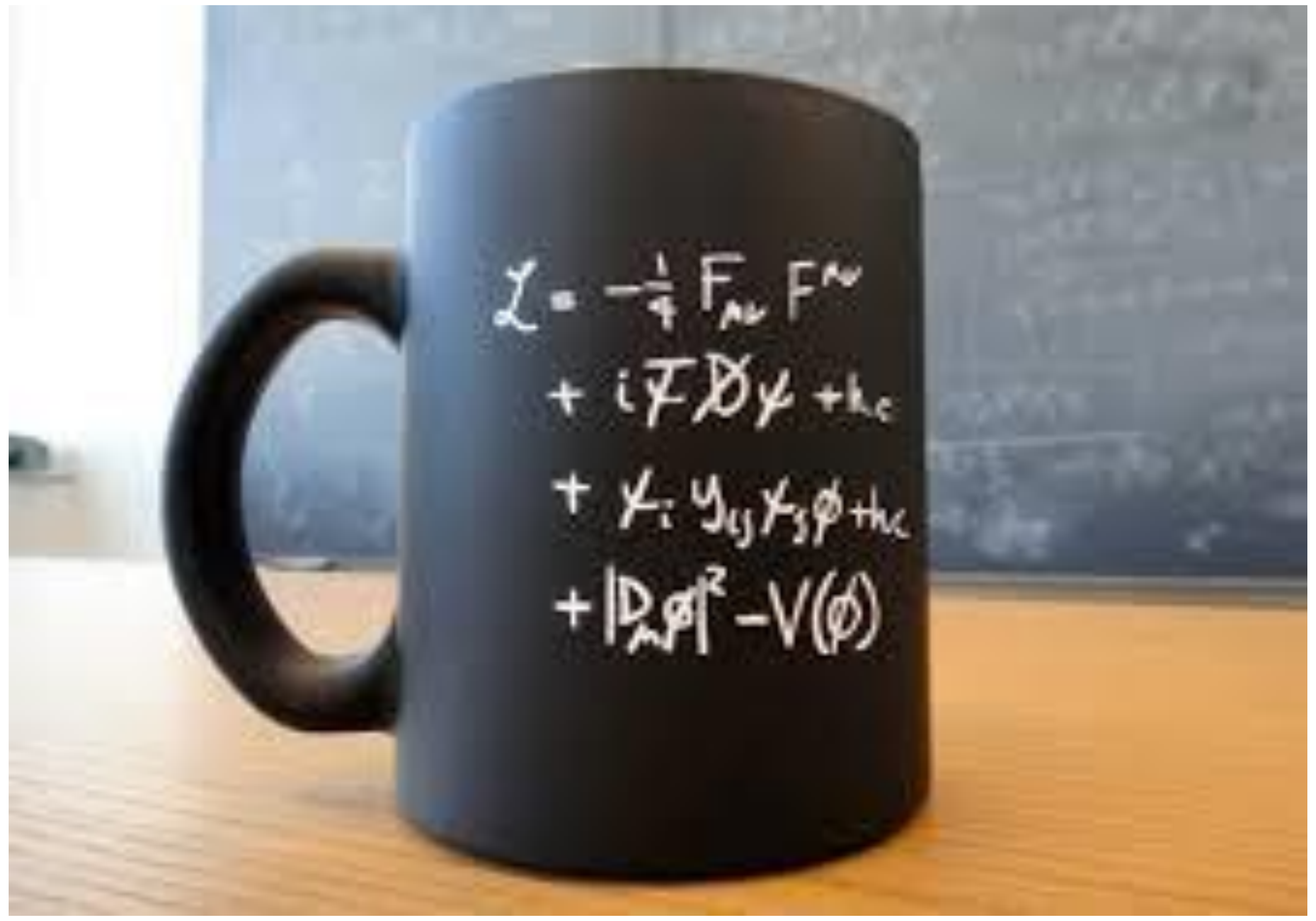
Marko Pesut

University of Zürich

*2407.10950 with Sebastiano Covone , Joe Davighi and Gino Isidori

Why BSM?



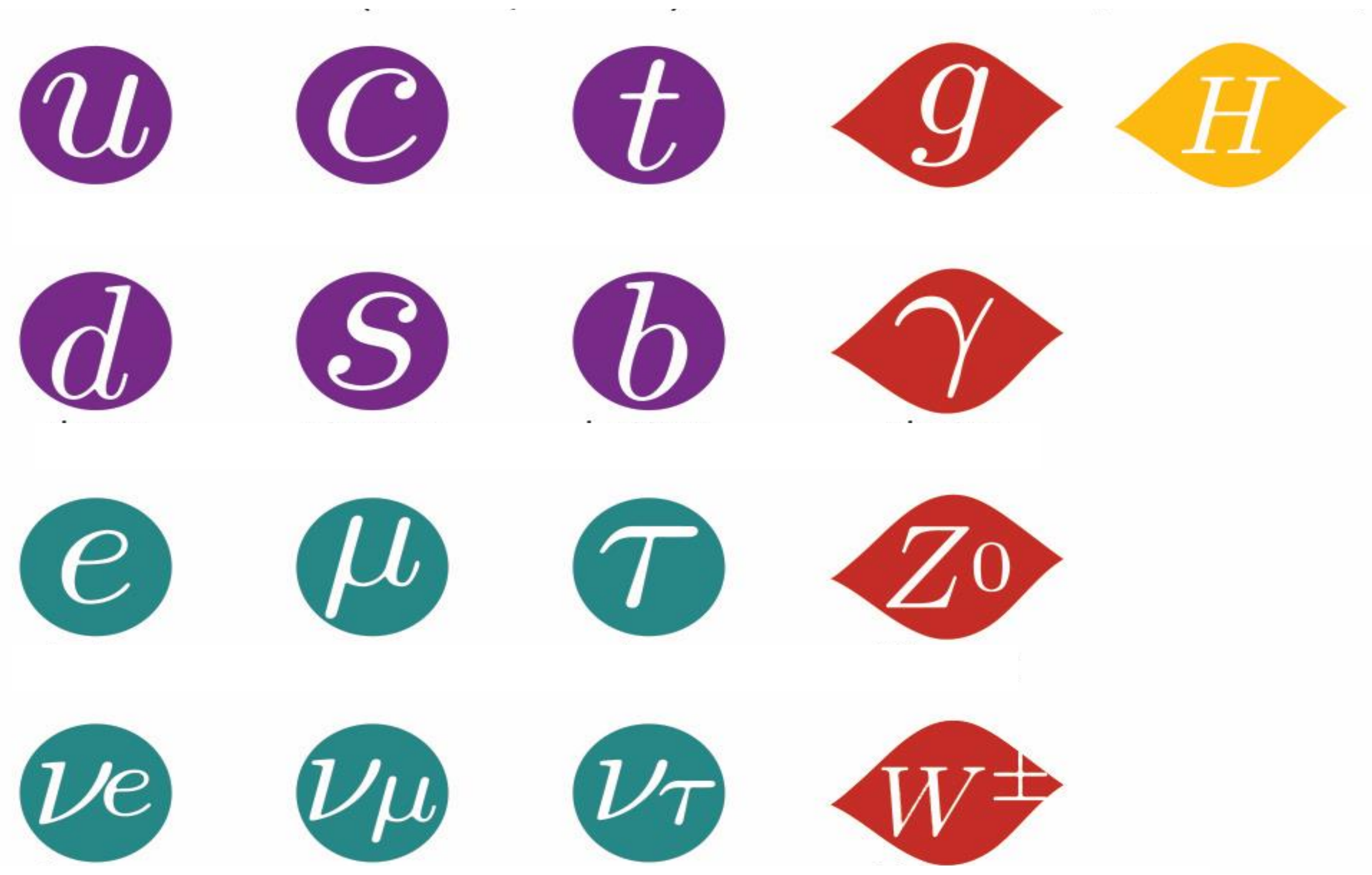


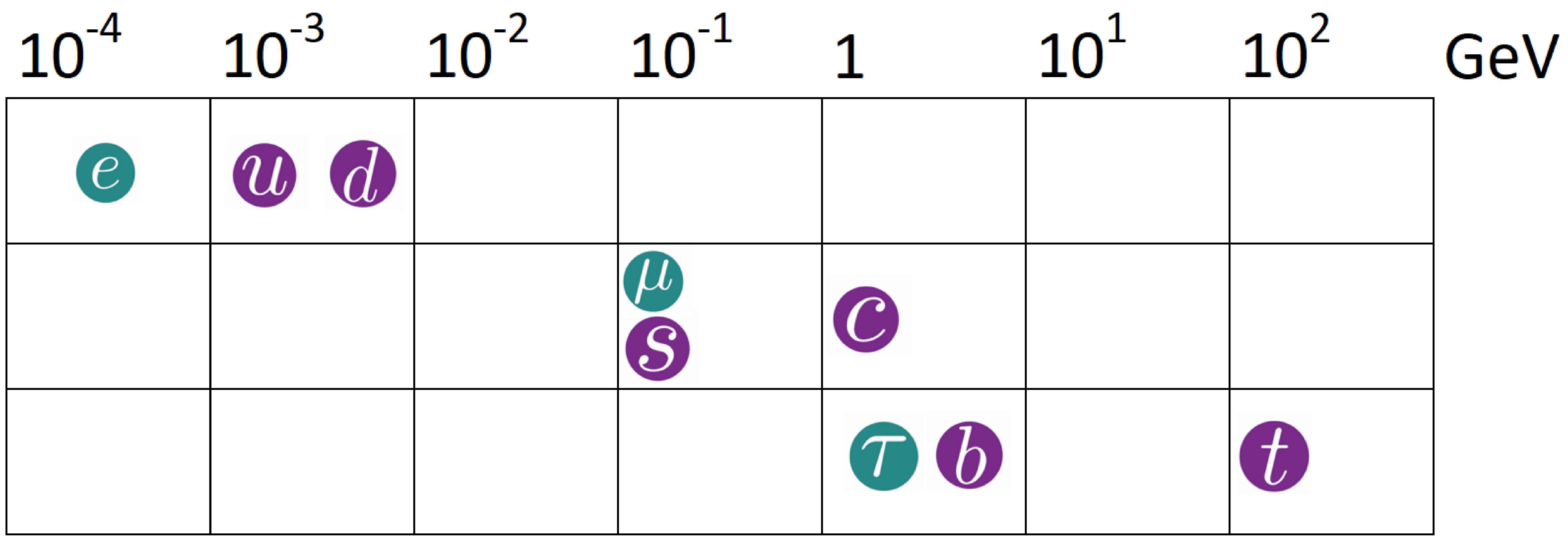
Open questions:

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

...

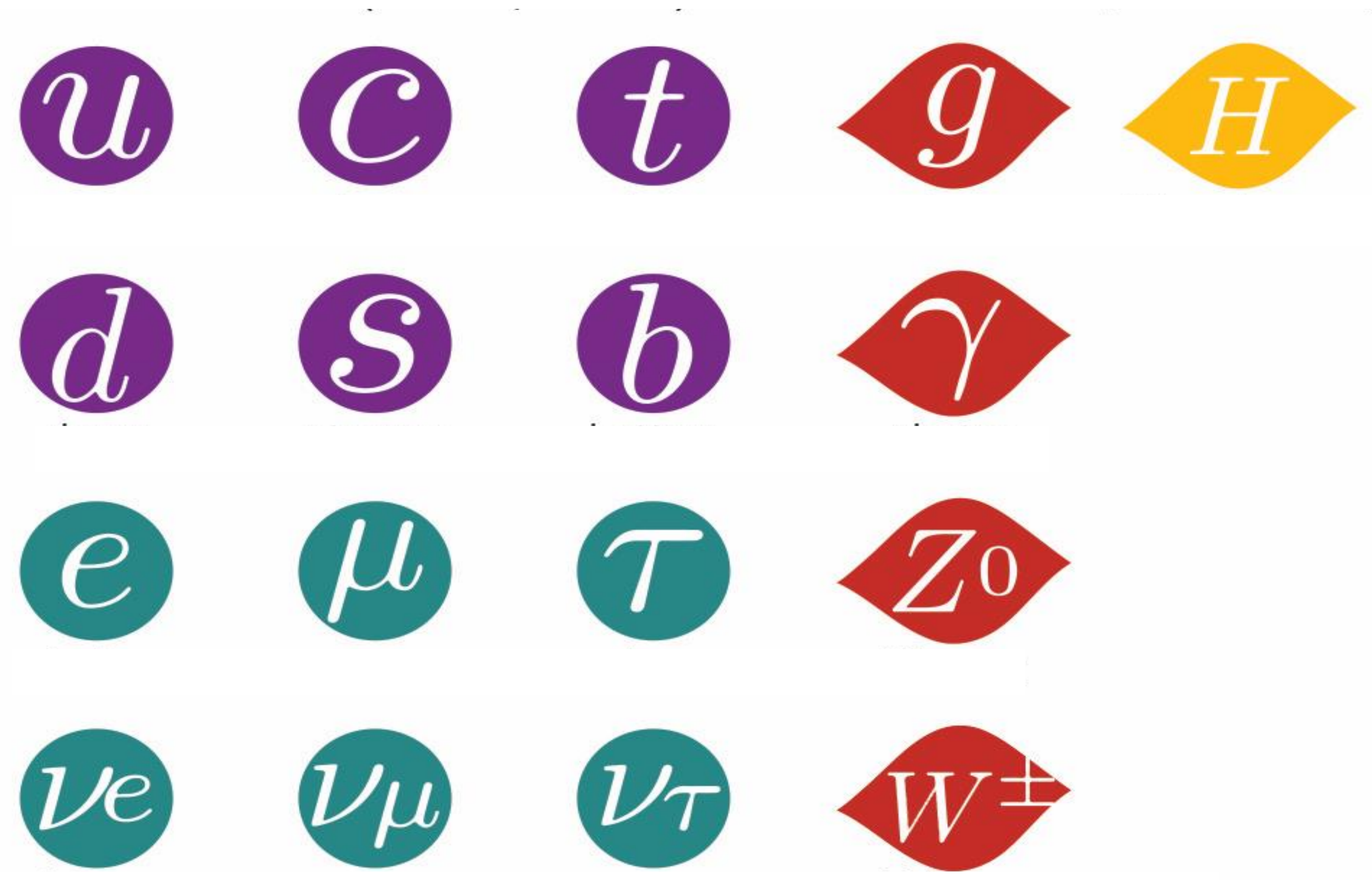
Flavour Puzzle

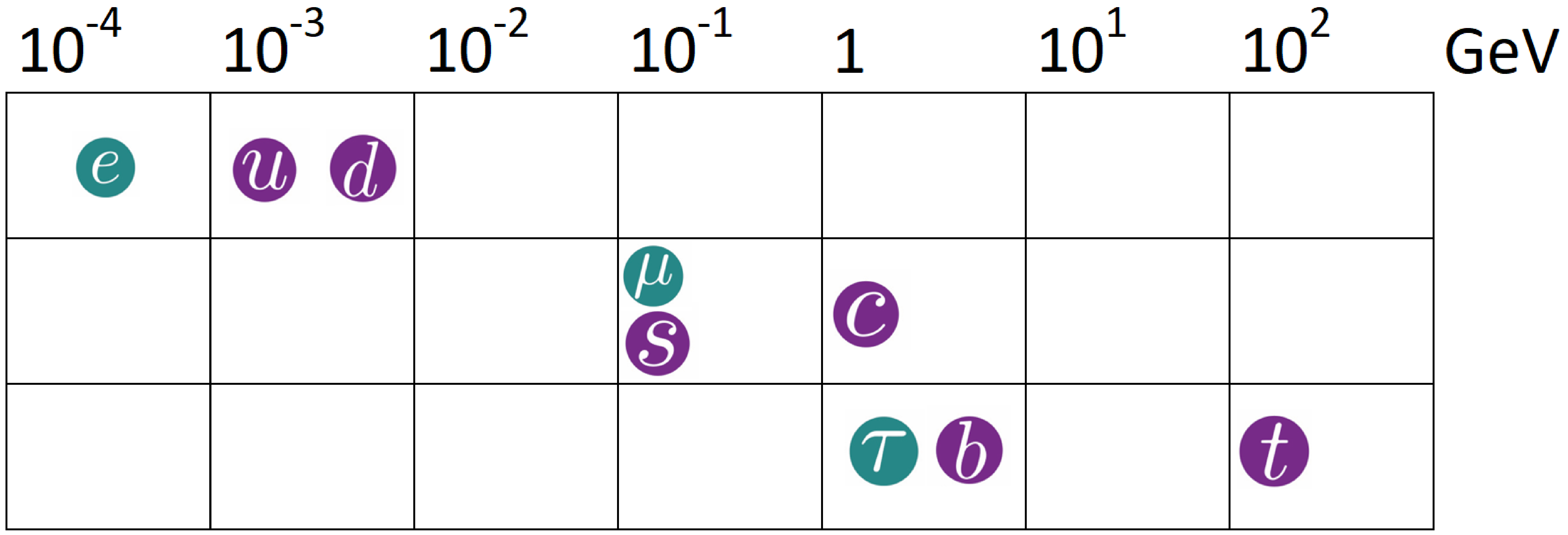




[See Gino’s & Barbieri’s talk]

Flavour Puzzle





[See Gino's & Barbieri's talk]

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

Flavour-universal

Yukawa hierarchies

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

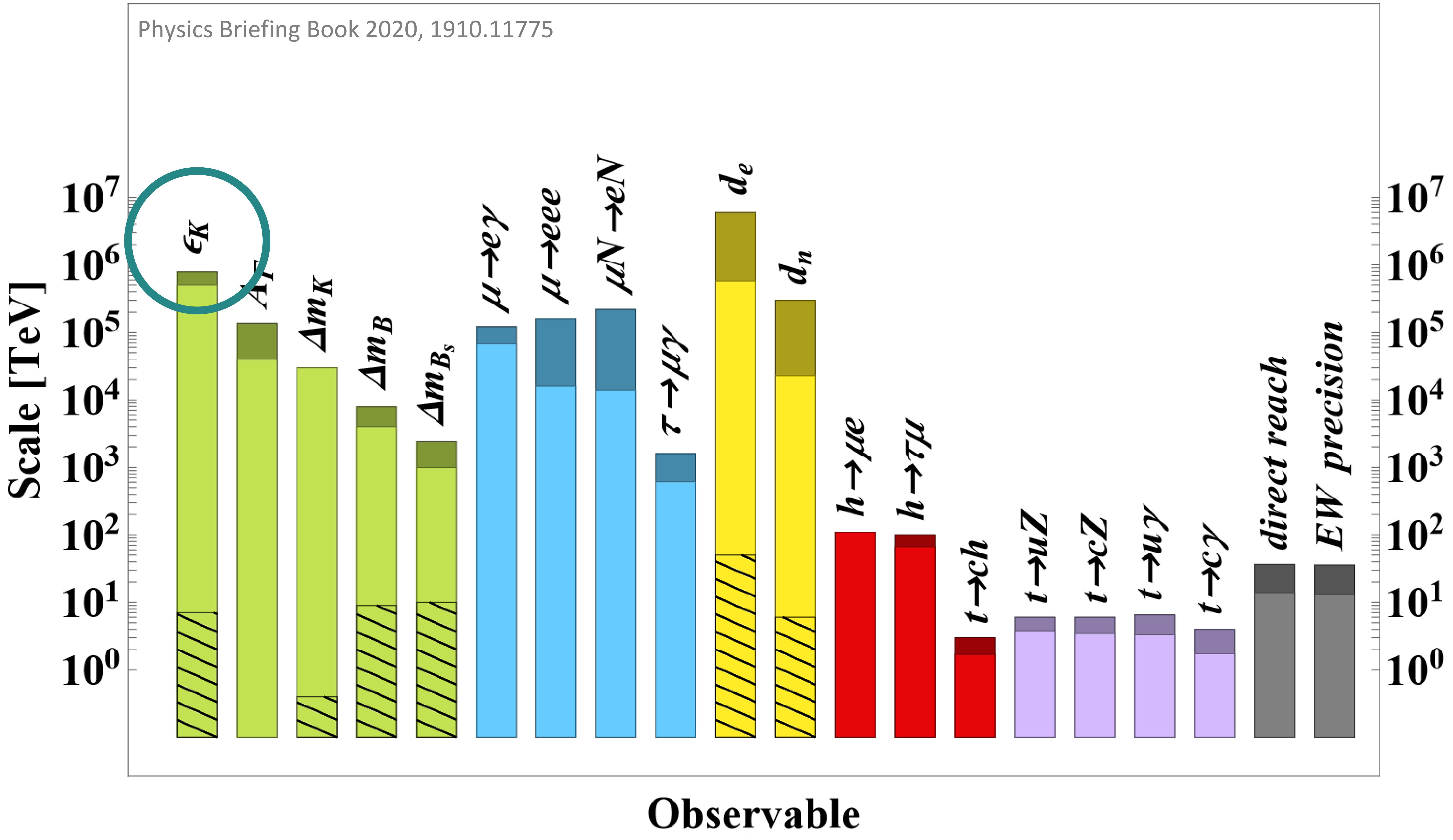
In the basis where Y_d is diagonal

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

Barbieri et al. 2011, Isidori & Straub 2012, Kagan et al. 2009, Blankenburg et al. 2012

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

Any heavy NP will destabilize the Higgs mass

$$m_H^2 \sim \Lambda_{\rm NP}^2 \quad \text{vs} \quad m_H = 125\,\text{GeV}$$

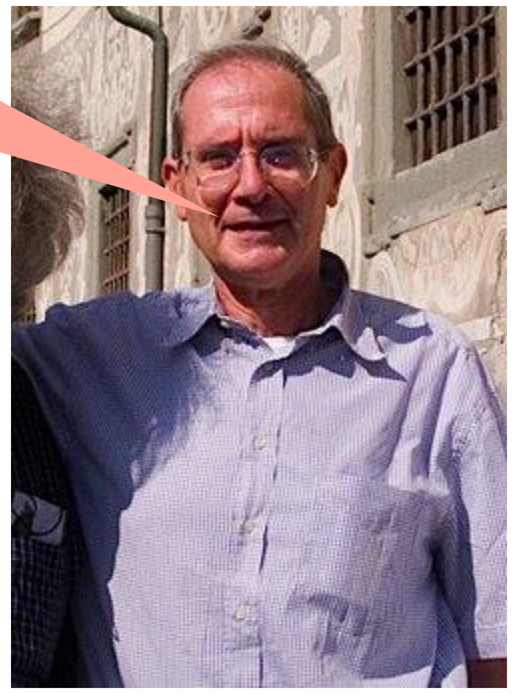
➡ Protection mechanism

[See Rattazzi's & Giudice's talk]

*Inescapable link between Higgs and Flavour**

➡ *Joint solution* to the Flavour Puzzle and the Higgs hierarchy problem

Mission for the youngsters !



➡ Hints provided by the SM and exp. data

*Davighi & Isidori 2023

*Inescapable link between Higgs and Flavour**

➡ *Joint solution* to the Flavour Puzzle and the **Higgs hierarchy problem**

Higgs Compositeness

No elementary scalars

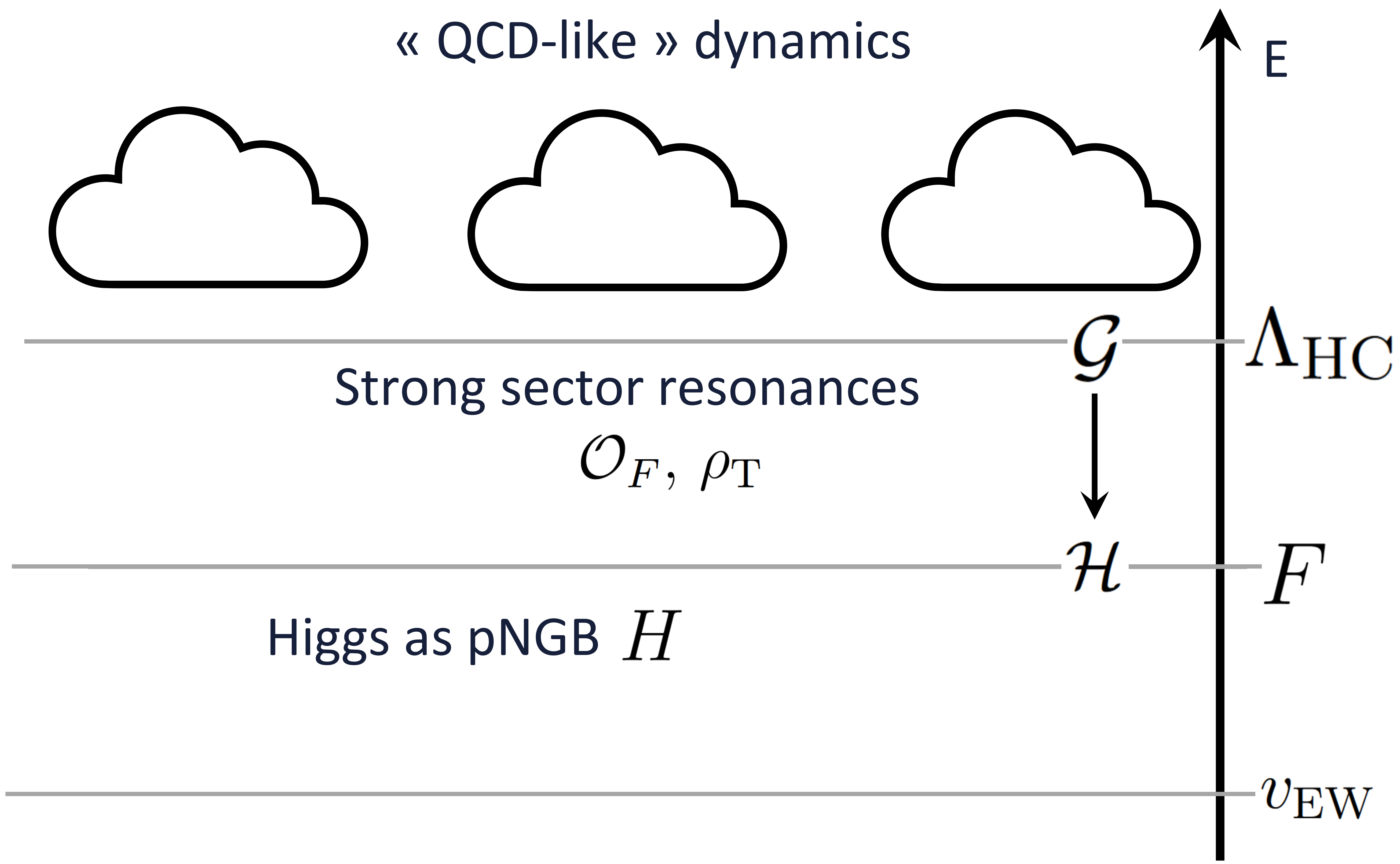
Higgs emerges as a composite pseudo-Goldstone boson of S.S.B

[See Rattazzi's & Giudice's talk]

Dugan et al. 1985,
Agashe, Contino & Pomarol 2005,…

*Davighi & Isidori 2023

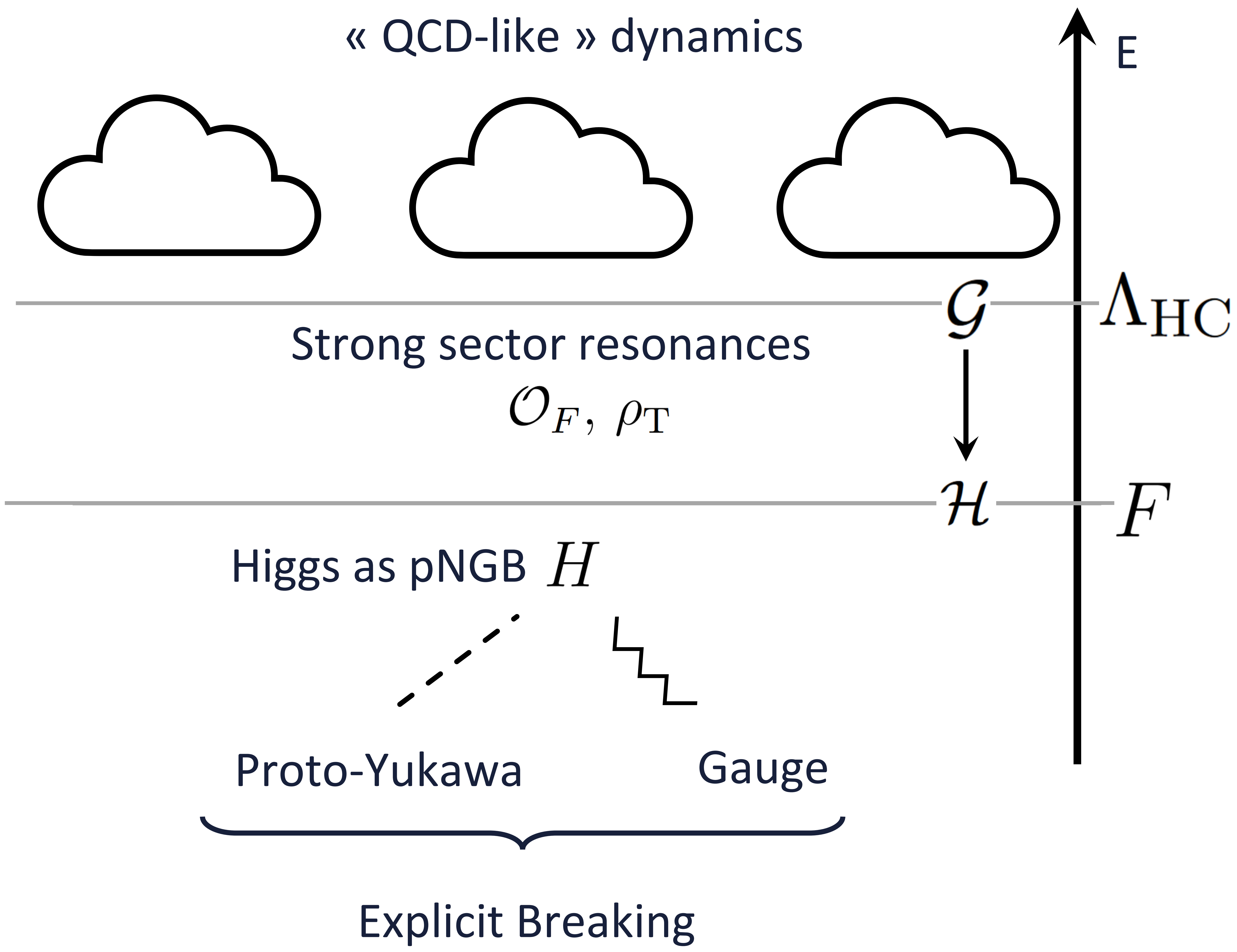
Higgs Compositeness



Compositeness scale cuts off quantum corrections to the Higgs potential

Dugan et al. 1985,
Agashe, Contino & Pomarol 2005,…

Higgs Compositeness



Dugan et al. 1985,
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Back to Flavour

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

Lessons from SM & EXP:

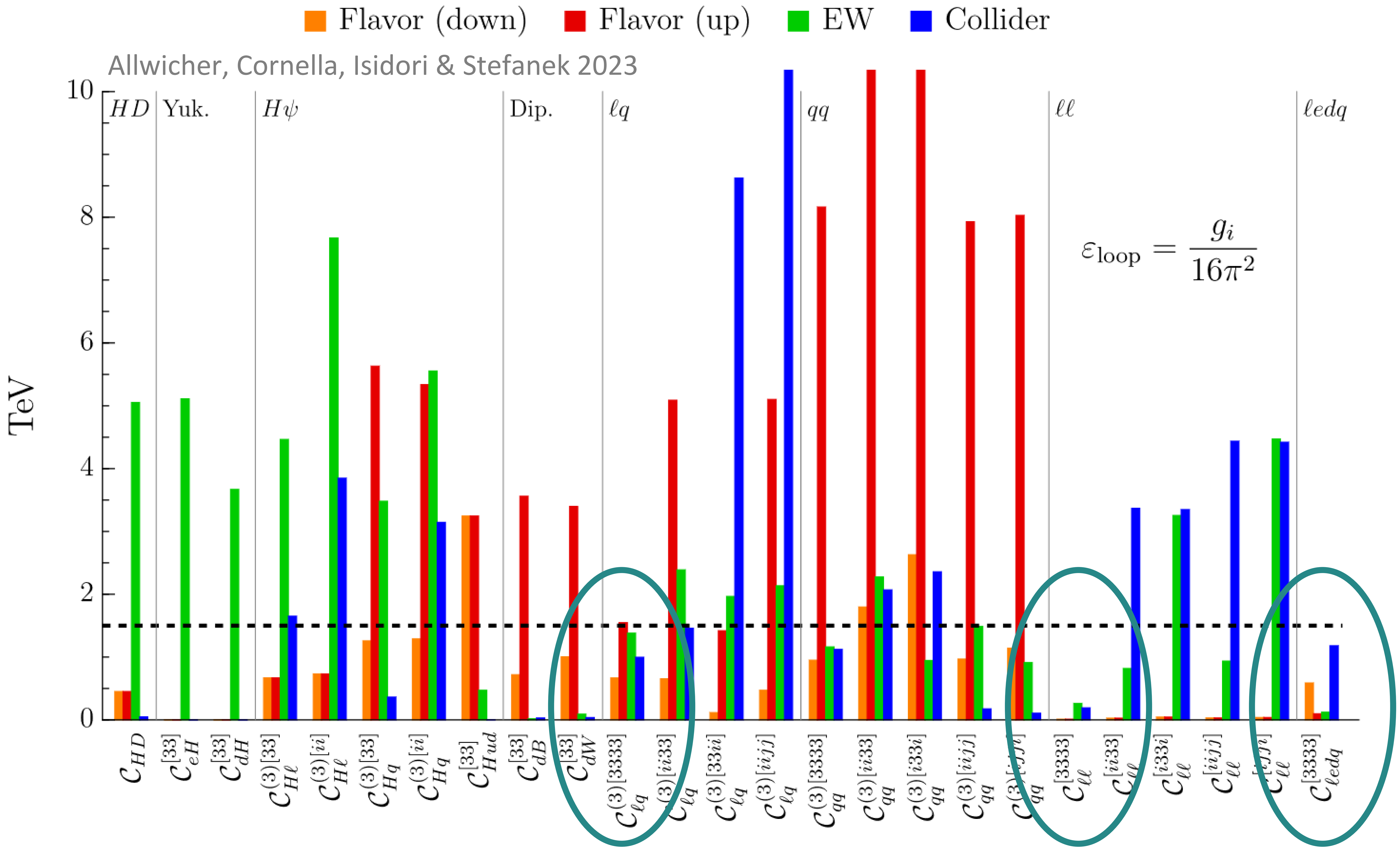
- Exact $U(3)^5$ flavour symmetry in the gauge and fermion sectors of the SM
- Peculiar breaking $U(3)^5 \to U(2)^n$ with only $y_t \sim \mathcal{O}(1)$ --> $Y_u \sim \begin{pmatrix} & < 0.01 & 0.04 \\ & & 1 \end{pmatrix}$
- No large breaking of $U(2)$ @TeV & stringent flavour bounds on light families

Any NP at the TeV scale has a *highly non-generic* flavour structure

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

Back to Flavour

3rd Gen. is the least constrained!



Flavour Deconstructing the Composite Higgs

- $U(2)^5$ as an accidental symmetry
- 3rd gen. NP is the least constrained & $y_{33} \sim 1$

Flavour Deconstructing the Composite Higgs

➡ $U(2)^5$ as an accidental symmetry

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

Flavour symmetries *encoded* in the gauge!

*Different options to Flavour deconstruct: Davighi & Isidori 2023
... or split the families -> Fuentes-Martin & Lizana 2024

[See Gino's & Barbieri's talk]

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[See Gino's & Barbieri's talk]

- Higgs Compositeness
- Flavour in CHM -> Partial Compositeness

Higgs as pNGB

Exploring the Flavor Symmetry Landscape, Glioti et al. 2024
-> Flavour symmetries options to reduce scale of NP

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

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

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

Flavour Deconstructing the Composite Higgs

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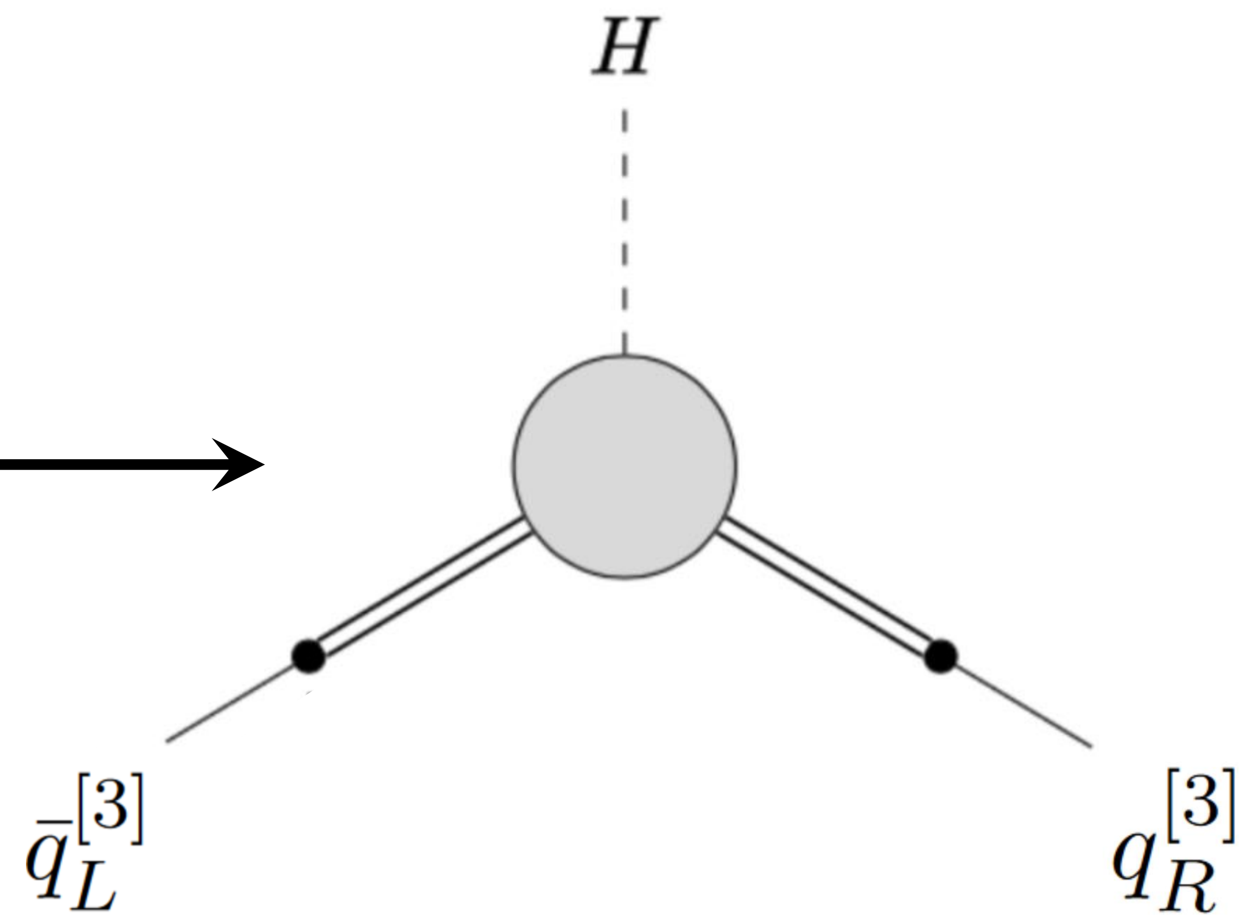
$$SU(3)_c \times SU(2)_L \times SU(2)_R^{[3]} \times U(1)_{B-L}^{[3]} \times U(1)_Y^{[12]}$$

Third-family Partial Compositeness:

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



D.B Kaplan (1991)

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

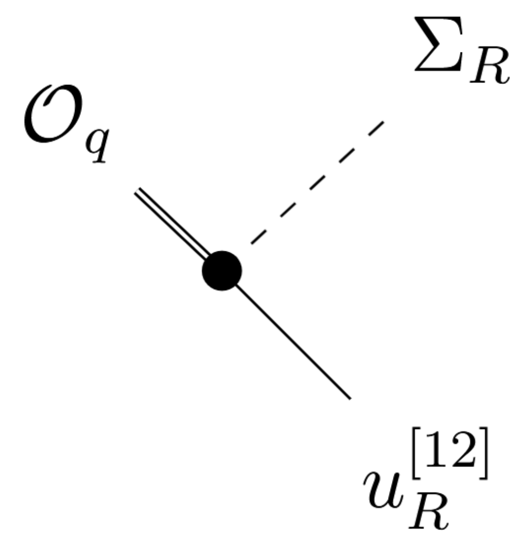
Λ_{HC} $\quad H \sim (\mathbf{2}, \mathbf{2})$

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

Horizontal Breaking

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

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



Flavour for light fam.

Two Z′ and a pair of $W_R^{\pm}$

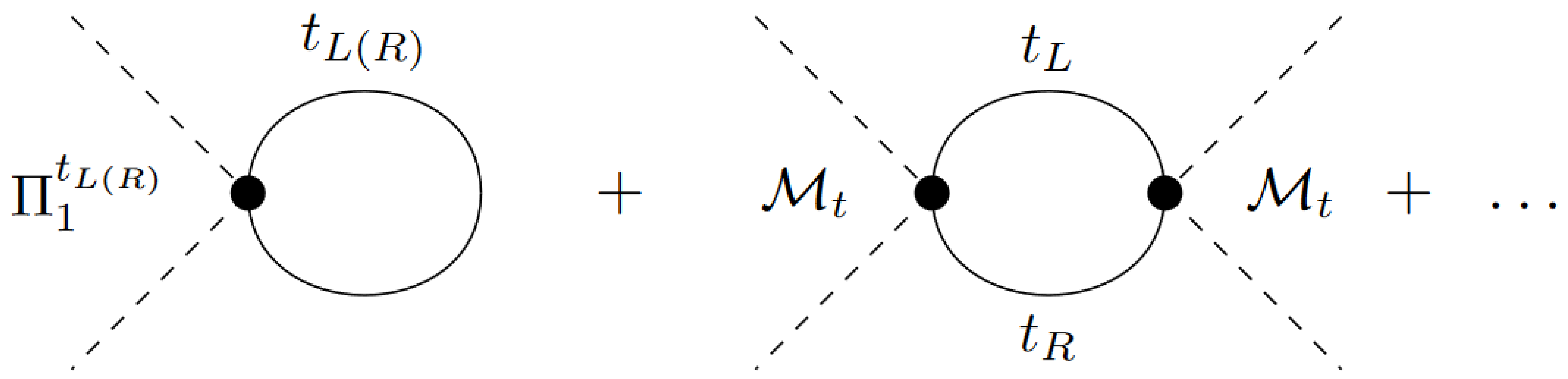
(Most of the pheno!)

Higgs Potential

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

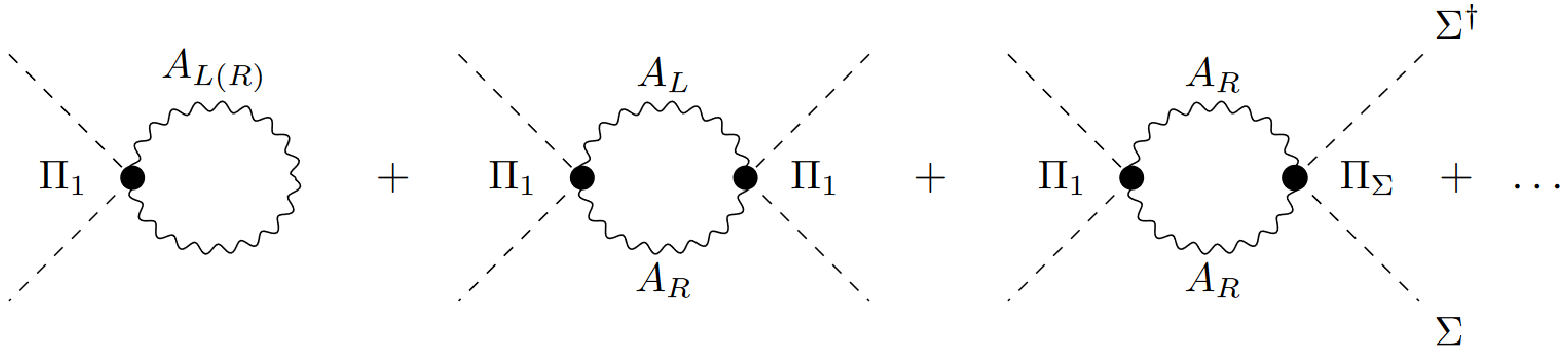
Fermion contribution

$\Delta V(h)_f$



Gauge contribution

$\Delta V(h)_A$



Higgs Potential

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

$$\left.\frac{c_1}{F^4}\right|_{\text{phys.}} = \frac{m_h^2}{F^2} \lesssim 0.06$$ (from Exp.)

$$\left.\frac{c_2}{F^4}\right|_{\text{phys.}} = \frac{2m_h^2}{v^2} \approx \frac{1}{2}$$ 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 $\longrightarrow$ $\boxed{M_T \approx 2.5F}$

Higgs Potential

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

Fermionic resonances

Top partner

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

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

(Natural in flavour non-universal scenario !)

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

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.

$$\left.\begin{array}{l} B \to X_s\gamma \\ \text{Bound on Z-pole obs.} \end{array}\right\} v_\Sigma \gtrsim 3\ \mathrm{TeV}$$

  - 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

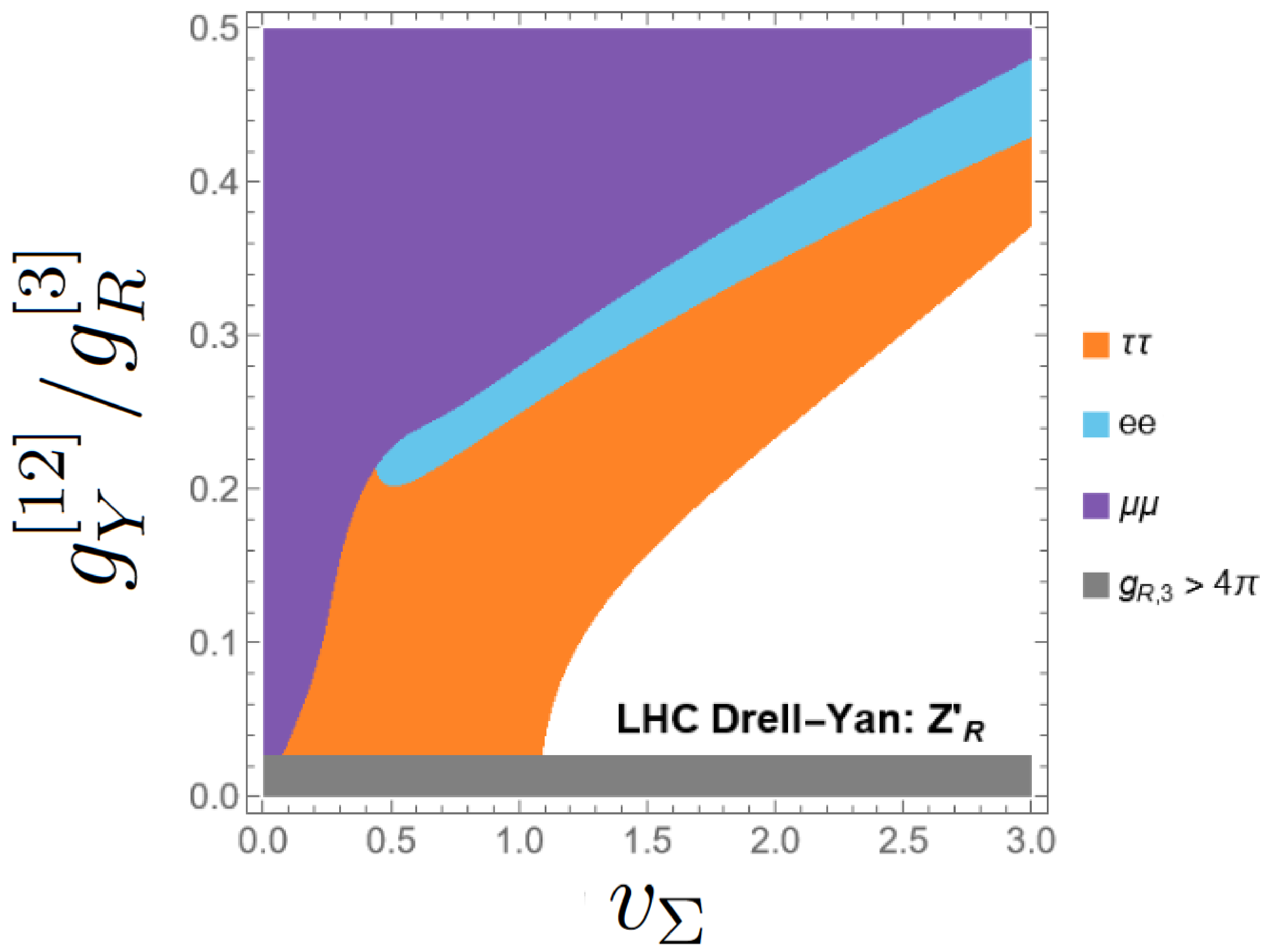
Typical scenario

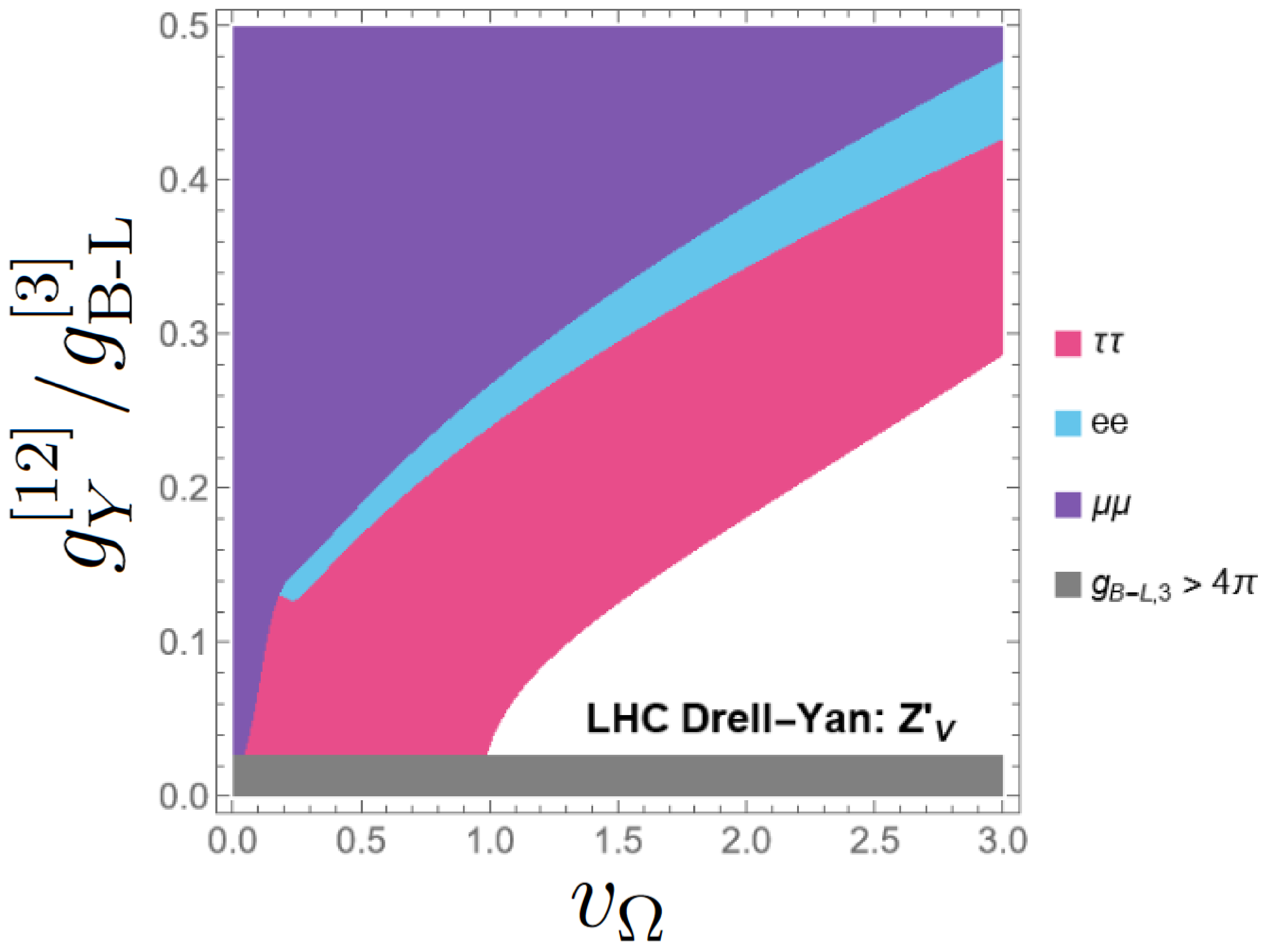
- Large 3rd gen. RH gauge coupling: $g_{R,3} = O(1)$
- Light Top partner $M_T \approx 2 \text{ TeV}$ and $M_\rho \approx 10 \text{ TeV}$
- Flavour deconstruction breaking $v_\Sigma \approx 3 \text{ TeV}$

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

$\longrightarrow$ 3% tuning in the potential

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





Allwicher et al. 2022

Conclusion

➡ Null results @LHC put pressure on *natural* solutions to the hierarchy problem...

Naturalness has played a crucial role in NP searches in the past ...

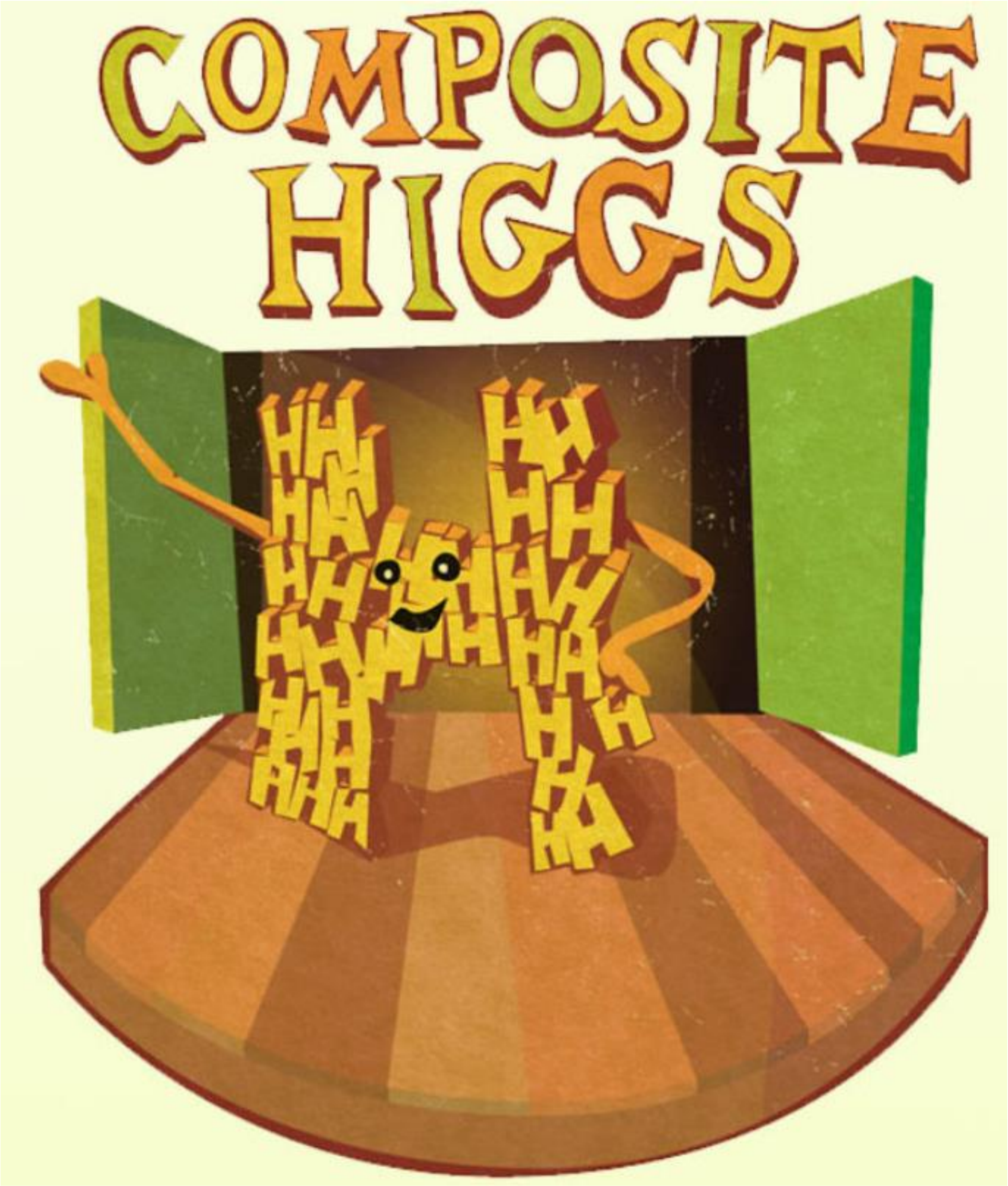
➡ Bounds on flavour violation suggest either a high NP scale or non-generic flavour of BSM

Approx. U(2)-preserving + 3rd gen. NP compatible with TeV scale

- Flavour non-universal NP @TeV compatible with exp. bounds & accessible at current and near future exp.

- Well-motivated *model* for addressing *simultaneously* Higgs & flavour

Thank You !

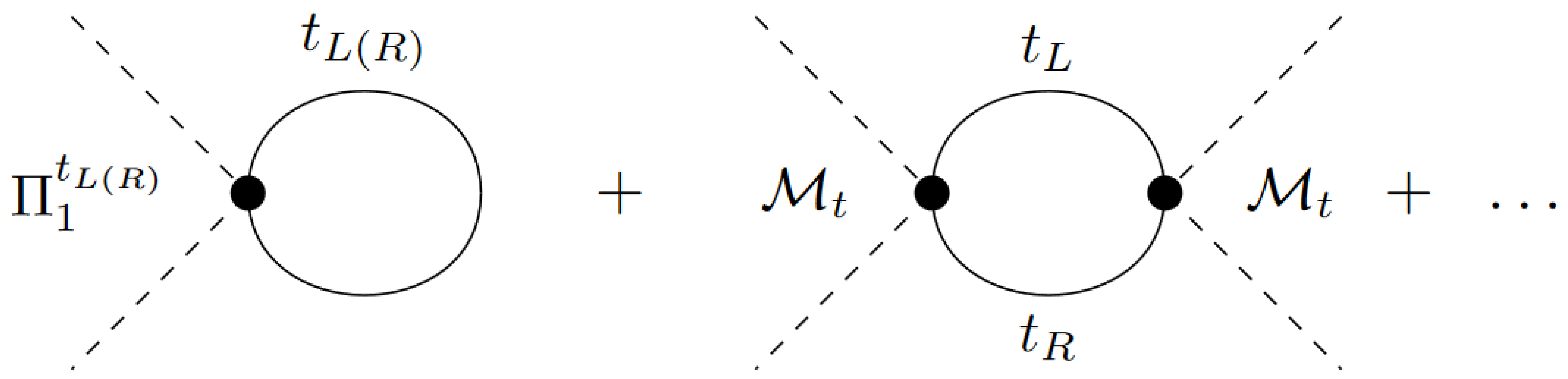


Higgs Potential

➡ Higgs potential induced at 1-loop

Fermion contribution

$\Delta V(h)_f$



$$\mathcal{L}_{\text{eff}} \supset \bar{q}_L \not{p} \left[\Pi_0^{q_L}(p^2) \mathbb{1} + \Pi_1^{t_L}(p^2) u_L^\dagger \Delta_+ u_L \right] q_L + \left\{ \bar{q}_L \left[\mathcal{M}_t(p^2) u_L^\dagger \Delta_+ u_R \right] q_R + \text{h.c.} \right\}$$

$$\Pi_1^{t_L}(0) = \frac{F^2}{M_T^2} \left(\lambda_L^t\right)^2 \kappa_L^t$$

$$|\mathcal{M}_t(0)| = y_t \sqrt{2} F$$

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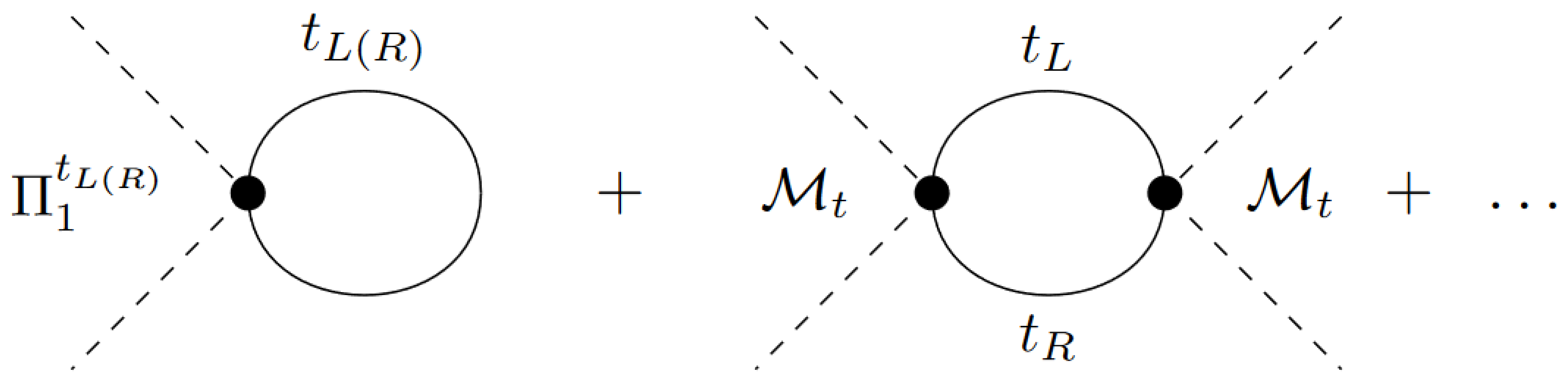

Coleman-Weinberg potential →

$$\Delta V(h)_f = -2N_c \int \frac{d^4 p_E}{(2\pi)^4} \left\{ \log\left[1 + \frac{\Pi_1^{t_L}}{\Pi_0^{q_L}} \sin^2\left(\frac{h}{2F}\right)\right] + \log\left[1 + \frac{|\mathcal{M}_t|^2 \sin^2\left(\frac{h}{2F}\right) \cos^2\left(\frac{h}{2F}\right)}{p_E^2 \left(\Pi_0^{q_L} + \Pi_1^{q_L} \sin^2\left(\frac{h}{2F}\right)\right)\left(\Pi_0^{q_R} - \Pi_1^{q_R} \sin^2\left(\frac{h}{2F}\right)\right)}\right] \right\}$$

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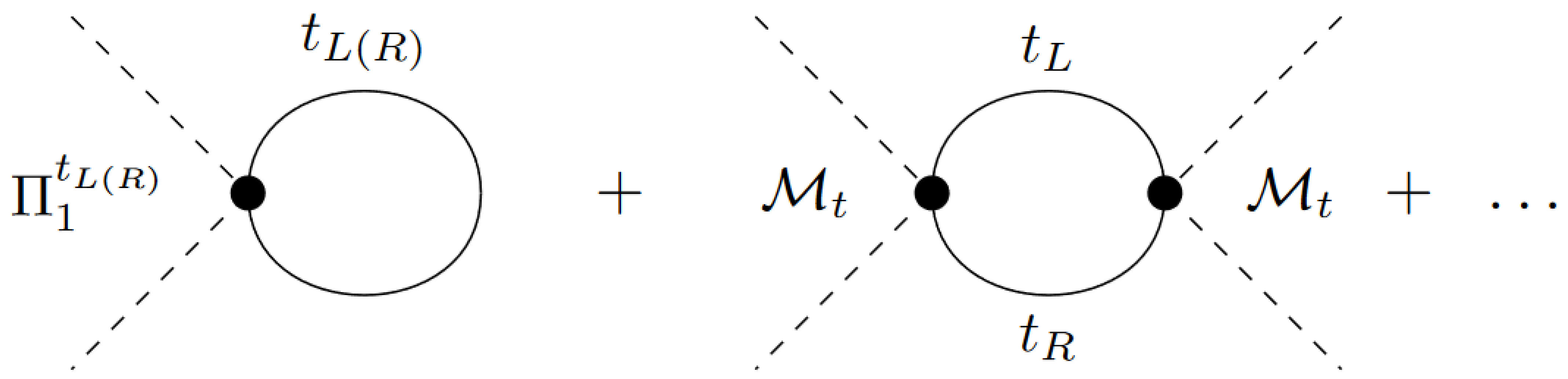

Coleman-Weinberg potential ⟶

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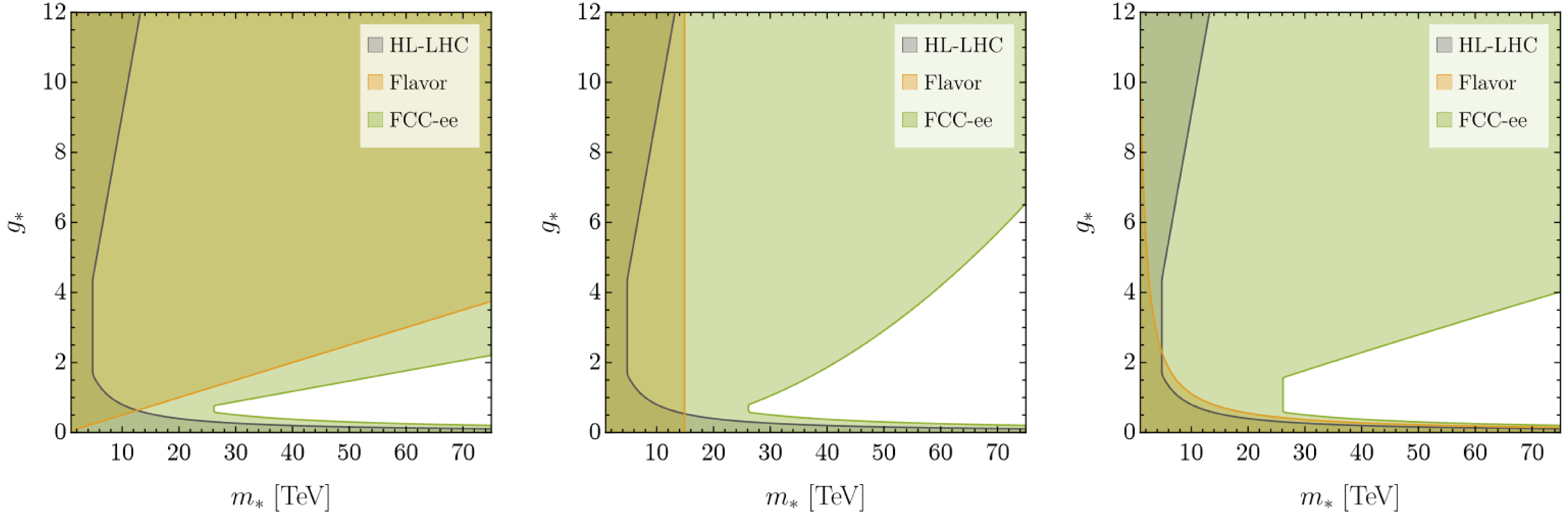
$$\left(\begin{aligned} &\mathcal{M}_t(q^2) = \mathcal{M}_t(0) \times \frac{M_T^2}{M_T^2 - q^2} \\ &\frac{\Pi_1^{t_L}(q^2)}{\Pi_1^{t_L}(0)} \frac{\Pi_0^{q_L}(0)}{\Pi_0^{q_L}(q^2)} = \frac{M_T^2}{M_T^2 - q^2} \frac{M_f^2}{M_f^2 - q^2} \end{aligned} \right)$$

⟶ Explicit expression in terms of model parameters

Composite Higgs @ HL-LHC and FCC-ee

$$(m_* = F g_*)$$

Stefanek 2024



(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!

$$m_* \gtrsim 25 \text{ TeV}$$

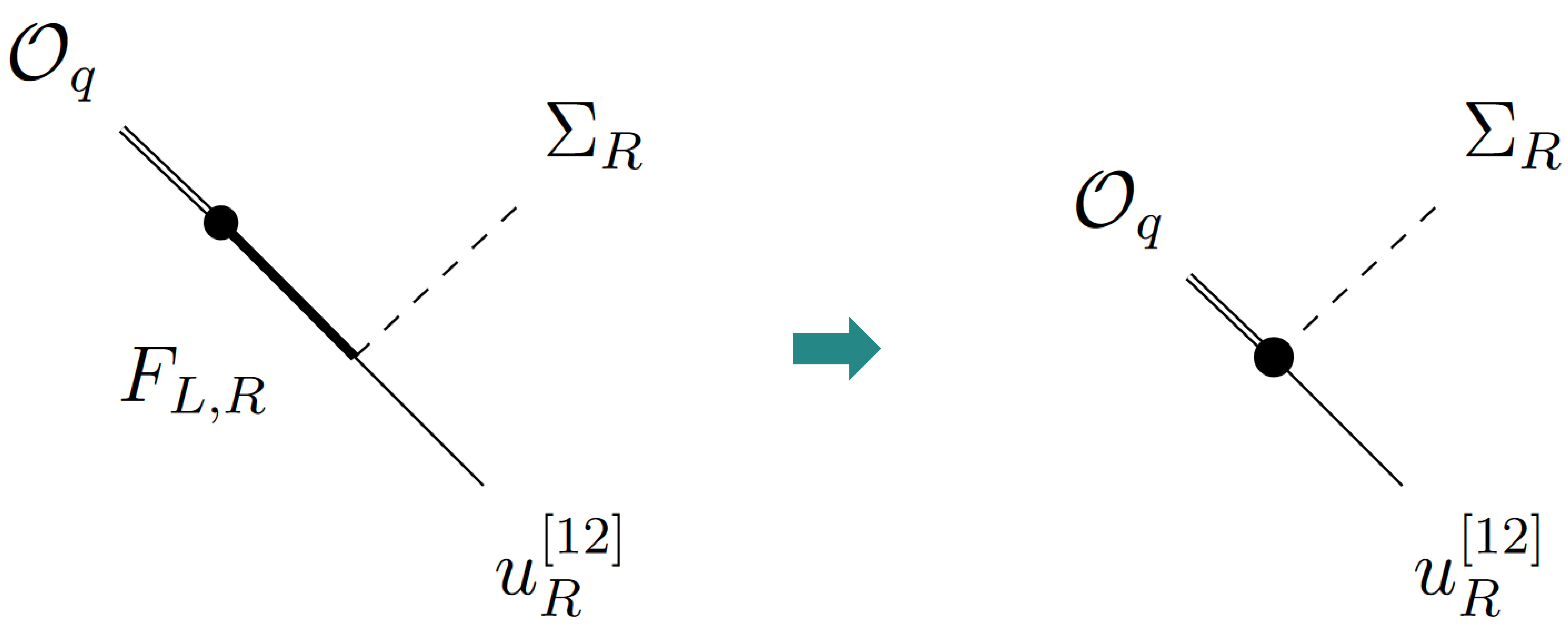
Flavour Deconstructing the Composite Higgs

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

Horizontal Breaking $\boxed{\langle \Sigma_R \rangle \quad \langle \Omega \rangle}$

$$\downarrow$$

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



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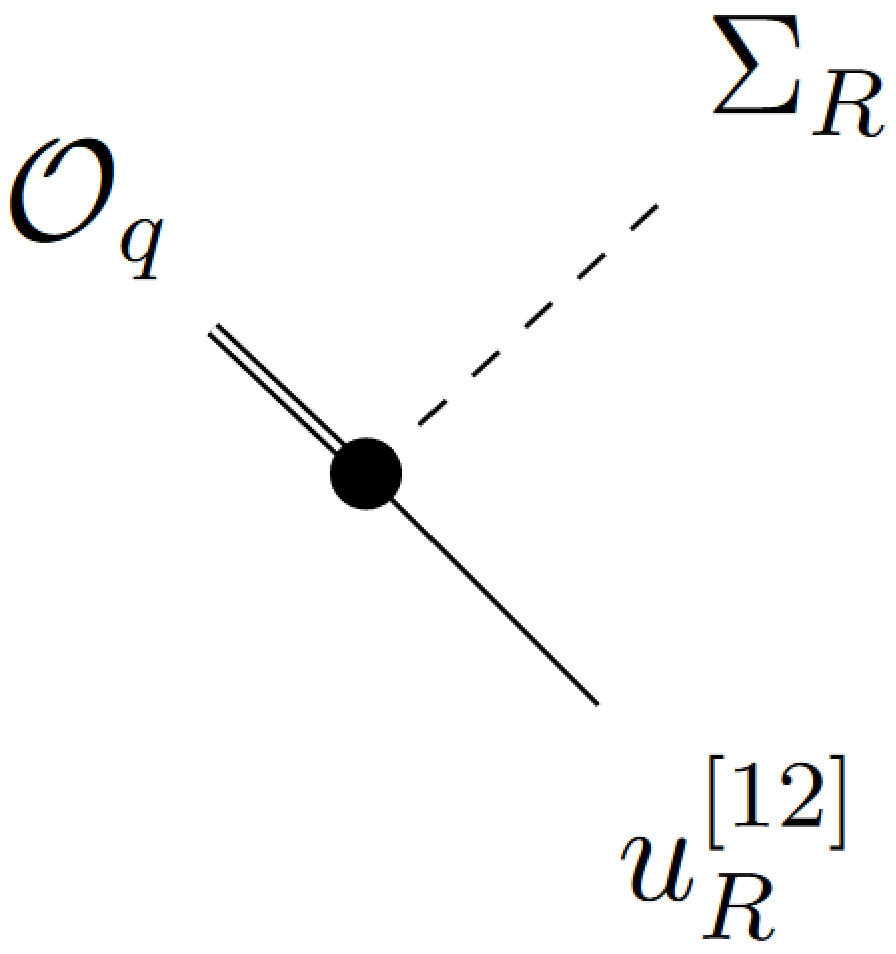

$$\xrightarrow[\epsilon_\Omega = \frac{\langle \Omega \rangle}{M_F}]{\epsilon_R = \frac{\langle \Sigma \rangle}{M_F}} \quad Y_{u,d,e} \sim \begin{pmatrix} \epsilon_R & \epsilon_\Omega \\ \epsilon_R \epsilon_\Omega & 1 \end{pmatrix}$$

Flavour Deconstructing the Composite Higgs

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

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

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

$\longrightarrow$ The deconstruction scale is ***anchored*** by its impact on the Higgs potential

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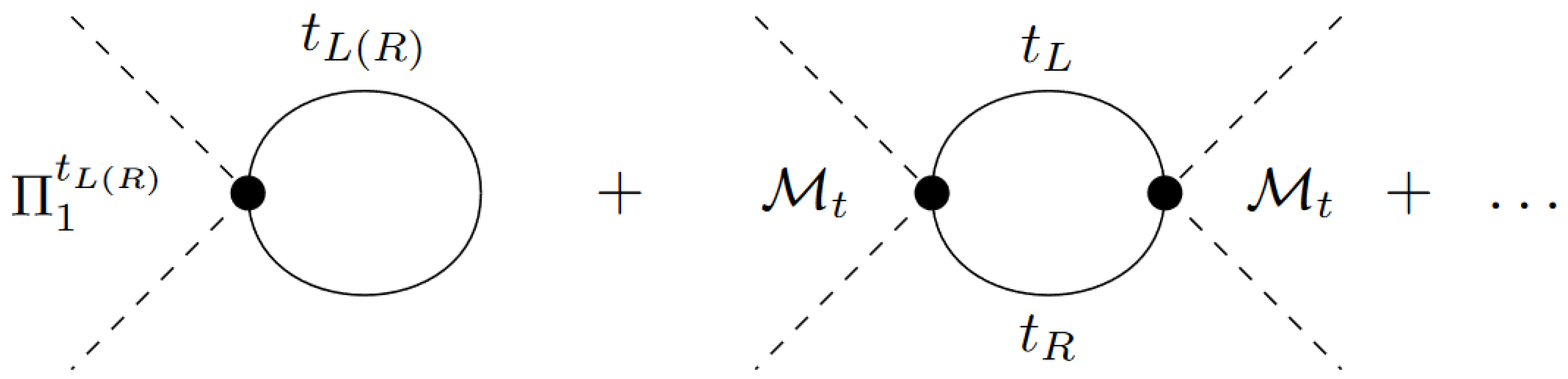
Higgs potential induced at 1-loop

Fermion contribution

$\Delta V(h)_f$



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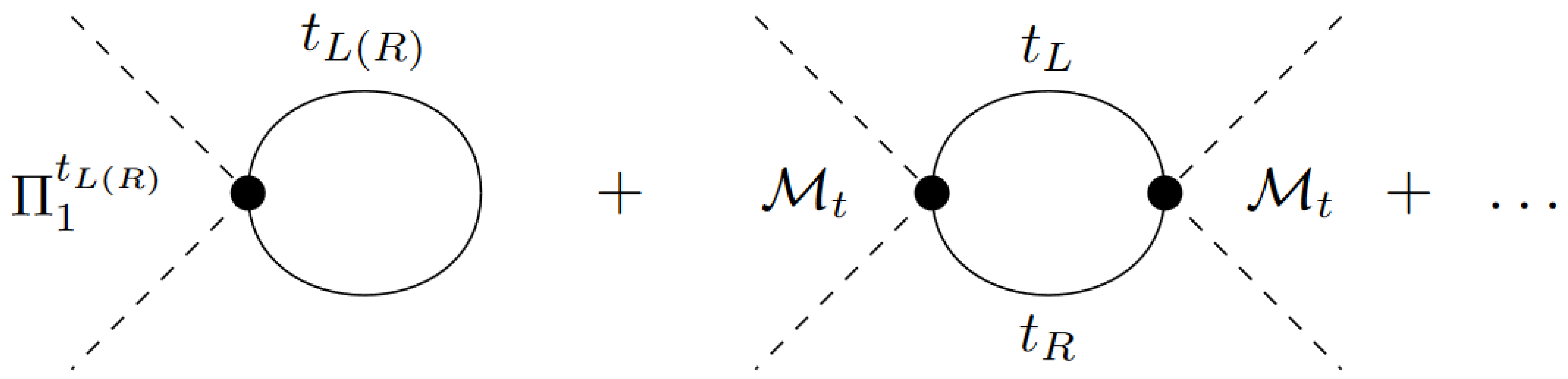

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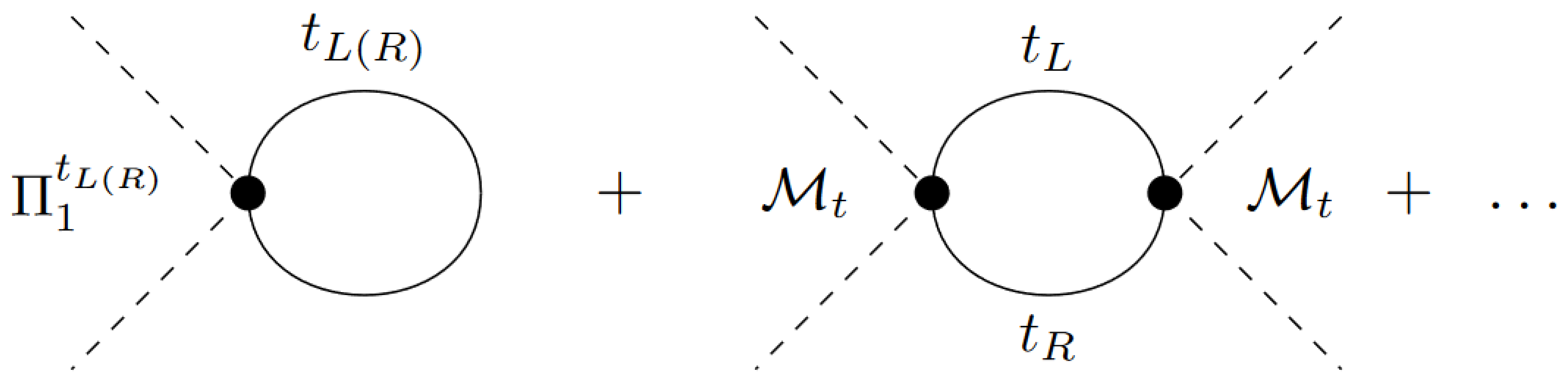


Coleman-Weinberg potential →

$$\Delta V(h)_f = -2N_c \int \frac{d^4 p_E}{(2\pi)^4} \left\{ \log\left[1 + \frac{\Pi_1^{t_L}}{\Pi_0^{q_L}} \sin^2\left(\frac{h}{2F}\right)\right] + \log\left[1 + \frac{|\mathcal{M}_t|^2 \sin^2\left(\frac{h}{2F}\right)\cos^2\left(\frac{h}{2F}\right)}{p_E^2 \left(\Pi_0^{q_L} + \Pi_1^{q_L}\sin^2\left(\frac{h}{2F}\right)\right)\left(\Pi_0^{q_R} - \Pi_1^{q_R}\sin^2\left(\frac{h}{2F}\right)\right)}\right]\right\}$$

$$\left(\begin{aligned} &\mathcal{M}_t(q^2) = \mathcal{M}_t(0) \times \frac{M_T^2}{M_T^2 - q^2} \\ &\frac{\Pi_1^{t_L}(q^2)}{\Pi_1^{t_L}(0)} \frac{\Pi_0^{q_L}(0)}{\Pi_0^{q_L}(q^2)} = \frac{M_T^2}{M_T^2 - q^2} \frac{M_f^2}{M_f^2 - q^2} \end{aligned} \right)$$

→ Explicit expression in terms of model parameters

The Hierarchy Problem

What possible theoretical frameworks can address the Hierarchy problem ?

« Beyond QFT / EFT » option

↓

Solution: « Elsewhere »

Multiverse / Anthropics
Cosmological evolution
(Failure of EFT)

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

SUSY

↓

Elementary scalars are protected by symmetry

Higgs Compositeness

↓

No elementary scalars

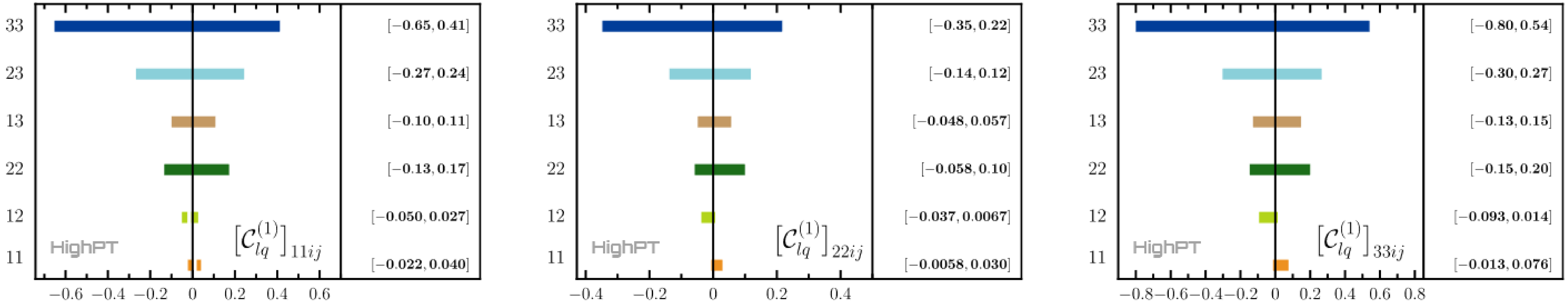
Higgs emerges as a composite pseudo-Goldstone boson of S.S.B

Dugan et al. 1985,
Agashe, Contino & Pomarol 2005,...

Back to Flavour

3rd Gen. is the least constrained

High-pt Drell-Yan tails



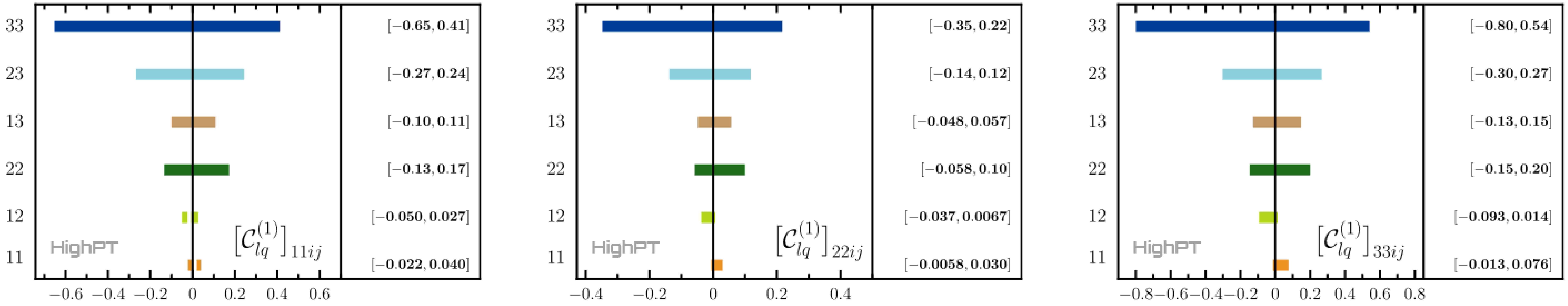
Allwicher et al. 2022

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

Back to Flavour

3rd Gen. is the least constrained

High-pt Drell-Yan tails



Allwicher et al. 2022

Experiments have imposed strong bounds on flavour **universal** NP

(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 Composite Higgs

Ingredients:

- Spontaneously broken strong sector: $\mathcal{G} \equiv Sp(4) \xrightarrow{\Lambda_{\rm HC}} SU(2)_L \times SU(2)_R^{[3]} \equiv \mathcal{H}$

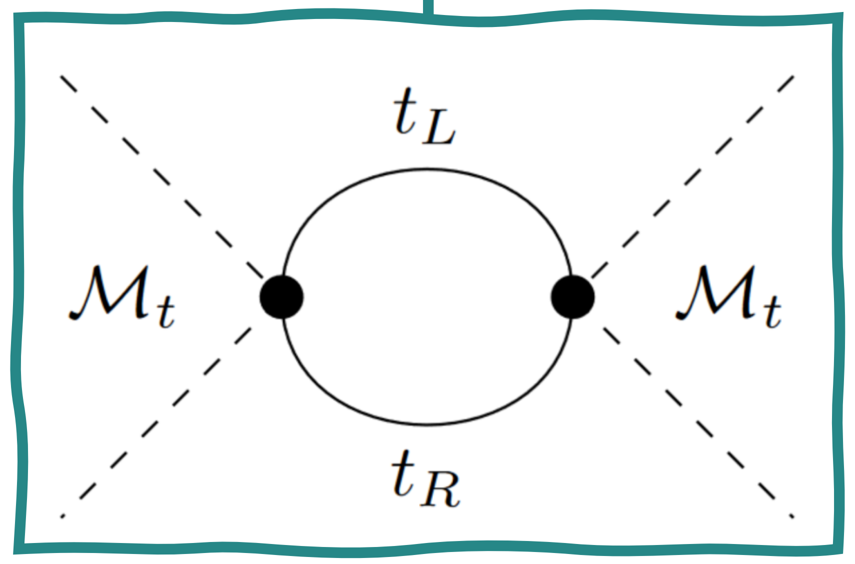
- Field Content:

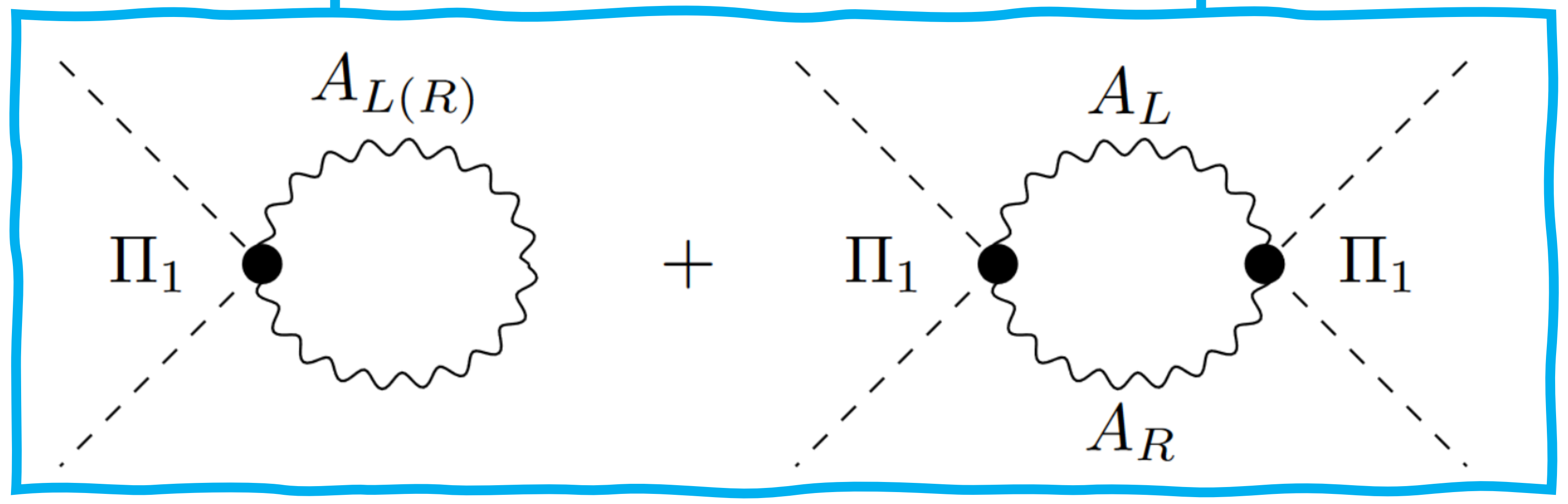
Elementary fields		$U(1)_{B-L}^{[3]}$	$U(1)_Y^{[12]}$	$SU(2)_L$	$SU(2)_R^{[3]}$
chiral light quarks	$q_L^{[12]}$	0	1/6	**2**	**1**
	$u_R^{[12]}$	0	2/3	**1**	**1**
	$d_R^{[12]}$	0	−1/3	**1**	**1**
chiral 3rd gen. quarks	$q_L^{[3]}$	1/6	0	**2**	**1**
	$q_R^{[3]}$	1/6	0	**1**	**2**
vector-like quarks	F_L^q	1/6	0	**2**	**1**
	F_R^q	0	1/6	**1**	**2**
scalar link fields	Σ_R	0	1/2	**1**	**2**
	Ω_q	−1/6	1/6	**1**	**1**
	Ω_ℓ	1/2	−1/2	**1**	**1**

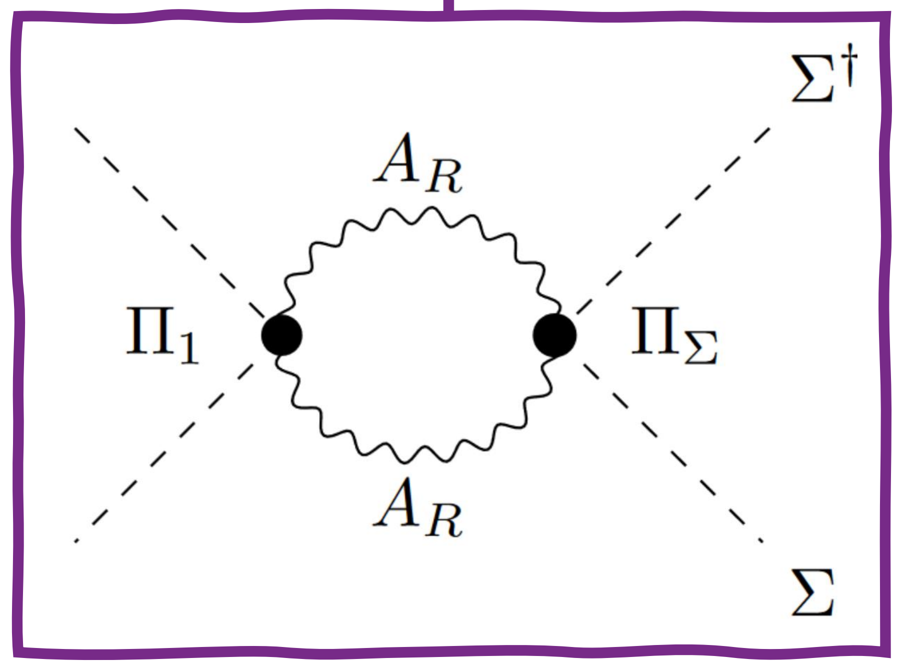
Higgs Potential

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

$$\frac{c_2}{F^4} = \frac{N_c y_t^2}{4\pi^2}\frac{M_T^2}{F^2} + \overbrace{\frac{9g_R^2}{32\pi^2}\delta_\pi\left(1-\frac{g_R^2 v_\Sigma^2}{2M_\rho^2}\right)\frac{M_\rho^2}{F^2} - \frac{9g_R^4}{64\pi^2}\log\left(\frac{M_\rho^2}{M_{W_R}^2}\right)}^{\text{Gauge contributions}} + \mathcal{O}(g_L g_R, g_L^2)$$







Flavour and Higgs Compositeness

➡ How do we couple fermions to the Higgs ?

OG approach in strongly-coupled EWSB models:

Strong resonances
-> Naturalness

$$\mathcal{L} \supset \frac{\lambda_b}{\Lambda_{\rm UV}^{d-1}} \bar{q}_L \mathcal{O}_S b_R \longrightarrow y_{t,b} \simeq \lambda_{t,b} \left(\frac{F}{\Lambda_{\rm UV}} \right)^{d-1}$$

Scalar Op.
from the
strong sector

Strong interactions are
resolved
-> Flavour

- Difficult to have $y_t \sim \mathcal{O}(1)$ and $\Lambda_{\rm UV}$ high enough to avoid extra flavour-violation
- Reintroduces the Hierarchy problem for $\mathcal{O}_S^2$
- Enforce hierarchy of $\lambda_{t,b}$ in the UV because only one scalar op $\mathcal{O}_S$

Wulzer & Panico 2015
Agashe et al. 2005,
Rattazzi et al. 2008

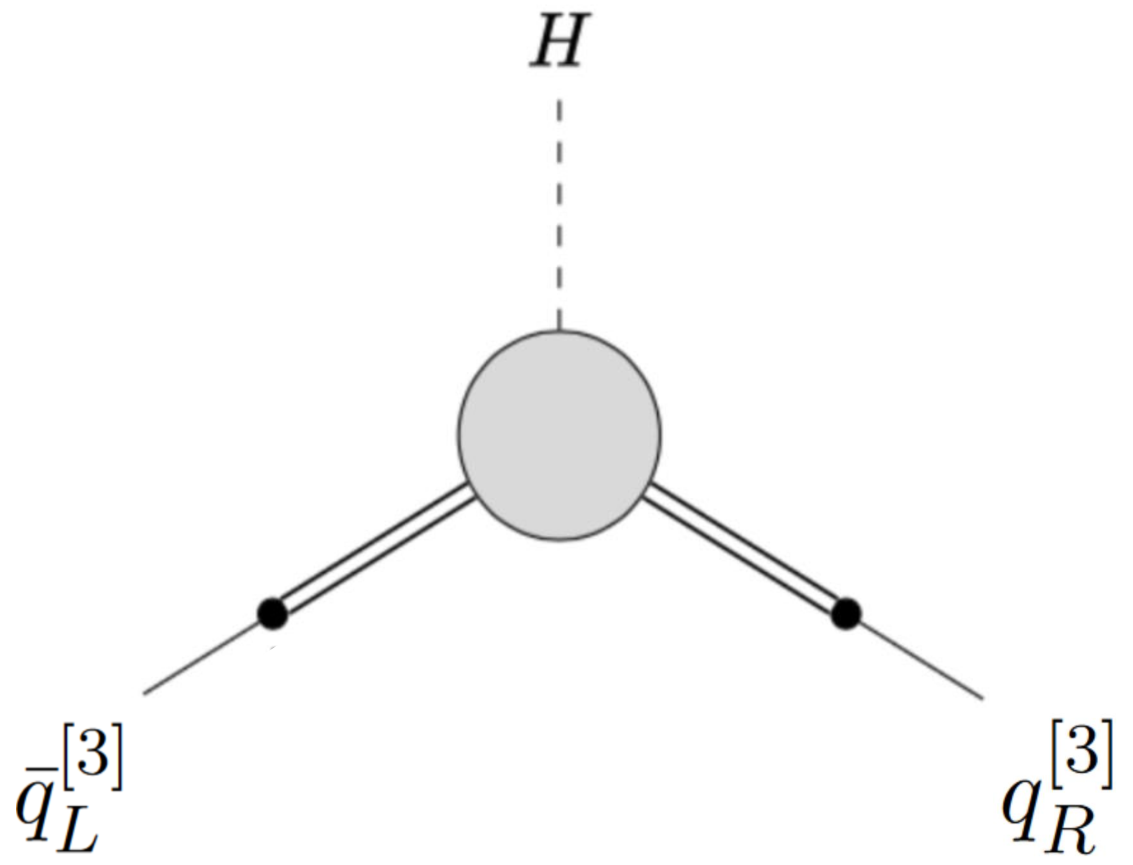
Partial Compositeness

➡ How do we couple fermions to the Higgs ?

Partial Compositeness:

$$\mathcal{L} \supset \lambda_L \bar{q}_L \mathcal{O}_R \longrightarrow |y_q| = \lambda_L^q \lambda_R^{q*} \kappa_{LR}^q \frac{F}{\sqrt{2} M_q}$$

Composite partner

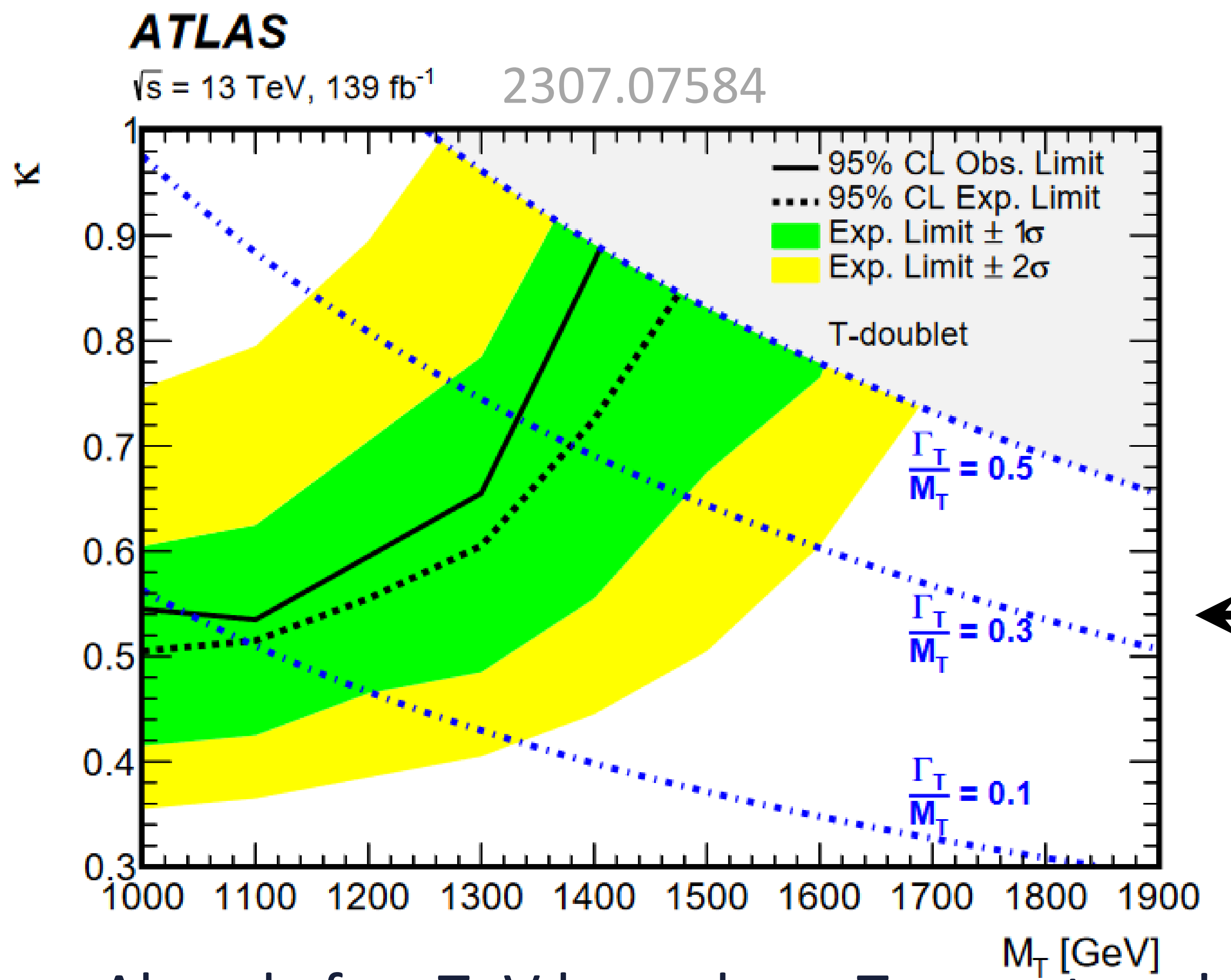


- Fermionic Ops -> No risk of reintroducing a hierarchy problem for $\mathcal{O}_F^2$
- Partners for each fermions -> can reproduce Yukawa pattern

Kaplan 1991
Wulzer & Panico 2015

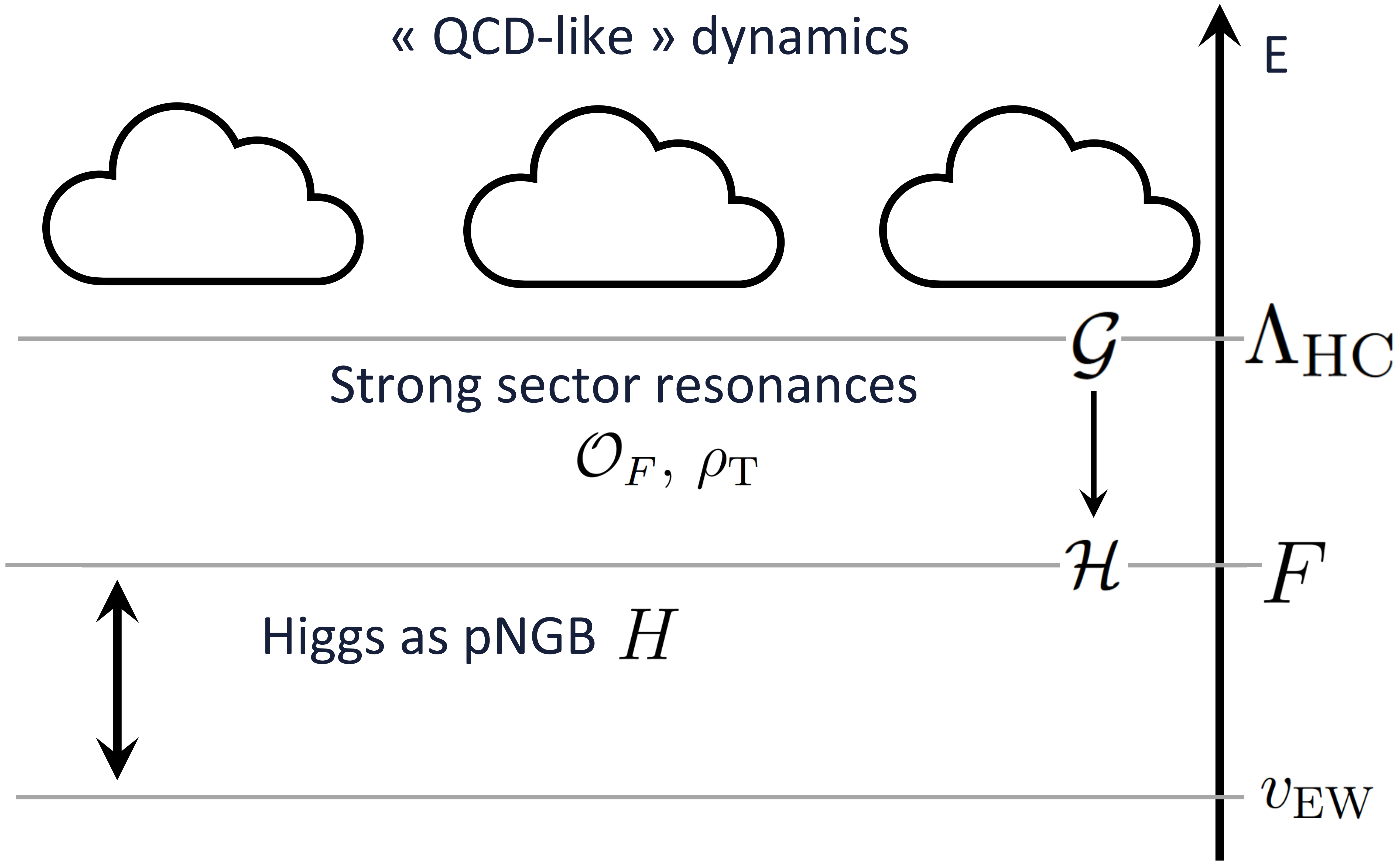
Higgs Compositeness

Compositeness scale cannot be too low!



Already few TeV bounds on Top partner !

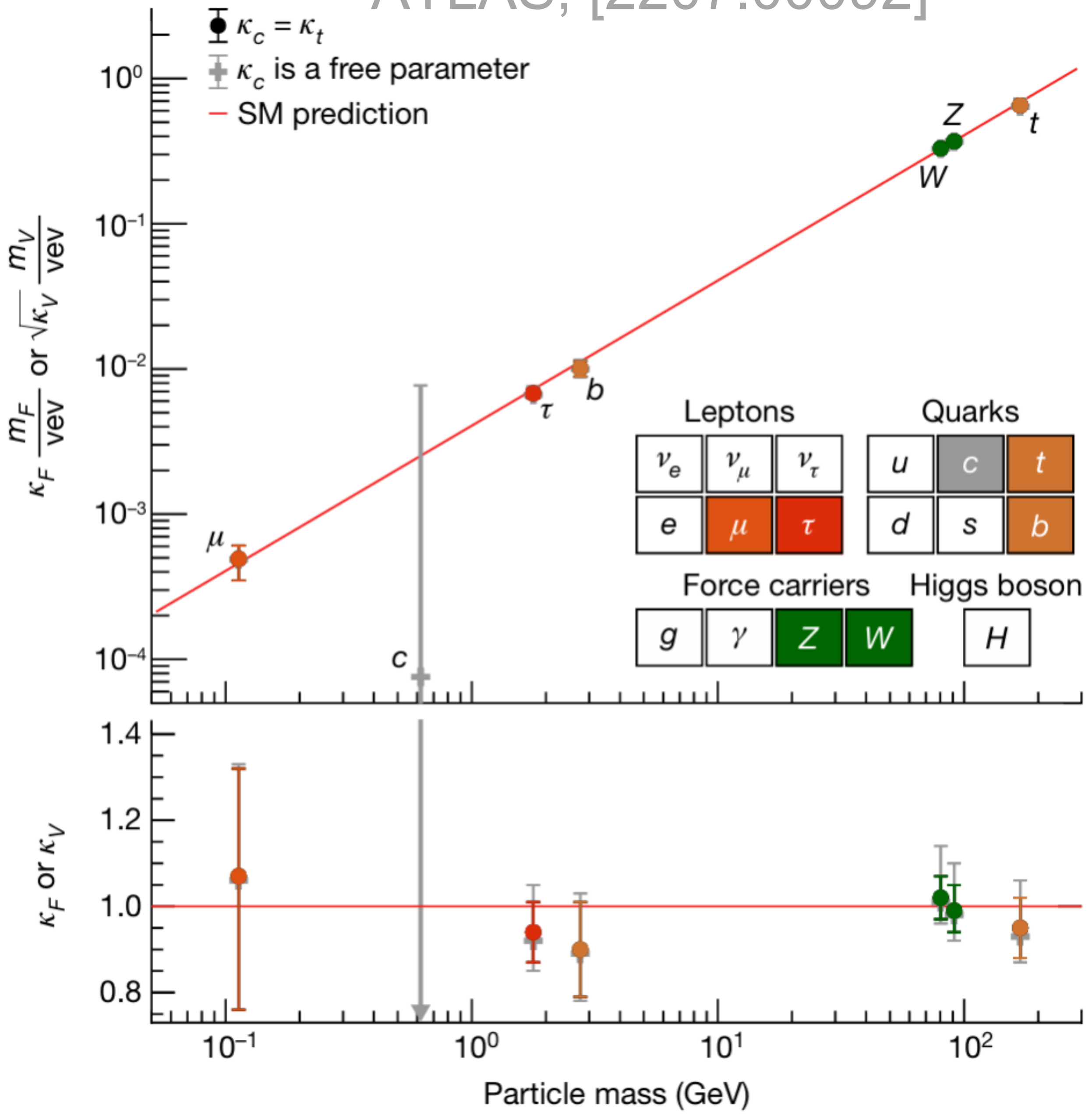
Mass Gap

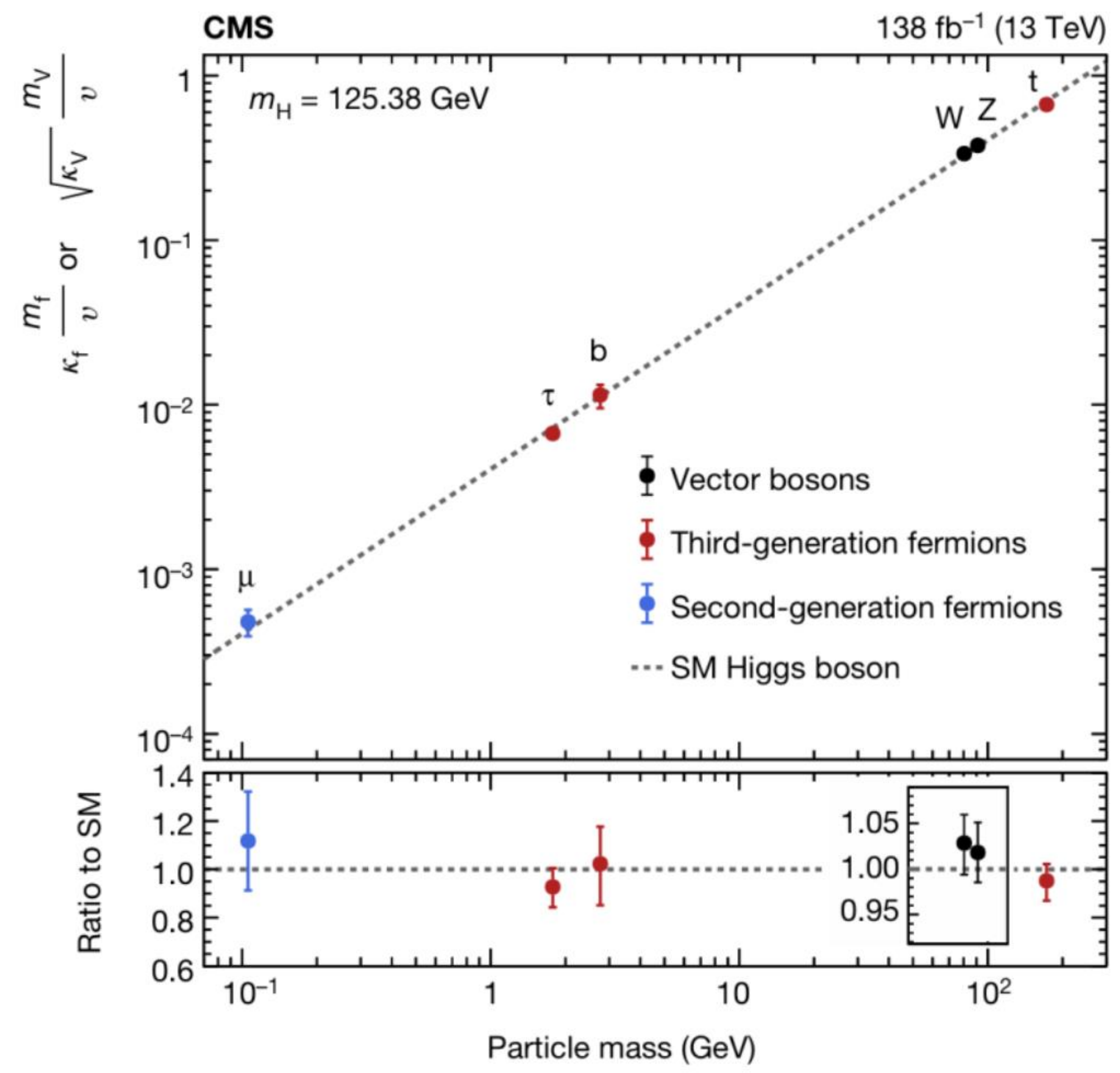


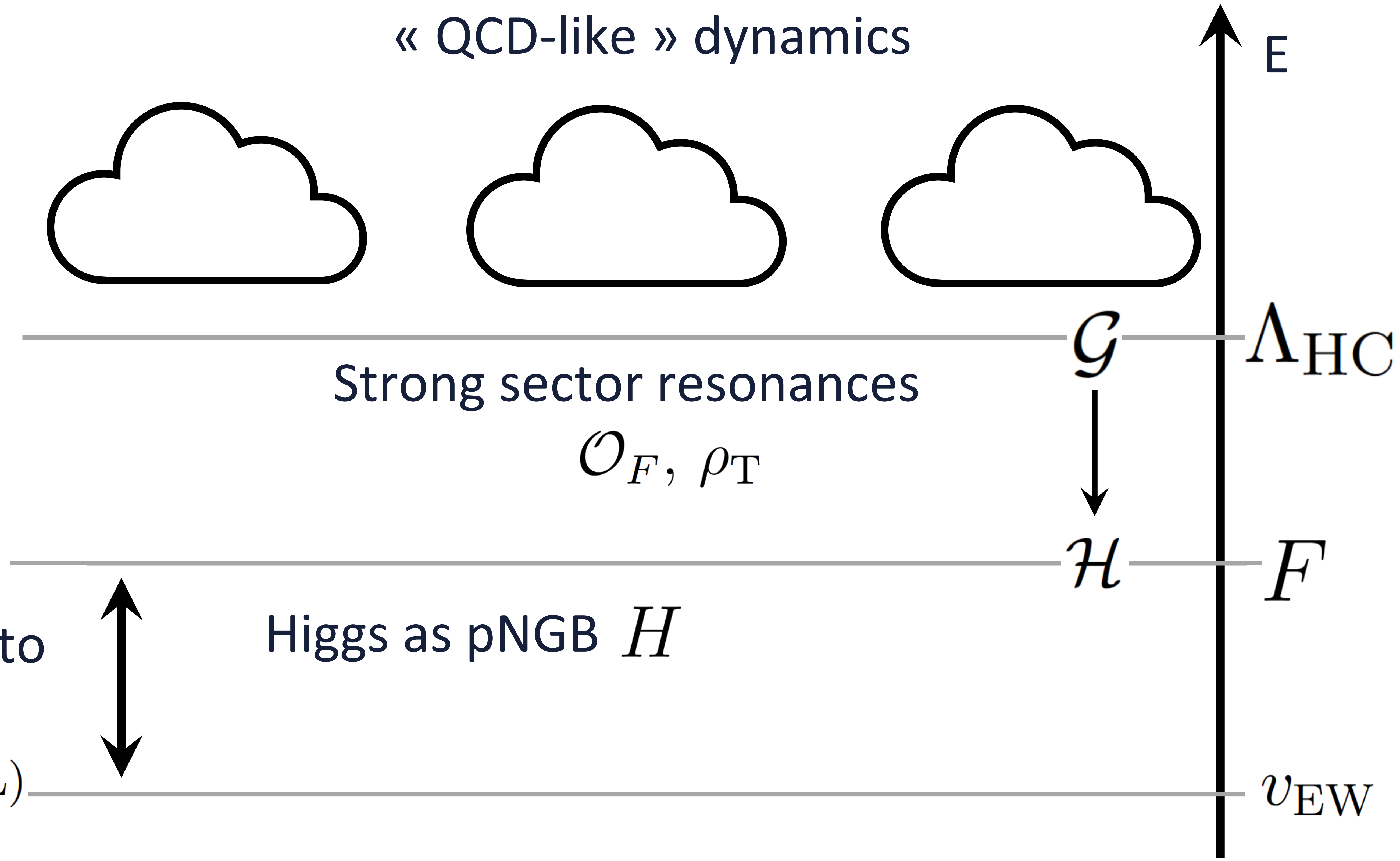
Wulzer & Panico 2015
Agashe et al. 2005,
...

Higgs Compositeness

ATLAS, [2207.00092]







Higgs is SM-like to good approx.

$\xi < 0.06$ (95% CL)

Compositeness corrects SM predictions

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

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

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

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

Flavour Deconstructing the Composite Higgs

$G_{12} \times G_{3+H} \longrightarrow G_{SM}$

$$SU(2)_R^{[3]} \times U(1)_{B-L}^{[3]} \times U(1)_Y^{[12]} \xrightarrow[\langle\Omega\rangle]{\langle\Sigma_R\rangle} U(1)_Y$$

Composite Higgs

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

Davighi & Isidori 2023
Glioti et al. 2024

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

Flavour Deconstructing the Composite Higgs

G_{12} x G_{3+H} $\longrightarrow$ G_{SM}

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

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

$$U(1)_Y$$

Composite Higgs

$$Sp(4)^{\,*}$$

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

$$SU(2)_L \times SU(2)_R^{[3]}$$

- Flavour non-universal NP @TeV mainly coupled to 3rd generation

  → $U(2)^5$ protection

  → Low compositeness scale -> naturalness

  → Explain SM flavour

Davighi & Isidori 2023
Glioti et al. 2024

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

Flavour Deconstructing the Composite Higgs

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

- Composite scalars needed for flavour deconstruction breaking
- Suppression in light Yukawas from heavy pNGBs -> no VLFs needed