

# BSM Higgs Overview

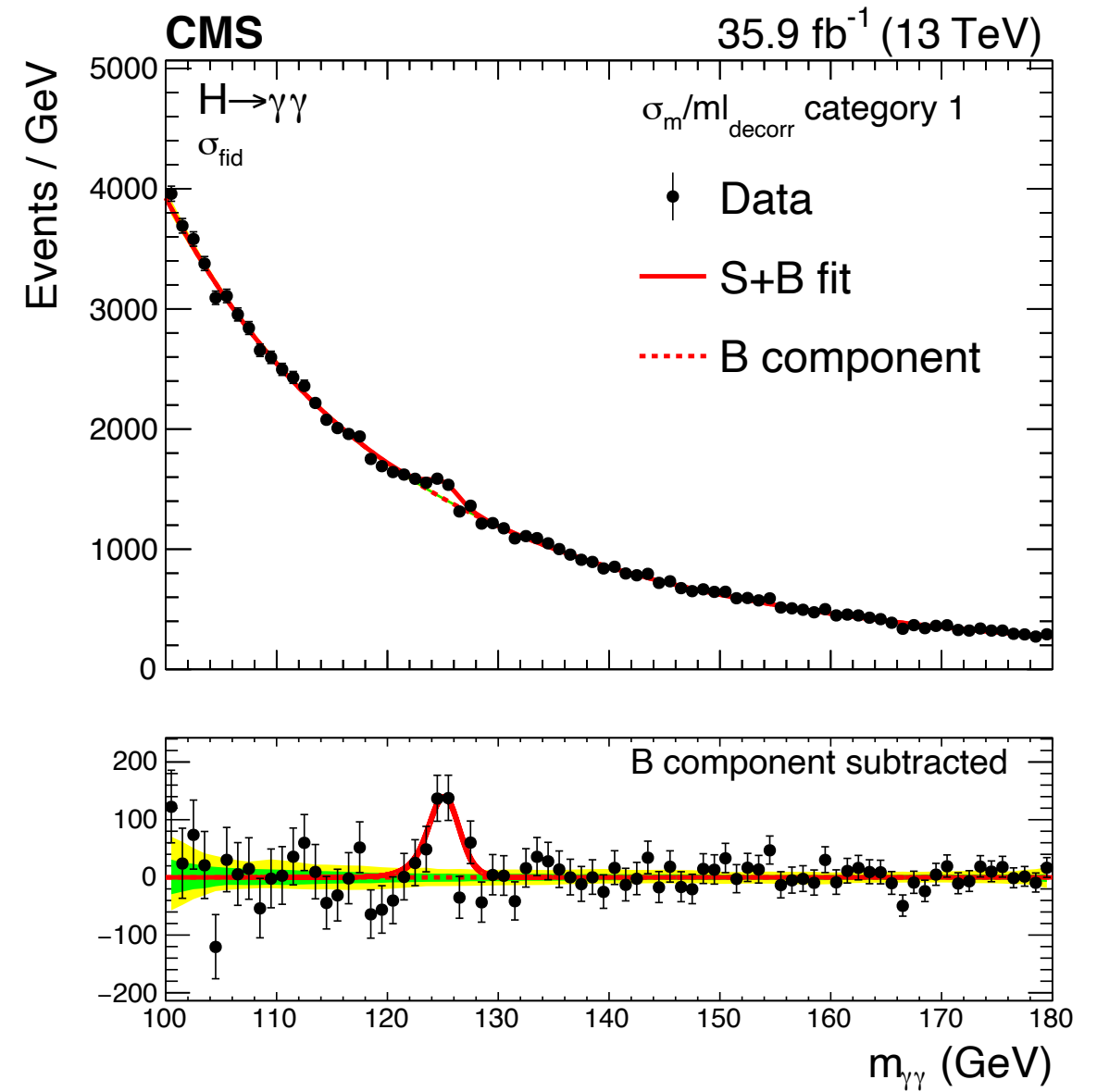
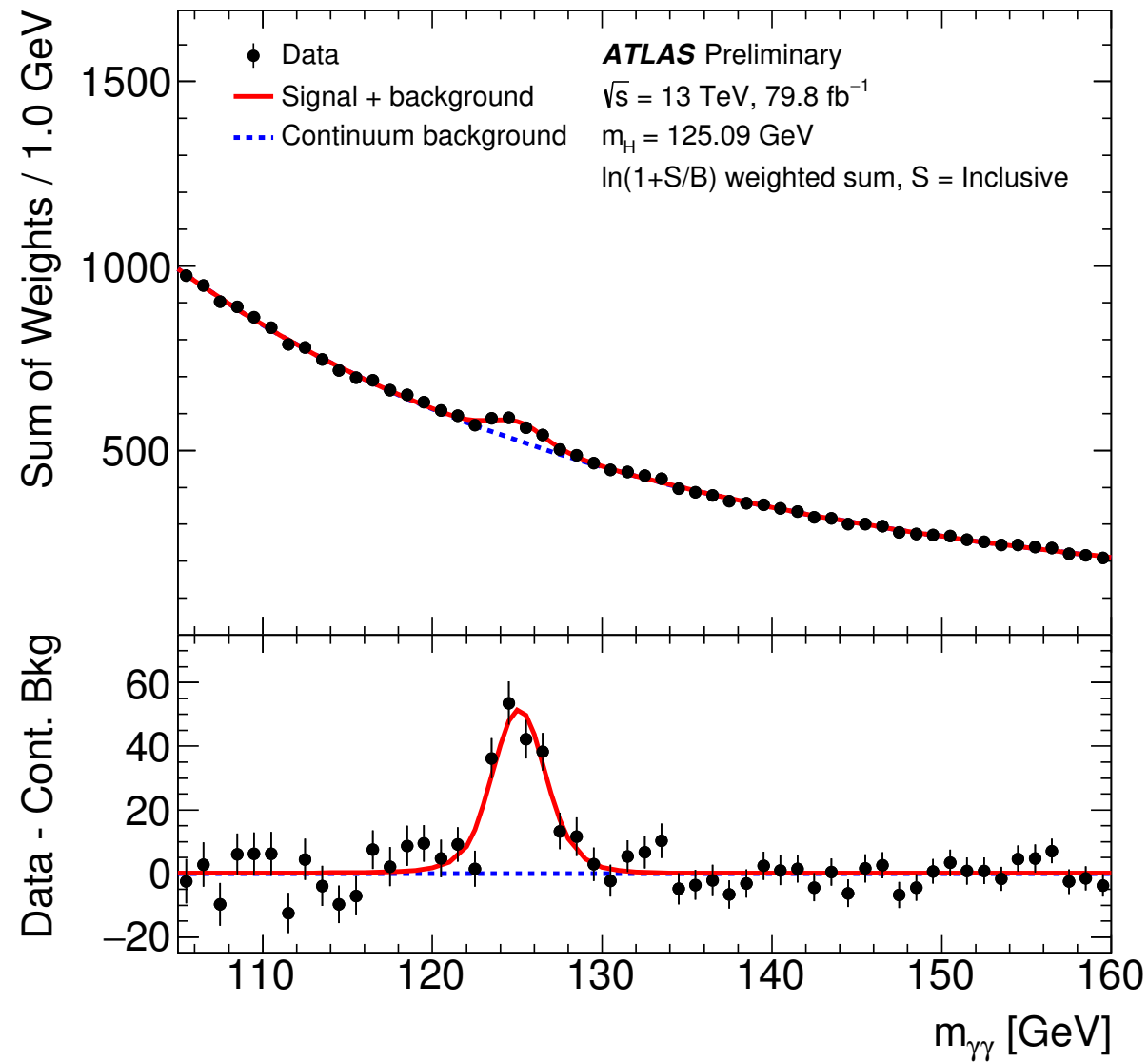
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# Outline

- Physics behind the SM
- Physics beyond the SM

# Milestone



A great leap towards the dynamics of EWSB!

# Behind the SM

- Quantum Mechanics + Lorentz invariance
- Gauge Invariance/Redundancy
- Renormalizability

# Renormalizability as a consequence

$$\Lambda_{\text{UV}} \lesssim 10^{18} \text{GeV}$$

$$\mathcal{L} \sim (\partial\phi)^2 + m^2\phi^2 + \lambda_4\phi^4 + \lambda_6\phi^6 + \lambda_8\phi^8 + \dots$$

RGE

$$m_t, m_{W,Z} \sim \mathcal{O}(100 \text{GeV})$$

$$\mathcal{L} \sim (\partial\phi)^2 + m^2\phi^2 + \lambda_4\phi^4 + \mathcal{O}\left(\frac{E^2}{\Lambda_{\text{UV}}^2}\right)$$

Wilson 71'  
Wilson and Kogut 74'  
Polchinski 83'

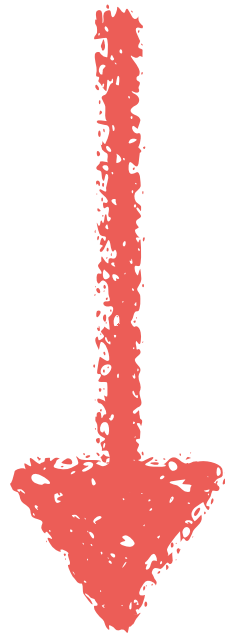
# Behind the SM

- SM as an effective field theory
- $C$ ,  $CP$ ,  $U(3)^5$  are all accidental symmetries
- All the terms consistent with symmetries will be generated from RGE

Are all the small parameters  
natural?

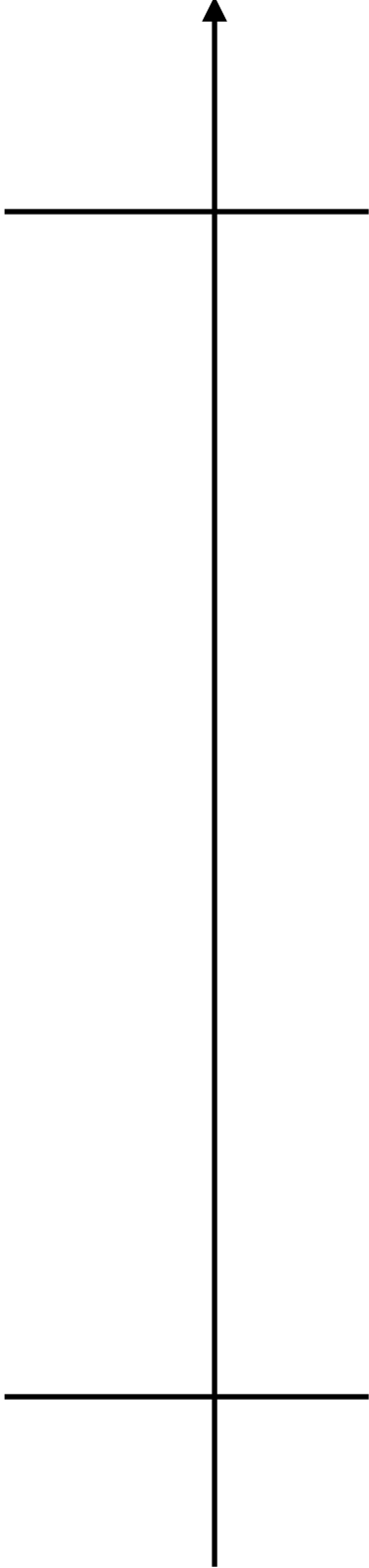
# t' Hooft Naturalness

A small parameter is natural  
if setting it to zero leads to an enhanced symmetry



Guideline for model building

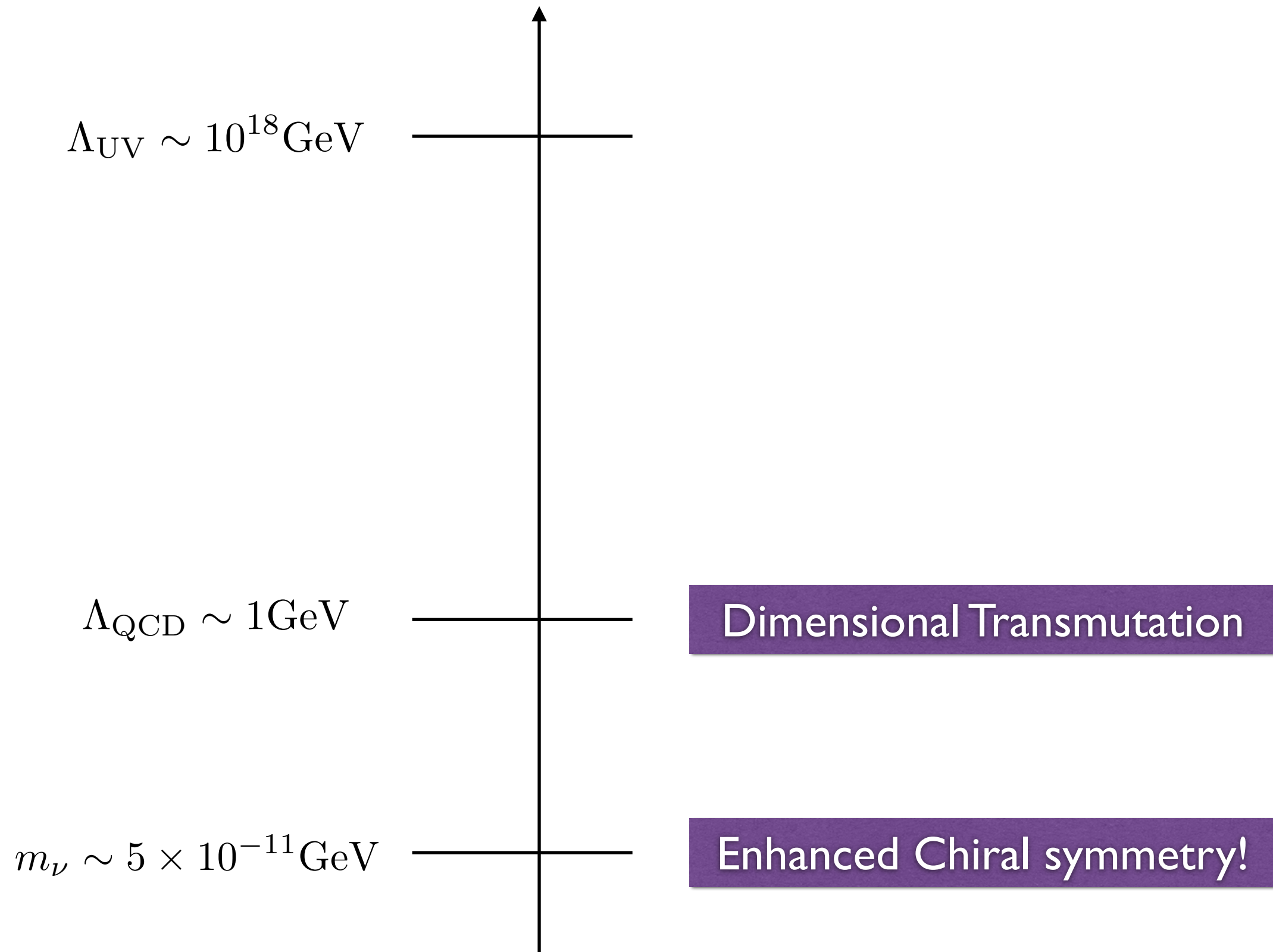
# t' Hooft Naturalness: SM Lesson


$$\Lambda_{UV} \sim 10^{18} \text{ GeV}$$

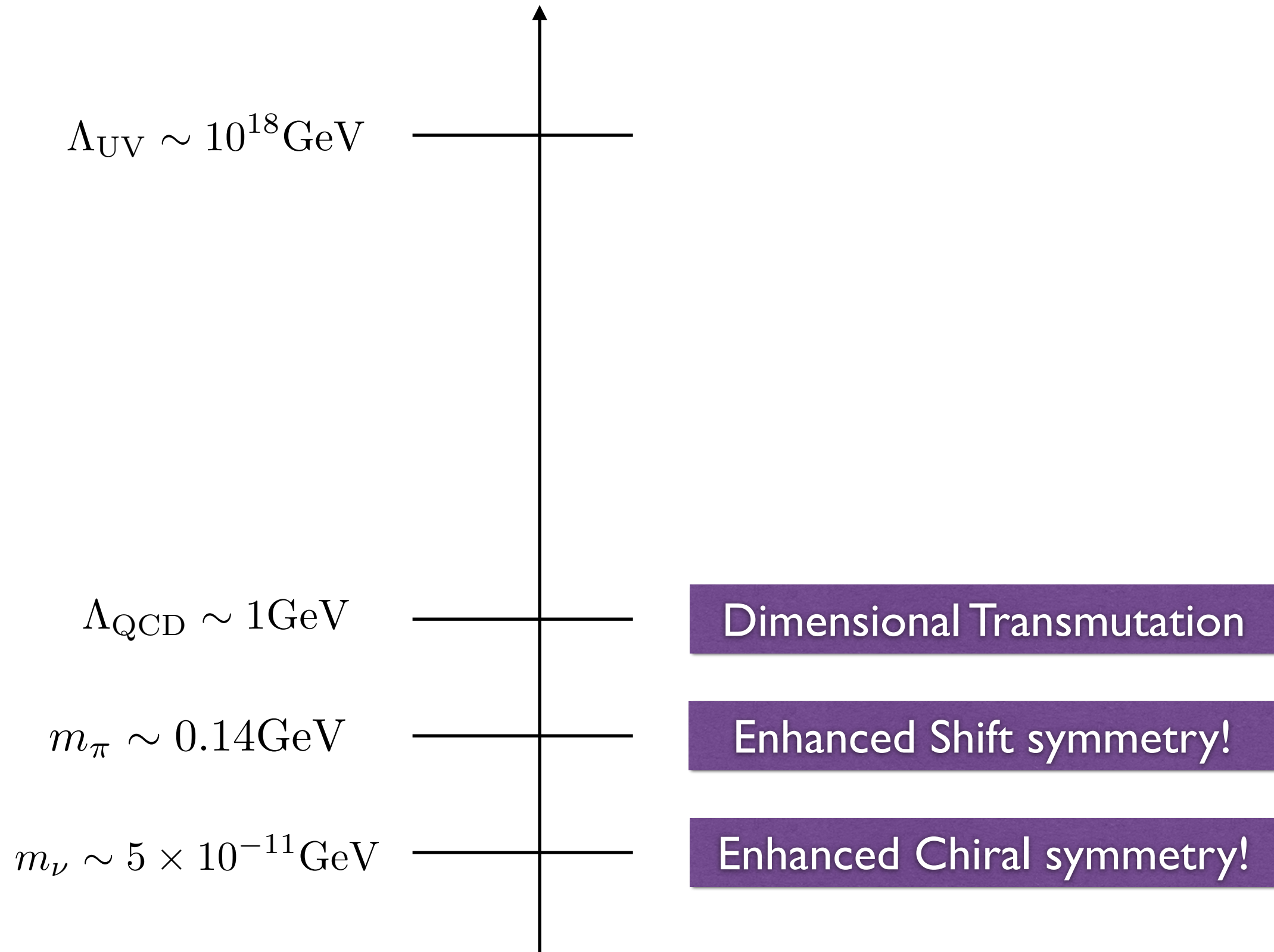
$$m_\nu \sim 5 \times 10^{-11} \text{ GeV}$$

Enhanced Chiral symmetry!

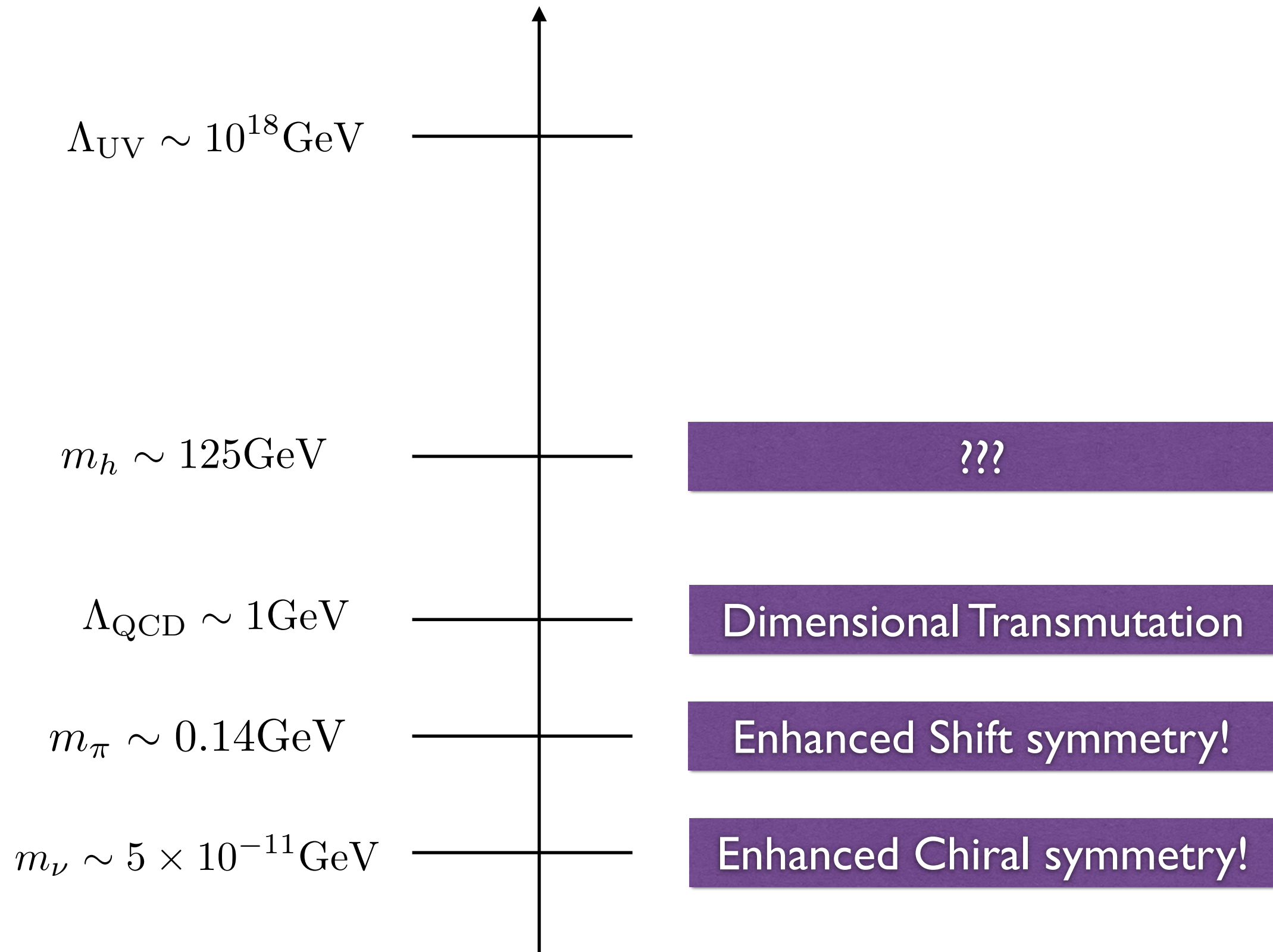
# t' Hooft Naturalness: SM Lesson



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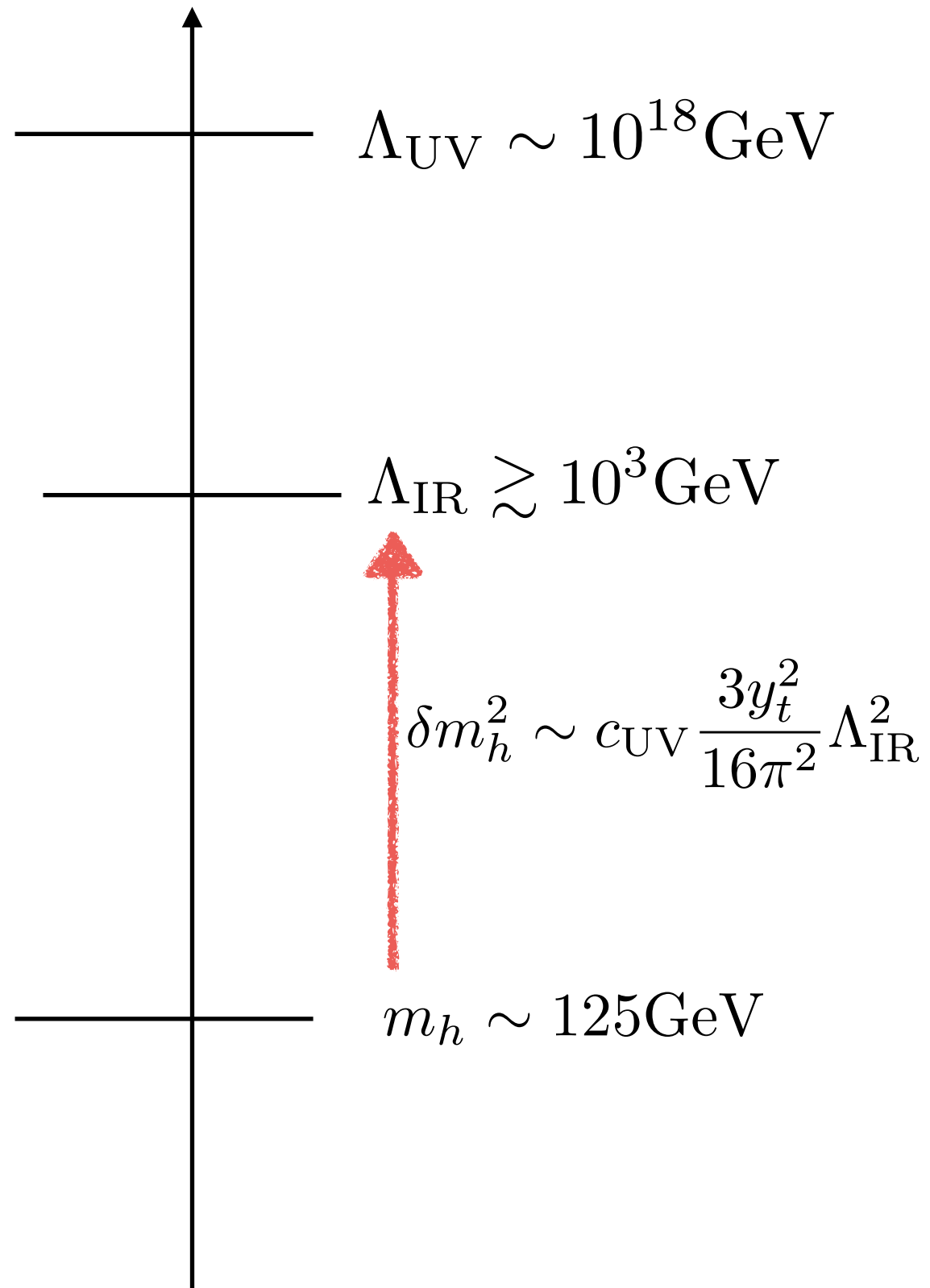


# t' Hooft Naturalness: SM Lesson



# Hierarchy problem

Need engineering the UV  
parameter



# Naturalness as Guideline

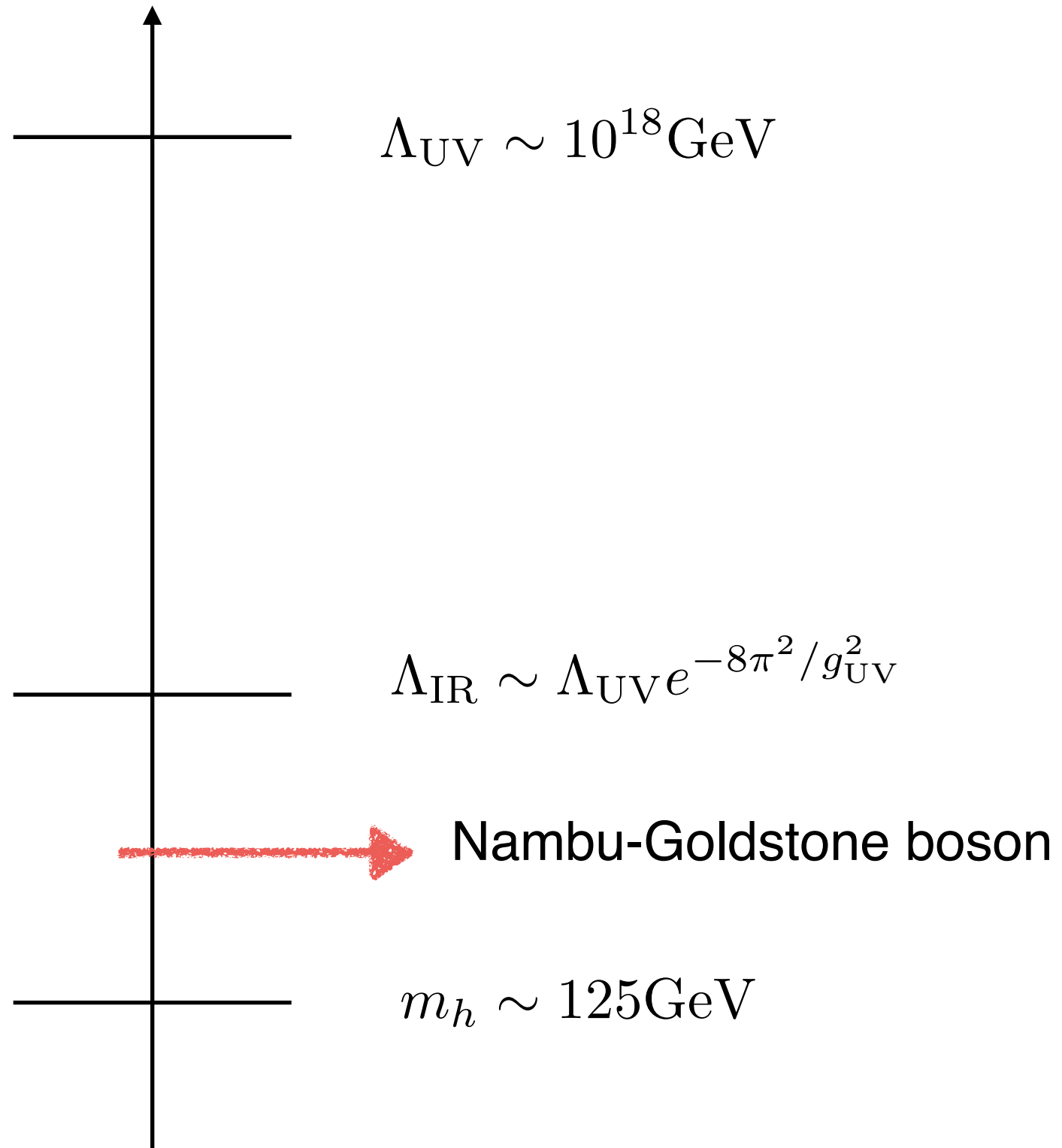
- Compositeness

$$\Lambda_{\text{IR}} \sim \Lambda_{\text{UV}} e^{-8\pi^2/g_{\text{UV}}^2} \longrightarrow \text{Dimensional Transmutation}$$

- Supersymmetry

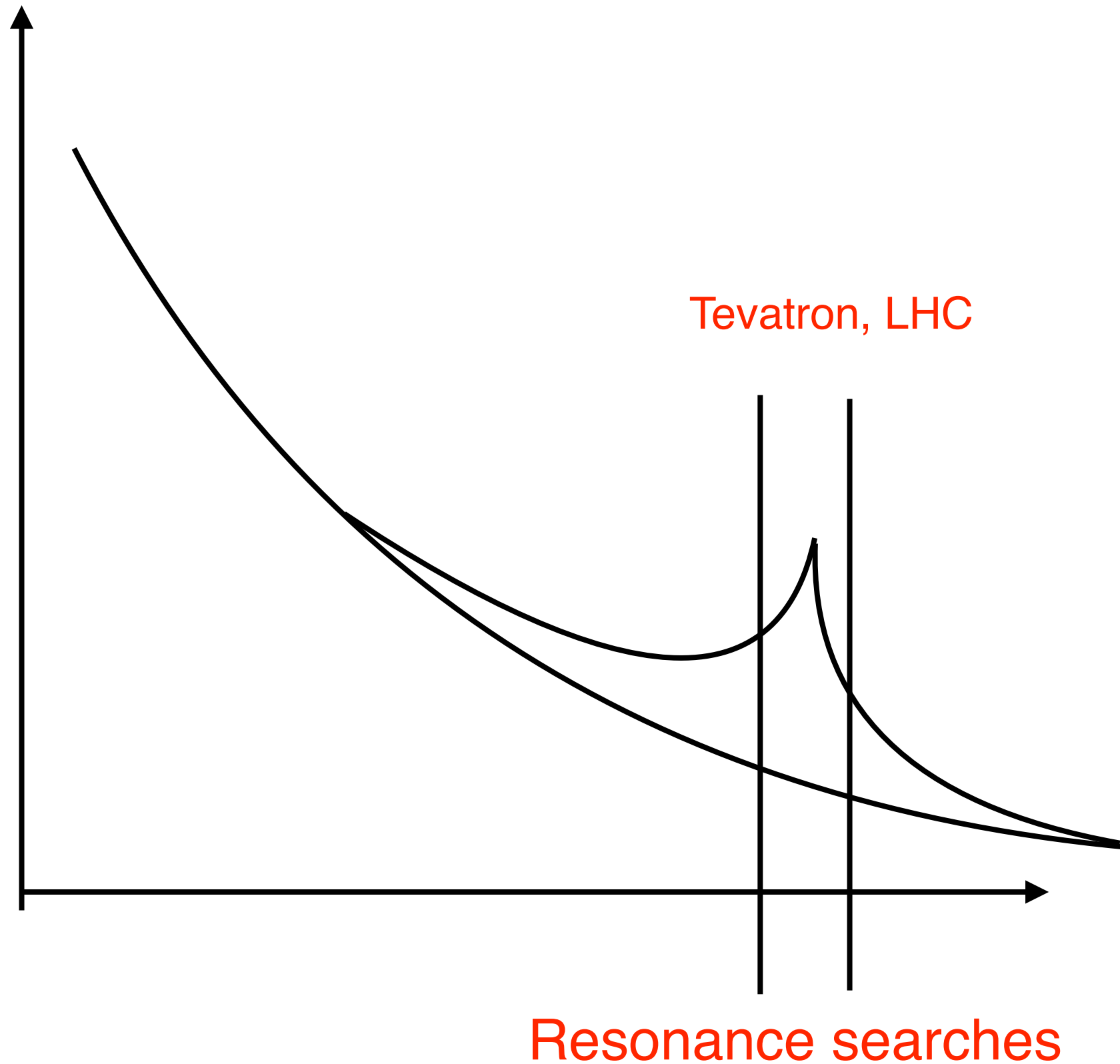
$$Q|\phi\rangle = |\psi\rangle \longrightarrow \text{Enhanced chiral symmetry}$$

# Compositeness

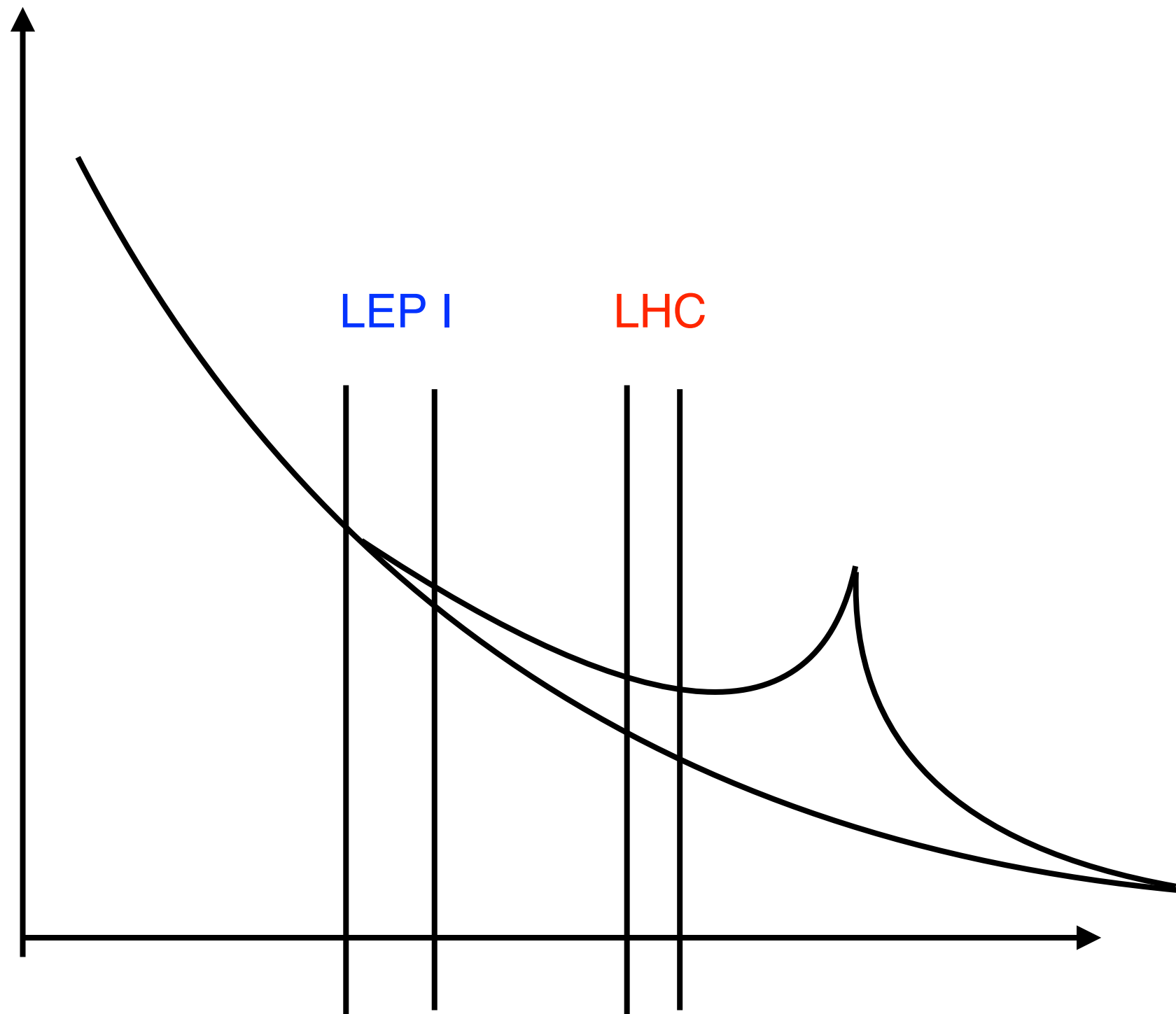


Enhanced shift symmetry!

# Two approaches for new physics

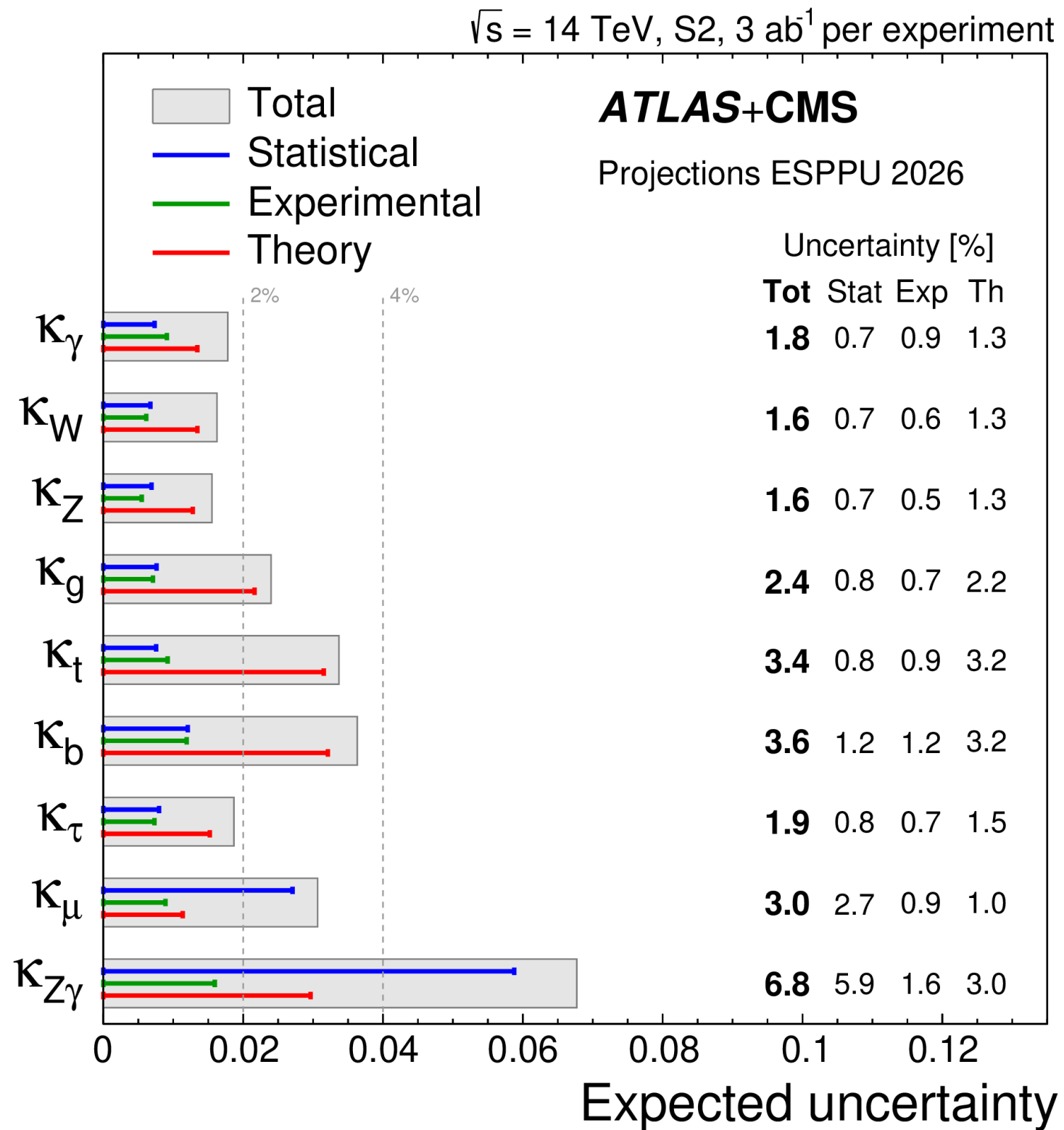


# Two approaches for new physics

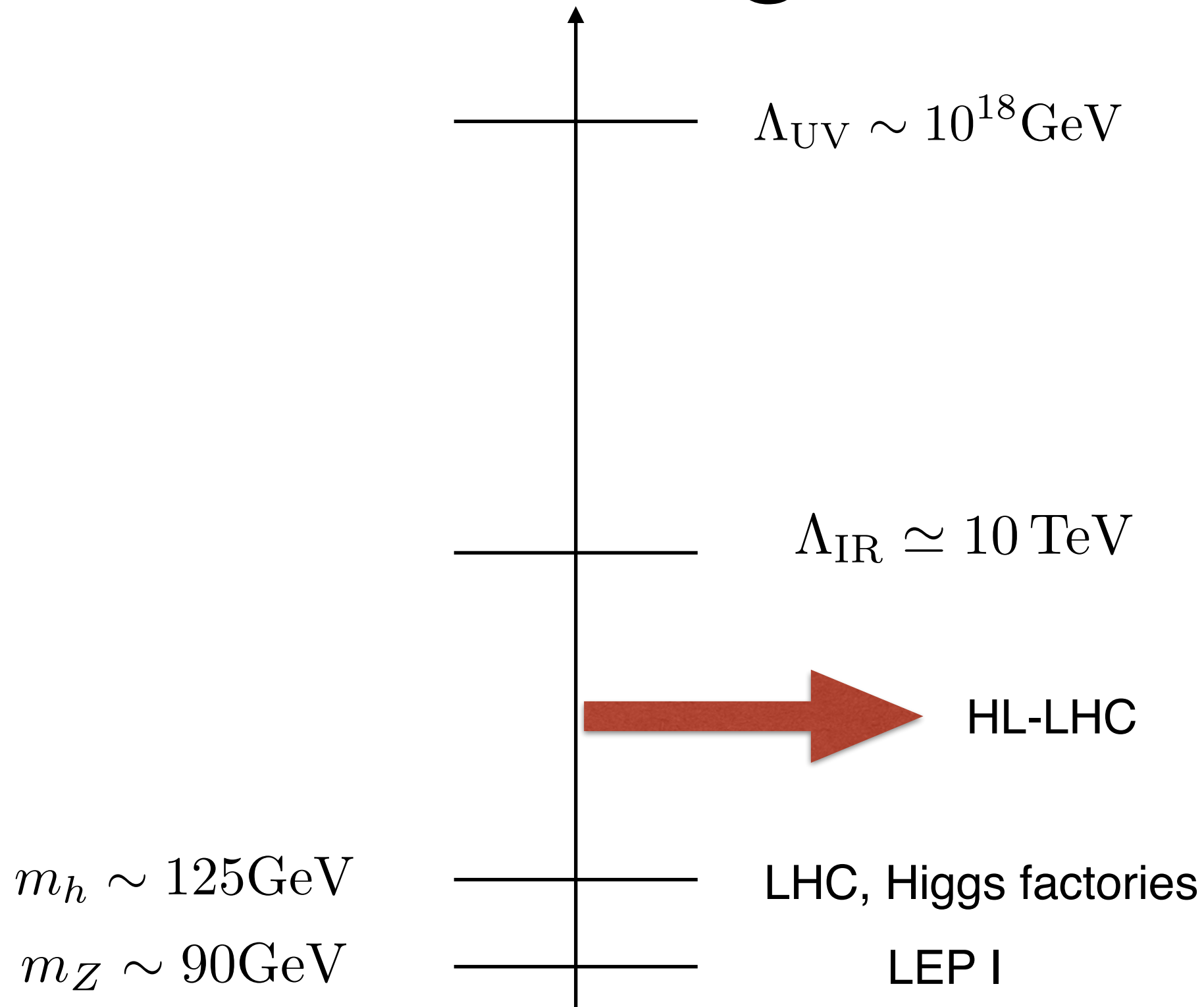


Precision measurement

# Higgs Coupling Measurements



# Indirect Signatures



# Indirect Signature

- One coupling – one scale

$$m_* \sim g_* f$$

- A set of selection rules

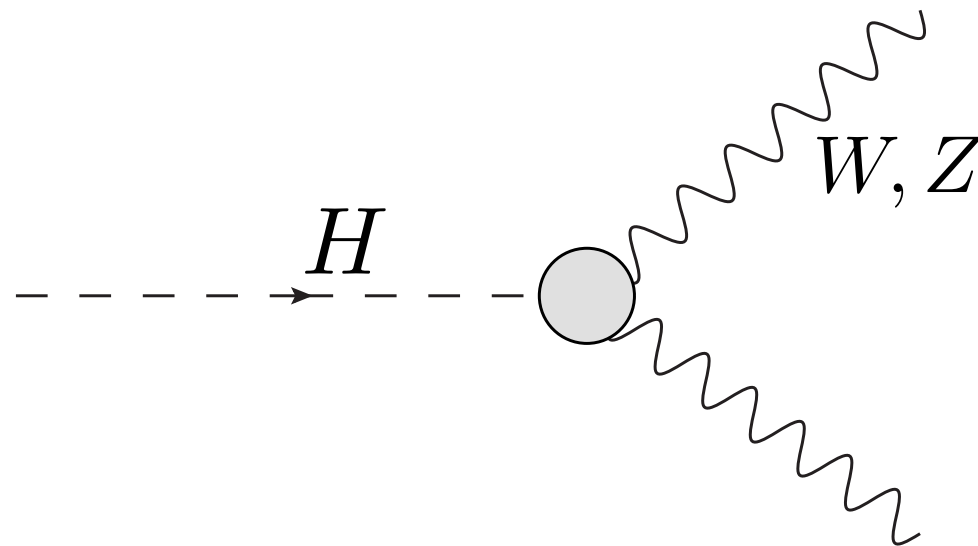
- ▶ Preserve the non-linearity:  $g_*$

- ▶ Explicit breaking

$$y_f, g, g'$$

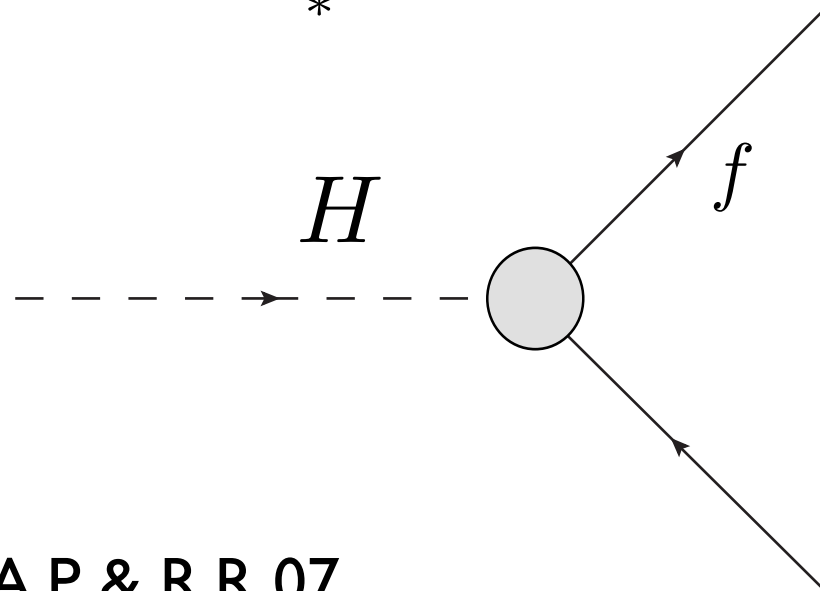
# Indirect Signature

$$\mathcal{O}_H = \frac{\partial_\mu (H^\dagger H) \partial^\mu (H^\dagger H)}{2m_*^2} \Rightarrow c_H \sim g_*^2$$



$$\sim -g_*^2 \frac{v^2}{2m_*^2}$$

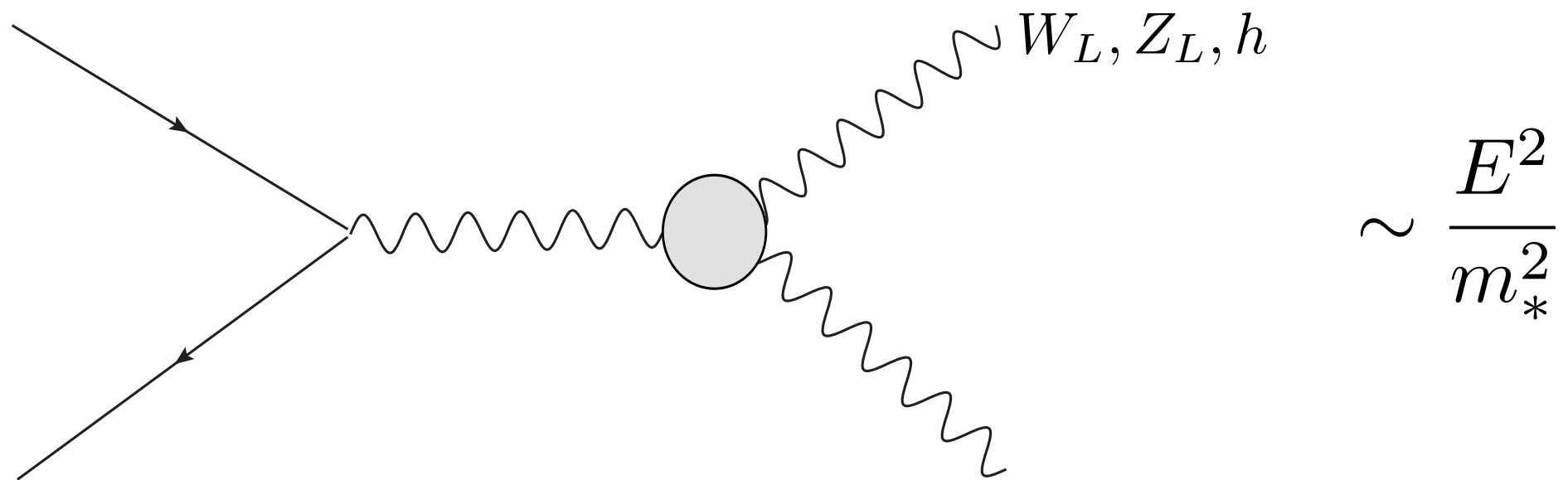
$$\mathcal{O}_y = y_f \frac{H^\dagger H}{m_*^2} \bar{f}_L H f_R \Rightarrow c_y \sim g_*^2$$



$$\sim -g_*^2 \frac{v^2}{2m_*^2}$$

# Indirect Signature

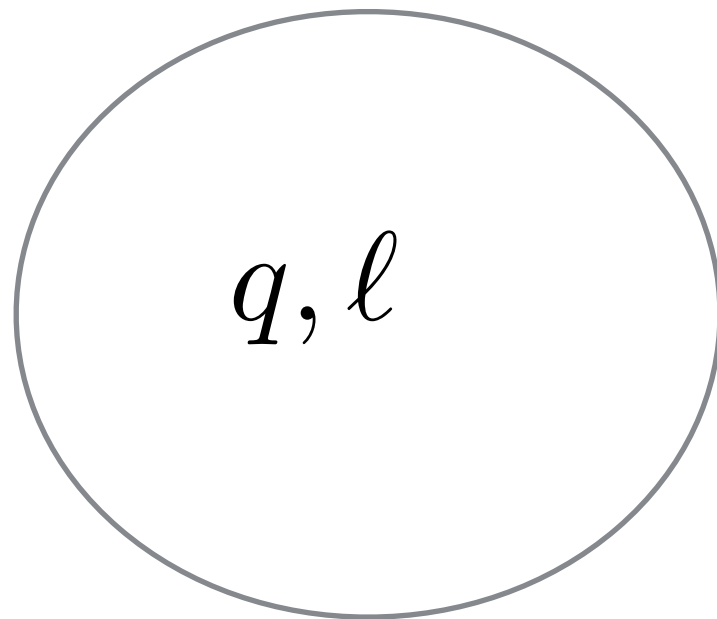
$$\mathcal{O}_W = \frac{ig}{2m_*^2} (H^\dagger \sigma^a \overleftrightarrow{D}^\mu H) D^\nu W_{\mu\nu}^a \Rightarrow c_W \sim 1$$



HL-LHC can play a role!

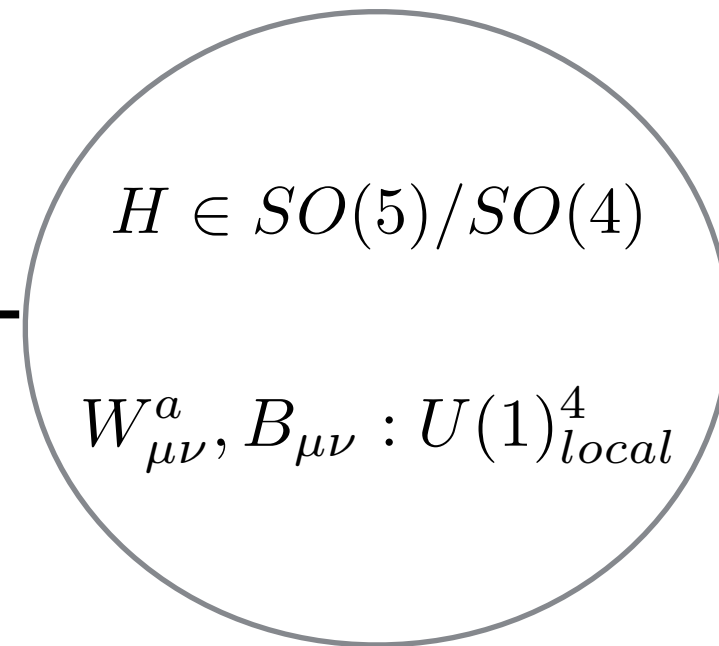
# Strong multipolar interactions

Elementary



$y_f, g, g'$

Strong

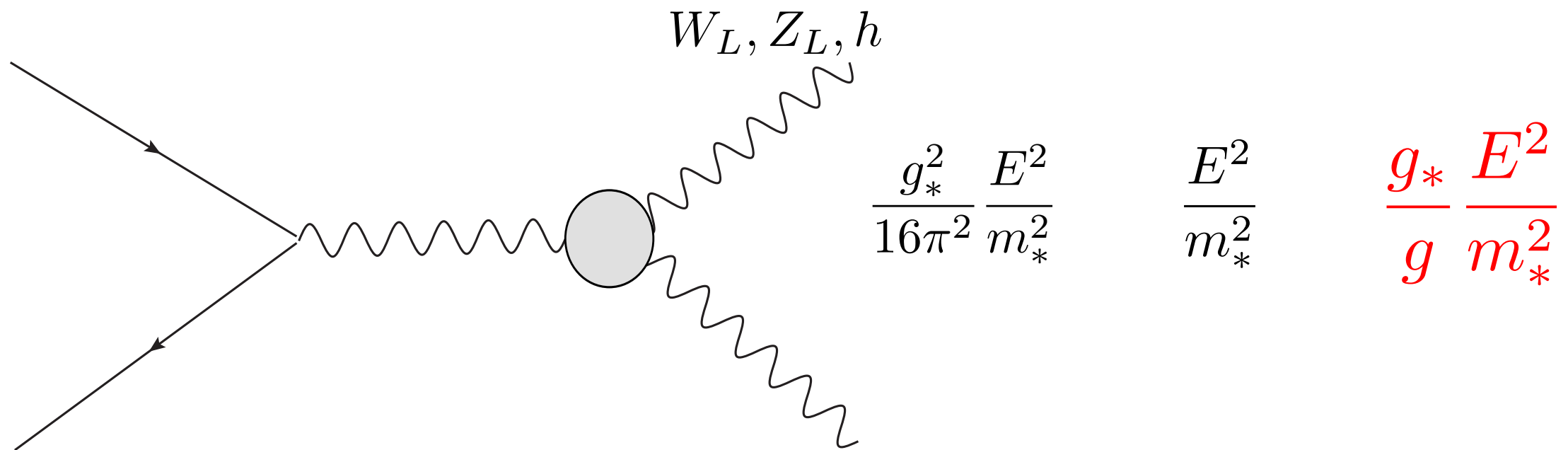


– New power-counting rules

$$W_{\mu\nu}^a, B_{\mu\nu} : g_*$$

# Strong multipolar interactions

$$\mathcal{O}_{HW} = \frac{ig}{m_*^2} (D^\mu H)^\dagger \sigma^a (D^\nu H) W_{\mu\nu}^a \Rightarrow c_{HW} \sim \frac{g_*^2}{16\pi^2}, \quad 1 \quad \frac{g_*}{g}$$



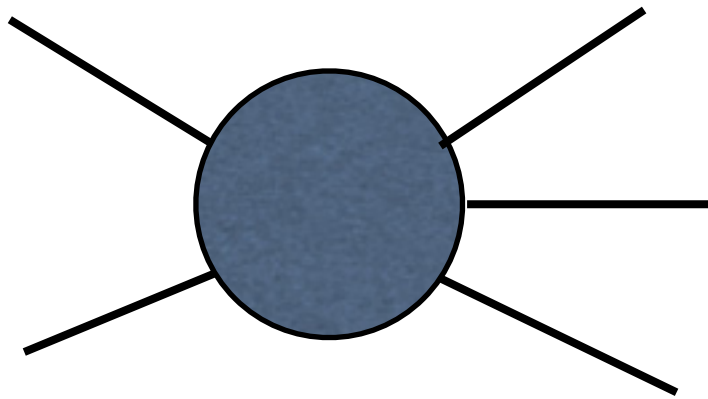
# Non-Interference for BSM Amplitudes

| $A_4$              | $ h(A_4^{\text{SM}}) $ | $ h(A_4^{\text{BSM}}) $ |
|--------------------|------------------------|-------------------------|
| $VVVV$             | 0                      | 4,2                     |
| $VV\phi\phi$       | 0                      | 2                       |
| $VV\psi\psi$       | 0                      | 2                       |
| $V\psi\psi\phi$    | 0                      | 2                       |
| $\psi\psi\psi\psi$ | 2,0                    | 2,0                     |
| $\psi\psi\phi\phi$ | 0                      | 0                       |
| $\phi\phi\phi\phi$ | 0                      | 0                       |

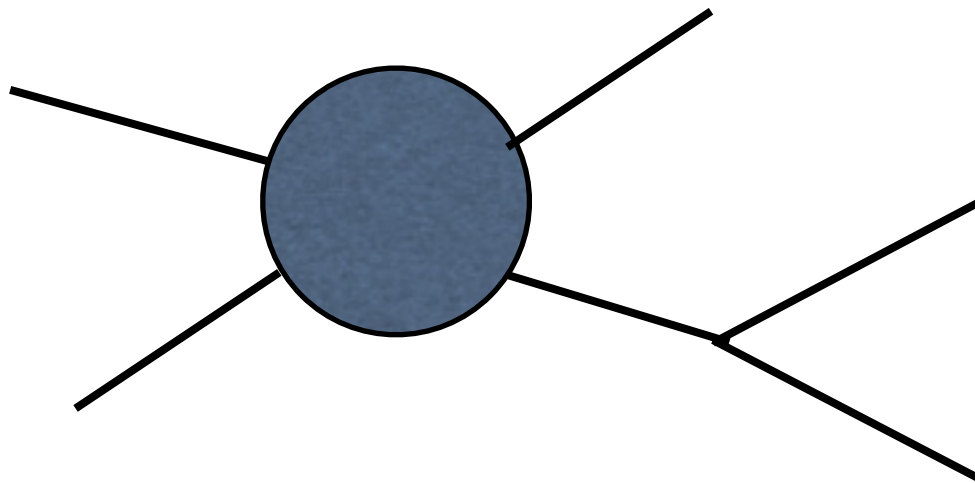
At dimension-six level, it seems that BSM doesn't want to entangle with SM

# Two ways out

- Add one more final state



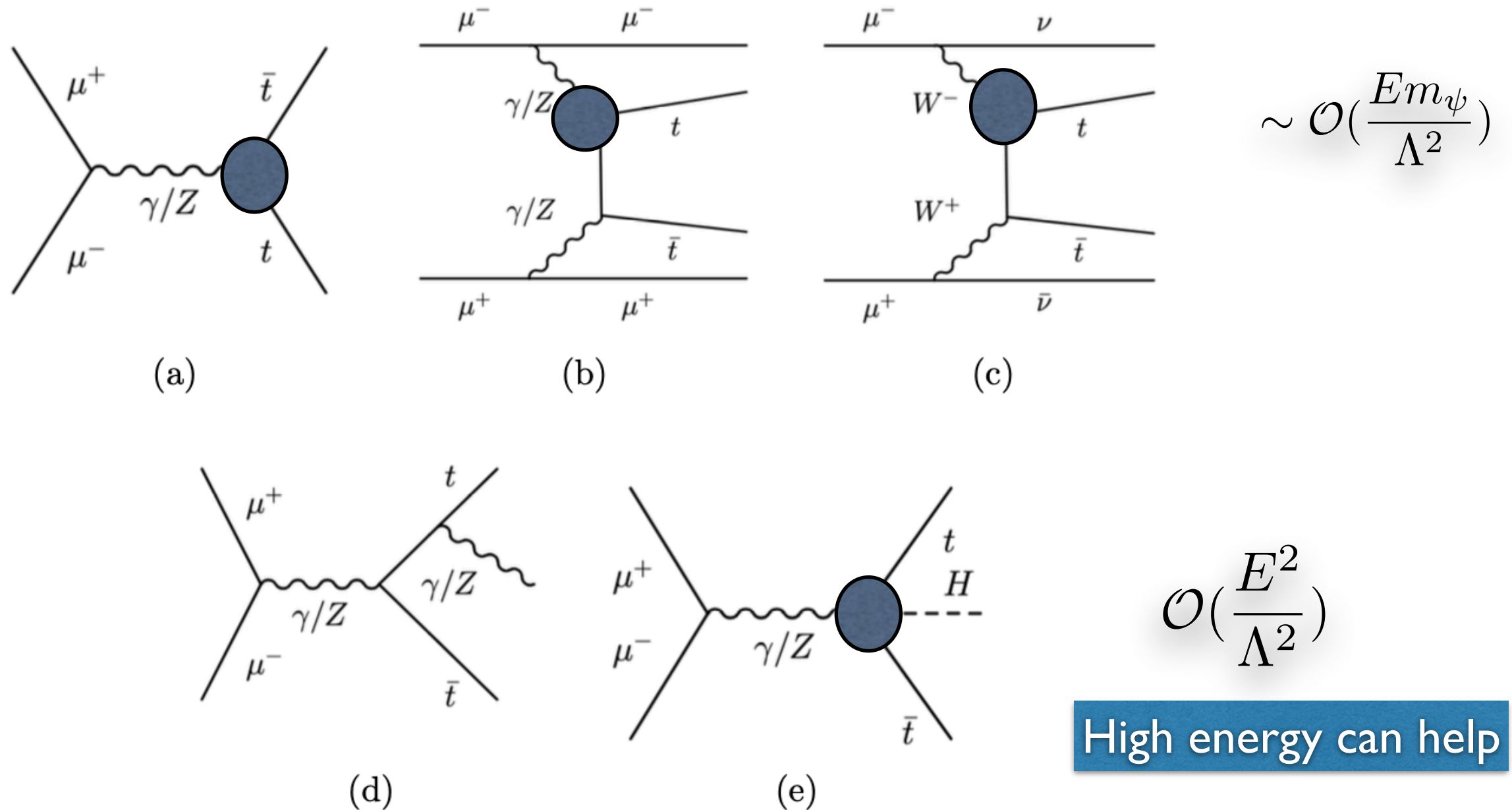
- Spin-correlation/Quantum Entanglement



Azimuthal angles

# Top Electroweak dipole Moment

$$\frac{g' y_\psi}{\Lambda^2} \psi_L^{(2)} \sigma^{\mu\nu} \psi_R H B_{\mu\nu} \quad C_{\psi B} \sim \frac{g_*}{g'}$$

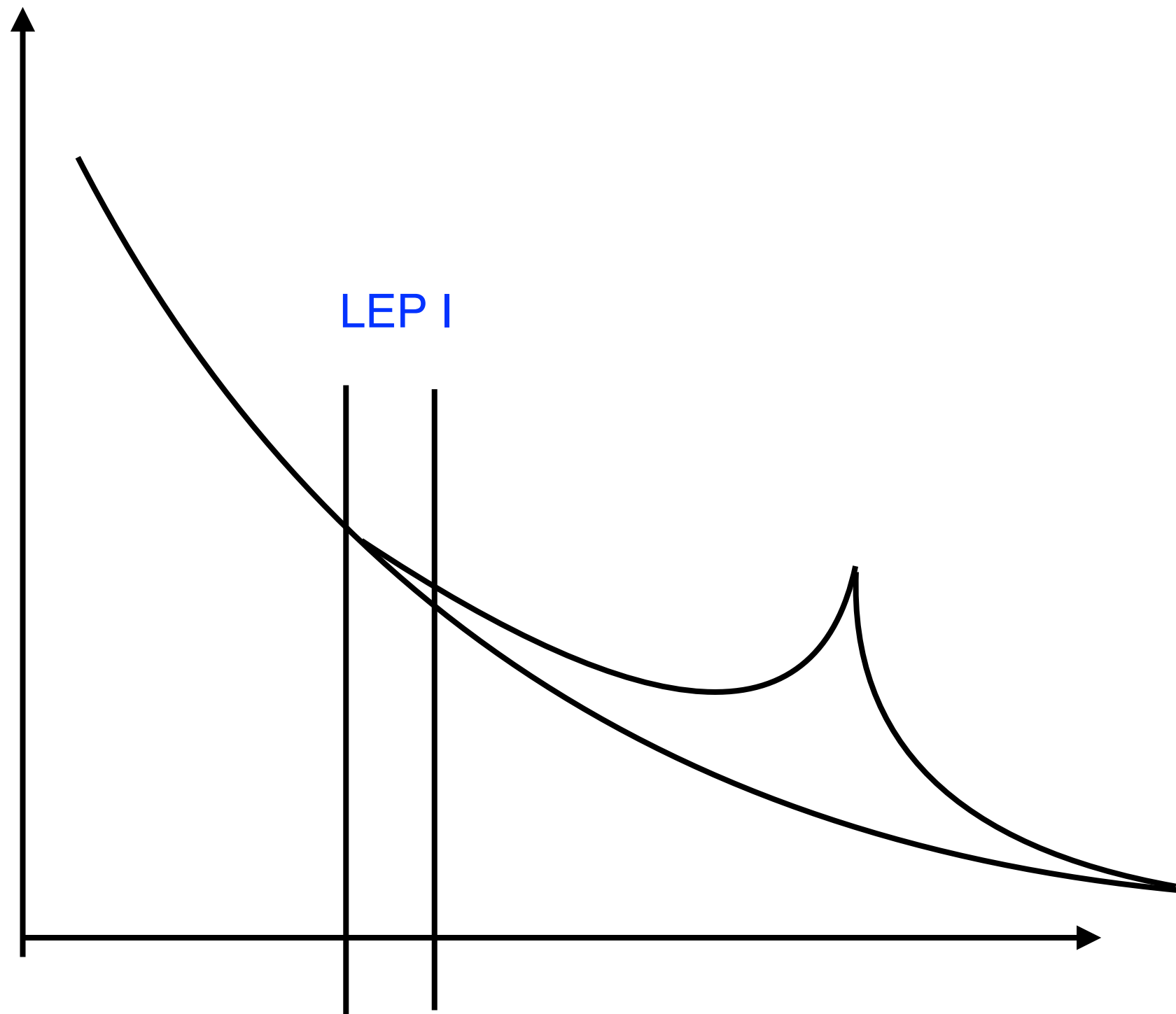


# Conclusion

- We enter into an era of data-driven model-building
- Try crazy ideas and try innovative experiments, Hopefully something will come up!

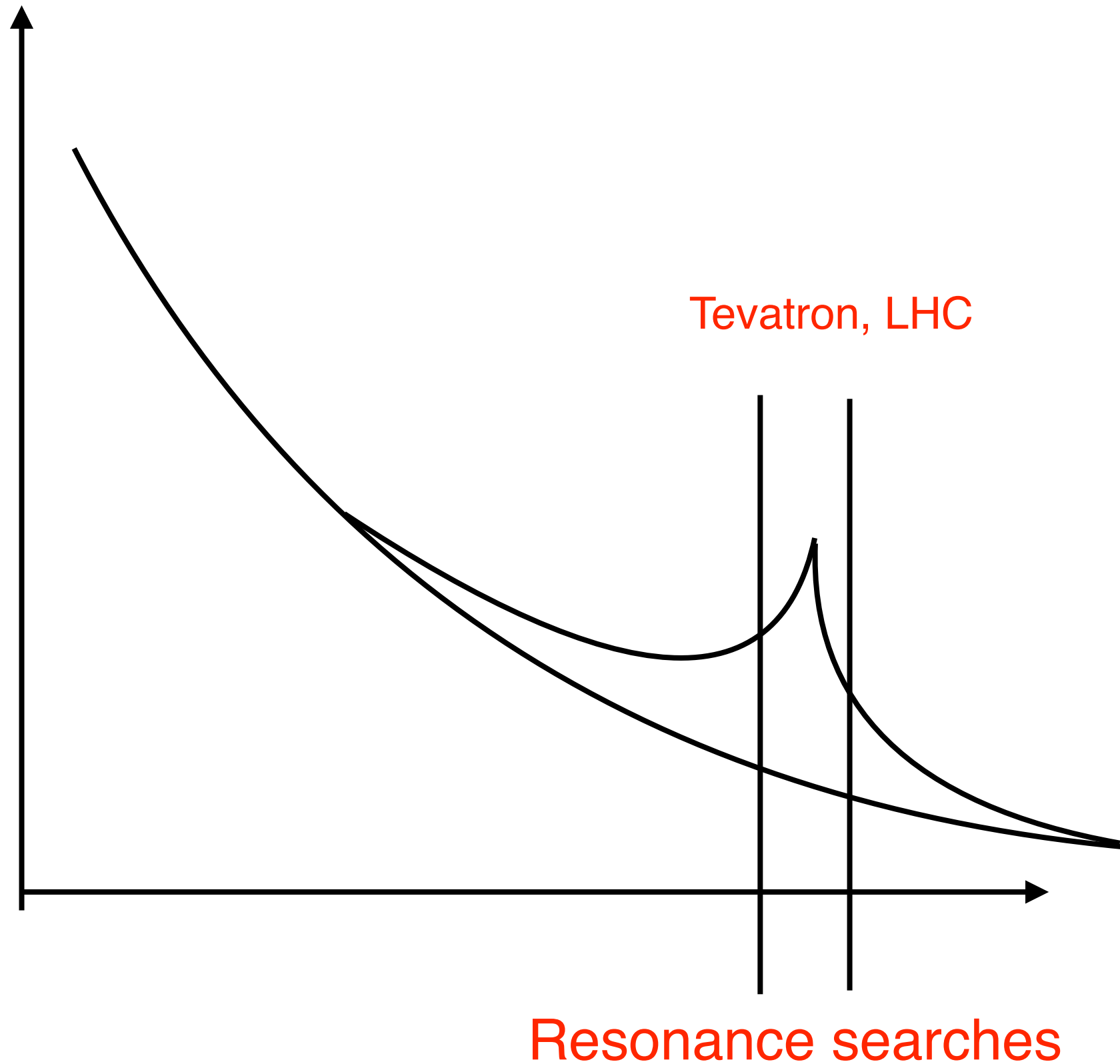
Back-up Slides

# Two approaches for new physics

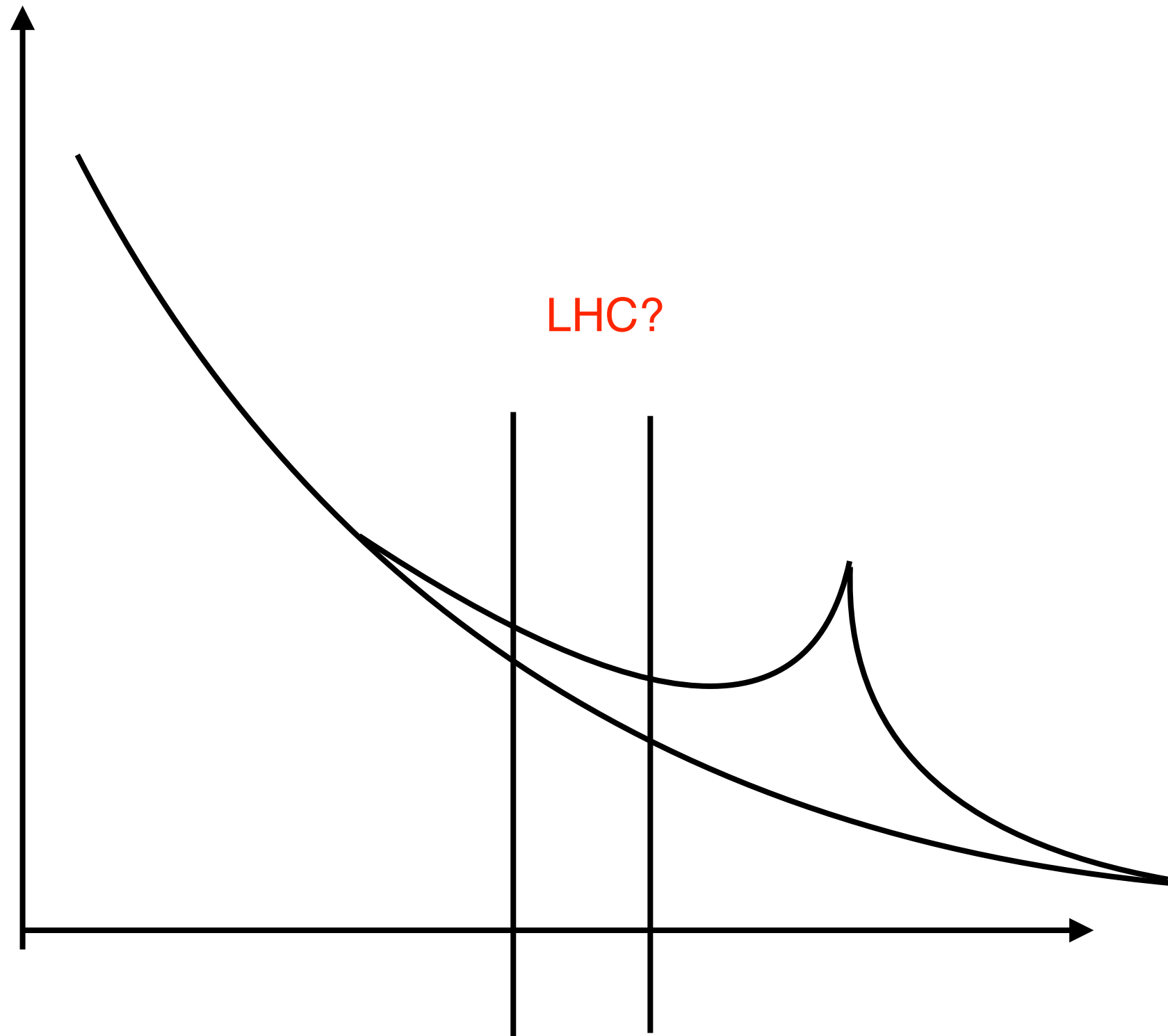


Precision measurement

# Two approaches for new physics



# Can HL-LHC do precision measurement?



# Uncertainty

- Lepton colliders:  $\sim 0.1\%$
- Hadron Colliders: 3% - 20%

# Effective Operators

$$\begin{aligned}
 \mathcal{O}_W &= \frac{ig}{2} \left( H^\dagger \sigma^a \overleftrightarrow{D}^\mu H \right) D^\nu W_{\mu\nu}^a, & \mathcal{O}_B &= \frac{ig'}{2} \left( H^\dagger \overleftrightarrow{D}^\mu H \right) \partial^\nu B_{\mu\nu} \\
 \mathcal{O}_{2W} &= -\frac{1}{2} D^\mu W_{\mu\nu}^a D_\rho W^{a\rho\nu}, & \mathcal{O}_{2B} &= -\frac{1}{2} \partial^\mu B_{\mu\nu} \partial_\rho B^{\rho\nu} \\
 \mathcal{O}_{HW} &= ig (D^\mu H)^\dagger \sigma^a (D^\nu H) W_{\mu\nu}^a, & \mathcal{O}_{HB} &= ig' (D^\mu H)^\dagger (D^\nu H) B_{\mu\nu} \\
 \mathcal{O}_{3W} &= \frac{1}{3!} g \epsilon_{abc} W_\mu^{a\nu} W_{\nu\rho}^b W^{c\rho\mu}, & \mathcal{O}_T &= \frac{g^2}{2} (H^\dagger \overleftrightarrow{D}^\mu H) (H^\dagger \overleftrightarrow{D}_\mu H) H \\
 \mathcal{O}_R^u &= ig'^2 \left( H^\dagger \overleftrightarrow{D}_\mu H \right) \bar{u}_R \gamma^\mu u_R, & \mathcal{O}_R^d &= ig'^2 \left( H^\dagger \overleftrightarrow{D}_\mu H \right) \bar{d}_R \gamma^\mu d_R \\
 \mathcal{O}_L^q &= ig'^2 \left( H^\dagger \overleftrightarrow{D}_\mu H \right) \bar{Q}_L \gamma^\mu Q_L, & \mathcal{O}_L^{(3)q} &= ig^2 \left( H^\dagger \sigma^a \overleftrightarrow{D}_\mu H \right) \bar{Q}_L \sigma^a \gamma^\mu Q_L
 \end{aligned}$$

$$\mathcal{L} = \mathcal{L}_{\text{SM}} + \sum_i \frac{c_i}{\Lambda^2} \mathcal{O}_i + \dots$$

# Helicity structure for WW

$$q_L \bar{q}_R \rightarrow W^+ W^-$$

| $(h_{W^+}, h_{W^-})$ | SM                  | $\mathcal{O}_W$           | $\mathcal{O}_{HW}$        | $\mathcal{O}_B$           | $\mathcal{O}_{HB}$       | $\mathcal{O}_{3W}$       |
|----------------------|---------------------|---------------------------|---------------------------|---------------------------|--------------------------|--------------------------|
| $(\pm, \mp)$         | 1                   | 0                         | 0                         | 0                         | 0                        | 0                        |
| $(0, 0)$             | 1                   | $\frac{E^2}{\Lambda^2}$   | $\frac{E^2}{\Lambda^2}$   | $\frac{E^2}{\Lambda^2}$   | $\frac{E^2}{\Lambda^2}$  | 0                        |
| $(0, \pm), (\pm, 0)$ | $\frac{m_W}{E}$     | $\frac{Em_W}{\Lambda^2}$  | $\frac{Em_W}{\Lambda^2}$  | $\frac{Em_W}{\Lambda^2}$  | $\frac{Em_W}{\Lambda^2}$ | $\frac{Em_W}{\Lambda^2}$ |
| $(\pm, \pm)$         | $\frac{m_W^2}{E^2}$ | $\frac{m_W^2}{\Lambda^2}$ | $\frac{m_W^2}{\Lambda^2}$ | $\frac{m_W^2}{\Lambda^2}$ | 0                        | $\frac{E^2}{\Lambda^2}$  |

$$q_R \bar{q}_L \rightarrow W^+ W^-$$

| $(h_{W^+}, h_{W^-})$ | SM                  | $\mathcal{O}_W$                     | $\mathcal{O}_{HW}$        | $\mathcal{O}_B$           | $\mathcal{O}_{HB}$       | $\mathcal{O}_{3W}$                  |
|----------------------|---------------------|-------------------------------------|---------------------------|---------------------------|--------------------------|-------------------------------------|
| $(\pm, \mp)$         | 0                   | 0                                   | 0                         | 0                         | 0                        | 0                                   |
| $(0, 0)$             | 1                   | $\frac{m_W^2}{\Lambda^2}$           | $\frac{m_W^2}{\Lambda^2}$ | $\frac{E^2}{\Lambda^2}$   | $\frac{E^2}{\Lambda^2}$  | 0                                   |
| $(0, \pm), (\pm, 0)$ | $\frac{m_W}{E}$     | $\frac{m_W^2 m_Z^2}{\Lambda^2 E^2}$ | $\frac{Em_W}{\Lambda^2}$  | $\frac{Em_W}{\Lambda^2}$  | $\frac{Em_W}{\Lambda^2}$ | $\frac{m_W^2 m_Z^2}{\Lambda^2 E^2}$ |
| $(\pm, \pm)$         | $\frac{m_W^2}{E^2}$ | $\frac{m_W^2}{\Lambda^2}$           | $\frac{m_W^2}{\Lambda^2}$ | $\frac{m_W^2}{\Lambda^2}$ | 0                        | $\frac{m_W^2}{\Lambda^2}$           |

# Mass scale reach HL-LHC

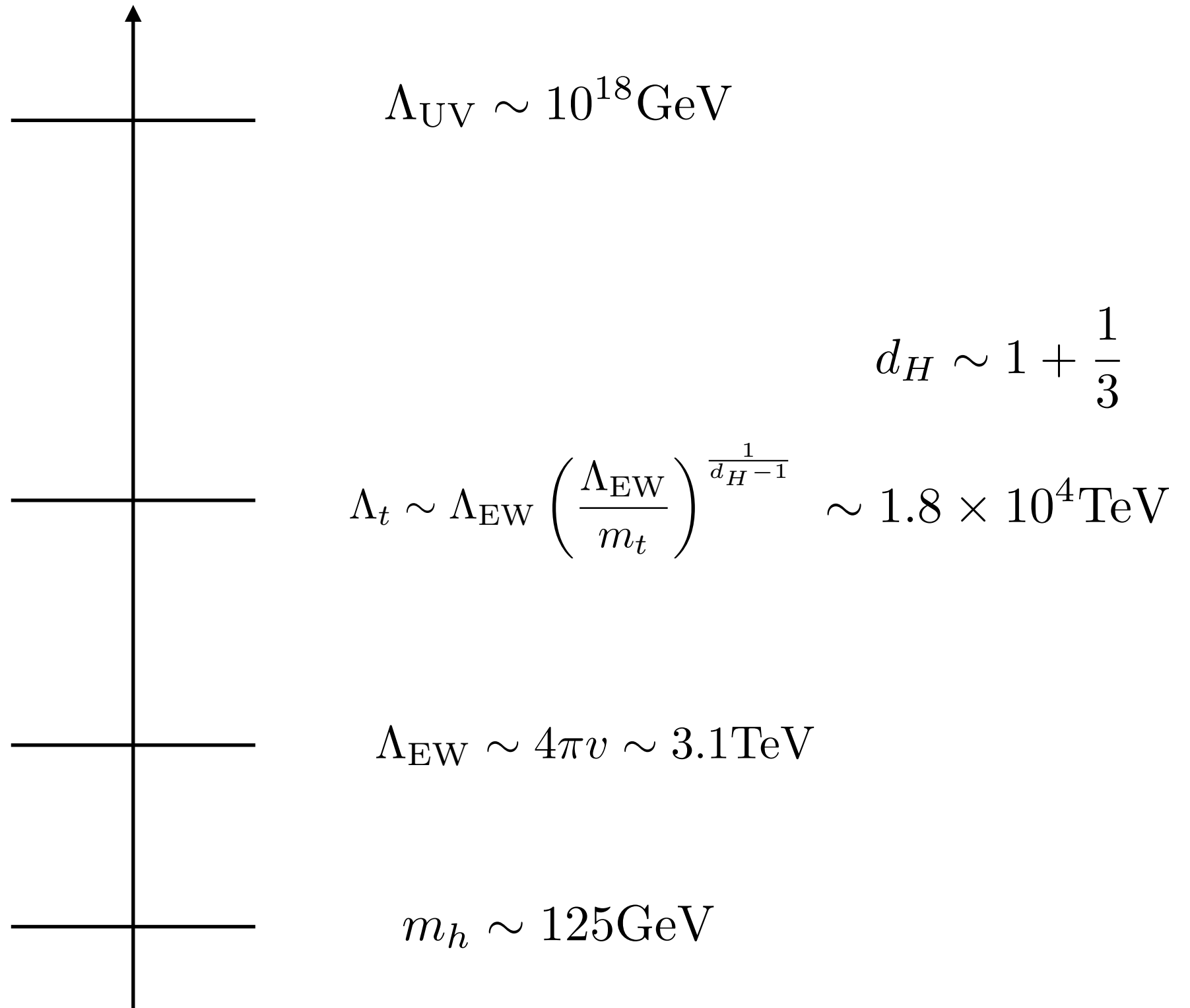
| Model              | Di-boson                      | S-parameter | LHC $h \rightarrow Z\gamma$  | LHC $h \rightarrow \gamma\gamma$ | LHC dilepton                  |
|--------------------|-------------------------------|-------------|------------------------------|----------------------------------|-------------------------------|
| SILH               | 4.0                           | 2.5         | $1.7\sqrt{\frac{g_*}{4\pi}}$ | 0.34                             | $0.69\sqrt{\frac{4\pi}{g_*}}$ |
| Remedios           | $10.6\sqrt{\frac{g_*}{4\pi}}$ |             |                              |                                  | 13.4                          |
| Remedios+MCHM      | $10.6\sqrt{\frac{g_*}{4\pi}}$ | 2.5         | 1.7                          | 6.5                              | 13.4                          |
| Remedios+ $ISO(4)$ | $17.6\sqrt{\frac{g_*}{4\pi}}$ | 2.5         | $7.5\sqrt{\frac{g_*}{4\pi}}$ | 6.5                              | 13.4                          |

DL and L.T.Wang '18

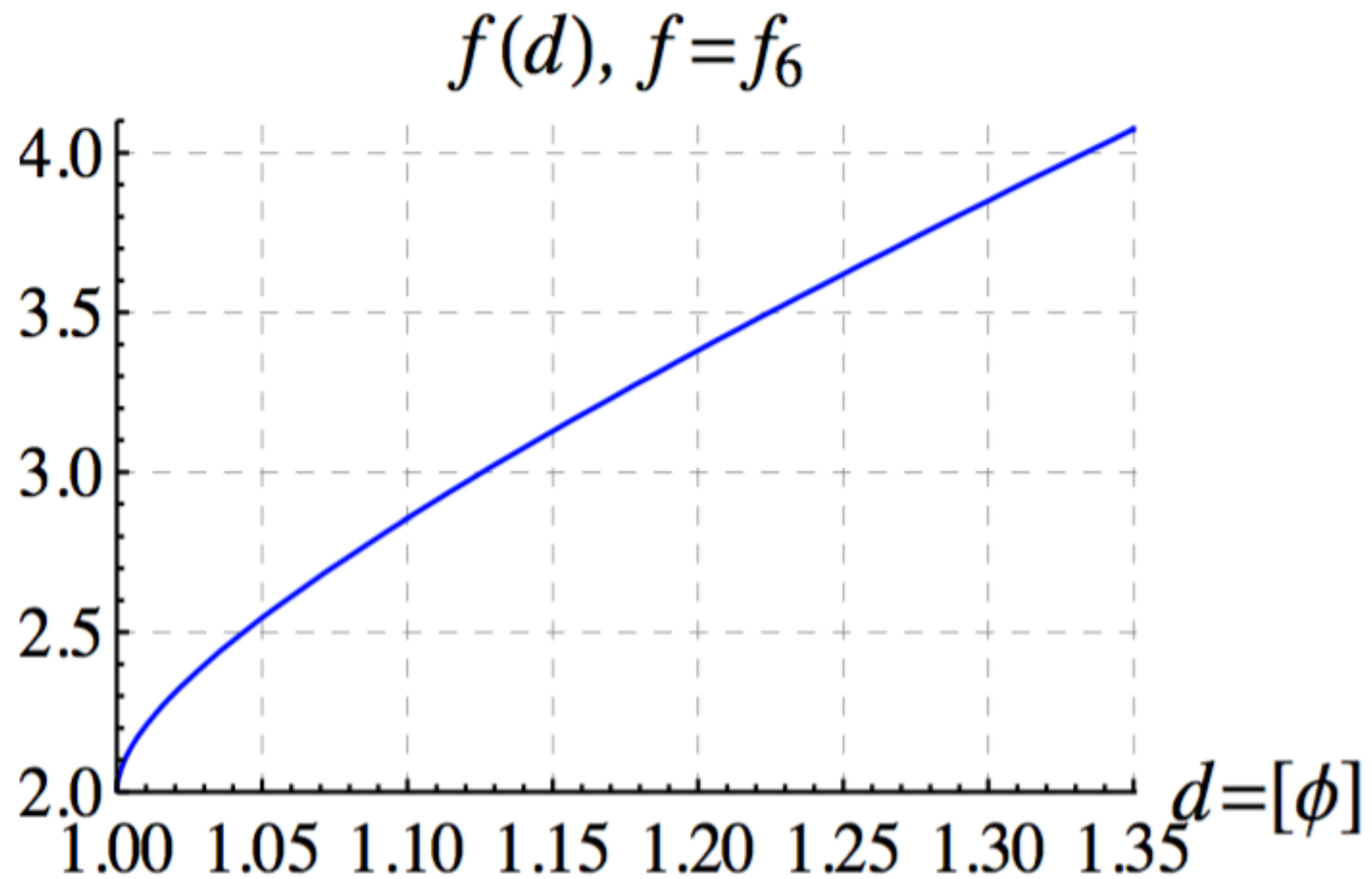
see also R. Franceschini et al

Dilepton: M. Farina et al

# Conformal Technicolor



# Conformal Technicolor



From R. Rattazzi, V. Rychkov, E. Tonni and A. Vichi 08