Conjugate Fermions

Restoring Naturalness in Composite Higgs Models

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In collaboration with Andrei Angelescu, Andreas Bally & Florian Goertz
Based on 2309.05698

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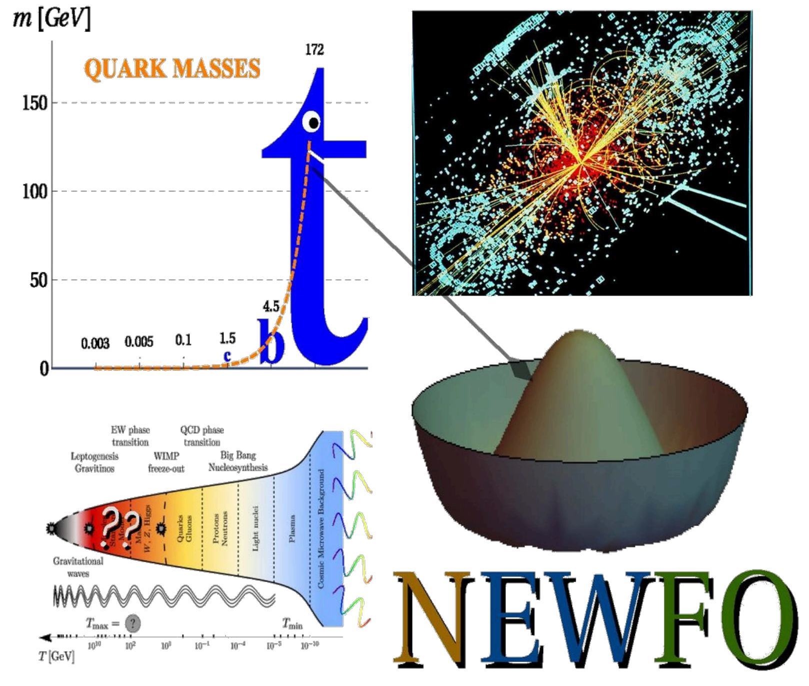
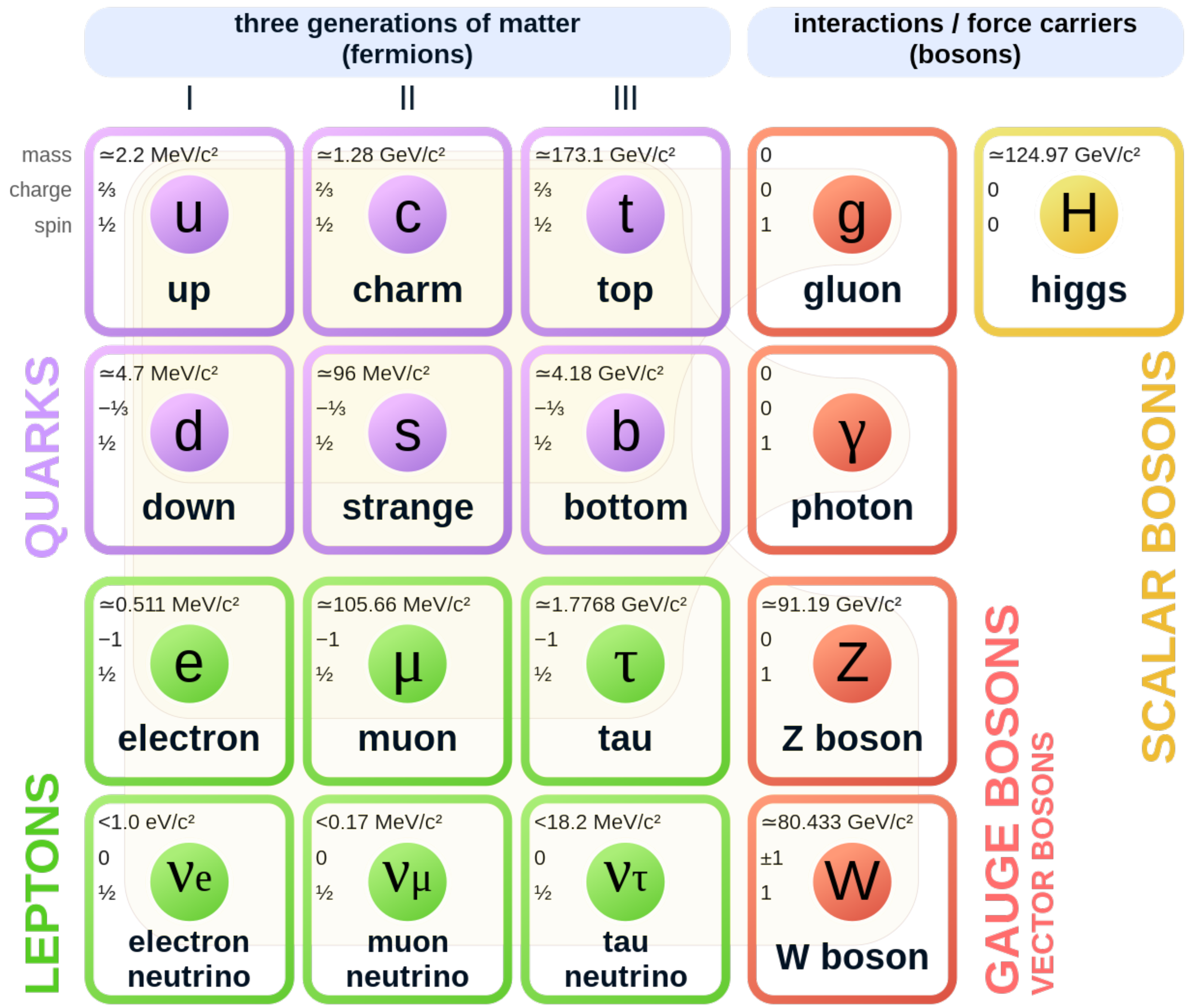


Content…

…of the talk:

- Composite Higgs
- Mirror Fermion Mechanism
- Explicit Model
- Numerical Scan
- Phenomenology of Exotics
- Outlook

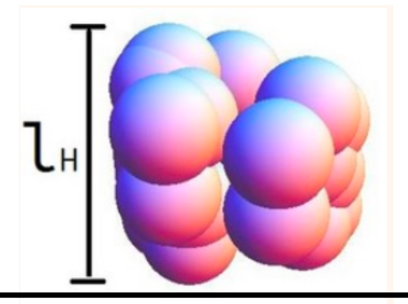
…of the Standard Model:



Kaplan, Georgi, Dimopoulos, …

Composite Higgs

Corrections @ $\mathcal{O}$(TeV)



Analogue:
Pions in QCD

$$\mathcal{L} \supset \mathcal{L}_{\rm el} + \mathcal{L}_{\rm comp} + \mathcal{L}_{\rm mix}$$

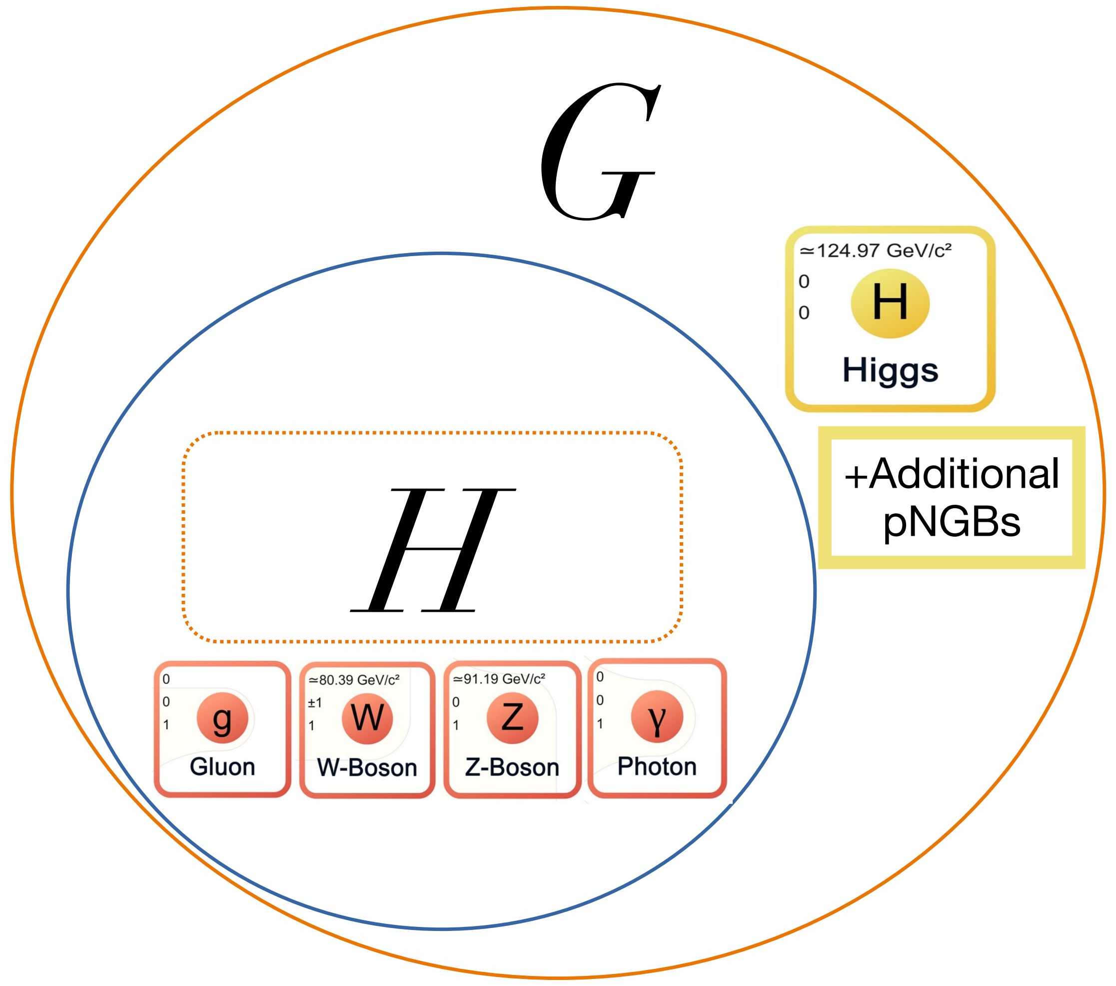
Higgs

$G \overset{\text{SSB}}{\to} H \supset G_{\text{SM}}$

n degrees of freedom
(# broken generators)

$\Rightarrow$ **Higgs** Doublet H $\mathbf{(1,2)_{1/2}}$ (4 dof)

additional pNGBs (n-4 dof)



Higgs as a pseudo-Nambu Goldstone Boson

No tree-level potential $\Rightarrow$ naturally light Higgs
(protected by shift symmetry & compositeness)

Kaplan, Agashe, Contino, Nomura, Pomarol, …

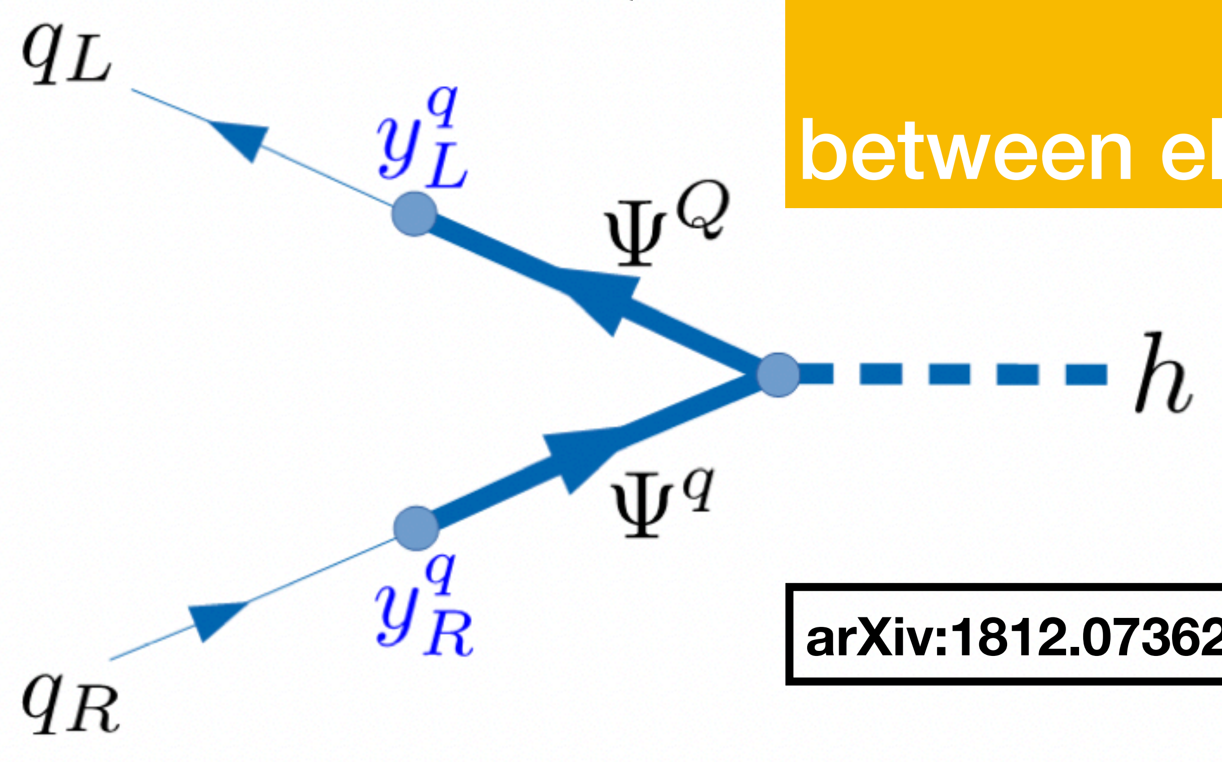
Partial Compositeness

$$\mathcal{L} \supset \mathcal{L}_{\mathrm{el}} + \mathcal{L}_{\mathrm{comp}} + \mathcal{L}_{\mathrm{mix}}$$

Standard Model

Lightest Mass Eigenstates:
SM Fields

Other Mass Eigenstates:
Composite Partners



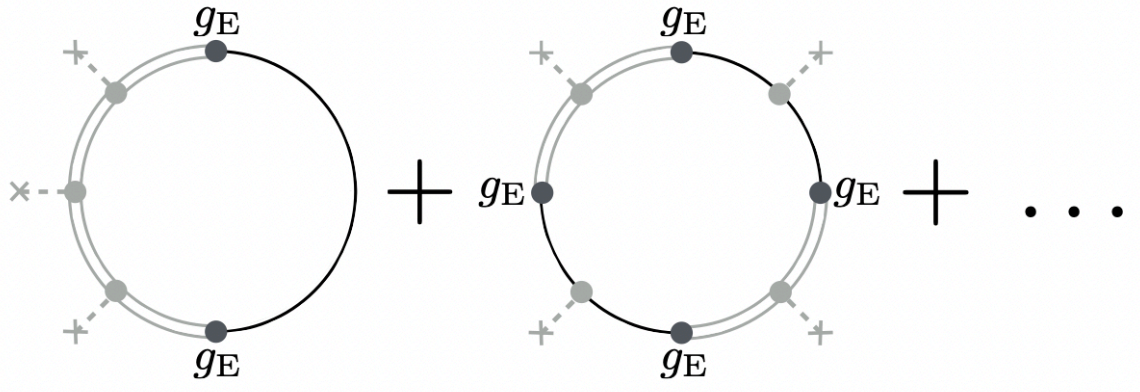
Linear Mixing
between elementary & composite states

arXiv:1812.07362

Yukawa coupling
$y_t \propto y_R^q \, y_L^q$

Explicit Breaking of global symmetry by SM fields which transform under G_{SM} but not G

main source: top quark



arXiv:1506.01961

$$|\mathrm{SM}_n\rangle = \cos\varphi_n \, |\mathrm{elementary}_n\rangle + \sin\varphi_n \, |\mathrm{composite}_n\rangle$$

After **EWSB**: masses for SM fermions induced

Common CH Problems

- tuning Higgs potential
- LHC constraints
  on light composite resonances

Panico, Redi, Tesi, Wulzer (2013)

$V_h = -\alpha \frac{h^2}{f^2} + \beta \frac{h^4}{f^4}$ $\frac{v^2}{f^2} \propto \frac{\alpha}{\beta}$	minimal tuning: $\Delta_{\text{min}} = f^2/v^2$ double-tuning: if β sub-leading wrt α

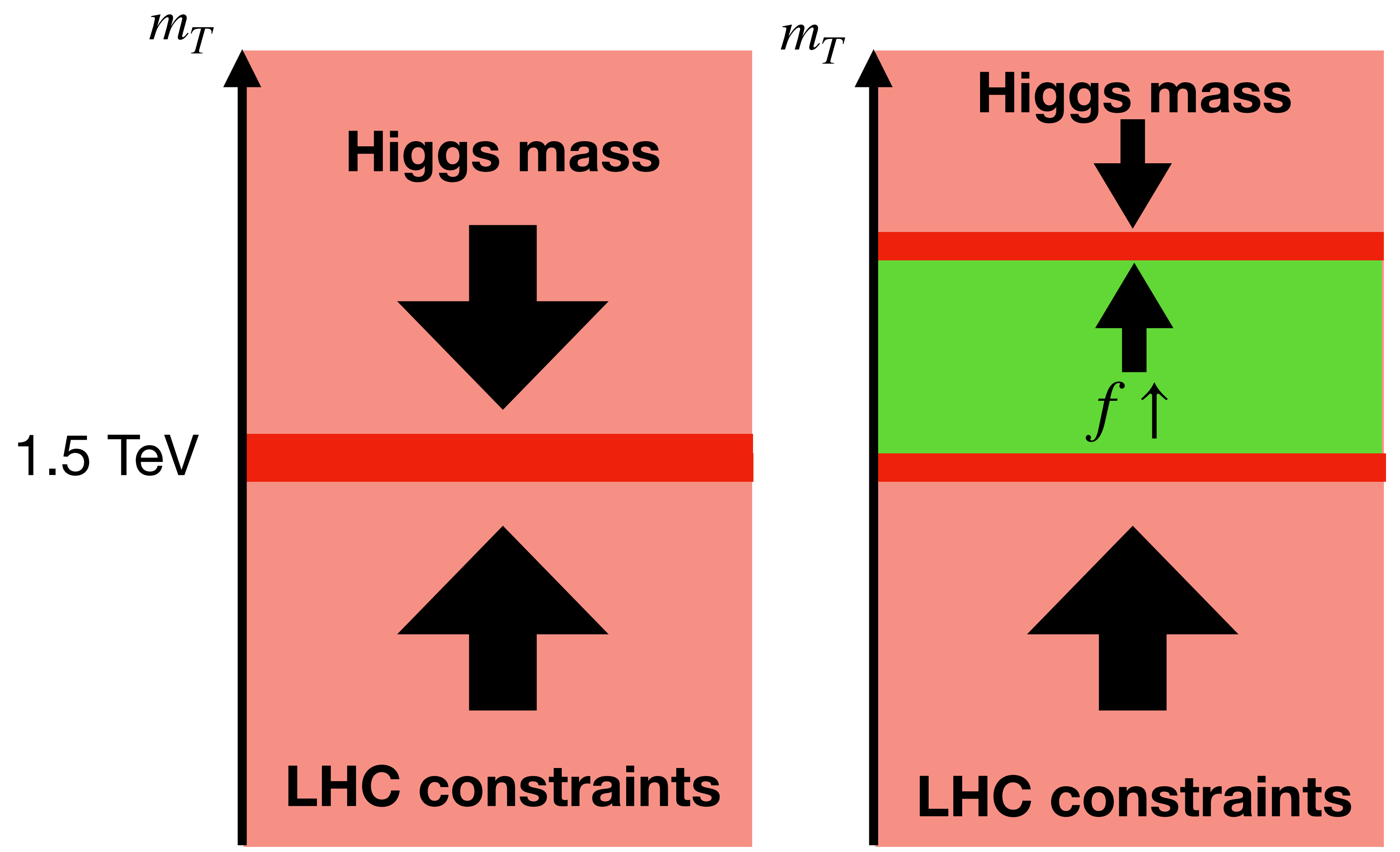
Composite partners decay preferably to heavy SM fields

$\Rightarrow$ Sensitive to collider searches:

top partner mass $\geq$ 1.5 TeV

$$m_H \propto \frac{\min(m_T)}{f} m_t$$

CMS, arXiv:2209.0737;
ATLAS, arXiv:2210.15413;
+many more!

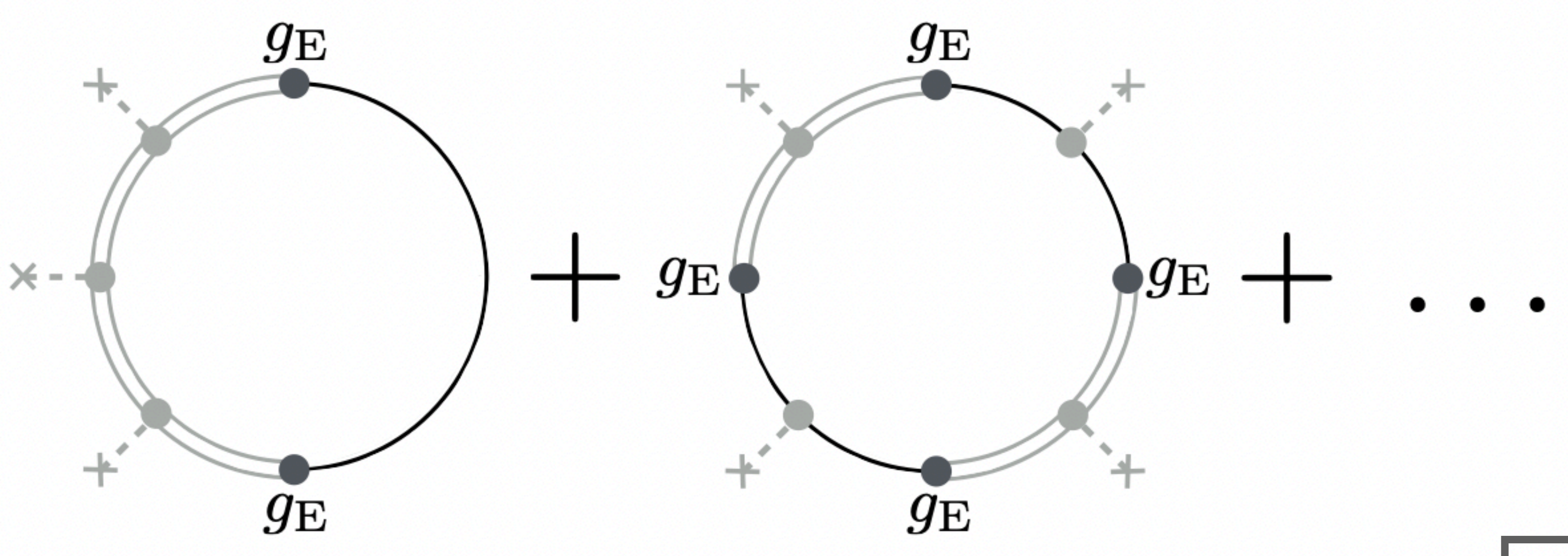


Anglescu, Bally, Goertz, MH
arXiv:2309.05698

Mirror Fermions

Mechanism

*The **quadratic contribution of a chiral fermion** ψ to the pNGB potential of a coset G/H is **cancelled** when a **new chiral fermion** ψ' with **conjugated gauge quantum numbers** is added, called mirror fermion, if the fermions talk to the same composite operator in a real representation $\mathbf{R}$ of the group G which decomposes as $\mathbf{R} \to \mathbf{C} \oplus \bar{\mathbf{C}}$ under H, with $\mathbf{C}$ a complex representation and $\bar{\mathbf{C}}$ its complex conjugate.*



arXiv:1506.01961

Explicitly:
We can cancel the quadratic contribution of the top quark to the Higgs potential!

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Mirror Fermions

Proof

$$\boxed{\mathcal{L}_{\rm PC} = \lambda\,\bar{\psi}\Delta\,\mathcal{O}^{\mathbf{R}} + \lambda'\,\bar{\psi}'\Delta'\,\mathcal{O}^{\mathbf{R}} + \text{ h.c.}}$$

CCWZ mechanism: Callan, Coleman, Wess, Zumino (1969)
how to write general low-energy effective Lagrangians

spurions: elementary fields embedded in incomplete G multiplets

$$\Delta^{(\prime)i} = \begin{cases} 1 & i \in \{\alpha\} \quad (i \in \{\dot{\alpha}\}) \\ 0 & \text{otherwise} \end{cases}$$

$$\mathbf{R} \to \mathbf{C} \oplus \bar{\mathbf{C}}$$
$$i \qquad \alpha \quad \dot{\alpha}$$

$U^\dagger \Delta \equiv \left(\Delta_D^{\mathbf{C}}, \Delta_D^{\bar{\mathbf{C}}}\right)$ „dressed“ spurions

Goldstone matrix:
$$U = \exp\left(i\Pi_{\hat{a}} T^{\hat{a}}\right)$$

C contribution to Higgs potential: ($\bar{\text{C}}$ contribution analogously)

$$V^{\mathbf{C}} \propto \lambda^2 (\Delta_D^{\mathbf{C}})^\dagger \Delta_D^{\mathbf{C}} + \lambda'^2 (\Delta_D'^{\mathbf{C}})^\dagger \Delta_D'^{\mathbf{C}}$$

$$\boxed{(\Delta_D^{\bar{\mathbf{C}}})^\dagger \Delta_D^{\bar{\mathbf{C}}} = (\Delta_D'^{\mathbf{C}})^\dagger \Delta_D'^{\mathbf{C}}} \quad \mathbf{R} \to \mathbf{C} \oplus \bar{\mathbf{C}}$$

$\boxed{\lambda = \lambda'}$

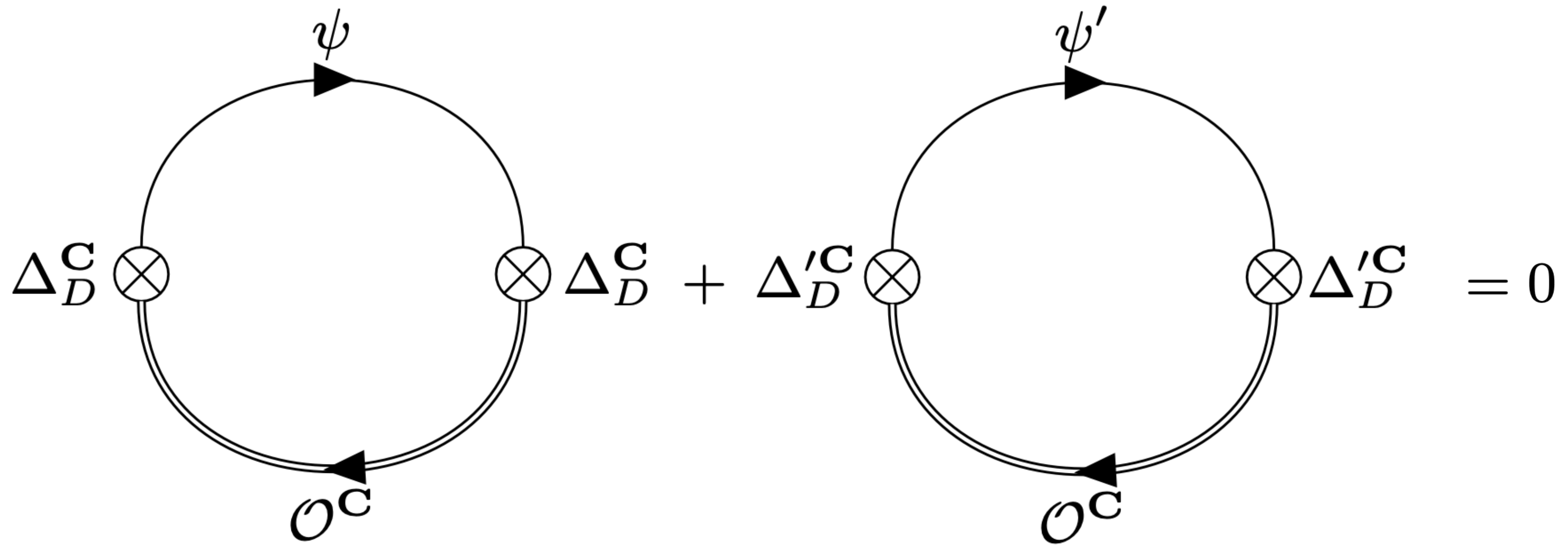
Unitarity of U

$$\propto \lambda^2 (\Delta_D^{\mathbf{C}})^\dagger \Delta_D^{\mathbf{C}} + \lambda'^2 (\Delta_D^{\bar{\mathbf{C}}})^\dagger \Delta_D^{\bar{\mathbf{C}}} \propto \lambda^2 \Delta^\dagger U U^\dagger \Delta \doteq \lambda^2 N$$

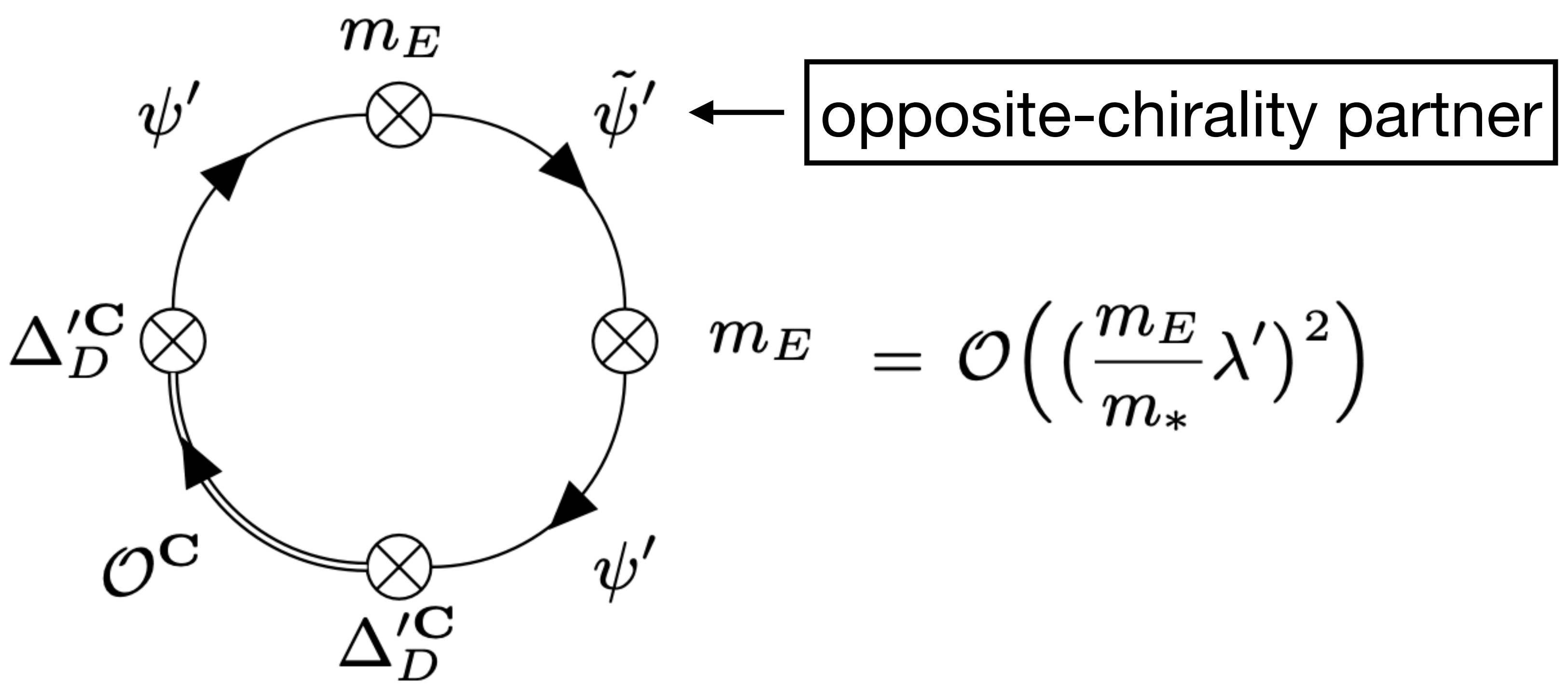
No contribution at leading order to Higgs potential!

Three ingredients why the cancellation works!

$$\boxed{\mathbf{R} \to \mathbf{C} \oplus \bar{\mathbf{C}} \quad , \quad \lambda = \lambda' \quad , \quad m_E \ll m_*}$$



Dirac mass for mirror fermion necessary
⇒ additional contribution to potential



$SU(5) \supset SU(3) \times SU(2) \times U(1)$

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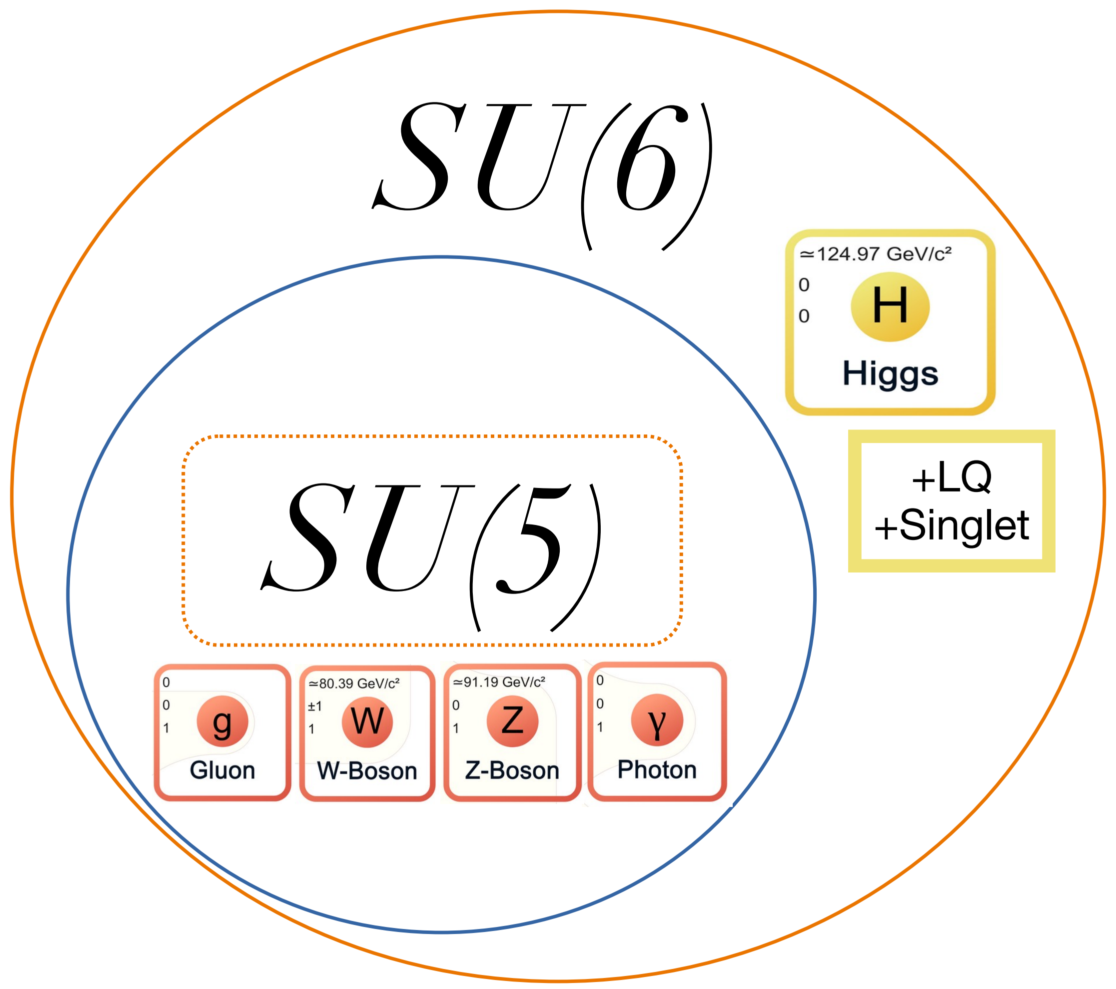
Mirror Fermions

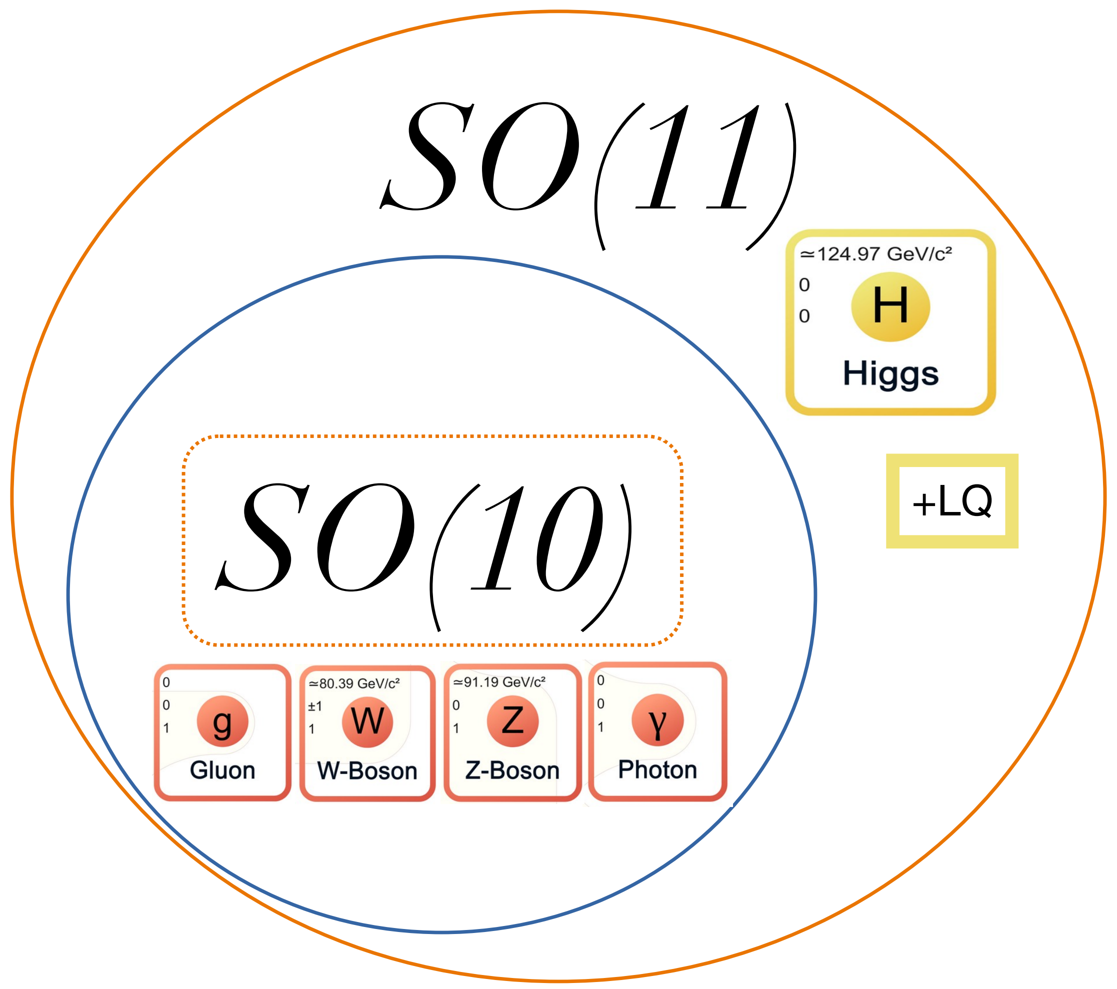
Explicit Model - Composite Grand Unified Theories

minimal:



$$\mathbf{20} \rightarrow \mathbf{10} \oplus \overline{\mathbf{10}}$$

non-custodial ⇒ tree-level corrections to T parameter



$$\mathbf{32} \rightarrow \mathbf{16} \oplus \overline{\mathbf{16}}$$

custodial!

$$\mathbf{10} \rightarrow \underbrace{(\mathbf{3},\mathbf{2})_{\mathbf{1/6}}}_{\boxed{q_L}} \oplus \underbrace{(\mathbf{3}^*,\mathbf{1})_{-\mathbf{2/3}}}_{\boxed{\omega_R}} \oplus (\mathbf{1},\mathbf{1})_{\mathbf{1}}$$

$$\mathbf{10}^* \rightarrow \underbrace{(\mathbf{3}^*,\mathbf{2})_{-\mathbf{1/6}}}_{\boxed{\theta_L}} \oplus \underbrace{(\mathbf{3},\mathbf{1})_{\mathbf{2/3}}}_{\boxed{t_R}} \oplus (\mathbf{1},\mathbf{1})_{-\mathbf{1}}$$

Scan:
f = 1600 GeV
$\lambda_L = \lambda_R$
m_t(f) ~ 150 GeV
parameter range [-5 f , 5 f]
b_R included

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arXiv:2309.05698

Mirror Fermions

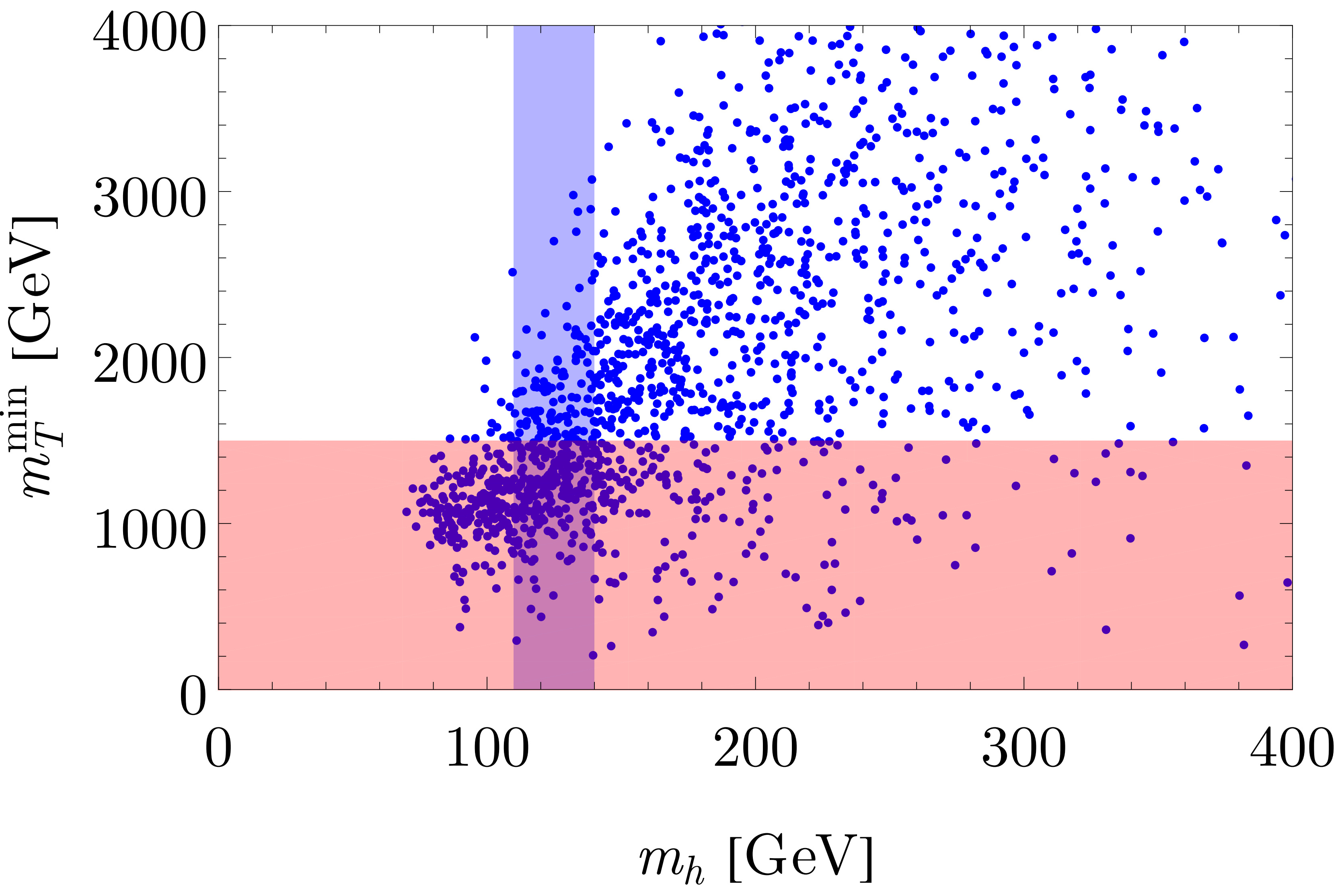
Numerical Scan

mass eigenstates arising from mirror fermion sector ≡ exotics

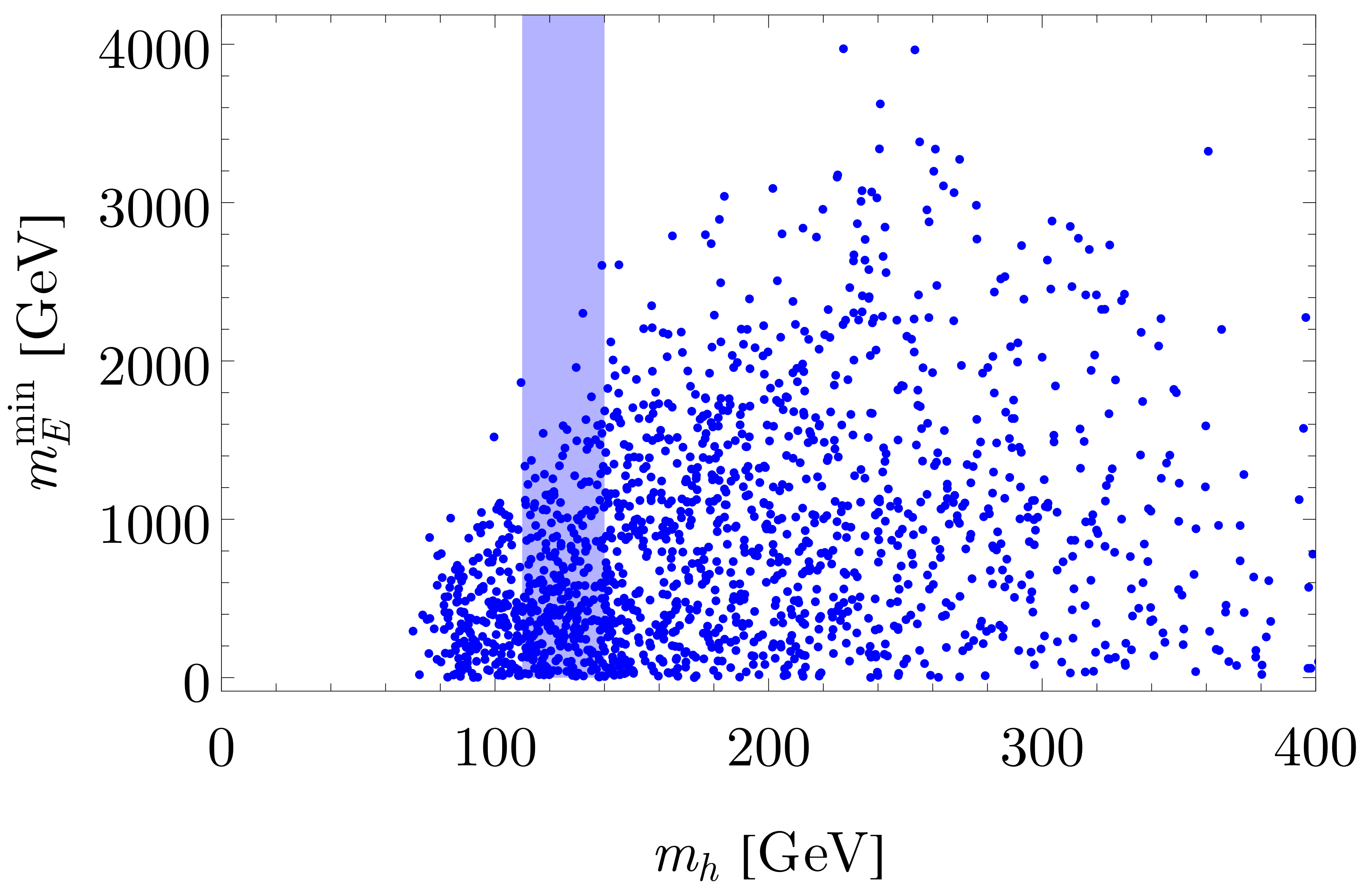
Top Partner ≥ 1500 GeV

CMS, arXiv:2209.0737;
ATLAS, arXiv:2210.15413;
+many more!

Lightest Top Partner



Lightest Exotic



Coleman-Weinberg potential

$$V(H) = -\frac{2N_c}{8\pi^2}\int dp\, p^3 \log\left[\prod_i \left(p^2 + m_i^2(H)\right)\right]$$

in 3-site model

Arkani-Hamed, Cohen, Georgi (2001); Panico, Wulzer (2011)

Top Partners can be heavy
⇒ no conflict with LHC limits

Scan:
f = 1600 GeV
$\lambda_L = \lambda_R$
m_t(f) ~ 150 GeV
parameter range [-5 f , 5 f]
b_R included

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Mirror Fermions

Fine-Tuning

Top Partner $\gtrsim$ 1500 GeV

CMS, arXiv:2209.0737;ATLAS, arXiv:2210.15413;…
+many more!

Higgs mass + vev

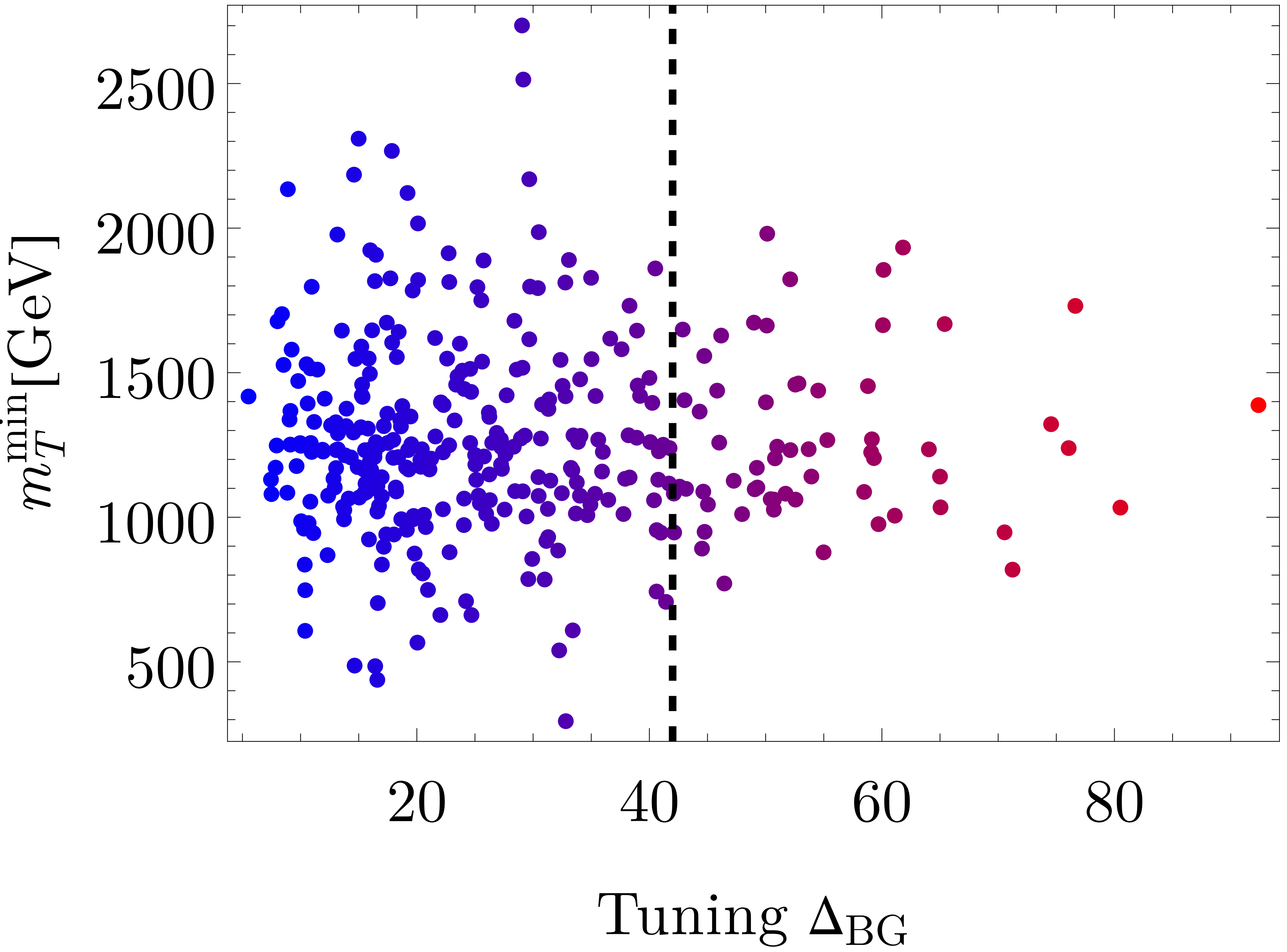
parameters 3-site model

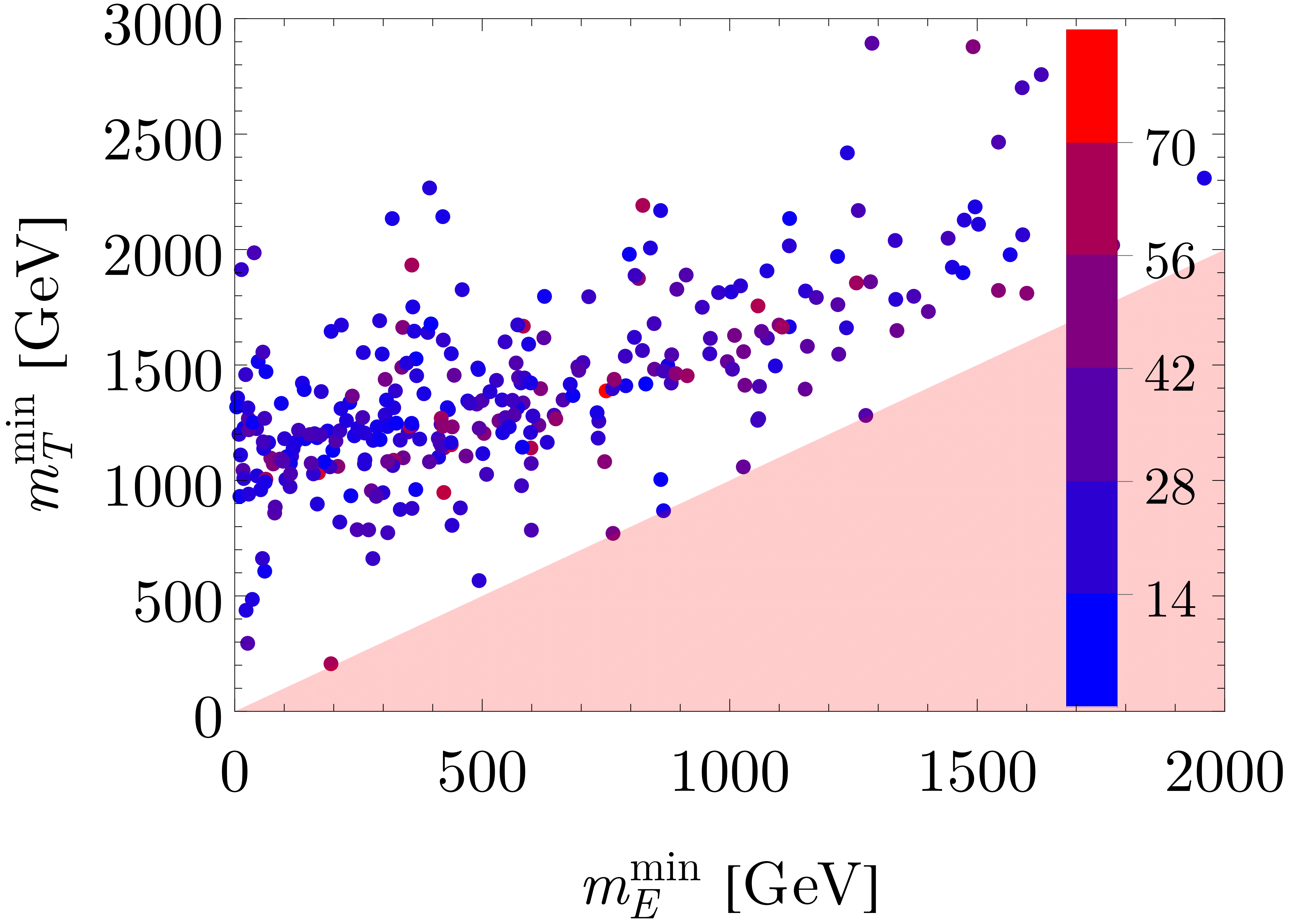
maximum sensitivity of observables to parameters

$$\Delta_{\mathrm{BG}} = \max_i \left| \frac{\partial \log O(x_i)}{\partial \log x_i} \right|$$

Barbieri & Giudice (1988)

$\Delta_{\min} = f^2/v^2 \sim 42$





$\Delta_{\mathrm{BG}} \ll \Delta_{\min}$
$\Rightarrow$ small tuning

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Mirror Fermions

Phenomenology Exotics

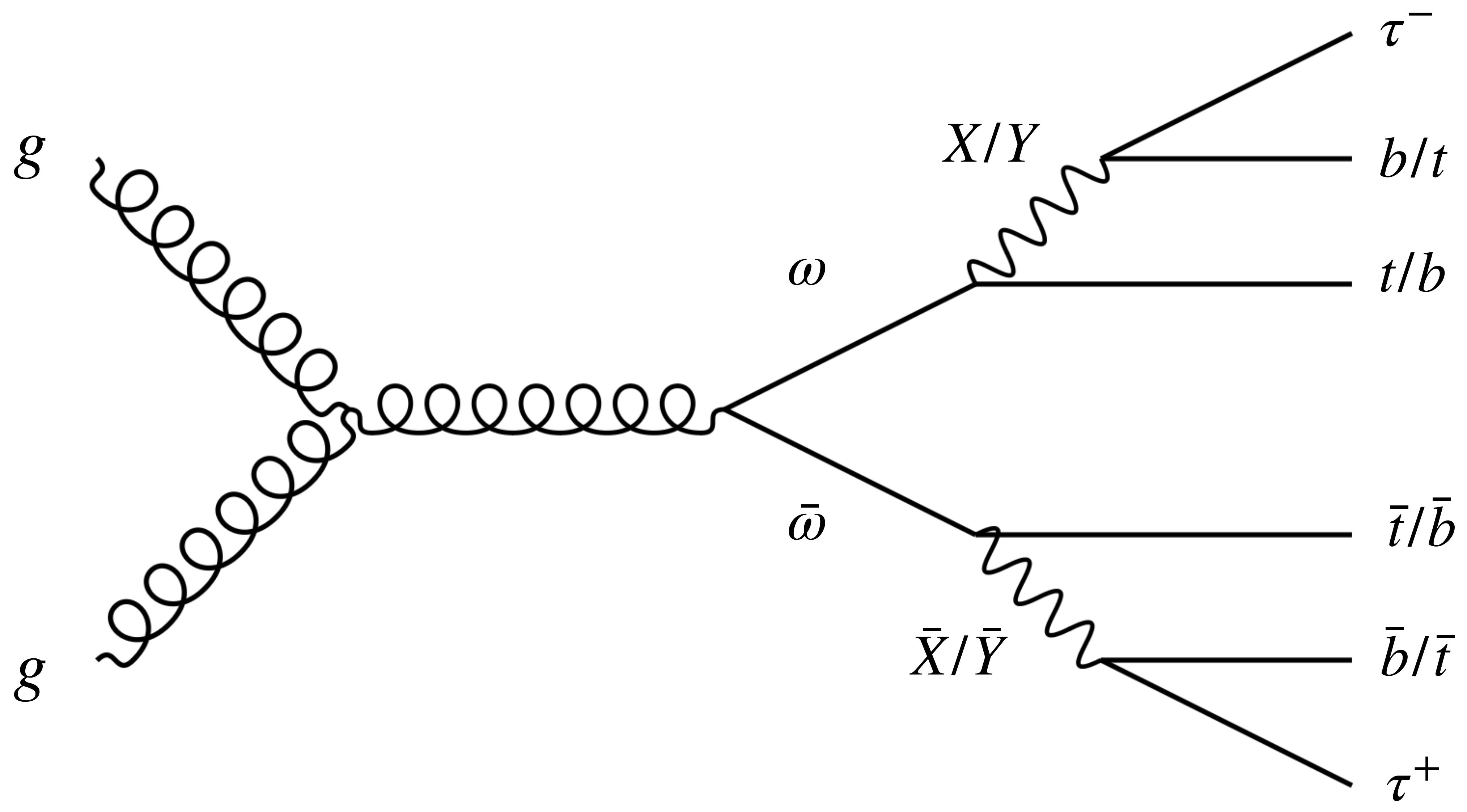
no perfect fermion unification

- accidental baryon number symmetry ⇒ exotics ω carry B = 2/3! **+ no proton decay**

  see: Angelescu, Bally, Blasi, Goertz (2021); Hosotani, Yamatsu (2015)

- baryon number & electromagnetic charge conservation lead to 6 particle final state!

  $$\omega\bar{\omega} \to t\bar{t}b\bar{b}\tau^+\tau^-$$



- To the best of our knowledge: no dedicated search at LHC

baryon number is global symmetry
⇒ no proton decay

unexplored signature for exotic decay
⇒ no existing LHC limits

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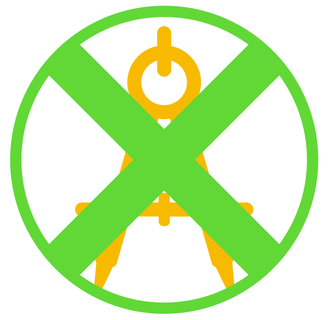
arXiv:2309.05698

Conclusion

Hope for Naturalness at the LHC!

- Novel mechanism to cancel quadratic contribution to the Higgs potential with unexplored signatures $\boxed{\mathbf{R} \to \mathbf{C} \oplus \bar{\mathbf{C}}}$

- Common Problems solved

CH
-  ~~tuning Higgs potential~~ — **Mirror Fermion Mechanism**
-  ~~LHC constraints on light composite resonances~~ — **Top partners can be heavy + Unexplored signature of exotic decay**

GUT
-  ~~proton decay~~ — Baryon Number Conservation

Backup Slides

SU(6)

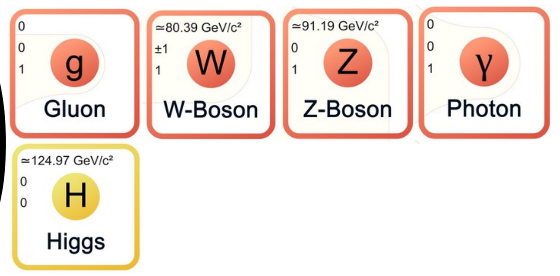
$$A_\mu = \left(\begin{array}{cc|ccc|c} (++) & (++) & (+-) & (+-) & (+-) & (--) \\ (++) & (++) & (+-) & (+-) & (+-) & (--) \\ \hline (+-) & (+-) & (++) & (++) & (++) & (--) \\ (+-) & (+-) & (++) & (++) & (++) & (--) \\ (+-) & (+-) & (++) & (++) & (++) & (--) \\ \hline (--) & (--) & (--) & (--) & (--) & (--) \end{array}\right)$$

Anglescu, Bally, Goertz, MH
arXiv:2309.05698

Mirror Fermions

Holographic Completion

- Higgs: 5th component of 5D gauge field in warped space-time $A_M^A = \begin{pmatrix} \boxed{A_\mu^A} \\ \boxed{A_5^A} \end{pmatrix}$



- t_R IR-localised $\Rightarrow m_E$ small

$$m_E \sim \frac{M_{\rm UV}}{R} \times \begin{cases} 1 & (c > 0.5) \\ (R'/R)^{c-1/2}\,(1-c) & (c < 0.5) \end{cases}$$

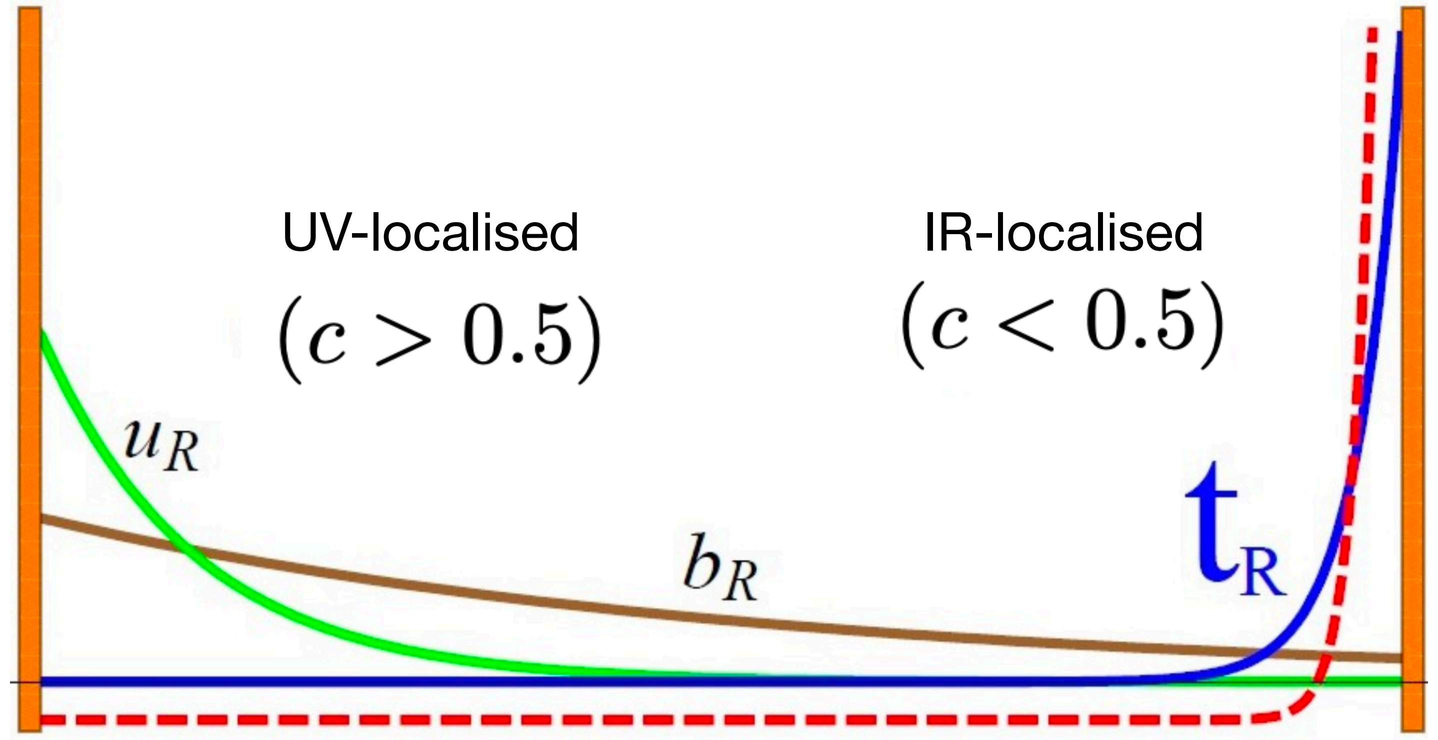
- fermion & mirror fermion in same bulk field $\Rightarrow$ same localisation $\Rightarrow \lambda = \lambda'$

Metric

$$ds^2 = (R/z)^2\left(\eta_{\mu\nu}\,dx^\mu dx^\nu - dz^2\right)$$

Translation

bulk field	⟺	elementary fields
localisation in bulk wrt Higgs	⟺	strength of linear mixing
KK-Modes	⟺	composite resonances
IR-localised	⟺	composite sector
UV-localised	⟺	elementary sector
UV brane-localised field	⟺	elementary fields that do not talk to composite sector



Goertz

See for details i.e. Angelescu, Bally, Blasi, Goertz (2021)

Conserved Baryon Number

- q_L and u_R in separate H multiplets
  ⇒ interaction via X/Y not possible ⇒ $p \to \pi_0 + e^+$ not possible

- hidden baryon symmetry: B conserved at each vertex ⇒ proton stable to all orders in perturbation theory

- consistently assigning baryon number to SM fields ⇒ B = 2/3 for exotics!

- symmetry is anomalous, but can be gauged Agashe, Servant (2004); Agashe, Servant (2005)

Higgs-Gluon Coupling

Contribution from Exotics

- loop corrections to Higgs-gluon coupling

Ellis, Gaillard, Nanopoulos (1976)

$$\delta g_{Hgg} \propto \sum_{M_i > m_H} \frac{Y_{ii}}{M_i}$$

from new heavy fermions with $M_i > m_H$:

Azatov, Galloway (2012)

$$\delta g_{Hgg}^{\text{ex}} \sim \frac{\partial \log(\det M_{\text{ex}})}{\partial v} = 0$$

not trivial! reason: opposite-chirality partners do not talk directly to Higgs

Contribution from top and bottom partners suppressed by v^2/f^2