# Weak scale triggers in the SMEFT

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EXCELENCIA SEVERO OCHOA

Asymmetry
Essential Asymmetries of Nature

# The hierarchy problem 101

**For a scalar, $m_h^2 = 0$ has nothing special**

Radiative correction naturally give $\delta m_h^2 \sim \dfrac{g^2}{16\pi^2}\Lambda_H^2$

Absent a mechanism, the “expected” size is $m_h^2 \sim \Lambda_H^2$

Yet we observe $m_h^2 \ll \Lambda_H^2$

***That’s the hierarchy problem***

# Traditional approach: symmetry at the TeV

**Why is $m_h^2 \ll \Lambda_{\mathrm{NP}}^2$ ??**

***Symmetry-based solutions make $m_h^2 = 0$ special in the fundamental theory of Nature***

**Supersymmetry:** chiral symmetry of fermion superpartners protects scalar masses

**Composite Higgs:** Higgs as a pseudo-Nambu-Goldstone boson (approx. shift symmetry)

# … but we don't see them

**LHC:** no new particles around $\sim 1 - 3$ TeV

$\Rightarrow$ classic TeV solutions are under pressure

Some options remain (e.g. neutral naturalness) but…

***It is important to explore alternative approaches***

# New directions: cosmological Naturalness

## *Relaxion-type models*

During inflation the Higgs potential is scanned via a rolling scalar, which is then stopped by a phase transition involving the VEV of the Higgs

## *Crunching models*

Different patches of the Universe have different parameters for the Higgs potential, but some form of dynamics makes the patches with small or large Higgs VEVs dynamically unstable, leading to a rapid crunch.

# New directions: cosmological Naturalness

## *Scanning*

The Higgs mass squared takes many different values either in our Universe (Nnaturalness, relaxion) or in the Multiverse (crunching models, anthropic selection, ….)

## *Selection*

Something is “triggered” in the evolution of the Universe when the Higgs mass crosses the weak scale: scanning stops (relaxion), the CC changes dramatically (crunching,…)

## *Observation*

Today we measure an unnaturally small value of the weak scale as a consequence of an early Universe event that we can’t (yet) observe

# New directions: cosmological Naturalness

A common structural ingredient: **weak scale triggers**

*Trigger operators make $m_h^2 \simeq 0$ special for the evolution of our universe*

Any value of $m_h^2$ is permitted and $m_h^2 \simeq M_{\rm Pl}^2$ remains the most natural possibility but our universe sees a value $m_h^2 \ll M_{\rm Pl}^2$ due to its cosmological evolution

# Weak scale triggers

***Is there anything that changes locally in Nature when we change the Higgs mass squared?***

Is there any gauge invariant local operator $\mathcal{O}_T$ such that

$$\frac{d \log \langle \mathcal{O}_T \rangle}{d \log m_h^2} = O(1)$$

# A weak scale trigger in the SM

***Is there anything that changes locally in Nature when we change the Higgs mass squared?***

In the SM the unique option is

$$\mathrm{Tr}\left[G_{\mu\nu}\tilde{G}^{\mu\nu}\right]$$

It plays a central role in relaxion models and in crunching scenarios

# A weak scale trigger in the SM

Coupling a scalar field $\phi$ to the SM trigger $\frac{\phi}{f} Tr\,[G_{\mu\nu}\tilde{G}^{\mu\nu}]$ generates a potential for $\phi$ at the QCD phase transition of the form:

$$V(\phi) \simeq \frac{\Lambda_{\rm QCD}^4}{2}\left(\bar{\theta} + \frac{\phi}{f}\right)^2$$

where $\Lambda_{\rm QCD}^4 \sim m_\pi^2 f_\pi^2 \frac{m_u m_d}{(m_u + m_d)^2}$ is a monotonic function of the Higgs VEV

# Triggers beyond the SM: type-0 2HDM

*Trigger operator $\mathcal{O}_T = H_1 H_2$: a protected order parameter for EWSB*

A discrete symmetry protects $\langle H_1 H_2 \rangle$ from being generated as a UV-sized spurion: it is *off* before EWSB, and *on* after EWSB

$\langle \mathcal{O}_T \rangle \sim v_1 v_2$ in the broken phase

Trigger $\Rightarrow$ extra Higgs states cannot fully decouple:
$\mathcal{O}(100\ \text{GeV} - \text{few}\ 100\ \text{GeV})$

Arkani-Hamed, D'Agnolo & Kim (2020)

# Triggers beyond the SM: $F\tilde{F}$ + VLF

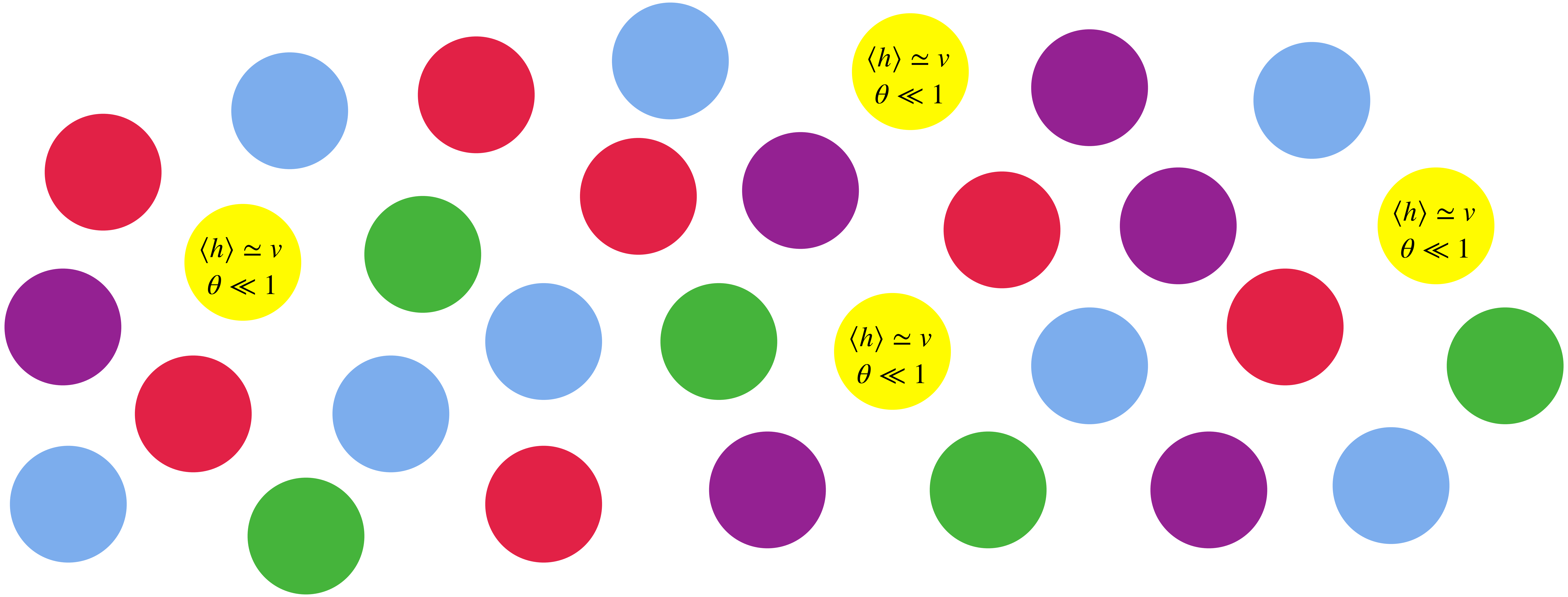
***Trigger operator $\mathcal{O}_T = F\tilde{F}$ + VLF: nonperturbative barrier that turns on at EWSB***

A new confining group with VLF charged under $SU(2)_L \times U(1)_Y$ whose masses depend at $O(1)$ on the Higgs VEV: the relevant trigger is the EWSB-dependence of the nonperturbative amplitude controlled by fermion masses

# The use of triggers: *Sliding Naturalness*

## Landscape of $m_h^2, \theta$ and CC values

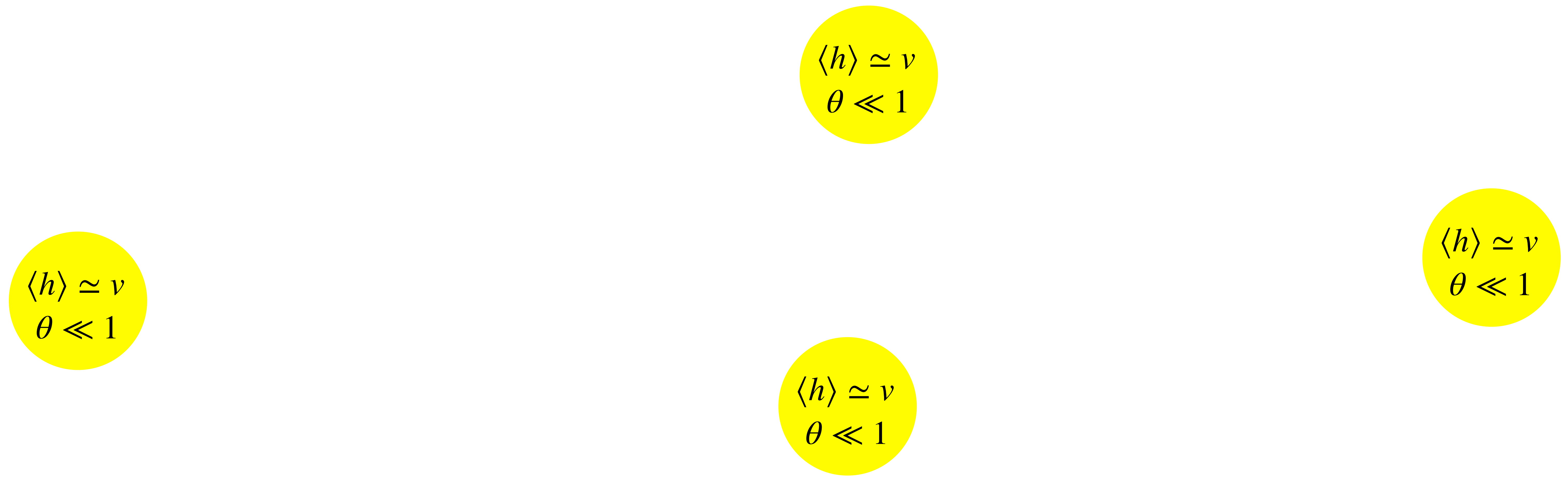
Can be realized e.g. in the *Friendly Landscape* of Arkani-Hamed, Dimopoulos & Kachru (2005)




D'Agnolo & Teresi (2021)

# The use of triggers: *Sliding Naturalness*

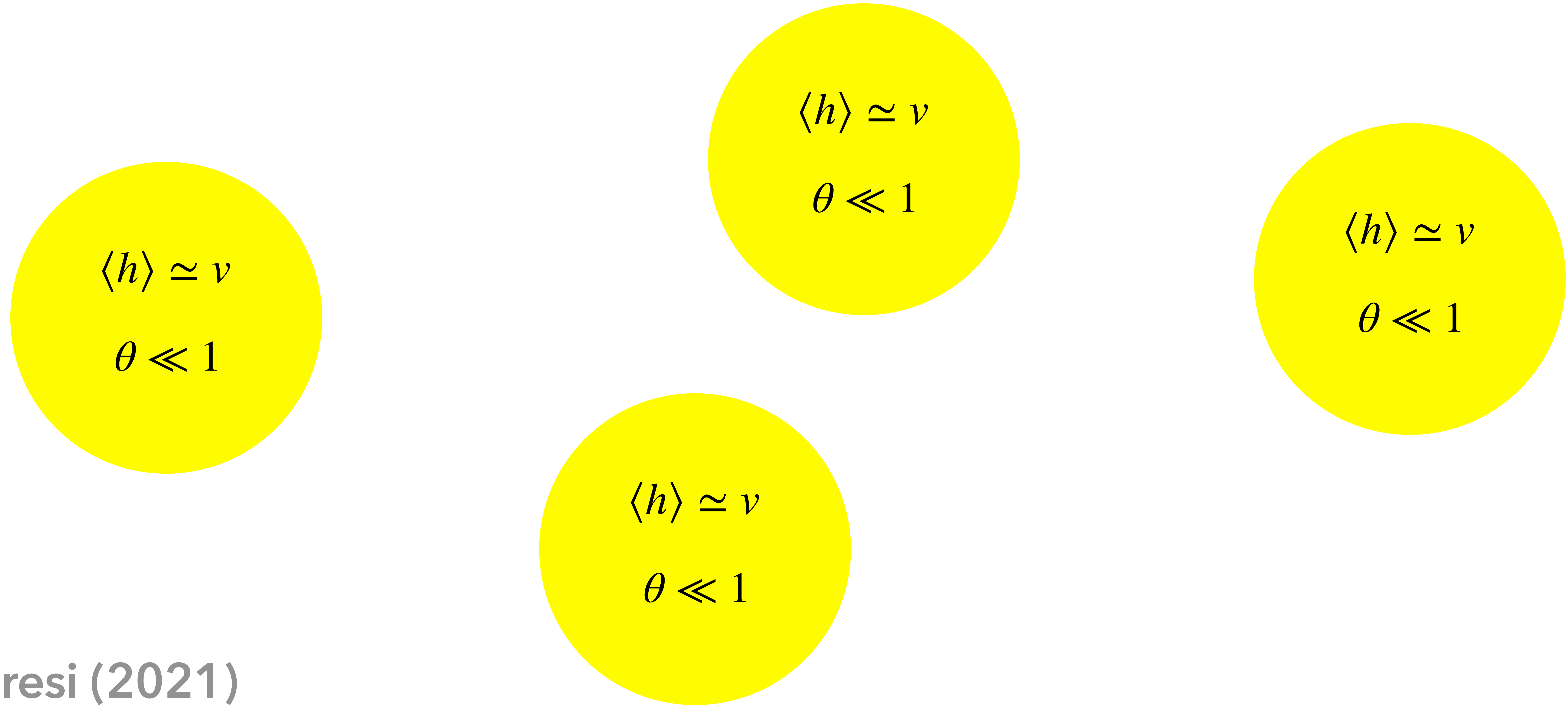
After reheating and a time $t_c \sim 1/H(\Lambda_{\rm QCD}) \sim 10^{-5}$ s




D'Agnolo & Teresi (2021)

# The use of triggers: *Sliding Naturalness*

Only universes with the observed values of $\langle h \rangle$ and $\theta$ can live cosmologically long times



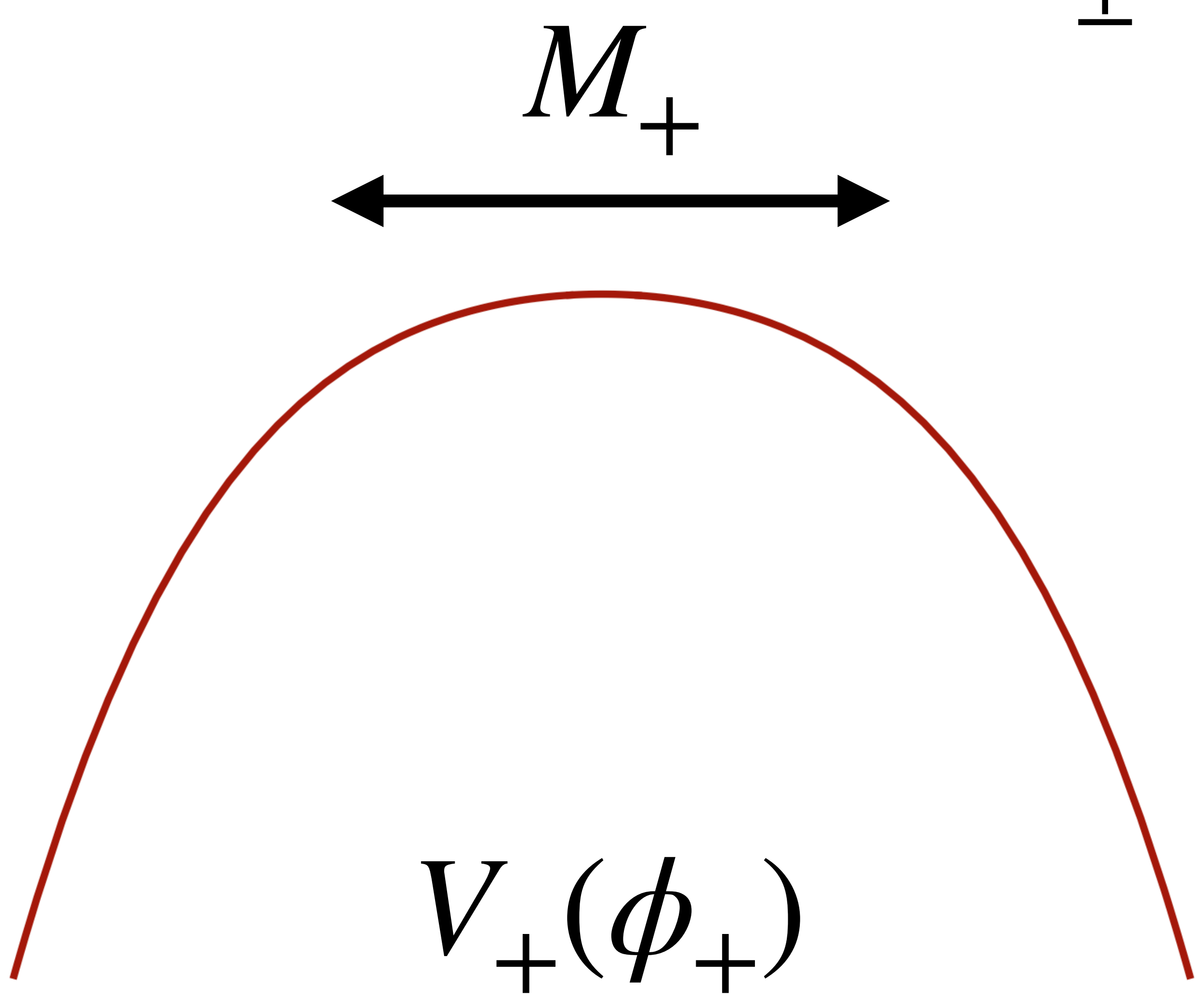

D'Agnolo & Teresi (2021)

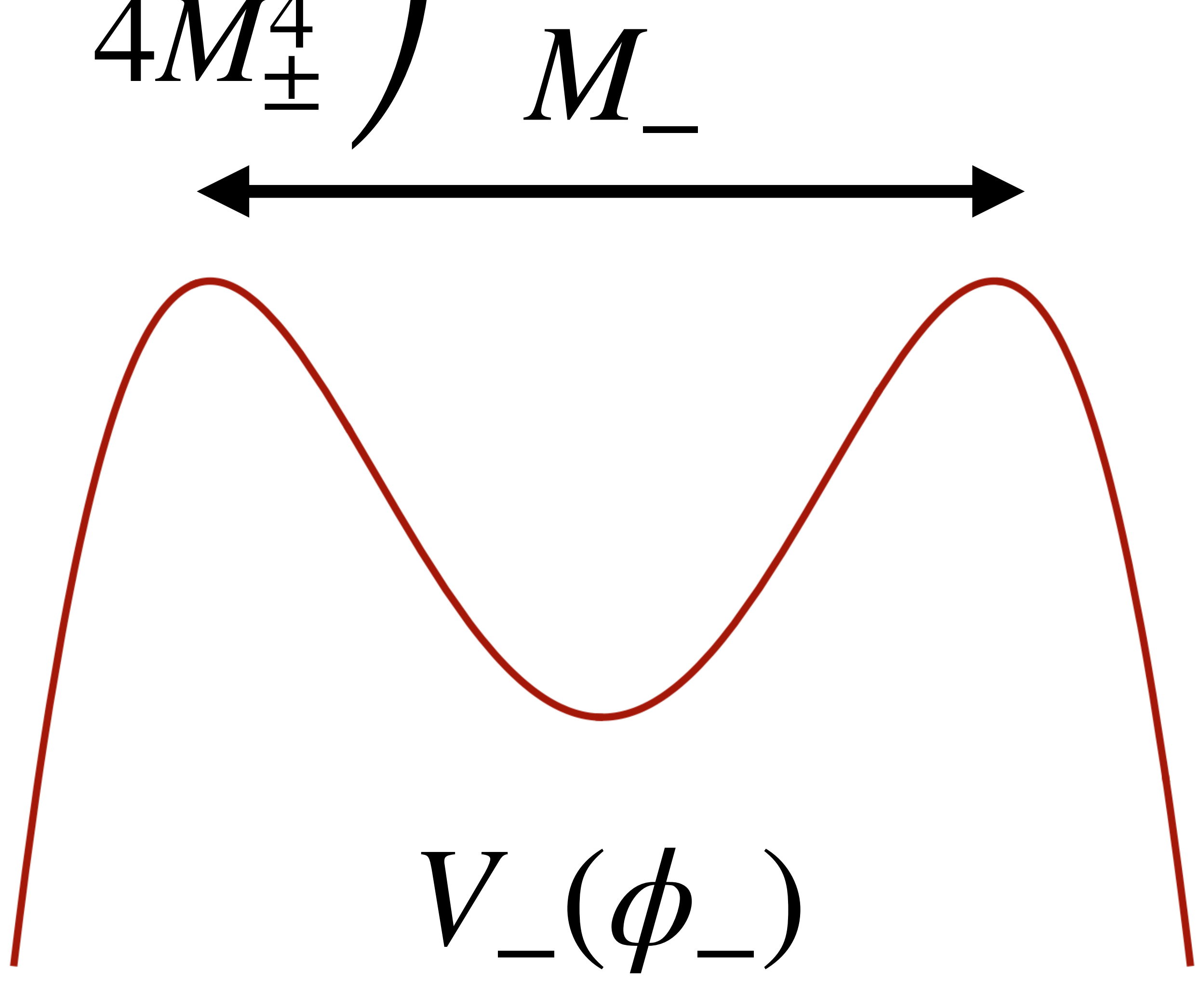
# The use of triggers: *Sliding Naturalness*

**A pedagogical model (zoom in on shallow minimum)**

We introduce two scalar fields with potential:

$$V_\pm = m_{\phi_\pm}^2 M_\pm^2 \left( \mp \frac{\phi_\pm^2}{2M_\pm^2} - \frac{\phi_\pm^4}{4M_\pm^4} \right)$$



# The use of triggers: *Sliding Naturalness*

We add the axion-like coupling to $Tr\,[G\tilde{G}]$:

$$V_{\phi_\pm H} = -\frac{\alpha_s}{8\pi}\left(\bar{\theta} + \frac{\phi_+}{F_+} + \frac{\phi_-}{F_-}\right) Tr\left[G\tilde{G}\right]$$

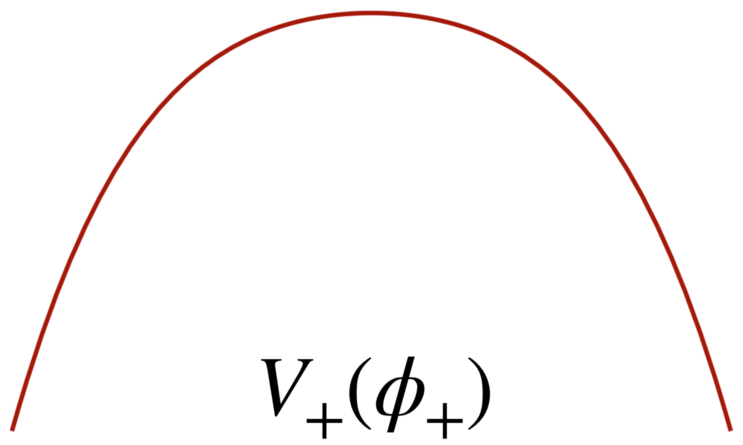
with $F_\pm \gg M_\pm$ (technically natural)

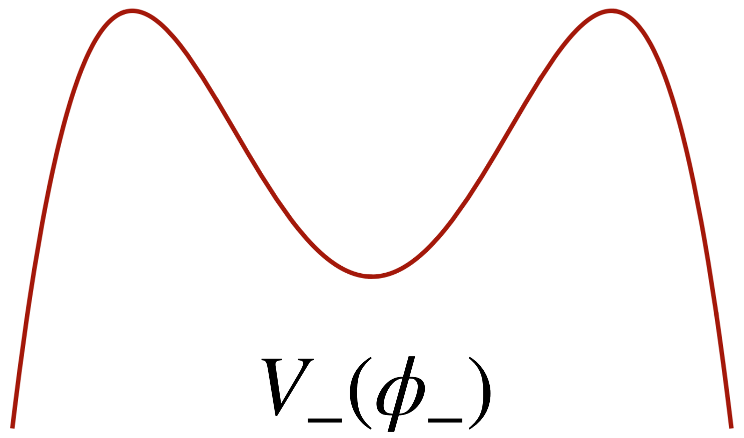
# The use of triggers: *Sliding Naturalness*

At low energies the potential $V_{H\phi}$ becomes

$$V_{\phi_\pm H} = -\frac{\alpha_s}{8\pi}\left(\bar{\theta} + \frac{\phi_+}{F_+} + \frac{\phi_-}{F_-}\right) Tr\left[G\tilde{G}\right]$$

We have to evaluate **strong dynamics** and **UV instantons** contributions to $V(\phi_\pm)$ from $SU(3)_c$ in all patches



# The use of triggers: *Sliding Naturalness*

At low energies $V_{\phi_\pm H}$ becomes

$$V_{\phi_\pm H} \simeq \left(\Lambda^4_{\rm strong}(\langle h \rangle) + \Lambda^4_{\rm inst}(\langle h \rangle)\right)\left(\theta + \frac{\phi_+}{F_+} + \frac{\phi_-}{F_-}\right)^2$$

to be compared to

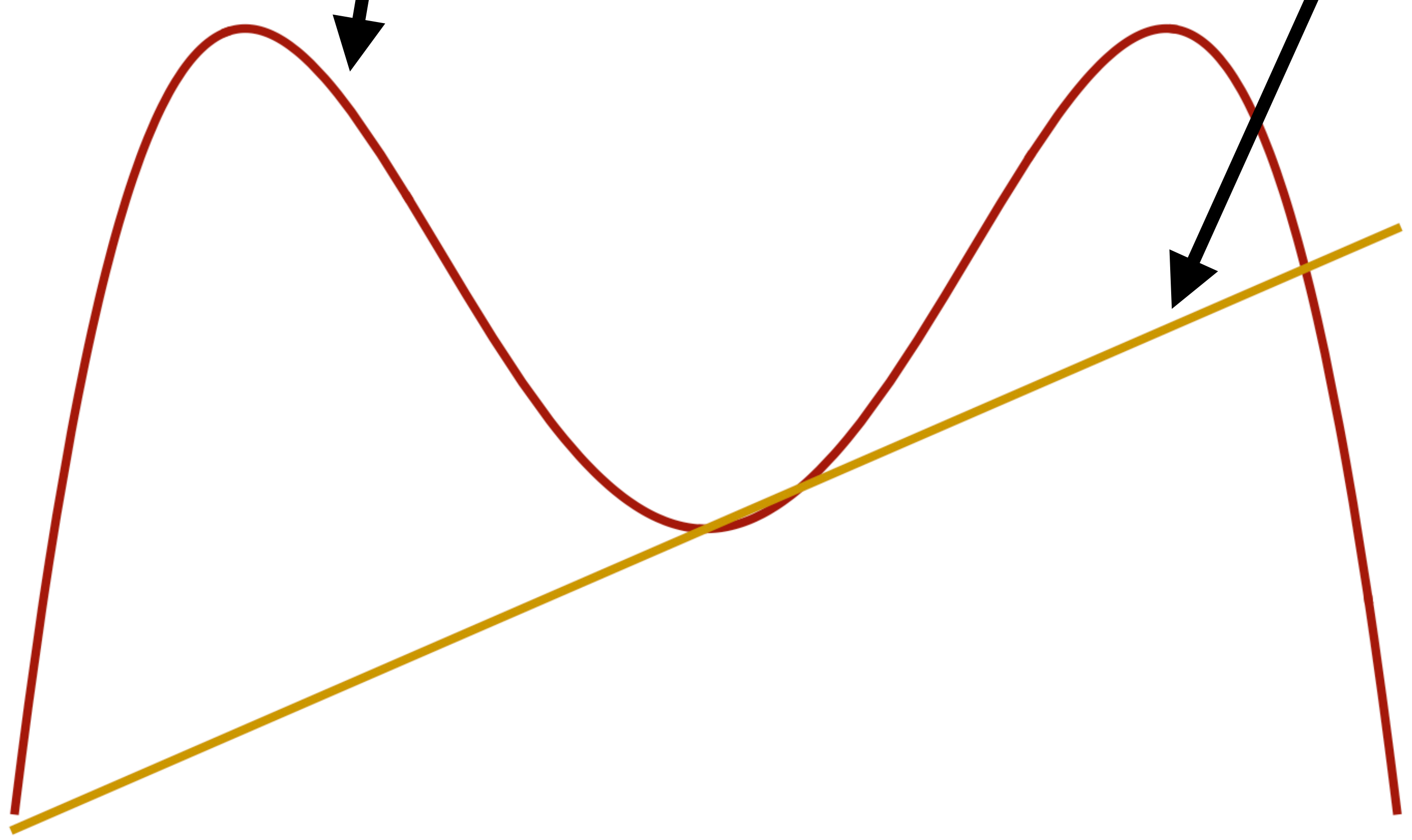
$$V_{\phi_\pm H} \simeq \Lambda^4_{\rm us}(\langle h \rangle)\left(\theta + \frac{\phi_+}{F_+} + \frac{\phi_-}{F_-}\right)^2$$

$$\Lambda^4_{\rm us}(\langle h \rangle) \simeq m_\pi^2 f_\pi^2 \frac{m_u m_d}{(m_u + m_d)^2} \qquad \text{for} \qquad m_{u,d} \lesssim 4\pi f_\pi$$

# The use of triggers: *Sliding Naturalness*

Upon some assumptions the potential of $\phi\_$ looks like:

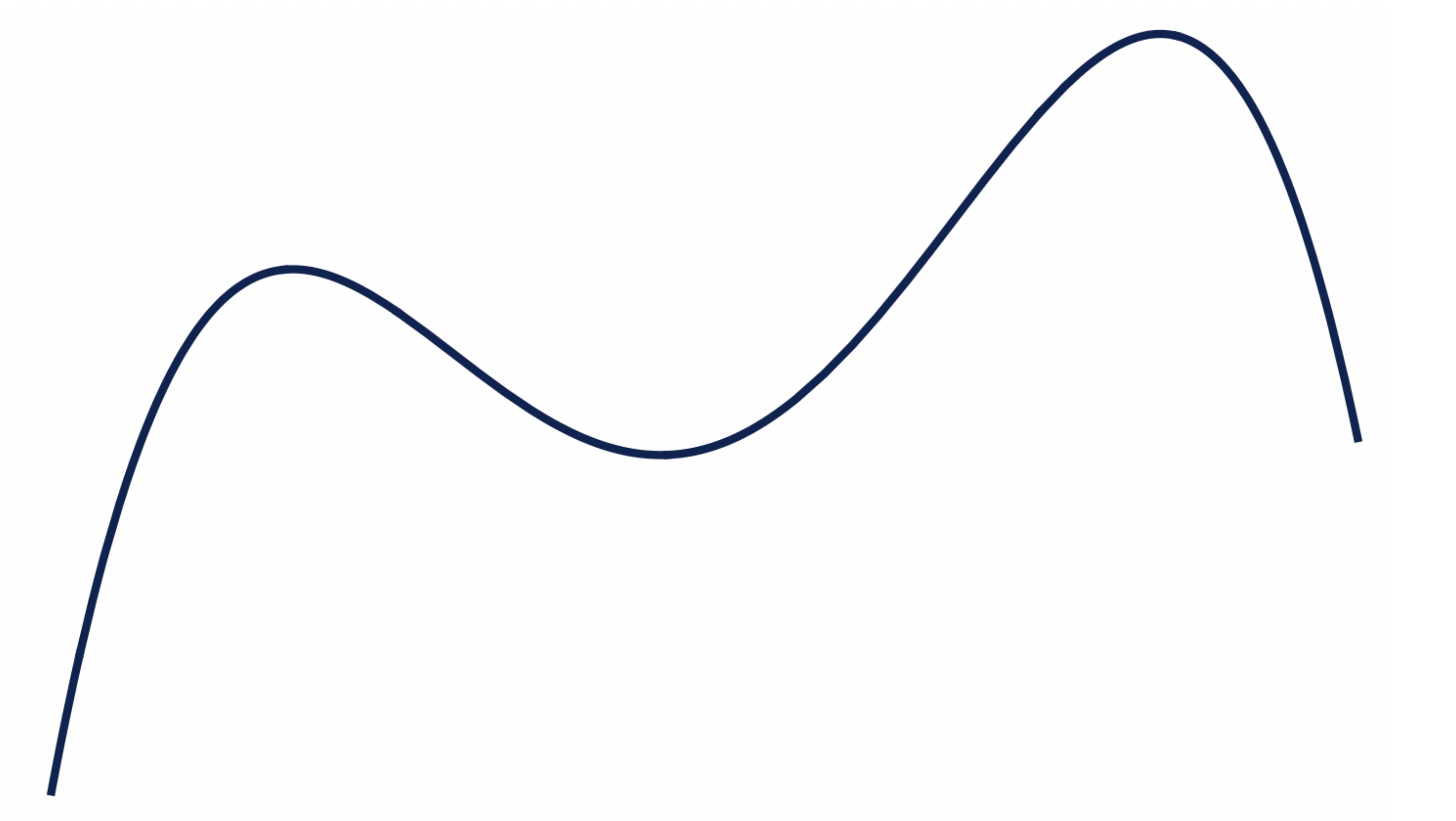
$$V_- \simeq \frac{1}{2} m_{\phi_-}^2 \phi_-^2 - \frac{m_{\phi_-}^2}{4M_-^2}\phi_-^4 + \Lambda_{\rm tot}^4(\langle h \rangle)\theta_{\rm eff}^- \frac{\phi_-}{F_-}$$



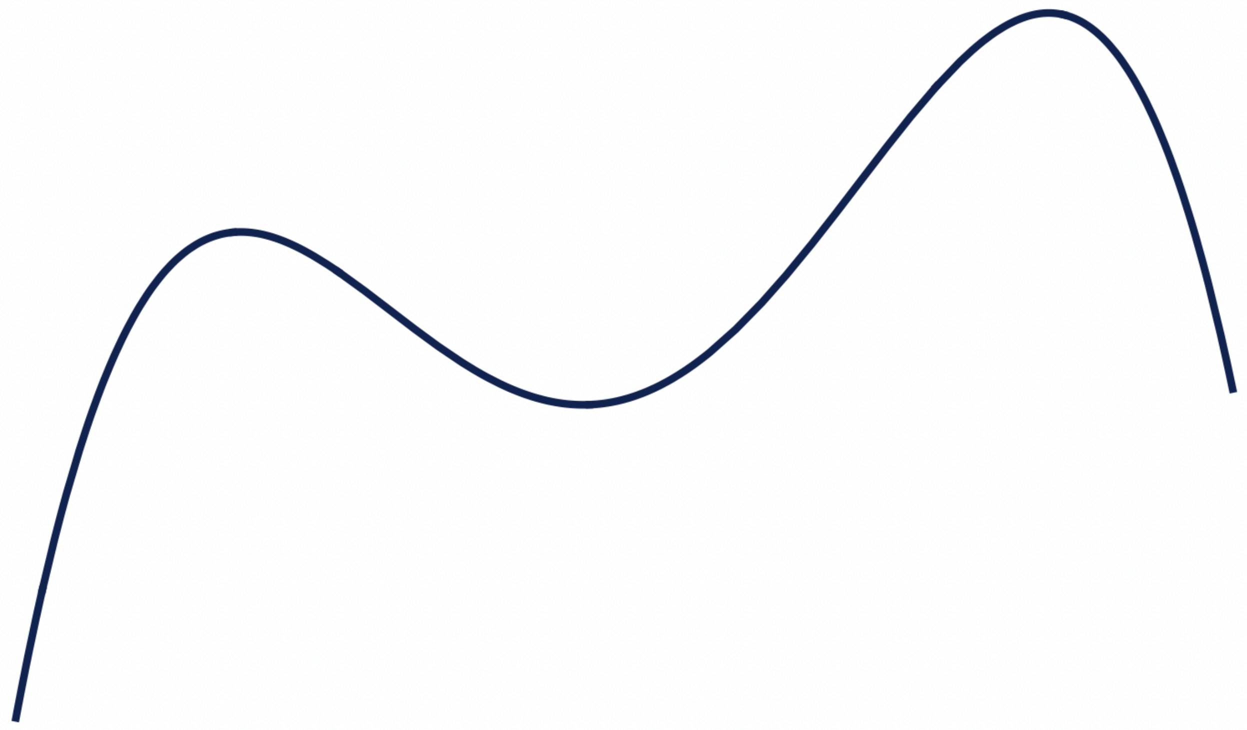
# The use of triggers: *Sliding Naturalness*

Upon some assumptions the potential of $\phi_-$ looks like:

$$V_- \simeq \frac{1}{2} m_{\phi_-}^2 \phi_-^2 - \frac{m_{\phi_-}^2}{4M_-^2} \phi_-^4 + \Lambda_{\rm tot}^4(\langle h \rangle) \theta_{\rm eff}^- \frac{\phi_-}{F_-}$$



# The use of triggers: *Sliding Naturalness*



The local minimum around the origin is safe if:

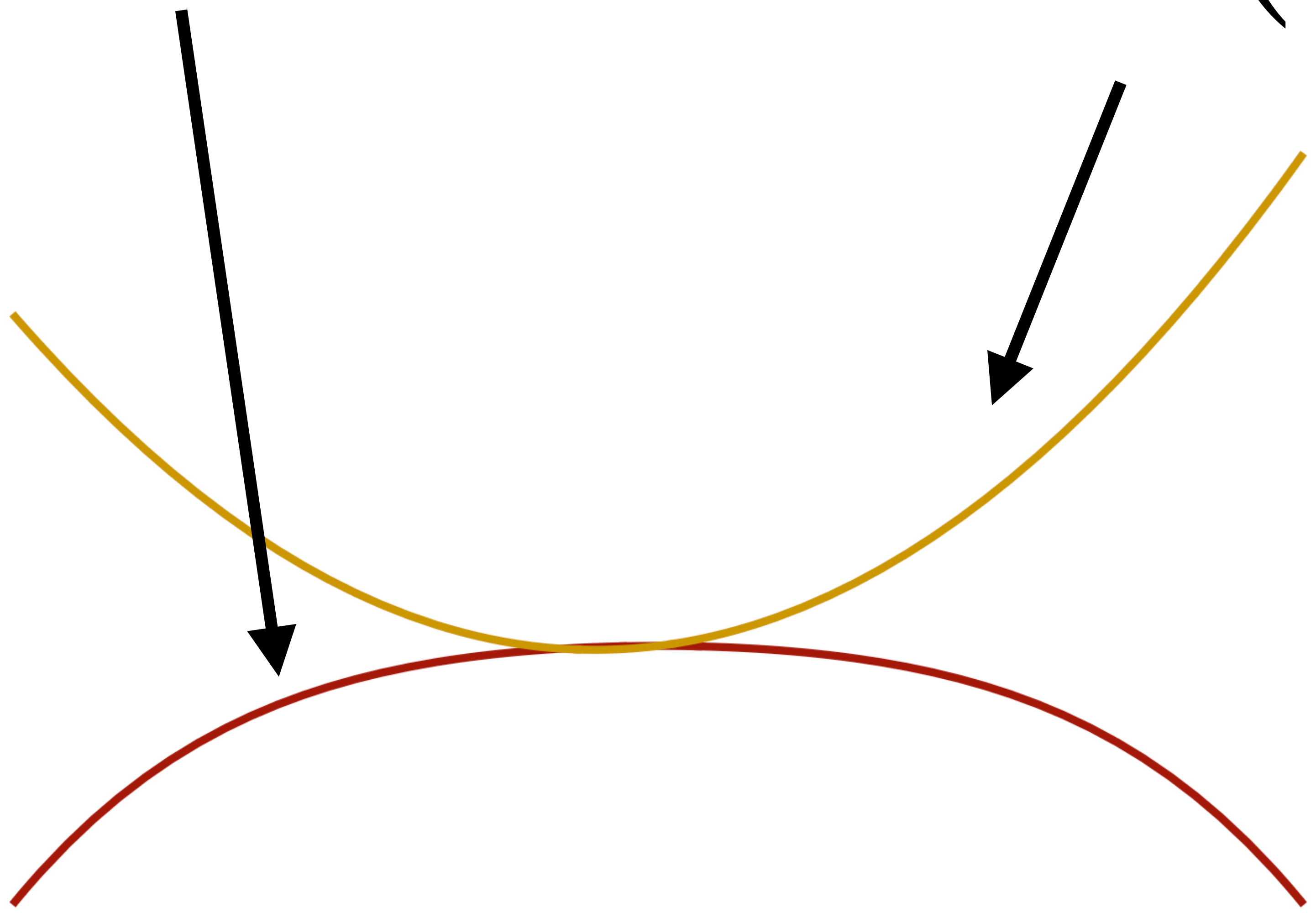
$$\Lambda_{\text{tot}}^4(\langle h \rangle) \lesssim \frac{m_{\phi_-}^2}{\theta_{\text{eff}}^-} M_- F_-$$

i.e. the mass term dominates the tadpole

# The use of triggers: *Sliding Naturalness*

Upon some assumptions the potential of $\phi_+$ looks like:

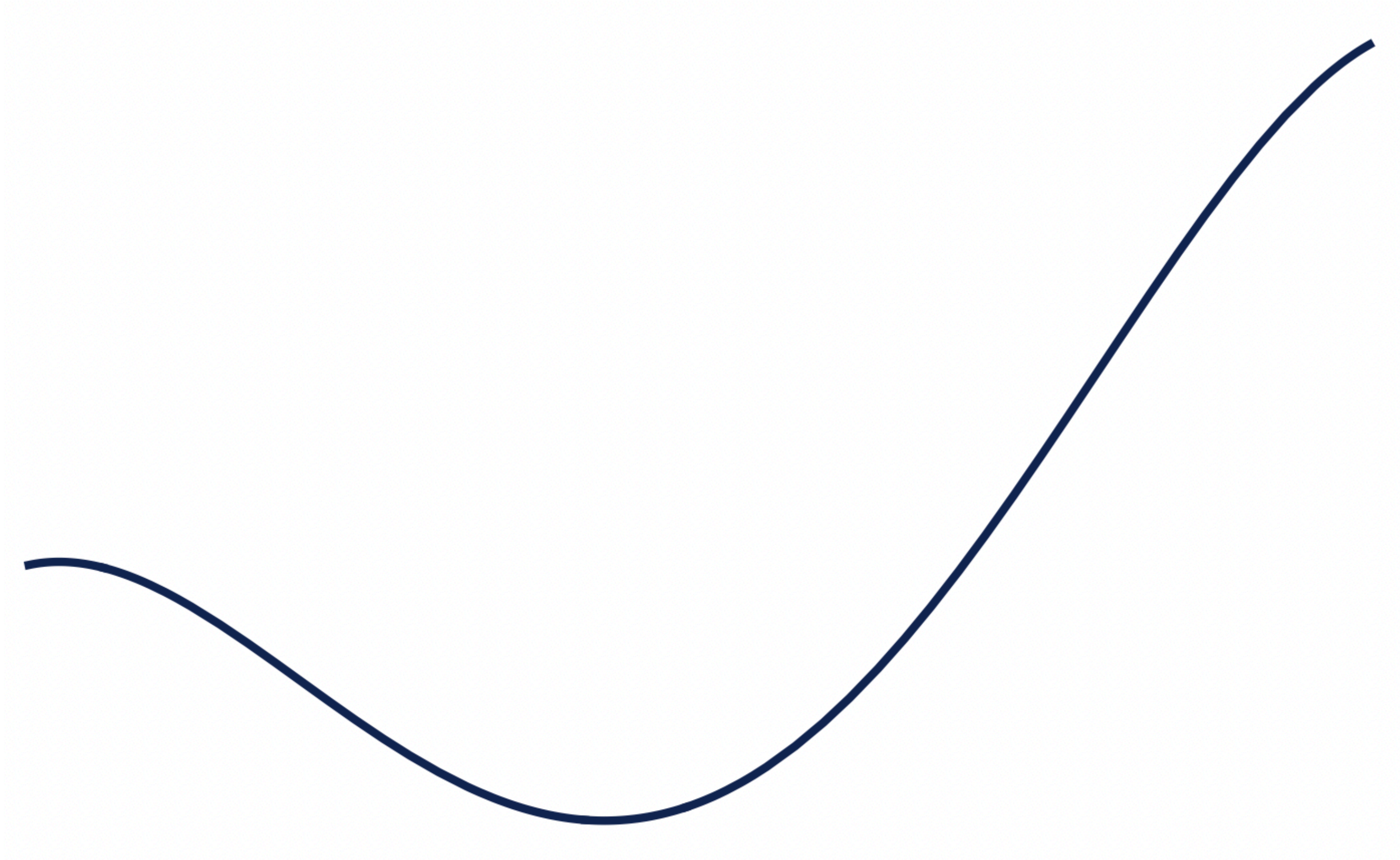
$$V_+ = -\frac{1}{2}m^2_{\phi_+}\phi_+^2 - \frac{m^2_{\phi_+}}{4M_+^2}\phi_+^4 + \Lambda^4_{\rm tot}(\langle h \rangle)\left(\theta^+_{\rm eff}\frac{\phi_+}{F_+} + \frac{\phi_+^2}{2F_+^2}\right)$$



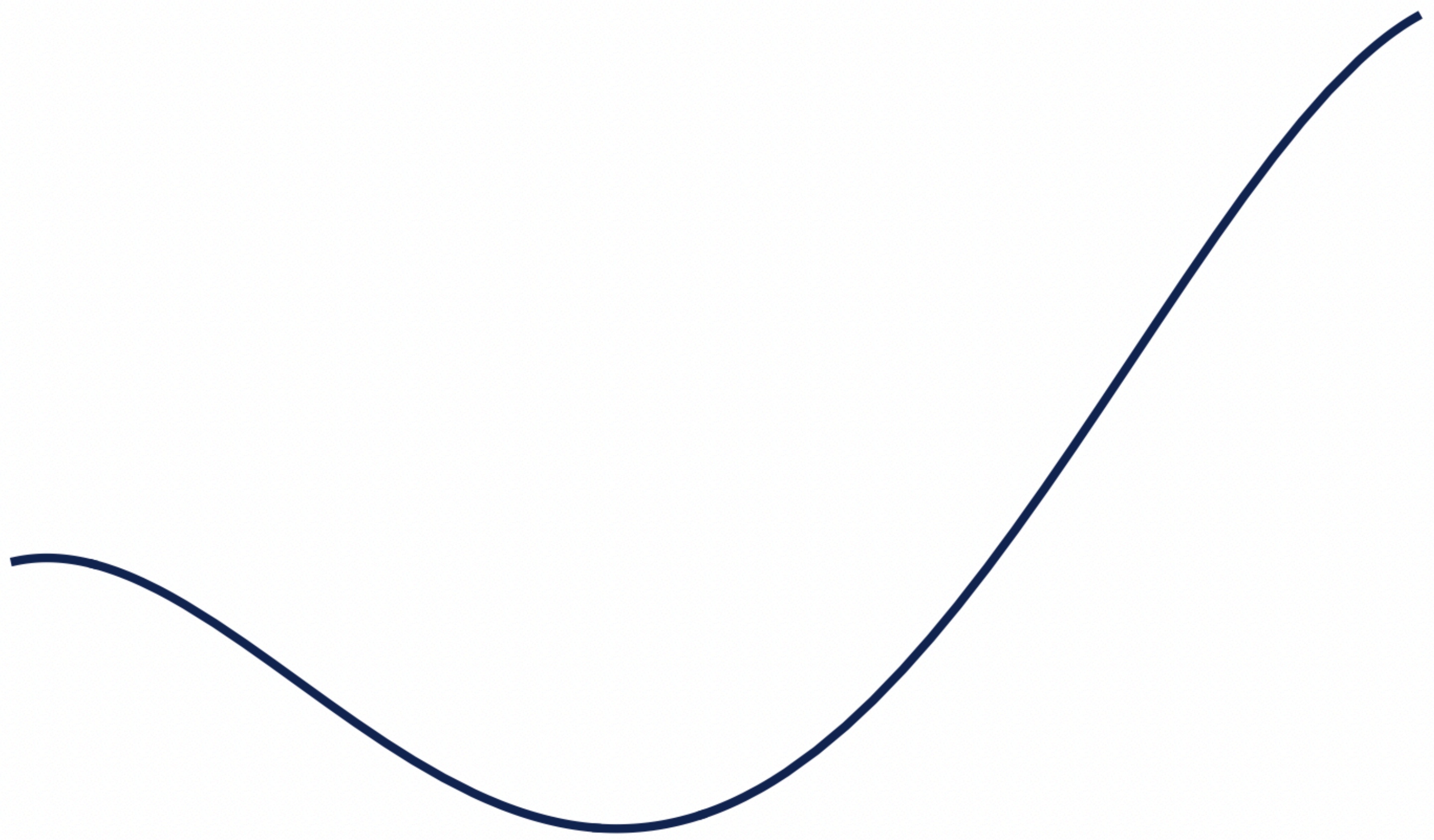
# The use of triggers: *Sliding Naturalness*

With these assumptions the potential of $\phi_+$ looks like:

$$V_+ = -\frac{1}{2}m_{\phi_+}^2\phi_+^2 - \frac{m_{\phi_+}^2}{4M_+^2}\phi_+^4 + \Lambda_{\text{tot}}^4(\langle h \rangle)\left(\theta_{\text{eff}}^+\frac{\phi_+}{F_+} + \frac{\phi_+^2}{2F_+^2}\right)$$



# The use of triggers: *Sliding Naturalness*



A safe local minimum around the origin is created if:

$m_{\phi_+}^2 F_+^2 \lesssim \Lambda_{\text{tot}}^4(\langle h \rangle)$ <u>and</u> $\theta_{\text{eff}}^+ \lesssim \dfrac{M_+}{F_+}$

i.e. the $\Lambda_{\text{tot}}^4(\langle h \rangle)$ term dominates the negative mass term of $\phi_+$ at the origin

# The use of triggers: *Sliding Naturalness*

*All the universes that survive have a light doublet with a VEV* $\langle h \rangle$

$$m_{\phi_+}^2 F_+^2 \lesssim \Lambda_{\rm tot}^4(\langle h \rangle) \lesssim \frac{m_{\phi_-}^2}{\theta_{\rm eff}^-} M_- F_-, \qquad \text{and} \qquad \theta_{\rm eff}^+ \lesssim \frac{M_+}{F_+}$$

# The use of triggers: *Sliding Naturalness*

*Can we address other problems with those triggers?*

Doublet-triplet splitting problem in GUTs on top of the weak scale hierarchy problem and strong CP problem
**Csaki, D'Agnolo, Kuflik & PS (2024)**

+ the monopole problem in GUTs
**PS (work in progress)**

# Can we find new triggers?

*Can we find new triggers using only the fields we already know exist?*

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*Can we find new triggers using only the fields we already know exist?*

This provides a model-independent search of new minimal building blocks for cosmological naturalness without introducing additional weak-scale electroweak charged states

A null result would tell us that any successful trigger mechanism must come with **new, testable degrees of freedom** near the weak scale, sharpening the experimental targets.

# Can we find new triggers?

*Why not simply build new BSM triggers?*

# The SMEFT at dimension six

| $(\bar{L}L)(\bar{L}L)$ | | $(\bar{R}R)(\bar{R}R)$ | | $(\bar{L}L)(\bar{R}R)$ | |
|---|---|---|---|---|---|
| $Q_{ll}$ | $(\bar{l}_p\gamma_\mu l_r)(\bar{l}_s\gamma^\mu l_t)$ | $Q_{ee}$ | $(\bar{e}_p\gamma_\mu e_r)(\bar{e}_s\gamma^\mu e_t)$ | $Q_{le}$ | $(\bar{l}_p\gamma_\mu l_r)(\bar{e}_s\gamma^\mu e_t)$ |
| $Q_{qq}^{(1)}$ | $(\bar{q}_p\gamma_\mu q_r)(\bar{q}_s\gamma^\mu q_t)$ | $Q_{uu}$ | $(\bar{u}_p\gamma_\mu u_r)(\bar{u}_s\gamma^\mu u_t)$ | $Q_{lu}$ | $(\bar{l}_p\gamma_\mu l_r)(\bar{u}_s\gamma^\mu u_t)$ |
| $Q_{qq}^{(3)}$ | $(\bar{q}_p\gamma_\mu\tau^I q_r)(\bar{q}_s\gamma^\mu\tau^I q_t)$ | $Q_{dd}$ | $(\bar{d}_p\gamma_\mu d_r)(\bar{d}_s\gamma^\mu d_t)$ | $Q_{ld}$ | $(\bar{l}_p\gamma_\mu l_r)(\bar{d}_s\gamma^\mu d_t)$ |
| $Q_{lq}^{(1)}$ | $(\bar{l}_p\gamma_\mu l_r)(\bar{q}_s\gamma^\mu q_t)$ | $Q_{eu}$ | $(\bar{e}_p\gamma_\mu e_r)(\bar{u}_s\gamma^\mu u_t)$ | $Q_{qe}$ | $(\bar{q}_p\gamma_\mu q_r)(\bar{e}_s\gamma^\mu e_t)$ |
| $Q_{lq}^{(3)}$ | $(\bar{l}_p\gamma_\mu\tau^I l_r)(\bar{q}_s\gamma^\mu\tau^I q_t)$ | $Q_{ed}$ | $(\bar{e}_p\gamma_\mu e_r)(\bar{d}_s\gamma^\mu d_t)$ | $Q_{qu}^{(1)}$ | $(\bar{q}_p\gamma_\mu q_r)(\bar{u}_s\gamma^\mu u_t)$ |
| | | $Q_{ud}^{(1)}$ | $(\bar{u}_p\gamma_\mu u_r)(\bar{d}_s\gamma^\mu d_t)$ | $Q_{qu}^{(8)}$ | $(\bar{q}_p\gamma_\mu T^A q_r)(\bar{u}_s\gamma^\mu T^A u_t)$ |
| | | $Q_{ud}^{(8)}$ | $(\bar{u}_p\gamma_\mu T^A u_r)(\bar{d}_s\gamma^\mu T^A d_t)$ | $Q_{qd}^{(1)}$ | $(\bar{q}_p\gamma_\mu q_r)(\bar{d}_s\gamma^\mu d_t)$ |
| | | | | $Q_{qd}^{(8)}$ | $(\bar{q}_p\gamma_\mu T^A q_r)(\bar{d}_s\gamma^\mu T^A d_t)$ |
| $(\bar{L}R)(\bar{R}L)$ and $(\bar{L}R)(\bar{L}R)$ | | $B$-violating | | | |
| $Q_{ledq}$ | $(\bar{l}_p^j e_r)(\bar{d}_s q_t^j)$ | $Q_{duq}$ | $\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(q_s^{\gamma j})^T C l_t^k\right]$ | | |
| $Q_{quqd}^{(1)}$ | $(\bar{q}_p^j u_r)\varepsilon_{jk}(\bar{q}_s^k d_t)$ | $Q_{qqu}$ | $\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(u_s^\gamma)^T C e_t\right]$ | | |
| $Q_{quqd}^{(8)}$ | $(\bar{q}_p^j T^A u_r)\varepsilon_{jk}(\bar{q}_s^k T^A d_t)$ | $Q_{qqq}$ | $\varepsilon^{\alpha\beta\gamma}\varepsilon_{jn}\varepsilon_{km}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(q_s^{\gamma m})^T C l_t^n\right]$ | | |
| $Q_{lequ}^{(1)}$ | $(\bar{l}_p^j e_r)\varepsilon_{jk}(\bar{q}_s^k u_t)$ | $Q_{duu}$ | $\varepsilon^{\alpha\beta\gamma}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(u_s^\gamma)^T C e_t\right]$ | | |
| $Q_{lequ}^{(3)}$ | $(\bar{l}_p^j \sigma_{\mu\nu} e_r)\varepsilon_{jk}(\bar{q}_s^k \sigma^{\mu\nu} u_t)$ | | | | |

| $X^3$ | | $\varphi^6$ and $\varphi^4 D^2$ | | $\psi^2\varphi^3$ | |
|---|---|---|---|---|---|
| $Q_G$ | $f^{ABC}G_\mu^{A\nu}G_\nu^{B\rho}G_\rho^{C\mu}$ | $Q_\varphi$ | $(\varphi^\dagger\varphi)^3$ | $Q_{e\varphi}$ | $(\varphi^\dagger\varphi)(\bar{l}_p e_r\varphi)$ |
| $Q_{\widetilde{G}}$ | $f^{ABC}\widetilde{G}_\mu^{A\nu}G_\nu^{B\rho}G_\rho^{C\mu}$ | $Q_{\varphi\Box}$ | $(\varphi^\dagger\varphi)\Box(\varphi^\dagger\varphi)$ | $Q_{u\varphi}$ | $(\varphi^\dagger\varphi)(\bar{q}_p u_r\widetilde{\varphi})$ |
| $Q_W$ | $\varepsilon^{IJK}W_\mu^{I\nu}W_\nu^{J\rho}W_\rho^{K\mu}$ | $Q_{\varphi D}$ | $\left(\varphi^\dagger D^\mu\varphi\right)^\star\left(\varphi^\dagger D_\mu\varphi\right)$ | $Q_{d\varphi}$ | $(\varphi^\dagger\varphi)(\bar{q}_p d_r\varphi)$ |
| $Q_{\widetilde{W}}$ | $\varepsilon^{IJK}\widetilde{W}_\mu^{I\nu}W_\nu^{J\rho}W_\rho^{K\mu}$ | | | | |
| $X^2\varphi^2$ | | $\psi^2 X\varphi$ | | $\psi^2\varphi^2 D$ | |
| $Q_{\varphi G}$ | $\varphi^\dagger\varphi\, G_{\mu\nu}^A G^{A\mu\nu}$ | $Q_{eW}$ | $(\bar{l}_p\sigma^{\mu\nu}e_r)\tau^I\varphi W_{\mu\nu}^I$ | $Q_{\varphi l}^{(1)}$ | $(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar{l}_p\gamma^\mu l_r)$ |
| $Q_{\varphi\widetilde{G}}$ | $\varphi^\dagger\varphi\,\widetilde{G}_{\mu\nu}^A G^{A\mu\nu}$ | $Q_{eB}$ | $(\bar{l}_p\sigma^{\mu\nu}e_r)\varphi B_{\mu\nu}$ | $Q_{\varphi l}^{(3)}$ | $(\varphi^\dagger i\overleftrightarrow{D}_\mu^I\varphi)(\bar{l}_p\tau^I\gamma^\mu l_r)$ |
| $Q_{\varphi W}$ | $\varphi^\dagger\varphi\, W_{\mu\nu}^I W^{I\mu\nu}$ | $Q_{uG}$ | $(\bar{q}_p\sigma^{\mu\nu}T^A u_r)\widetilde{\varphi}\, G_{\mu\nu}^A$ | $Q_{\varphi e}$ | $(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar{e}_p\gamma^\mu e_r)$ |
| $Q_{\varphi\widetilde{W}}$ | $\varphi^\dagger\varphi\,\widetilde{W}_{\mu\nu}^I W^{I\mu\nu}$ | $Q_{uW}$ | $(\bar{q}_p\sigma^{\mu\nu}u_r)\tau^I\widetilde{\varphi}\, W_{\mu\nu}^I$ | $Q_{\varphi q}^{(1)}$ | $(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar{q}_p\gamma^\mu q_r)$ |
| $Q_{\varphi B}$ | $\varphi^\dagger\varphi\, B_{\mu\nu}B^{\mu\nu}$ | $Q_{uB}$ | $(\bar{q}_p\sigma^{\mu\nu}u_r)\widetilde{\varphi}\, B_{\mu\nu}$ | $Q_{\varphi q}^{(3)}$ | $(\varphi^\dagger i\overleftrightarrow{D}_\mu^I\varphi)(\bar{q}_p\tau^I\gamma^\mu q_r)$ |
| $Q_{\varphi\widetilde{B}}$ | $\varphi^\dagger\varphi\,\widetilde{B}_{\mu\nu}B^{\mu\nu}$ | $Q_{dG}$ | $(\bar{q}_p\sigma^{\mu\nu}T^A d_r)\varphi\, G_{\mu\nu}^A$ | $Q_{\varphi u}$ | $(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar{u}_p\gamma^\mu u_r)$ |
| $Q_{\varphi WB}$ | $\varphi^\dagger\tau^I\varphi\, W_{\mu\nu}^I B^{\mu\nu}$ | $Q_{dW}$ | $(\bar{q}_p\sigma^{\mu\nu}d_r)\tau^I\varphi\, W_{\mu\nu}^I$ | $Q_{\varphi d}$ | $(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar{d}_p\gamma^\mu d_r)$ |
| $Q_{\varphi\widetilde{W}B}$ | $\varphi^\dagger\tau^I\varphi\,\widetilde{W}_{\mu\nu}^I B^{\mu\nu}$ | $Q_{dB}$ | $(\bar{q}_p\sigma^{\mu\nu}d_r)\varphi\, B_{\mu\nu}$ | $Q_{\varphi ud}$ | $i(\widetilde{\varphi}^\dagger D_\mu\varphi)(\bar{u}_p\gamma^\mu d_r)$ |

Grzadkowski, Iskrzyński, Misiak & Rosiek (2017)

# Can we find new triggers in the SMEFT?

Recall that a trigger operator $\mathcal{O}$ should satisfy

$$\frac{d\log\langle\mathcal{O}\rangle}{d\log m_h^2} = O(1)$$

so that changing $m_h^2$ must change something locally in the vacuum

# Can we find new triggers in he SMEFT?

Recall that a trigger operator $\mathcal{O}$ should satisfy

$$\frac{d \log \langle \mathcal{O} \rangle}{d \log m_h^2} = O(1)$$

so that changing $m_h^2$ must change something locally in the vacuum

But how to estimate $\langle \mathcal{O} \rangle$?

# How to compute $\langle \mathcal{O} \rangle$?

Add a linear source for $\mathcal{O}$ and differentiate the generating functional

$$Z[\lambda] = \int \mathcal{D}\Phi \ \exp\left( i \int \mathcal{L}_{\mathrm{SM}} + \lambda \mathcal{O} \right) , \qquad \langle \mathcal{O}(x) \rangle = \frac{\delta W}{\delta \lambda(x)} \bigg|_{\lambda=0}$$

where $W[\lambda] = -\, i \log Z[\lambda]$

# The practical trick (probe scalar)

Promote the source to a light field $\phi$ with a tiny coupling $\xi$

$$\mathscr{L} \supset \frac{(\partial\phi)^2}{2} - \xi\phi\mathcal{O}_{\text{SMEFT}}$$

Integrate out SM fields gives an EFT potential with

$$V_{\text{eff}}(\phi) = \xi\phi\langle\mathcal{O}_{\text{SMEFT}}\rangle + O(\xi^2\phi^2)$$

This means we only need to evaluate the tadpole diagram for $\phi$

# The power-counting template

*What does $\langle \mathcal{O} \rangle$ look like in an EFT with cutoff $\Lambda_H$?*

In an EFT completed into a UV theory where the VEV is calculable at a scale $\Lambda_H$, all contributions to $\langle \mathcal{O} \rangle$ are of the form

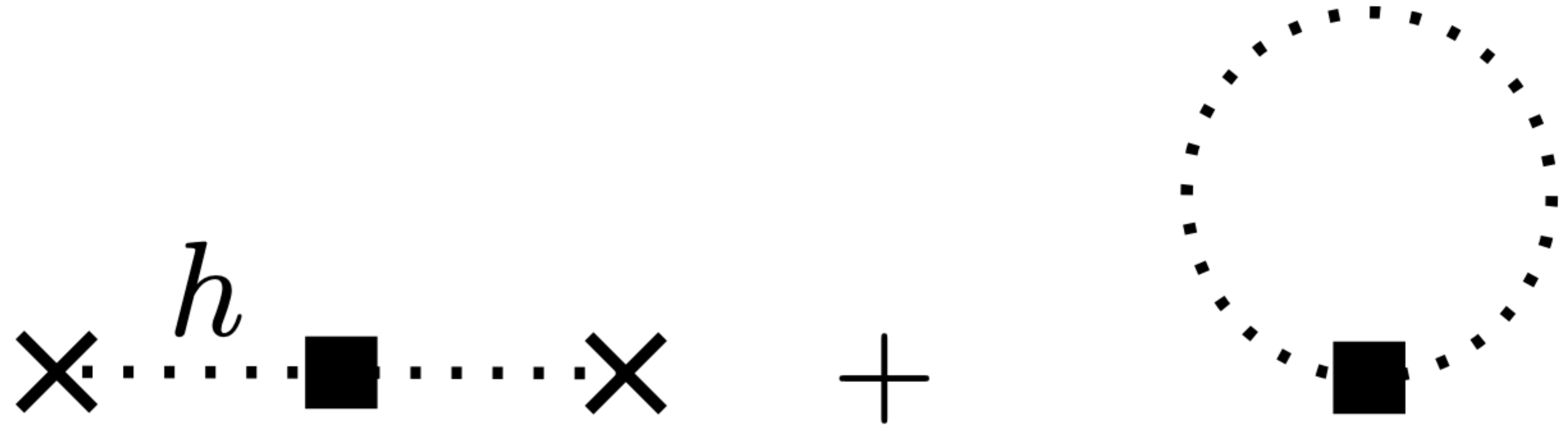
$$\langle \mathcal{O} \rangle = \sum_i \frac{\varepsilon_i}{(16\pi^2)^{\ell_i}} \Lambda_H^{d-n_i} \langle h \rangle^{n_i}$$

$n_i$ is the power of $\langle h \rangle$ enforced by symmetries and $\varepsilon_i$ are hard symmetry-breaking spurions (Yukawa, CKM, gauge couplings…)

# Example 0

Take $\mathcal{O}_H = H^\dagger H$

$$\langle |H|^2 \rangle \simeq$$



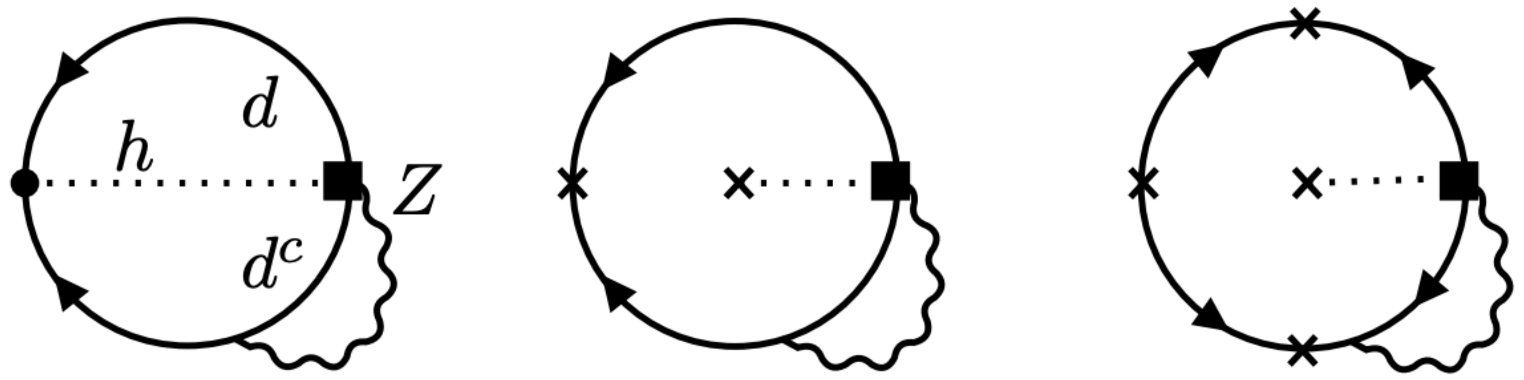

$$\langle \mathcal{O} \rangle = \sum_i \frac{\varepsilon_i}{(16\pi^2)^{\ell_i}} \Lambda_H^{d-n_i} \langle h \rangle^{n_i}$$

$$\langle \mathcal{O}_H \rangle = v^2 + c_2 \frac{\Lambda_H^2}{16\pi^2}$$

If the UV term is allowed, it wins unless $\Lambda_H \lesssim 4\pi v$

# Example 1

Take for instance $\mathcal{O}_{QHW} = \left(Q^\dagger \bar{\sigma}^{\mu\nu} d^{c\dagger}\right) \tau^I H W^I_{\mu\nu}$




$$\langle \mathcal{O} \rangle = \sum_i \frac{\varepsilon_i}{(16\pi^2)^{\ell_i}} \Lambda_H^{d-n_i} \langle h \rangle^{n_i}$$

$$\langle \mathcal{O}_{QHW} \rangle = \frac{g^2 y_d}{\sqrt{g^2 + g'^2}} \left( c^{(1)}_{QHW} \frac{\Lambda_H^6}{(16\pi^2)^3} + c^{(2)}_{QHW} v^2 \frac{\Lambda_H^4}{(16\pi^2)^2} + c^{(3)}_{QHW} v^4 y_d^2 \frac{\Lambda_H^2}{(16\pi^2)^2} \right) + \ldots$$

# Example 1

$$\langle \mathcal{O}_{QHW} \rangle = \frac{g^2 y_d}{\sqrt{g^2 + g'^2}} \left( c^{(1)}_{QHW} \frac{\Lambda_H^6}{(16\pi^2)^3} + c^{(2)}_{QHW} v^2 \frac{\Lambda_H^4}{(16\pi^2)^2} + c^{(3)}_{QHW} v^4 y_d^2 \frac{\Lambda_H^2}{(16\pi^2)^2} \right) + \ldots$$

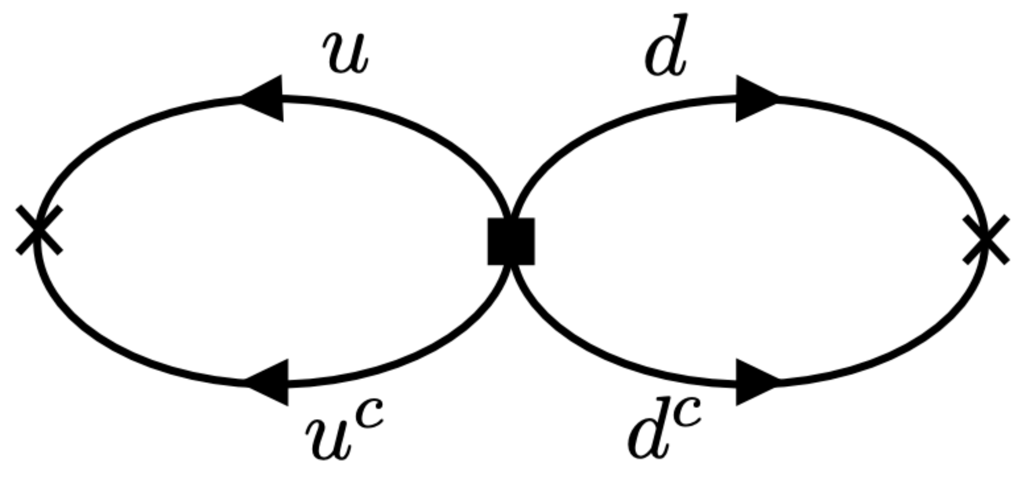
Trigger test: UV piece *vs* EWSB-sensitive piece

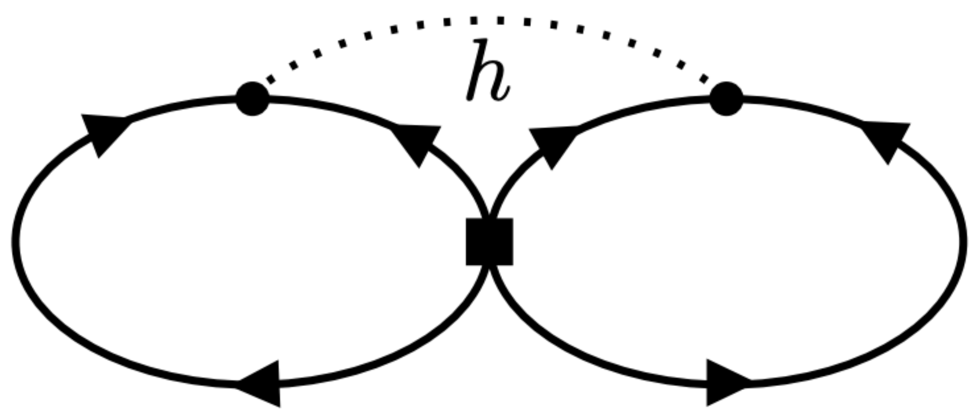
$$\frac{\Lambda_H^6/(16\pi^2)^3}{v^2 \Lambda_H^4/(16\pi^2)^2} \sim \frac{\Lambda_H^2}{16\pi^2 v^2}$$

Requiring EWSB term $\gtrsim$ UV term gives $\Lambda_H \lesssim 4\pi v$

# Example 2

Take for instance $\mathcal{O}_{LR} = (Qu^c)(Qd^c)$




$$\langle \mathcal{O} \rangle = \sum_i \frac{\varepsilon_i}{(16\pi^2)^{\ell_i}} \Lambda_H^{d-n_i} \langle h \rangle^{n_i}$$

$$\langle \mathcal{O}_{LR} \rangle = c_{1LR} \Lambda_{\rm QCD}^2 f_\pi^4 + c_{2LR} m_u m_d \frac{\Lambda_H^4}{(16\pi^2)^2} + c_{3LR} y_u y_d \frac{\Lambda_H^6}{(16\pi^2)^3}$$

# Example 2

$$\langle \mathcal{O}_{LR} \rangle = c_{1LR}\Lambda_{\rm QCD}^2 f_\pi^4 + c_{2LR} m_u m_d \frac{\Lambda_H^4}{(16\pi^2)^2} + c_{3LR} y_u y_d \frac{\Lambda_H^6}{(16\pi^2)^3}$$

Trigger test: UV piece *vs* EWSB-sensitive piece

$$\frac{y_u y_d \Lambda_H^6/(16\pi^2)^3}{(y_u v)(y_d v)\Lambda_H^4/(16\pi^2)^2} \sim \frac{\Lambda_H^2}{16\pi^2 v^2}$$

Requiring EWSB term $\gtrsim$ UV term gives $\Lambda_H \lesssim 4\pi v$

# Example 2

$$\langle \mathcal{O}_{LR} \rangle = c_{1LR}\Lambda^2_{\mathrm{QCD}} f^4_\pi + c_{2LR} m_u m_d \frac{\Lambda^4_H}{(16\pi^2)^2} + c_{3LR} y_u y_d \frac{\Lambda^6_H}{(16\pi^2)^3}$$

In the limit $y_{u,d} \to 0$ leaves only the QCD condensate contribution , which is IR and through it Higgs-VEV dependence can be made to track EWSB

But the SM spurions are not small enough to achieve this…

# No weak scale triggers in the SMEFT at dimension 6

Scanning SMEFT operators up to dimension-6 gives a null result:

**no operator yields a trigger that works beyond** $\Lambda_H \sim 4\pi v$

Most operators allow an $n = 0$ term (a $\Lambda_H^6$ term) $\Rightarrow$ UV-dominated VEV

The few "protected" candidates are spurion-suppressed, but not enough in the SM

# How exactly operators do fail?

*Four ways a SMEFT operator fails as a trigger*

No symmetry: $\langle \mathcal{O} \rangle$ is UV-dominated

Unbroken symmetry: $\langle \mathcal{O} \rangle = 0$

Hard breaking only: spurion-suppressed, but still $\Lambda_H \lesssim 4\pi v$

Hard+soft breaking: promising, but not enough in the SM

# Failure mode I: No symmetry

If nothing forbids an $n = 0$ term, then necessary $\langle \mathcal{O} \rangle \sim \Lambda_H^6$

| No Symmetry | $\Lambda_H$ |
|---|---|
| $(H^\dagger H)^3$ | $4\pi v$ |
| $\lvert H^\dagger D_\mu H\rvert^2$ | $4\pi v$ |
| $H^\dagger H \Box H^\dagger H$ | $4\pi v$ |
| $H^\dagger H B_{\mu\nu} B^{\mu\nu}$ | $4\pi v$ |
| $H^\dagger H \mathrm{Tr}[W_{\mu\nu} W^{\mu\nu}]$ | $4\pi v$ |
| $H^\dagger H \mathrm{Tr}[G_{\mu\nu} G^{\mu\nu}]$ | $4\pi v$ |
| $H^\dagger \tau^I H\, W^I_{\mu\nu} B^{\mu\nu}$ | $4\pi v$ |
| $(\psi^\dagger \bar\sigma^\mu \psi)^2$ | $4\pi v$ |
| $(\psi^\dagger \tau^I \bar\sigma^\mu \psi)^2$ | $4\pi v$ |
| $(\psi^\dagger \bar\sigma^\mu \psi)(\psi^{c\dagger} \bar\sigma_\mu \psi^c)$ | $4\pi v$ |
| $(\psi^{c\dagger} \bar\sigma^\mu \psi^c)^2$ | $4\pi v$ |
| $H^\dagger \tau^I\, W^I_{\mu\nu} (\psi^c \sigma^{\mu\nu} \psi)$ | $4\pi v$ |
| $H^\dagger B_{\mu\nu} (\psi^c \sigma^{\mu\nu} \psi)$ | $4\pi v$ |
| $(H^\dagger \overleftrightarrow{D}_\mu H)(\psi^\dagger \bar\sigma^\mu \psi)$ | $4\pi v$ |
| $(H^\dagger \overleftrightarrow{D}^I_\mu H)(\psi^\dagger \tau^I \bar\sigma^\mu \psi)$ | $4\pi v$ |
| $(H^\dagger \overleftrightarrow{D}_\mu H)(\psi^{c\dagger} \bar\sigma^\mu \psi^c)$ | $4\pi v$ |

For these operators we schematically have

$$\langle \mathcal{O} \rangle \sim \Lambda_H^6 + v^2 \Lambda_H^2 + v^4 \Lambda_H^2 + \cdots$$

# Failure mode II: Unbroken symmetry

If $\mathcal{O}$ is charged under an exact symmetry of the vacuum, then $\langle \mathcal{O} \rangle = 0$

| **Unbroken Symmetry** | Symmetry |
|---|---|
| $(HL)^2$ | Lepton Number |
| $QQQL$ | Baryon Number |
| $d^c u^c u^c e^c$ | Baryon and Lepton Number |
| $QQu^c e^c$ | Baryon and Lepton Number |
| $QLu^c d^c$ | Baryon and Lepton Number |

Concretely, this means there is no way to close the legs of the operator $\mathcal{O}$ with SM vertices to compute $\langle \mathcal{O} \rangle$

# Failure mode III: Hard breaking only

Approximate symmetries force spurions, but dimensionless spurions don't force extra powers of $v$

| Hard Breaking Only | $\Lambda_H$ | Symmetry |
|---|---|---|
| $(\psi_i^\dagger\bar\sigma^\mu\psi_j)(\psi_k^\dagger\bar\sigma_\mu\psi_l)$ | $4\pi v$ | Flavor |
| $(\psi_i^\dagger\tau^I\bar\sigma^\mu\psi_j)(\psi_k^\dagger\tau^I\bar\sigma_\mu\psi_l)$ | $4\pi v$ | Flavor |
| $(\psi_i^\dagger\bar\sigma^\mu\psi_j)(\psi_k^{c\dagger}\bar\sigma_\mu\psi_l^c)$ | $4\pi v$ | Flavor |
| $(\psi_i^{c\dagger}\bar\sigma^\mu\psi_j^c)(\psi_k^{c\dagger}\bar\sigma_\mu\psi_l^c)$ | $4\pi v$ | Flavor |
| $(H^\dagger\overleftrightarrow{D}_\mu H)(\psi_i^\dagger\bar\sigma^\mu\psi_j)$ | $4\pi v$ | Flavor |
| $(H^\dagger\overleftrightarrow{D}^I_\mu H)(\psi_i^\dagger\tau^I\bar\sigma^\mu\psi_j)$ | $4\pi v$ | Flavor |
| $(H^\dagger\overleftrightarrow{D}_\mu H)(\psi_i^c\sigma^\mu\psi_j^{c\dagger})$ | $4\pi v$ | Flavor |
| $(\tilde H^\dagger iD_\mu H)(u_i^{c\dagger}\bar\sigma^\mu d_j^c)$ | $4\pi v$ | Flavor |
| $(\psi_i^\dagger\bar\sigma^{\mu\nu}\psi_j^{c\dagger})\tau^I H\, W^I_{\mu\nu}$ | $4\pi v$ | Flavor |
| $(\psi_i^\dagger\bar\sigma^{\mu\nu}\psi_j^{c\dagger})H\, B_{\mu\nu}$ | $4\pi v$ | Flavor |
| $(\psi_i^\dagger\bar\sigma^{\mu\nu}T^A\psi_j^{c\dagger})H\, G^A_{\mu\nu}$ | $4\pi v$ | Flavor |
| $(Le^c)^\dagger(Q_i d_j^c)$ | $4\pi v$ | Flavor |
| $(Le^c)(Q_i u_j^c)$ | $4\pi v$ | Flavor |
| $(H^\dagger H)(\psi_i H\psi_j^c)$ | $4\pi v$ | Flavor |
| $(L_i\sigma^{\mu\nu}e_j^c)(Q_k\sigma_{\mu\nu}u_l^c)$ | $4\pi v$ | Flavor |
| $(Q_i u_j^c)(Q_k d_l^c)$ | $4\pi v$ | Flavor |
| $(Q_iT^Au_j^c)(Q_kT^Ad_l^c)$ | $4\pi v$ | Flavor |
| $H^\dagger\tau^I H\widetilde{W}^I_{\mu\nu}B^{\mu\nu}$ | $4\pi v$ | CP |

Schematically we have:

$$\langle \mathcal{O} \rangle = \epsilon_{\text{hard}} \left( \frac{\Lambda_H^6}{(16\pi^2)^L} + \frac{v^2\Lambda_H^4}{(16\pi^2)^{L-1}} + \cdots \right)$$

where $\epsilon_{\text{hard}}$ cancels in the trigger test

# Failure mode IV: Hard and soft breaking

Now symmetry breaking includes a dimensionful piece tied to EWSB/QCD, so $\langle \mathcal{O} \rangle$ can have a genuinely IR-tracking term

| **Hard and Soft Breaking** | $\Lambda_H$ | Symmetry |
|---|---|---|
| $(H^\dagger H)(QHq^c)$ | $4\pi v \max\left[1, \left(\frac{\Lambda_{\rm QCD} f_\pi^2}{y_q v^3}\right)^{1/6}\right]$ | Chiral |
| $(Qu^c)(Qd^c)$ | $4\pi v \max\left[1, \left(\frac{\Lambda_{\rm QCD} f_\pi^2}{y_u y_d v^3}\right)^{1/6}\right]$ | Chiral |
| $(QT^A u^c)(QT^A d^c)$ | $4\pi v \max\left[1, \left(\frac{\Lambda_{\rm QCD} f_\pi^2}{y_u y_d v^3}\right)^{1/6}\right]$ | Chiral |
| $(Q_i^\dagger \bar\sigma^\mu T^A Q_j)(q_i^{c\dagger} \bar\sigma_\mu T^A q_j^c)$ | $4\pi v \max\left[1, \left(\frac{\Lambda_{\rm QCD} f_\pi^2}{y_u y_d v^3}\right)^{1/6}\right]$ | Chiral |
| $(\psi^\dagger \bar\sigma^{\mu\nu} T^A \psi^{c\dagger}) H\, G^A_{\mu\nu}$ | $4\pi v \max\left[1, \left(\frac{m_0^2 f_\pi^2 \Lambda_{\rm QCD}}{y_d g_s v^5}\right)^{1/6}\right]$ | Chiral |
| $(L\sigma^{\mu\nu} e^c)(Q\sigma_{\mu\nu} u^c)$ | $4\pi v \max\left[1, \left(\frac{\Lambda_{\rm QCD} f_\pi^2}{y_u v^3}\right)^{1/4}\right]$ | Chiral |
| $(Le^c)^\dagger (Qd^c)$ | $4\pi v \max\left[1, \left(\frac{\Lambda_{\rm QCD} f_\pi^2}{y_d v^3}\right)^{1/4}\right]$ | Chiral |
| $(Le^c)(Qu^c)$ | $4\pi v \max\left[1, \left(\frac{\Lambda_{\rm QCD} f_\pi^2}{y_u v^3}\right)^{1/4}\right]$ | Chiral |

Structure:

$$\langle \mathcal{O} \rangle = \langle \mathcal{O} \rangle_{\rm IR} + \epsilon_{\rm hard} \frac{\Lambda_H^6}{(16\pi^2)^L} + \epsilon_{\rm hard} \frac{v^2 \Lambda_H^4}{(16\pi^2)^{L-1}} + \cdots$$

# The null result persists at higher dimensions

***Could dimension-8 operators rescue SMEFT triggers?***

No if the UV piece is allowed: the same UV/EWSB competition repeats at any dimension

Trigger test: comparing $\dfrac{\Lambda_H^d}{(16\pi^2)^L}$ vs $\dfrac{v^2\Lambda_H^{d-2}}{(16\pi^2)^{L-1}}$ gives again $\Lambda_H \lesssim 4\pi v$

# What does this mean for model building?

To go above $\Lambda_H \sim 4\pi v$ we need either to use $G\tilde{G}$ or go beyond the SM

*We can focus on the three already known trigger operators*

$$G\tilde{G} \qquad H_1 H_2 \qquad F\tilde{F}+\text{VLF}$$

# What does this mean for model building?

To go above $\Lambda_H \sim 4\pi v$ we need either to use $G\tilde{G}$ or go beyond the SM

***We can focus on the three already known trigger operators***

| $G\tilde{G}$ | $H_1H_2$ | $F\tilde{F}$+VLF |
|---|---|---|
| The "new physics" shows up through axion-like signatures | Additional Higgs states: HL-LHC target | At least a light VL $SU(2)_L$ doublet: HL-LHC target |

# Conclusions

# Merci :)

Institut de Física
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EXCELENCIA
SEVERO
OCHOA

Asymmetry
Essential Asymmetries of Nature