Higgs boson and Compositeness

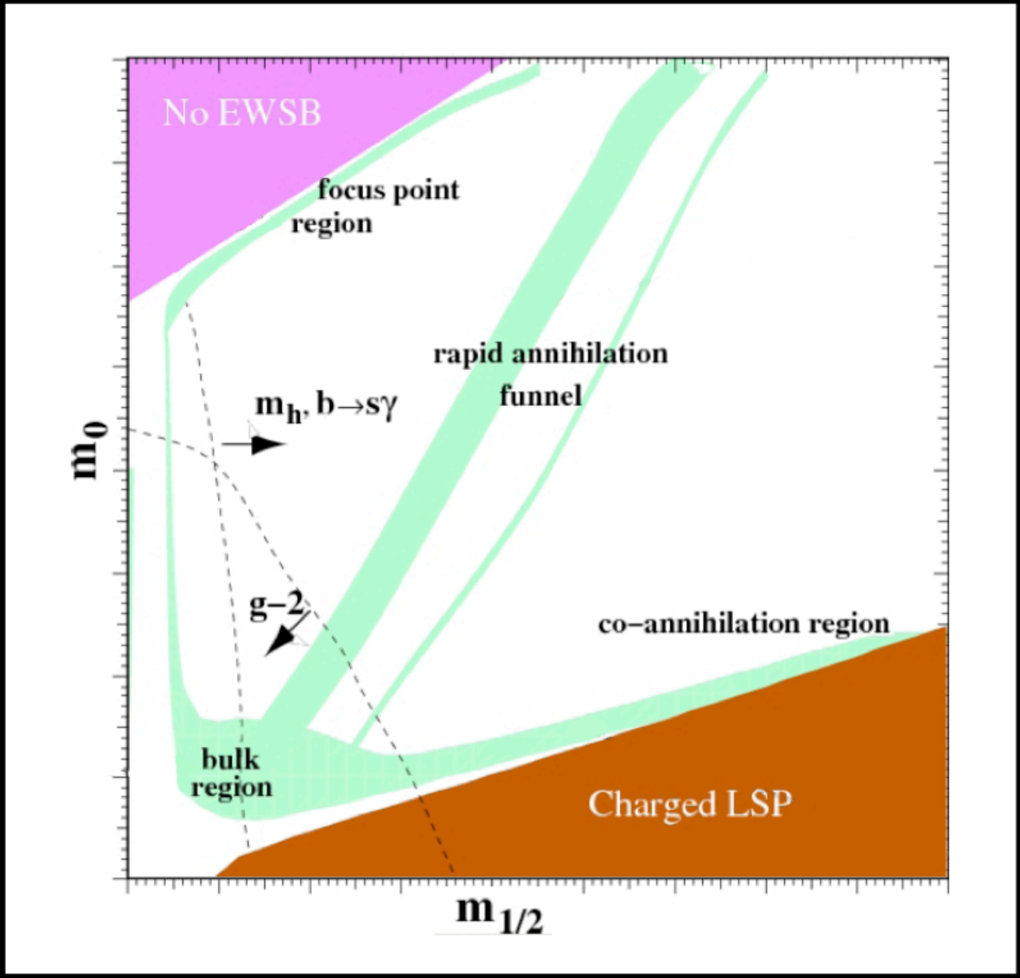
Slava Rychkov

UPMC PARIS UNIVERSITAS

ENS

It's easy to get lost in the BSM parameter space...

...if you use a wrong map

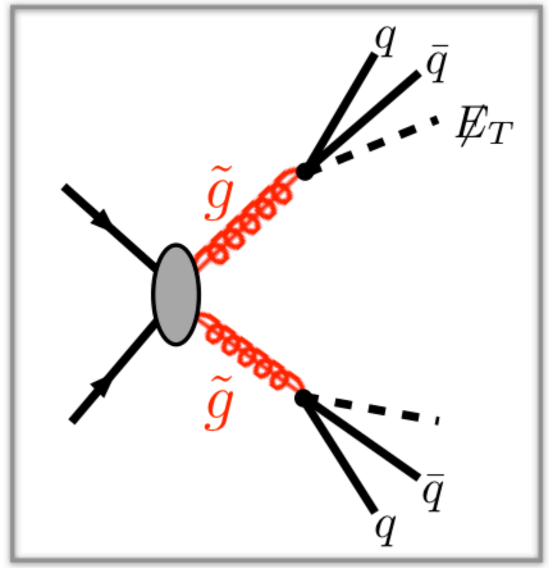


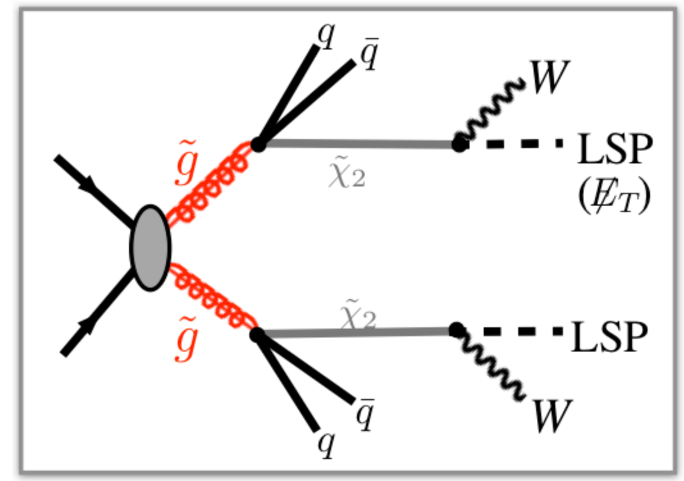
mSUGRA parameter space in terms of
"unphysical" GUT scale parameters $\mathbf{m_0, m_{1/2}}$

Way to go: Simplified Models

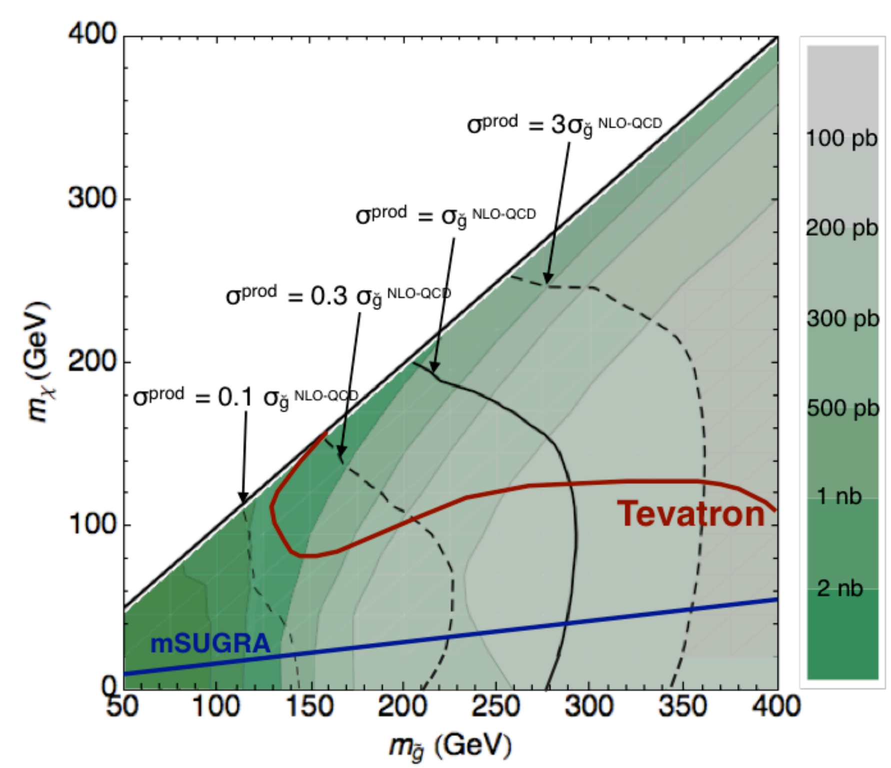
lhcnewphysics.org

E.g.: *Hadronic SUSY*





Limits are put in terms of
directly observable parameters:
3 masses (gluino, LSP, NLSP) + gluino σ



[Alves,Izaguirre,Wacker 1008.0407]

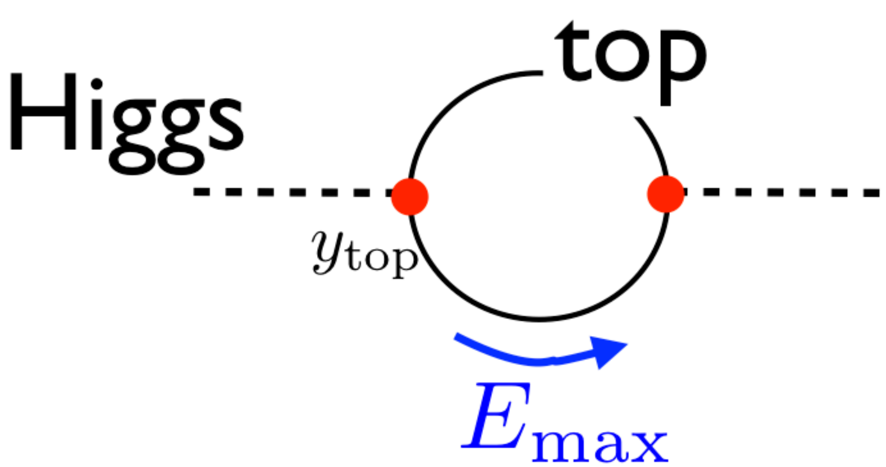
Any alternative to SUSY?

SUSY

- beautiful
- largest symmetry possible
- plays a role in string theory
- the only known *natural* way to have a light *elementary* Higgs boson

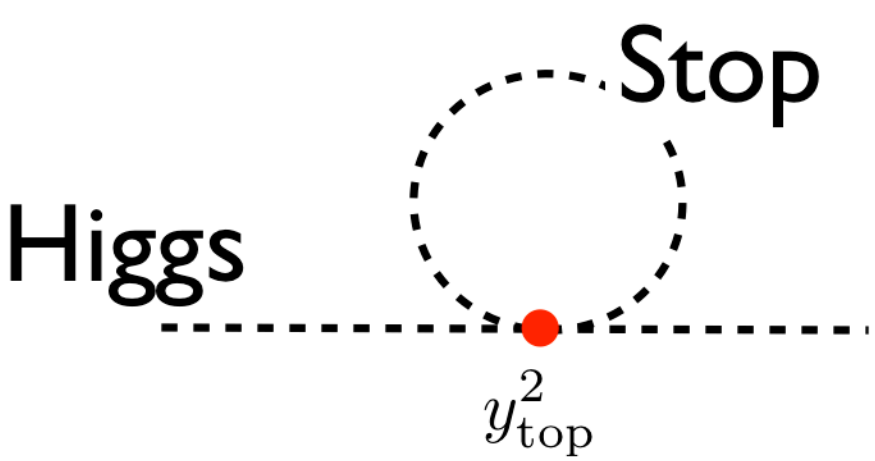
SUSY

- the only known *natural* way to have a light *elementary* Higgs boson



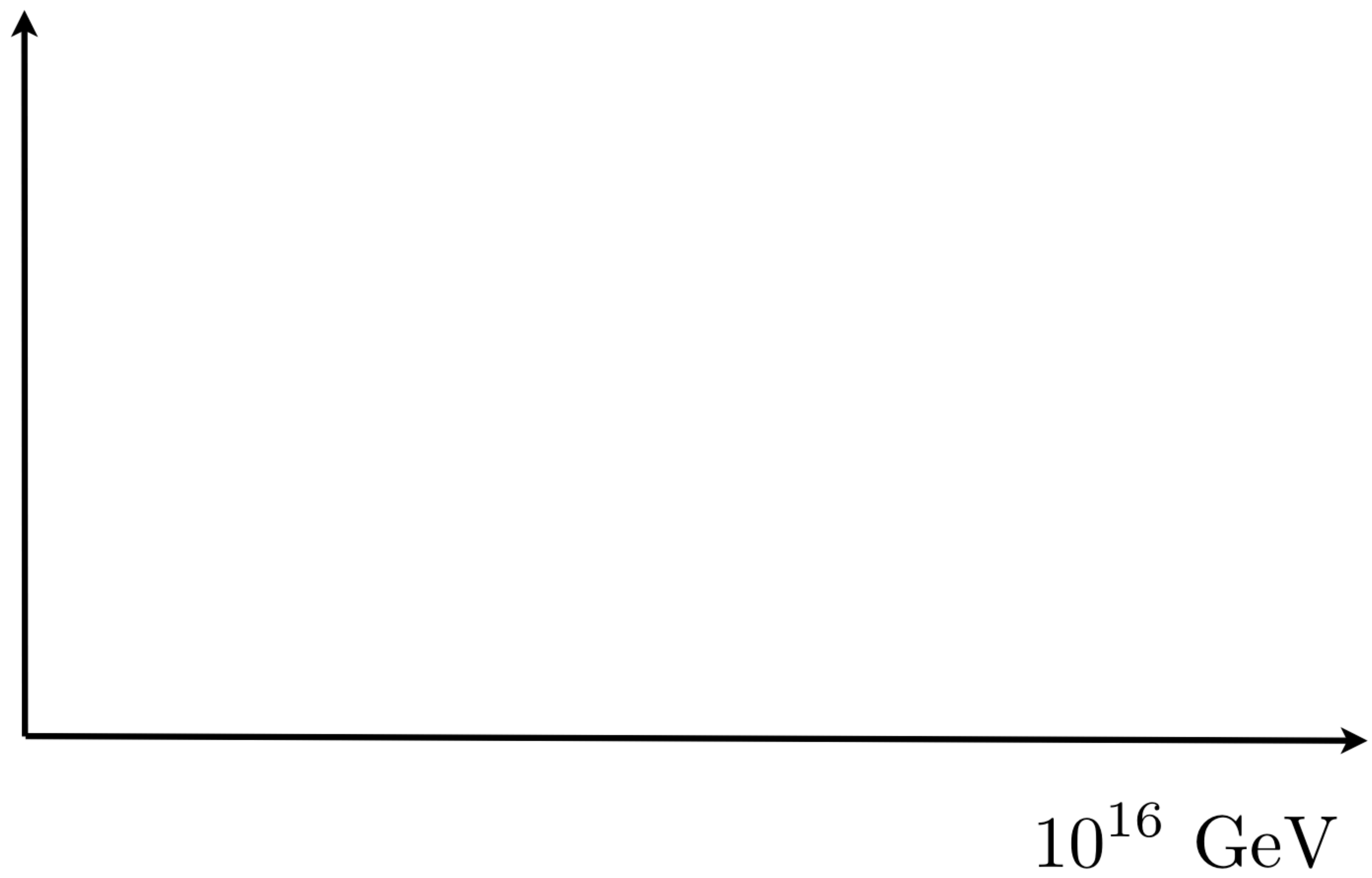
$$\Delta m^2_{\rm Higgs} = -y^2_{\rm top} E^2_{\rm max}$$

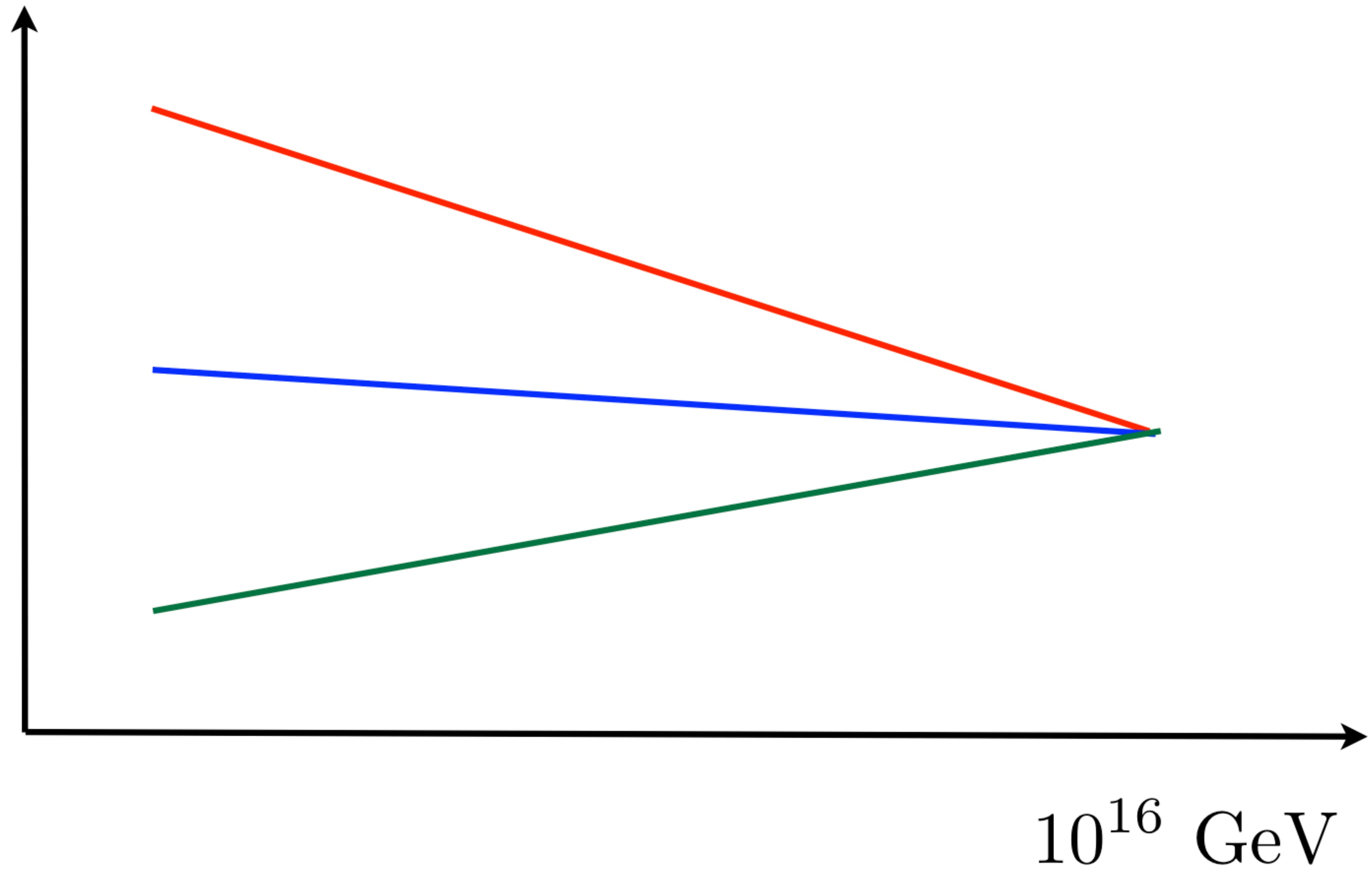
$$+$$



$$\Delta m^2_{\rm Higgs} = +\, y^2_{\rm top}(E^2_{\rm max} - m^2_{\rm stop})$$

$$\Delta m^2_{\rm Higgs} = -y^2_{\rm top} m^2_{\rm stop}$$


10^{16} GeV


10^{16} GeV

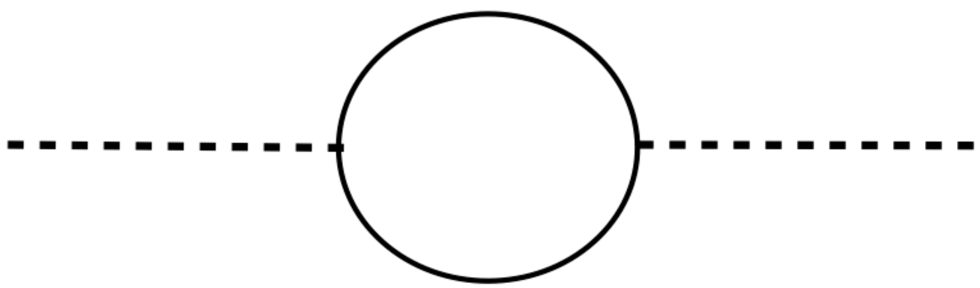
Alternative explanation for hierarchy?

m_{Higgs}

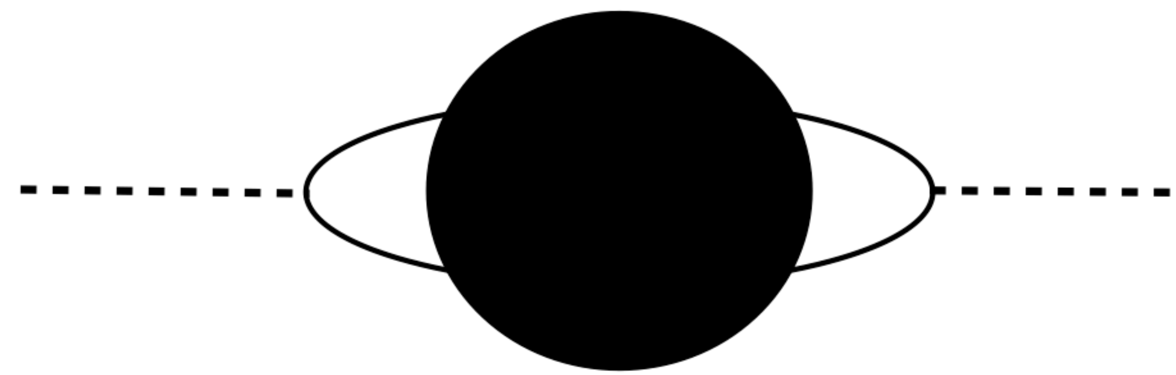
$v_{\text{EW}} = 174\text{GeV}$ ⟷ E_{max}

New physics in this range

Alternative XXX: Black Holes



$E \lesssim \text{TeV}$



$E \gg \text{TeV}$

$$\Delta m^2_{\text{Higgs}} \sim y^2_{\text{top}} (\text{TeV})^2$$

More a picture than a model...

Alternative X: No Higgs

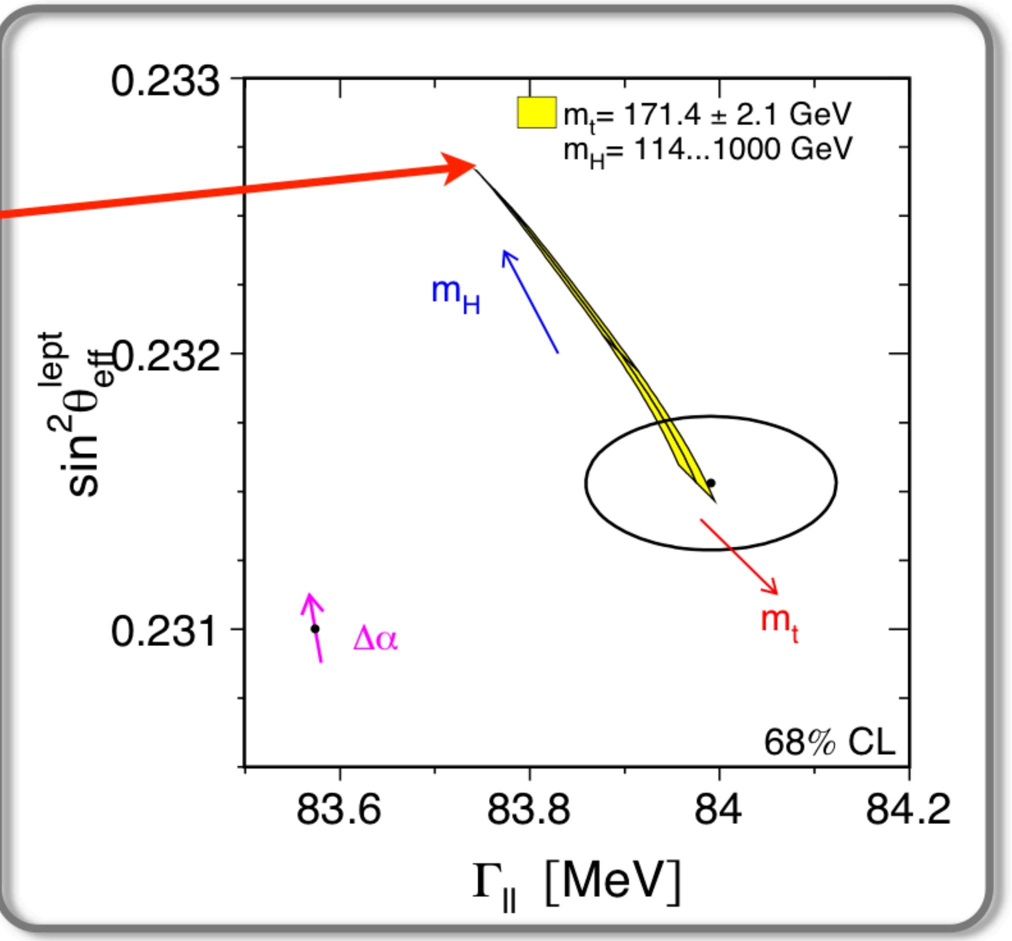
[≈ Standard Model in the limit $m_{\rm Higgs} \to {\rm TeV}$]

✔ No Higgs ⇒ no naturalness problem

✘ Strongly coupled ⇒ predictions impossible

(100% sensitive to the UV completion e.g. Technicolor)

✘ Problems with Electroweak Precision measurements

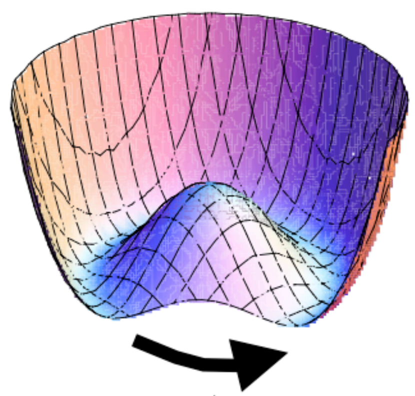


Better have light Higgs..

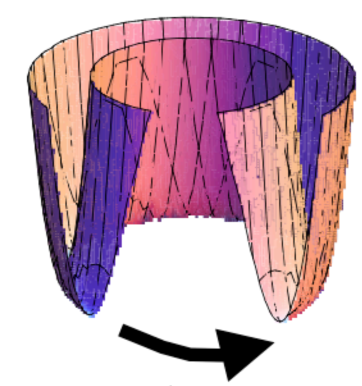
- SUSY is the only way to have it *elementary*
- **Spontaneously broken global symmetry** can give a *composite* Higgs boson

Spontaneous symmetry breaking: scalar potential

perturbative
(SM, SUSY)



Strongly coupled



Goldstone symmetry
(keeps these modes
massless)

Spontaneous symmetry breaking: scalar potential

perturbative
(SM, SUSY)

Strongly coupled

Goldstone bosons

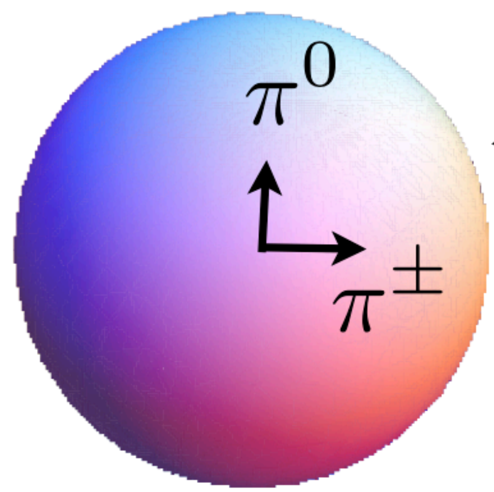
Example: pions in QCD

Global group $(m_u, m_d \to 0)$	$G = SU(2)_L \times SU(2)_R$	6 generators
Unbroken subgroup (isospin)	$\widetilde{G} = SU(2)$	3 generators
	$G \to \widetilde{G}$ by $\langle\bar{\psi}\psi\rangle \neq 0$	6-3=3 pions (Goldstone Thm)

Vacuum space $G/\widetilde{G}$

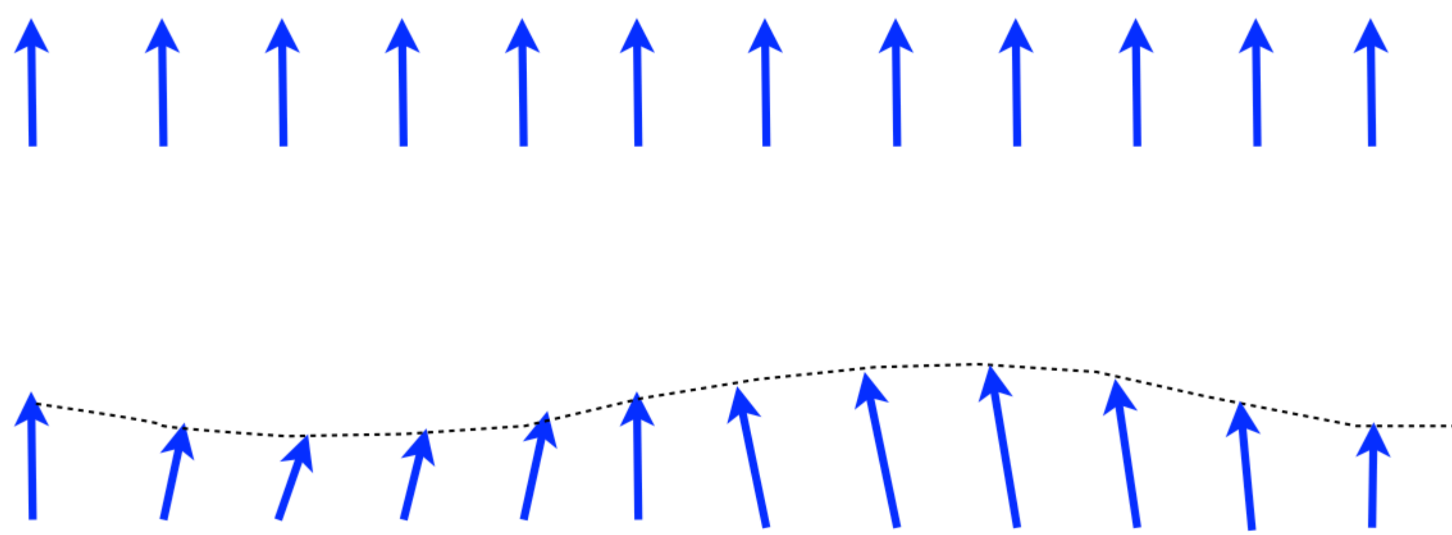
For pions in QCD: Sphere

Out[64]=



$$V(\phi) = \begin{cases} 0 & |\phi| = 1 \\ \infty & |\phi| \neq 1 \end{cases}$$

$\phi(x)$



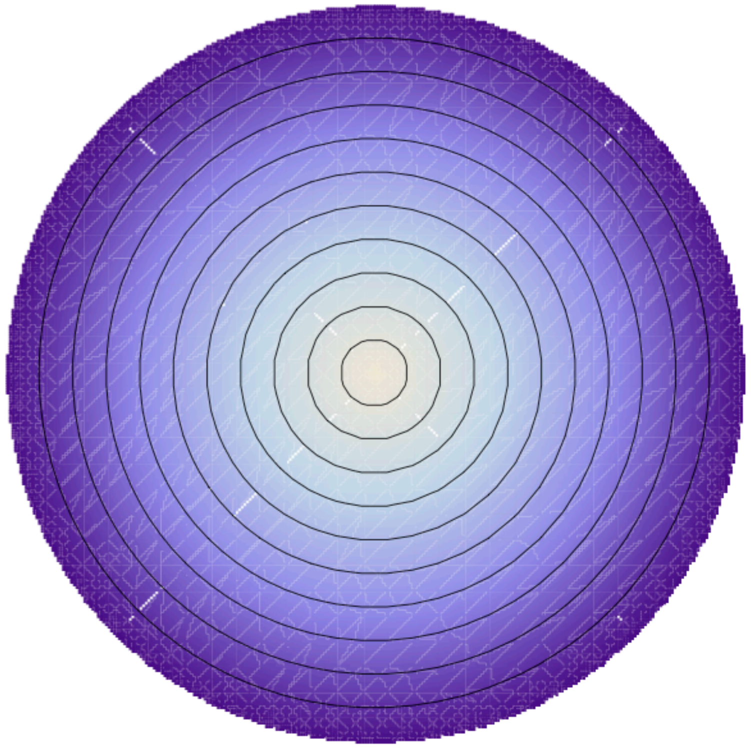
vacuum

massless pion wave

Goldstone ⇒ pseudo-Goldstone

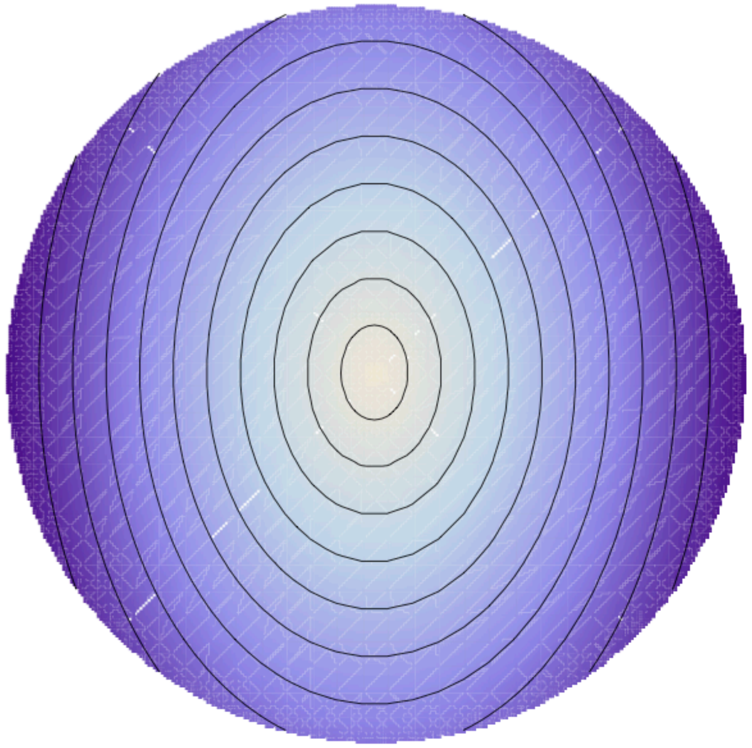
In QCD, SU(2)xSU(2) is broken explicitly by:

-quarks masses



$m_\pi^2 \sim m_q \Lambda_{\rm QCD}$

-EM interactions



$m_{\pi^+}^2 - m_{\pi^0}^2 \sim \alpha_{\rm EM} \Lambda_{\rm QCD}$

Light pions are still natural: $m_\pi \ll \Lambda_{\rm QCD}$

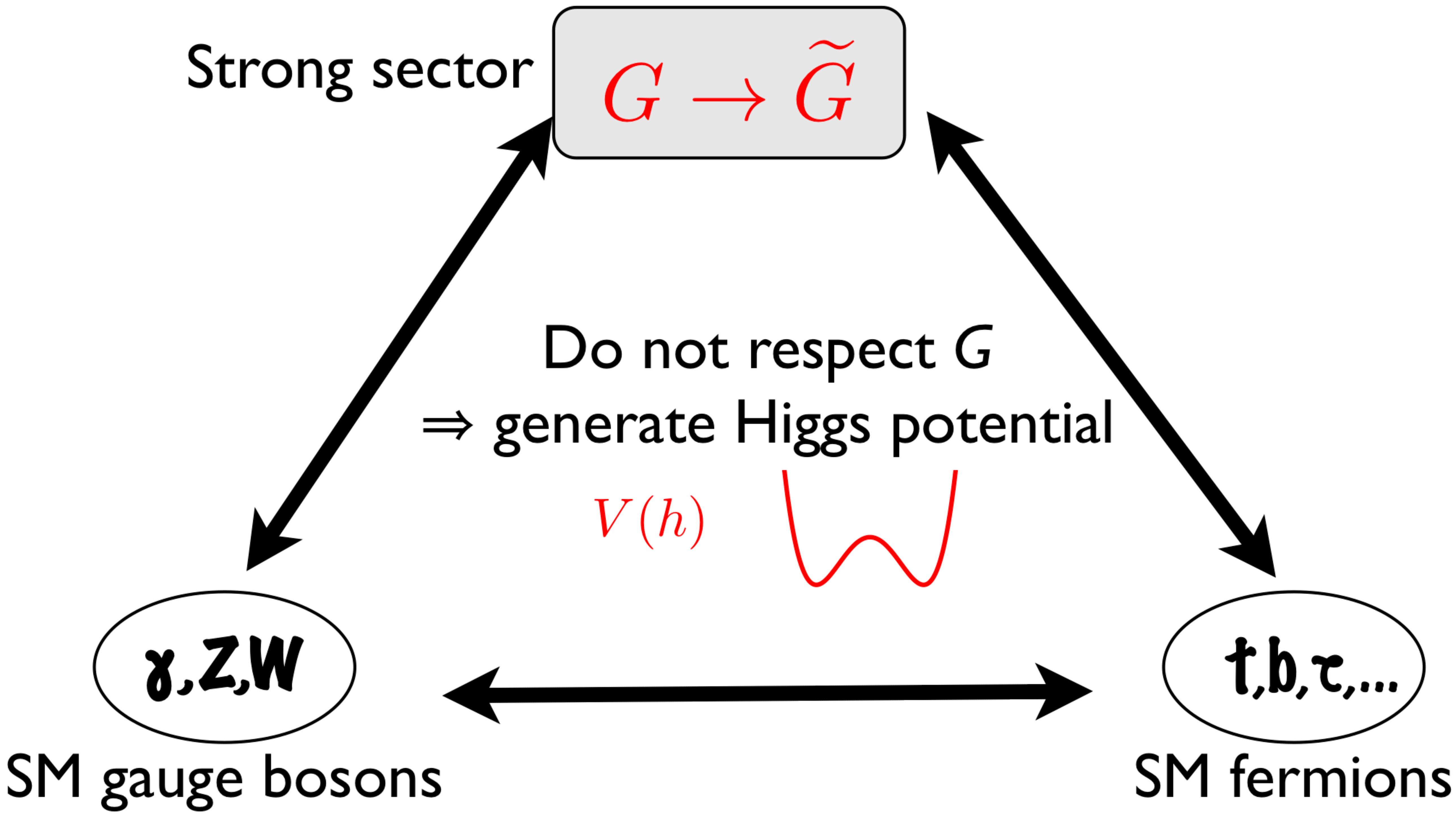
Main Idea of Composite Higgs

- Above few TeV, a strong sector with *large* symmetry group *G*

- At TeV scale, condensates form so that $G \to \widetilde{G}$

- Symmetry breaking gives several Goldstones:
  1) longitudinal W,Z
  2) composite Higgs boson h
  3) in non-minimal models, other scalars

Structure of the model

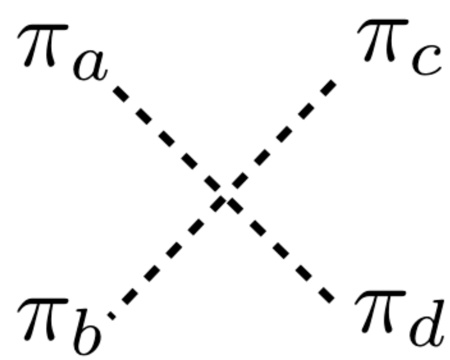


Predictions I: Scalar sector

Recall: pion interactions are fixed by symmetry (chiral Lagrangian)

$$\mathcal{L} = \mathrm{Tr}[(\partial U)^\dagger \partial U] \qquad U = e^{i\pi^a T^a}$$

4-pion scattering



$$\sim \frac{1}{f_\pi^2} \times (\text{known tensor})$$

E.g. $\pi^+\pi^- \to \pi^+\pi^-$ ⟷ $\pi^+\pi^- \to \pi^0\pi^0$

Higgs coupling suppression

Minimal model: SO(5)→SO(4)

$$\Phi = \begin{pmatrix} 0 \\ 0 \\ 0 \\ h \\ \sqrt{f^2 - h^2} \end{pmatrix}$$

} Longitudinal W,Z

$$|\partial\Phi|^2 = Z(\partial h)^2$$

$$Z = 1 + \frac{v^2}{f^2}$$

$$f = O(\text{TeV})$$

wave-function renormalization

⇒All Higgs couplings (to ZZ,WW,tt etc) are

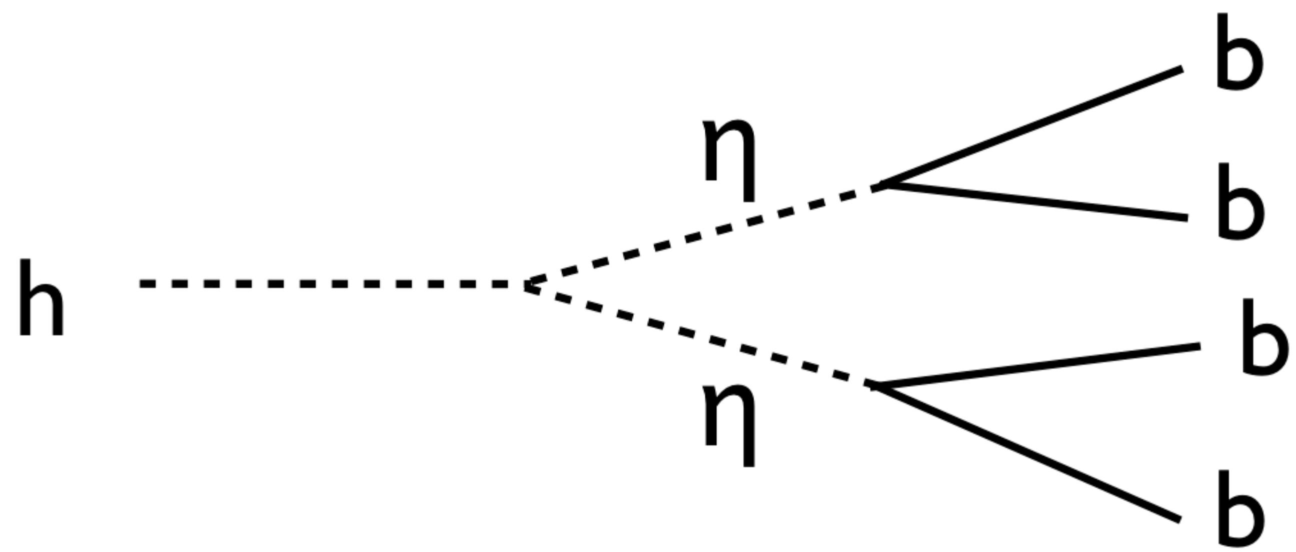
suppressed by $O(v^2/f^2) \sim 10\%$

Extended Higgs sectors I

Next-to-Minimal model: $SO(6) \rightarrow SO(5)$

- One extra Goldstone: SM singlet η
- Predicted $O(v/f)$ coupling $h \rightarrow \eta\eta$

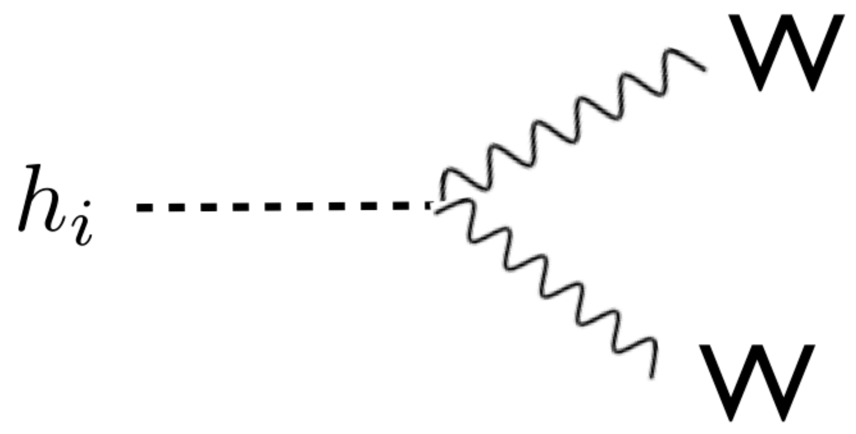
Can easily be the dominant decay mode



Extended Higgs sectors II

Non-Minimal model: SO(6)→SO(4)xSO(2)

- Goldstone spectrum = Two-Higgs doublet model (h,H,A,$H^{\pm}$)
- Changes in the Higgs-coupling sum rules:

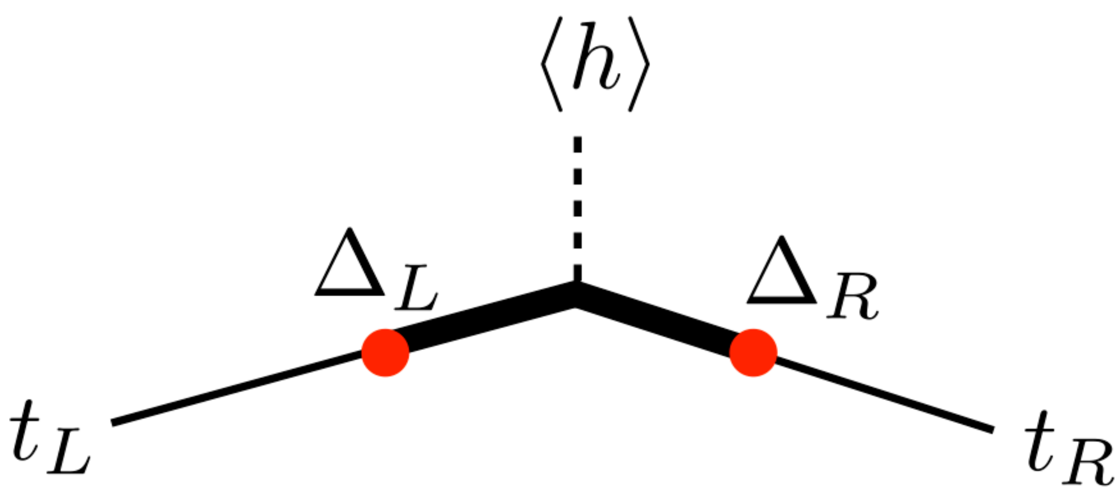


$$\sum_i g^2_{h_i WW} = g^2 m_W^2 \left(1 - \frac{2}{3}\frac{v^2}{f^2}\right)$$

Predictions in Fermion sector

- No FCNC
  ⇒ existence of composite nonchiral fermions

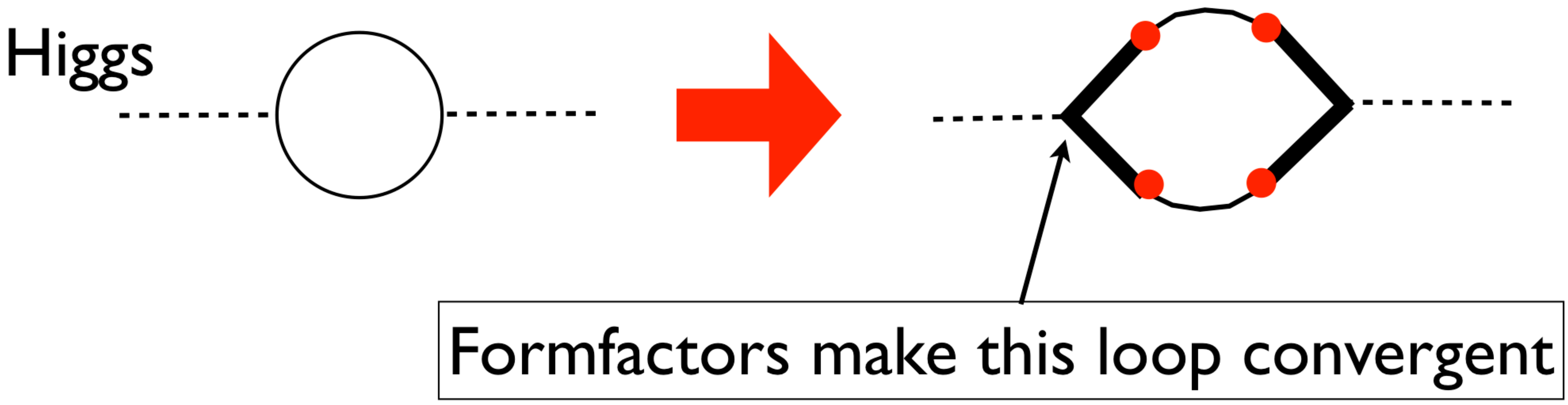
- SM fermions get mass via mixing with composites
  (*partial compositeness*)



$$m_{\mathrm{top}} = \frac{\Delta_L \Delta_R}{M_\Psi}$$

heavy composite top partner

Higgs mass correction is finite:



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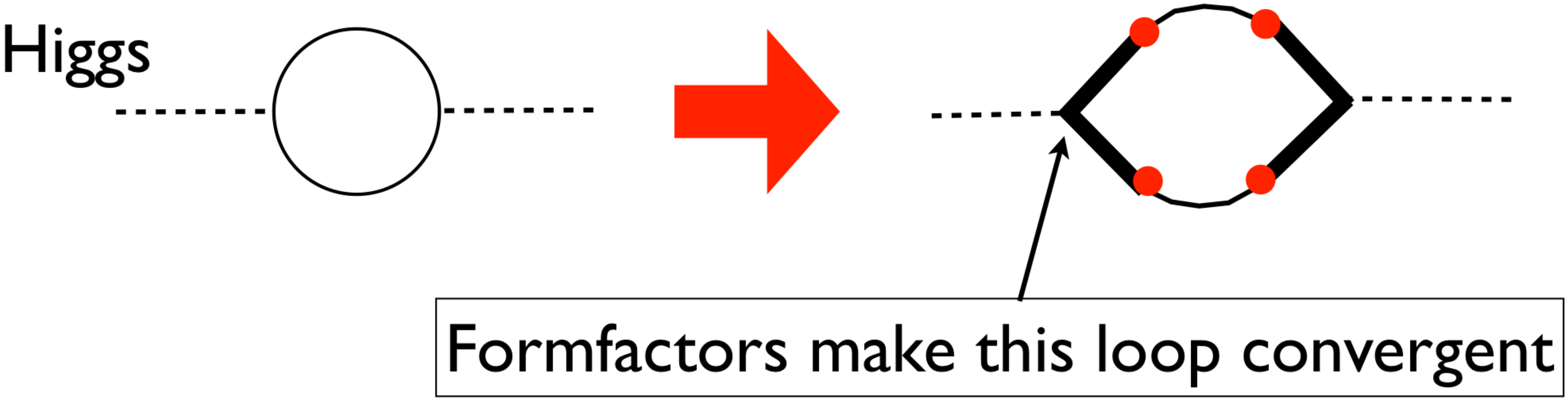
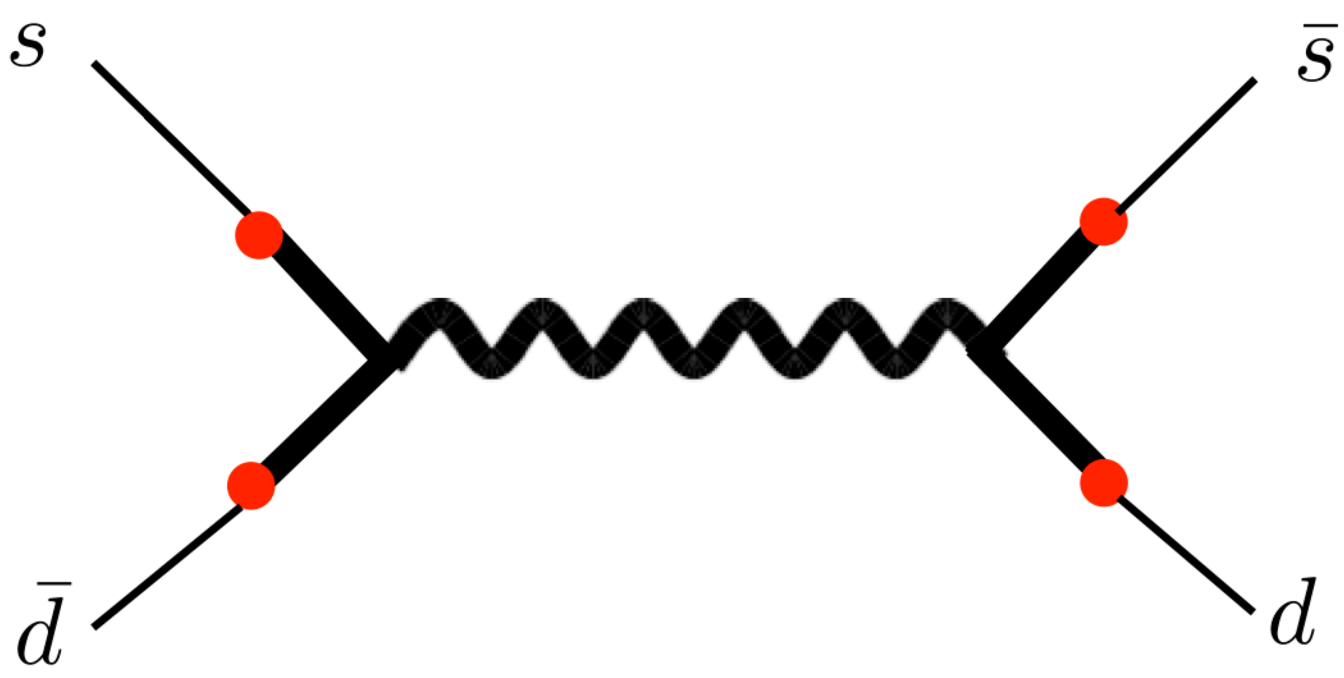


FCNC under control:



$$\frac{m_s m_d}{M_\Psi^2}\,\frac{1}{M_\Psi^2}\,(s\bar{d})^2$$

Zbb and exotic charges

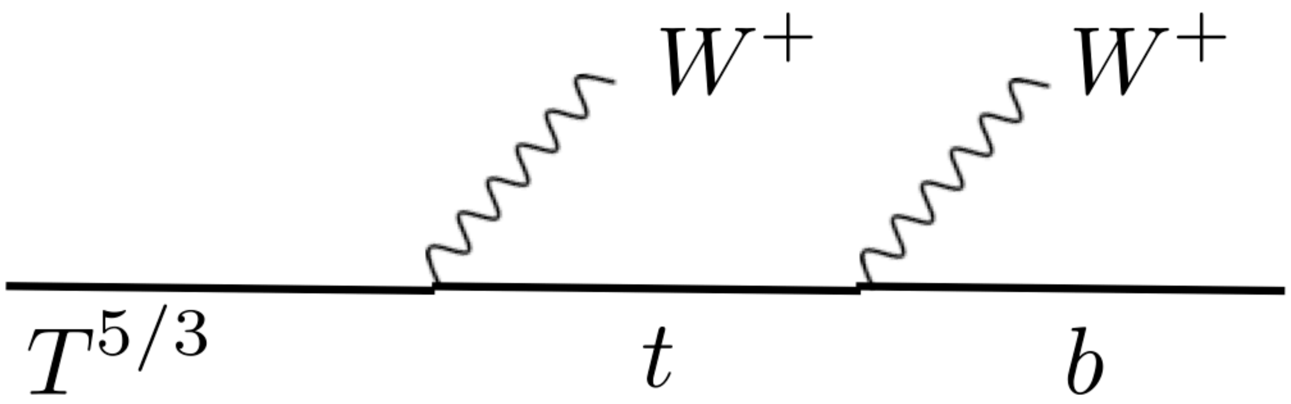
- Lightest composite fermions are Top partners

- Absence of large Zbb corrections ⇒

  strong constraint on Top partner multiplets ⇒

  Exotic charge 5/3 "composite quarks"

At the LHC: pair production and decay with same-sign dileptons:



Summary: Full spectrum of Composite Higgs models

few TeV (beyond LHC?)	Partners of other fermions; Heavy vector bosons
0.5-1 TeV	Top partners ("composite quarks")
100-200 GeV	Composite Higgs; extra scalars

Why do we like Composite Higgs

- Recover ability to make predictions (compared to Higgsless)
- Avoid tension with EWPT and Flavor tests
- Exciting experimental signatures
  - an interplay of direct discovery and precision measurements