Probing Composite Higgs with the Top Portal at CLIC

Oleksii Matsedonskyi

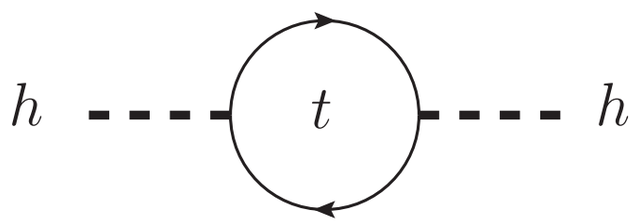
work in progress, in collaboration with G.Durieux and A.Wulzer

CERN, CLIC Workshop 2018

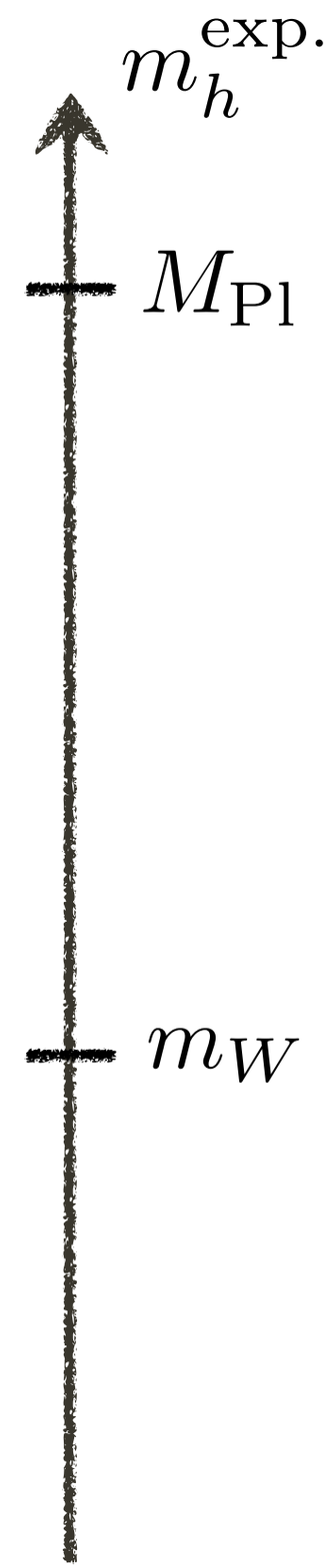
1. Hierarchy Problem and Composite Higgs

1. Hierarchy Problem and Composite Higgs

- Higgs mass is unstable under radiative corrections

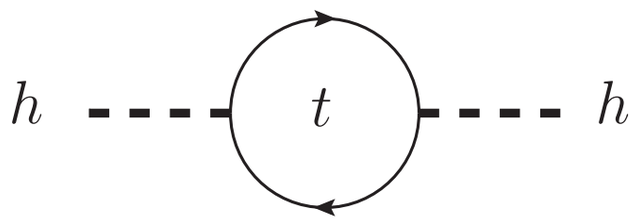


$$\delta m_h^2 \simeq \Lambda^2$$



1. Hierarchy Problem and Composite Higgs

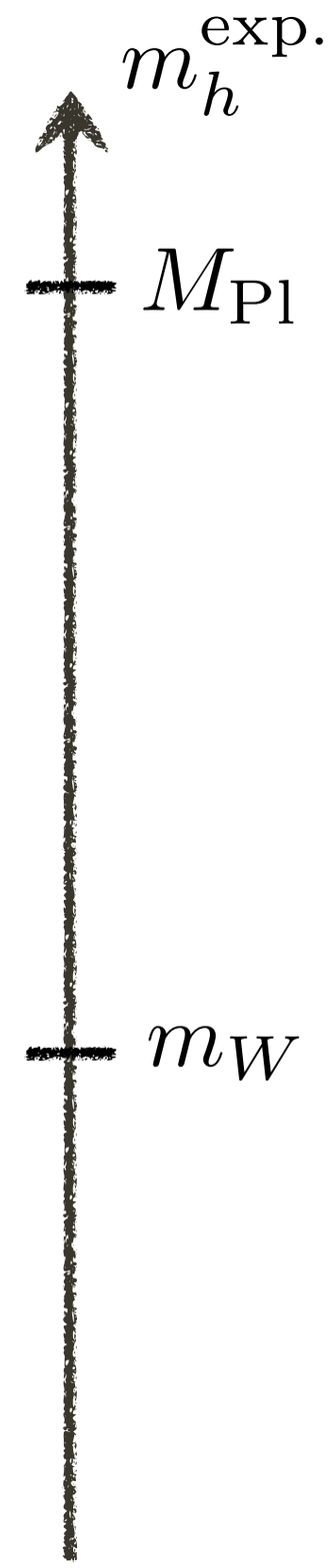
- Higgs mass is unstable under radiative corrections



$$\delta m_h^2 \simeq \Lambda^2$$

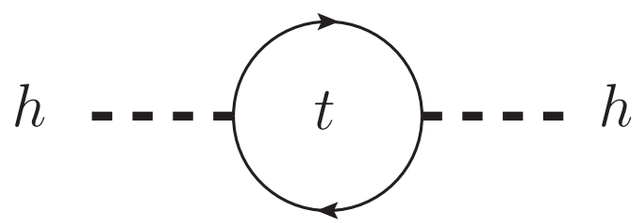
$$\Lambda \sim M_{Planck}$$

$$\text{tuning} \sim \frac{M_{Planck}^2}{m_h^2} \sim 10^{32}$$



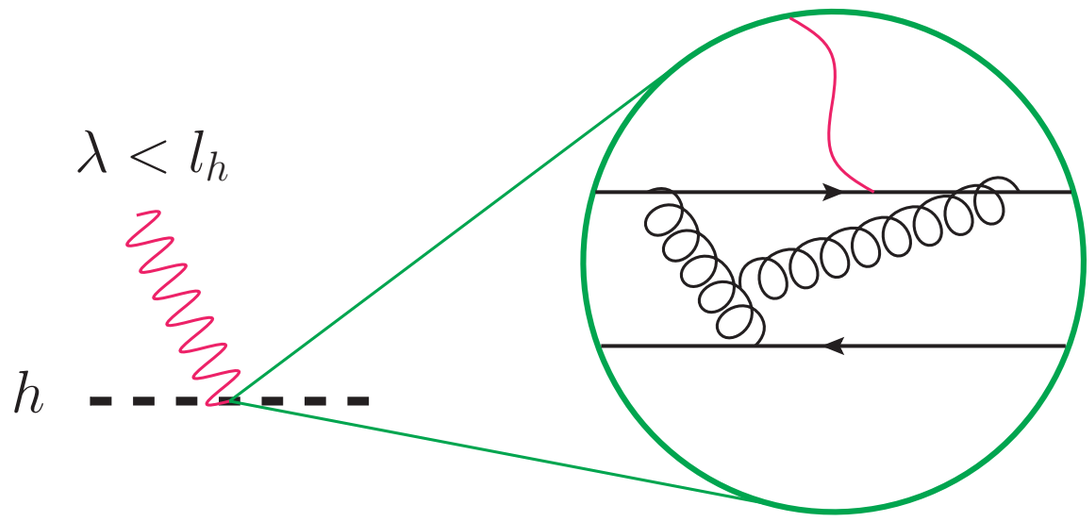
1. Hierarchy Problem and Composite Higgs

- Higgs mass is unstable under radiative corrections



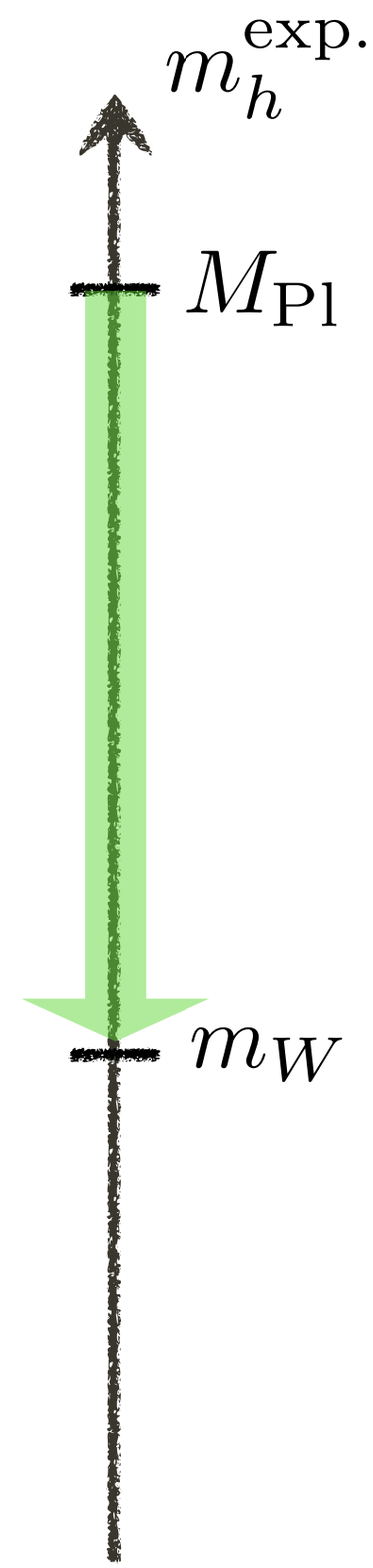
$$\delta m_h^2 \simeq \Lambda^2$$

- UV can be screened by TeV scale New Physics



$$\delta m_h^2 \simeq \frac{1}{l_h^2} \simeq m_\rho^2$$

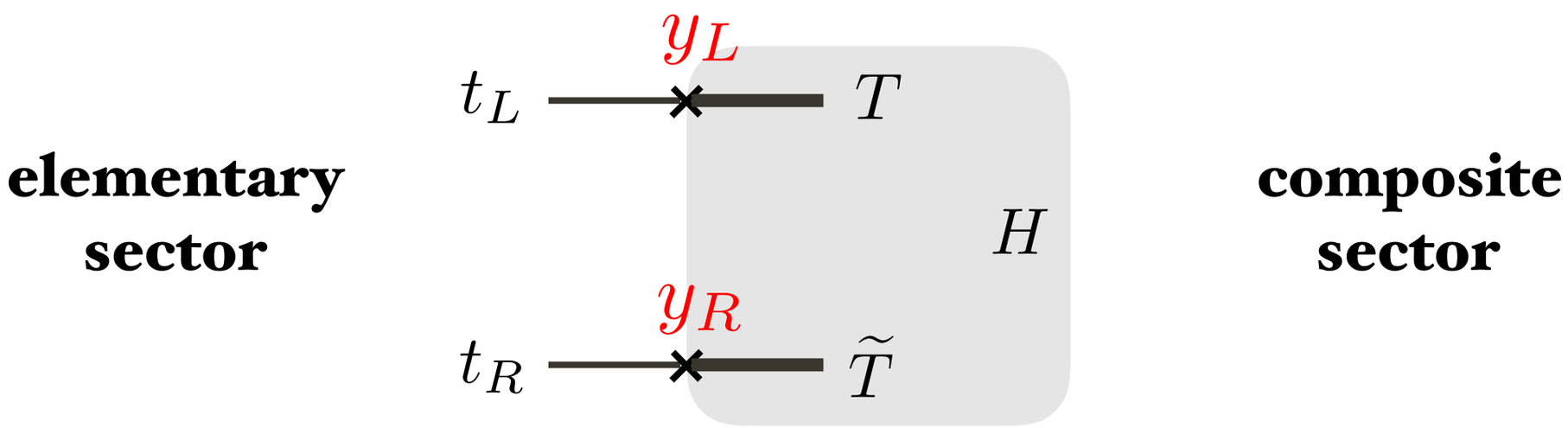
TeV-scale New Physics



2. CH and Top Portal

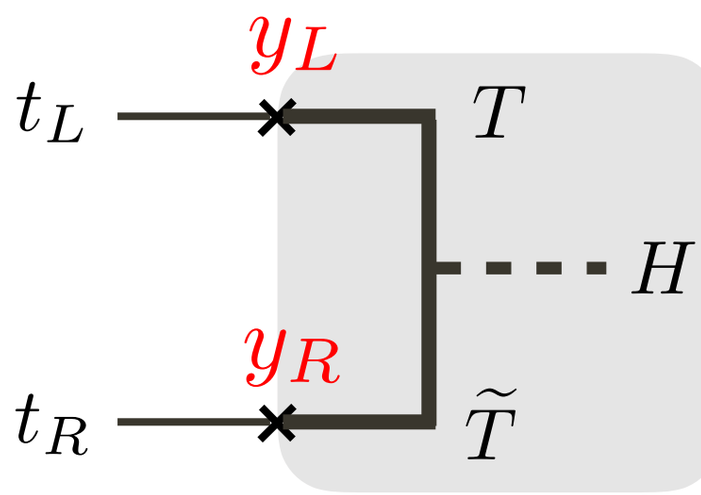
2. CH and Top Portal

- Elementary fields communicate with the new strong sector via linear mass mixings, these mixings are responsible for fermion mass



2. CH and Top Portal

- Elementary fields communicate with the new strong sector via linear mass mixings, these mixings are responsible for fermion mass



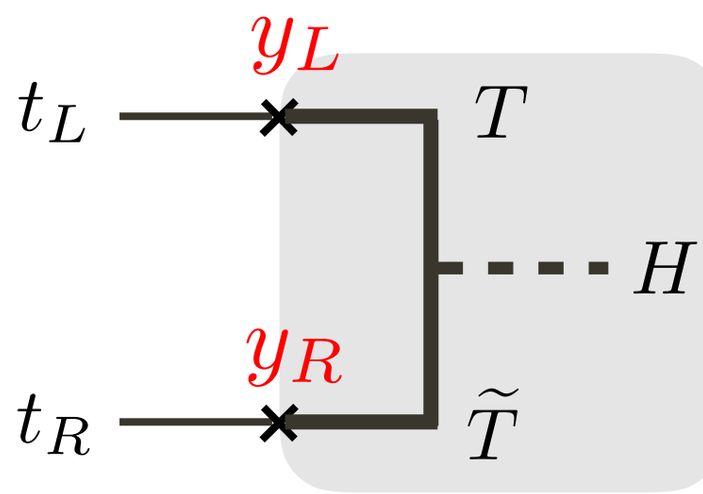
$$\lambda_t \sim \frac{y_L y_R}{g_\star}$$

$$g_\star \sim m_{T,\tilde{T}}$$

2. CH and Top Portal

- Elementary fields communicate with the new strong sector via linear mass mixings, these mixings are responsible for fermion mass

elementary tR

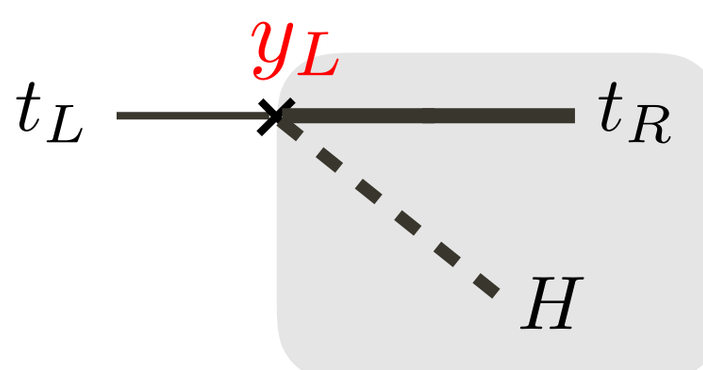


$$\lambda_t \sim \frac{y_L y_R}{g_\star}$$

$$g_\star \sim m_{T,\tilde{T}}$$

$$y_R \to g_\star$$

composite tR



$$\lambda_t \sim y_L$$

- Therefore the top quark has the strongest coupling to the composite sector. This motivates top studies at CLIC.

2. CH and Top Portal

- **What exactly can we see at CLIC?**

- The experimental bounds on the composite resonances now reach 1...3 TeV. It is reasonable to assume that there is none below the maximal CLIC c.o.m. energy. Hence, we will be testing the SM top sector only.

- We will look for the effects of the new composite dynamics on the top quark production.

2. CH and Top Portal

- **How do we want to describe the new physics effects?**

- Composite sector can be integrated out, leaving the **SM effective field theory**.

- We will use **dimensional analysis** and **selection rules** to fix the size of different operators (**dimension-6**).

- The operator coefficients will depend on y_L, y_R mixings, the typical composite sector coupling $g_\star$ and a strong condensate scale f

2. CH and Top Portal

- Generic term in the Lagrangian has the form

$$g_\star^2 f^4 \hat{\mathcal{L}} \left[\frac{y_L q_L}{(g_\star f)^{3/2}}, \frac{y_R t_R}{(g_\star f)^{3/2}}, \frac{\partial_\mu}{g_\star f}, \frac{g_X X_\mu}{g_\star f} \right]$$

- The cutoff (mass of the lightest resonances) is given by

$$m_\star \simeq g_\star f$$

- Additionally, there may be selection rules requiring extra suppression factors, and following from the structure of the UV theory

3. Top Portal Operators

3. Top Portal Operators

- We would like to list all the inequivalent operators sensitive mostly to the top mixings, and relevant for top production. These are top portal operators.

3. Top Portal Operators

- We would like to list all the inequivalent operators sensitive mostly to the top mixings, and relevant for top production. These are top portal operators.

dipoles

$$\mathcal{O}_{tqB} = [\bar{t}_R \sigma_{\mu\nu} \phi q_L] B^{\mu\nu} + \text{h.c.} \qquad \mathcal{O}_{tqW} = [\bar{t}_R \sigma_{\mu\nu} \phi \tau^i q_L] W^{i\,\mu\nu} + \text{h.c.}$$

3. Top Portal Operators

- We would like to list all the inequivalent operators sensitive mostly to the top mixings, and relevant for top production. These are top portal operators.

dipoles

$$\mathcal{O}_{tqB} = [\bar{t}_R \sigma_{\mu\nu} \phi q_L] B^{\mu\nu} + \text{h.c.} \qquad \mathcal{O}_{tqW} = [\bar{t}_R \sigma_{\mu\nu} \phi \tau^i q_L] W^{i\,\mu\nu} + \text{h.c.}$$

ttZ, tbW coupling modification

$$\mathcal{O}_{tD} = [\bar{t}_R \gamma_\mu t_R][\phi^\dagger \overleftrightarrow{D}^\mu \phi] \qquad \mathcal{O}_{qD}^{(1)} = [\bar{q}_L \gamma_\mu q_L][\phi^\dagger \overleftrightarrow{D}^\mu \phi] \qquad \mathcal{O}_{qD}^{(3)} = [\bar{q}_L \gamma_\mu \tau^i q_L][\phi^\dagger \overleftrightarrow{D}^{i\,\mu} \phi]$$

3. Top Portal Operators

- We would like to list all the inequivalent operators sensitive mostly to the top mixings, and relevant for top production. These are top portal operators.

dipoles

$$\mathcal{O}_{tqB} = [\bar{t}_R \sigma_{\mu\nu} \phi q_L] B^{\mu\nu} + \text{h.c.} \qquad \mathcal{O}_{tqW} = [\bar{t}_R \sigma_{\mu\nu} \phi \tau^i q_L] W^{i\,\mu\nu} + \text{h.c.}$$

ttZ, tbW coupling modification

$$\mathcal{O}_{tD} = [\bar{t}_R \gamma_\mu t_R][\phi^\dagger \overleftrightarrow{D}^\mu \phi] \qquad \mathcal{O}_{qD}^{(1)} = [\bar{q}_L \gamma_\mu q_L][\phi^\dagger \overleftrightarrow{D}^\mu \phi] \qquad \mathcal{O}_{qD}^{(3)} = [\bar{q}_L \gamma_\mu \tau^i q_L][\phi^\dagger \overleftrightarrow{D}^{i\,\mu} \phi]$$

energy-growing ttZ, tbW coupling modification

$$\mathcal{O}_{tB} = [\bar{t}_R \gamma_\mu t_R] D_\nu B^{\mu\nu} \qquad \mathcal{O}_{qB} = [\bar{q}_L \gamma_\mu q_L] D_\nu B^{\mu\nu} \qquad \mathcal{O}_{qW} = [\bar{q}_L \gamma_\mu \tau^i q_L] (D_\nu W^{\mu\nu})^i$$

3. Top Portal Operators

- We would like to list all the inequivalent operators sensitive mostly to the top mixings, and relevant for top production. These are top portal operators.

dipoles

$$\mathcal{O}_{tqB} = [\bar{t}_R \sigma_{\mu\nu} \phi q_L] B^{\mu\nu} + \text{h.c.} \qquad \mathcal{O}_{tqW} = [\bar{t}_R \sigma_{\mu\nu} \phi \tau^i q_L] W^{i\,\mu\nu} + \text{h.c.}$$

ttZ, tbW coupling modification

$$\mathcal{O}_{tD} = [\bar{t}_R \gamma_\mu t_R][\phi^\dagger \overleftrightarrow{D}^\mu \phi] \qquad \mathcal{O}_{qD}^{(1)} = [\bar{q}_L \gamma_\mu q_L][\phi^\dagger \overleftrightarrow{D}^\mu \phi] \qquad \mathcal{O}_{qD}^{(3)} = [\bar{q}_L \gamma_\mu \tau^i q_L][\phi^\dagger \overleftrightarrow{D}^{i\,\mu} \phi]$$

energy-growing ttZ, tbW coupling modification

$$\mathcal{O}_{tB} = [\bar{t}_R \gamma_\mu t_R] D_\nu B^{\mu\nu} \qquad \mathcal{O}_{qB} = [\bar{q}_L \gamma_\mu q_L] D_\nu B^{\mu\nu} \qquad \mathcal{O}_{qW} = [\bar{q}_L \gamma_\mu \tau^i q_L] (D_\nu W^{\mu\nu})^i$$

equivalent to four-fermion (tt)(ee)

$$(D_\nu W^{\nu\mu})^I = \frac{g}{2} \left(\phi^\dagger i \overleftrightarrow{D}^{\mu I} \phi + \bar{q} \gamma^\mu \tau^I q + \bar{l} \gamma^\mu \tau^I l \right)$$

3. Top Portal Operators

- We would like to list all the inequivalent operators sensitive mostly to the top mixings, and relevant for top production. These are top portal operators.

dipoles

$$\mathcal{O}_{tqB} = [\bar{t}_R \sigma_{\mu\nu} \phi q_L] B^{\mu\nu} + \text{h.c.} \qquad \mathcal{O}_{tqW} = [\bar{t}_R \sigma_{\mu\nu} \phi \tau^i q_L] W^{i\,\mu\nu} + \text{h.c.}$$

ttZ, tbW coupling modification

$$\mathcal{O}_{tD} = [\bar{t}_R \gamma_\mu t_R][\phi^\dagger \overleftrightarrow{D}^\mu \phi] \qquad \mathcal{O}_{qD}^{(1)} = [\bar{q}_L \gamma_\mu q_L][\phi^\dagger \overleftrightarrow{D}^\mu \phi] \qquad \mathcal{O}_{qD}^{(3)} = [\bar{q}_L \gamma_\mu \tau^i q_L][\phi^\dagger \overleftrightarrow{D}^{i\,\mu} \phi]$$

energy-growing ttZ, tbW coupling modification

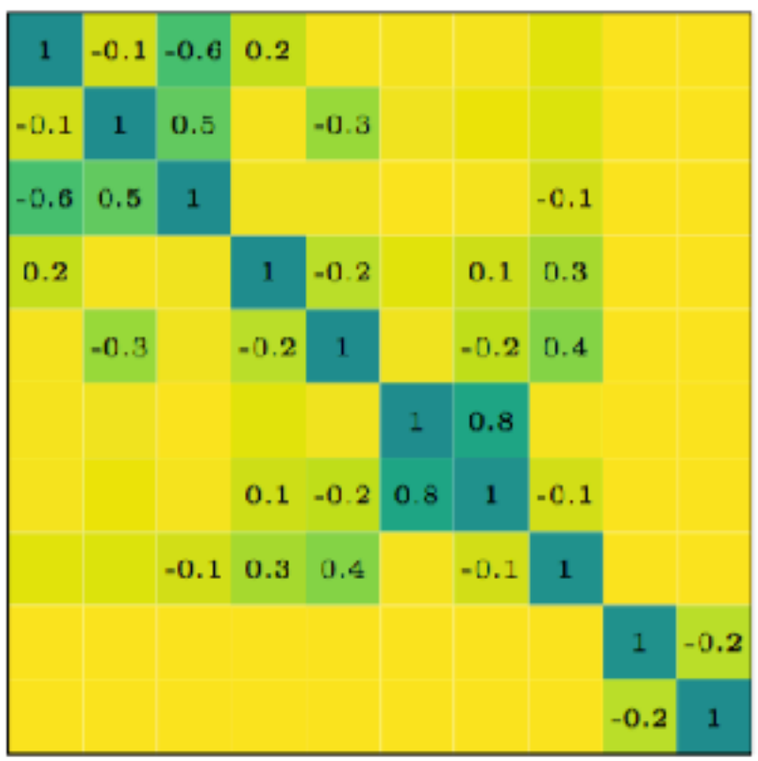
$$\mathcal{O}_{tB} = [\bar{t}_R \gamma_\mu t_R] D_\nu B^{\mu\nu} \qquad \mathcal{O}_{qB} = [\bar{q}_L \gamma_\mu q_L] D_\nu B^{\mu\nu} \qquad \mathcal{O}_{qW} = [\bar{q}_L \gamma_\mu \tau^i q_L] D_\nu W^{\mu\nu\,i}$$

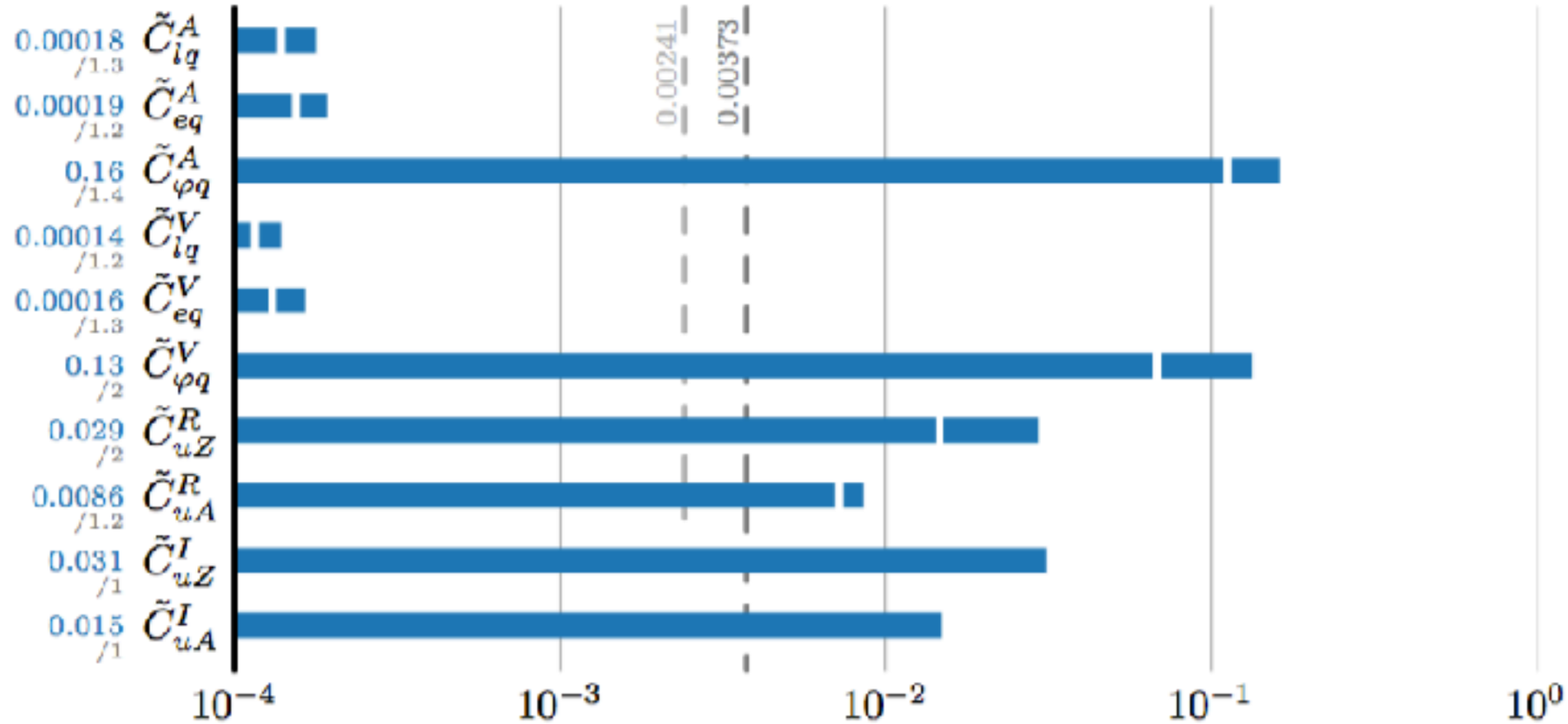
equivalent to four-fermion (tt)(ee)

$$D_\nu W^{\nu\mu\,I} = \frac{g}{2}\left(\phi^\dagger i \overleftrightarrow{D}^{\mu I} \phi + \bar{q}\gamma^\mu \tau^I q + \bar{l}\gamma^\mu \tau^I l\right)$$

3. Top Portal Operators

- future sensitivities, from Durieux,Zhang,Vos,Perello (work in progress)





*** sensitivities are given in TeV^-2, assuming real coefficients**

**** at 1 sigma**

3. Top Portal Operators

- sensitivities to each operator coefficient

$$\mathcal{O}_{tqB} = [\bar{t}_R \sigma_{\mu\nu} \phi q_L] B^{\mu\nu} + \text{h.c.}$$

$$2.2 \cdot 10^{-3}$$

$$\mathcal{O}_{tqW} = [\bar{t}_R \sigma_{\mu\nu} \phi \tau^i q_L] W^{i\,\mu\nu} + \text{h.c.}$$

$$3.9 \cdot 10^{-3}$$

$$\mathcal{O}_{tD} = [\bar{t}_R \gamma_\mu t_R][\phi^\dagger \overleftrightarrow{D}^\mu \phi]$$

$$2.9 \cdot 10^{-2}$$

$$\mathcal{O}_{qD}^{(1)} = [\bar{q}_L \gamma_\mu q_L][\phi^\dagger \overleftrightarrow{D}^\mu \phi]$$

$$2.9 \cdot 10^{-2}$$

$$\mathcal{O}_{qD}^{(3)} = [\bar{q}_L \gamma_\mu \tau^i q_L][\phi^\dagger \overleftrightarrow{D}^{i\,\mu} \phi]$$

$$2.9 \cdot 10^{-2}$$

$$\mathcal{O}_{tB} = [\bar{t}_R \gamma_\mu t_R] D_\nu B^{\mu\nu}$$

$$1.8 \cdot 10^{-4}$$

$$\mathcal{O}_{qB} = [\bar{q}_L \gamma_\mu q_L] D_\nu B^{\mu\nu}$$

$$2.4 \cdot 10^{-4}$$

$$\mathcal{O}_{qW} = [\bar{q}_L \gamma_\mu \tau^i q_L](D_\nu W^{\mu\nu})^i$$

$$2.1 \cdot 10^{-4}$$

*** sensitivities are given in TeV^-2, assuming real coefficients**

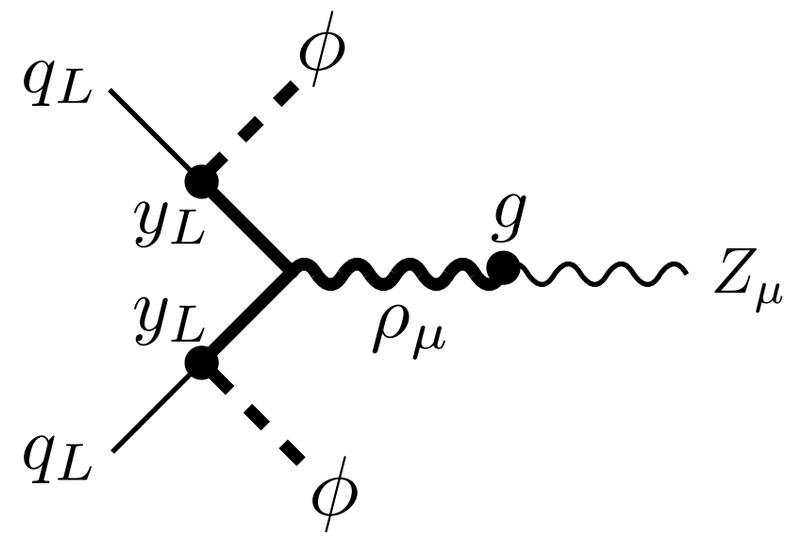
**** at 1 sigma**

4. Sensitivity to CH from the top production

4. Sensitivity to CH from the top production

- **Top portal**: zero-momentum **Zqq**, **Wtb** vertex correction

$$\left\{ \frac{y_L^2}{g_\star^2} \right\} \frac{1}{f^2} [\bar{q}_L \gamma_\mu q_L][\phi^\dagger \overleftrightarrow{D}^\mu \phi]$$



4. Sensitivity to CH from the top production

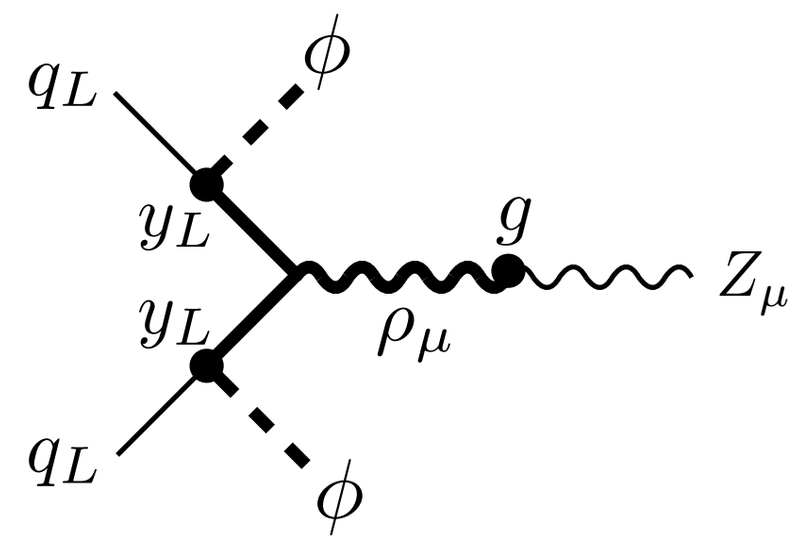
- **Top portal**: zero-momentum **Zqq**, **Wtb** vertex correction

suppressed by condensation scale

contains EW boson

$$\left\{\frac{y_L^2}{g_\star^2}\right\}\frac{1}{f^2}[\bar{q}_L\gamma_\mu q_L][\phi^\dagger \overleftrightarrow{D}^\mu \phi]$$

one yL for each qL



4. Sensitivity to CH from the top production

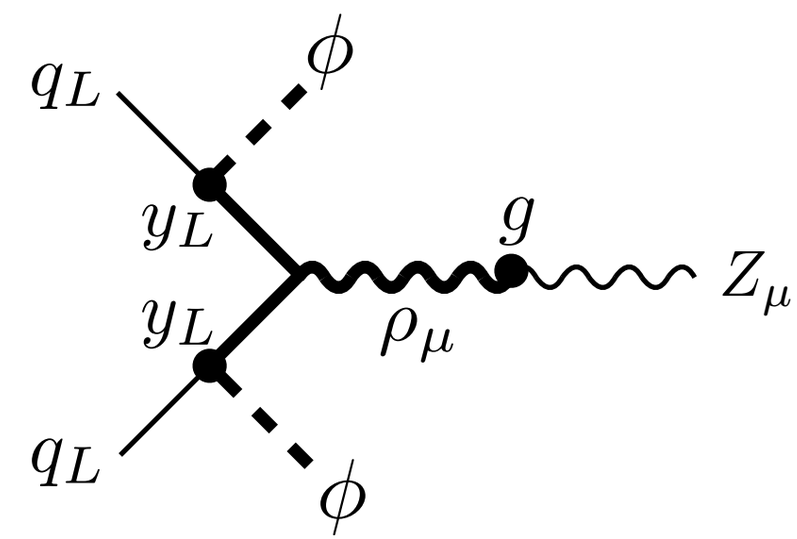
- **Top portal**: zero-momentum **Zqq**, **Wtb** vertex correction

suppressed by condensation scale

contains EW boson

$$\left\{\frac{y_L^2}{g_\star^2}\right\}\frac{1}{f^2}[\bar{q}_L\gamma_\mu q_L][\phi^\dagger \overleftrightarrow{D}^\mu \phi]$$

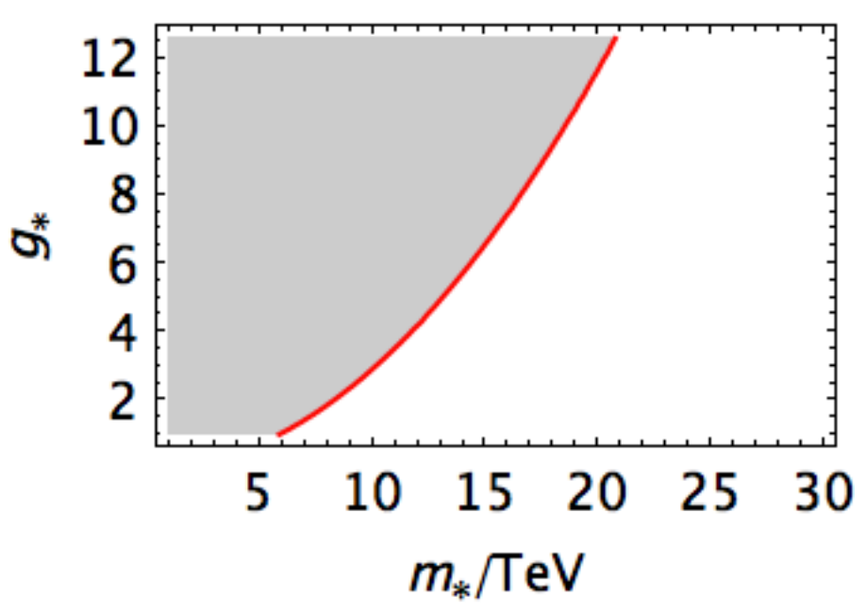
one yL for each qL



- expected sensitivity $c = 2.9 \cdot 10^{-2}$

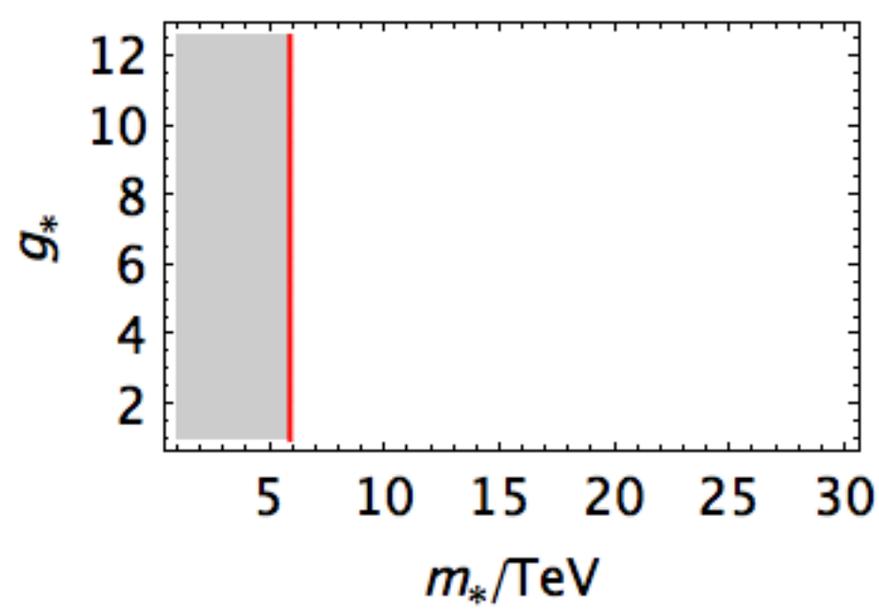
- elementary tR

$y_L = y_R = \sqrt{g_\star}$



- composite tR

$y_L = y_t$



4. Sensitivity to CH from the top production

- **Top portal**: zero-momentum **Ztt** vertex correction

$$\left\{ \frac{y_R^2}{g_\star^2} \frac{y_L^2}{g_\star^2} \right\} \frac{1}{f^2} [\bar{t}_R \gamma_\mu t_R][\phi^\dagger \overleftrightarrow{D}^\mu \phi]$$

4. Sensitivity to CH from the top production

- **Top portal**: zero-momentum $\mathbf{Ztt}$ vertex correction

$$\left\{ \frac{y_R^2}{g_\star^2} \frac{y_L^2}{g_\star^2} \right\} \frac{1}{f^2} [\bar{t}_R \gamma_\mu t_R][\phi^\dagger \overleftrightarrow{D}^\mu \phi]$$

extra suppression from PLR symmetry

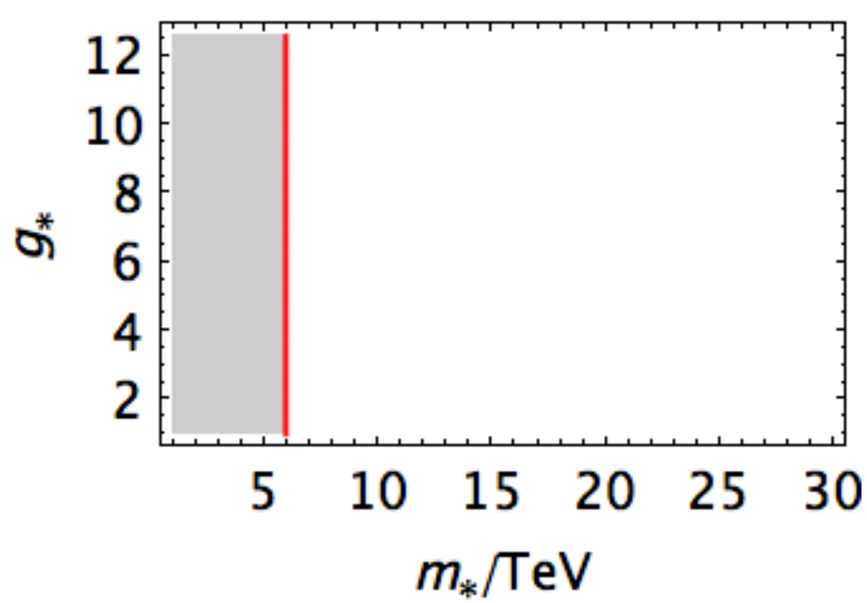
4. Sensitivity to CH from the top production

- **Top portal**: zero-momentum $\mathbf{Ztt}$ vertex correction

$$\left\{ \frac{y_R^2}{g_\star^2} \frac{y_L^2}{g_\star^2} \right\} \frac{1}{f^2} [\bar{t}_R \gamma_\mu t_R][\phi^\dagger \overleftrightarrow{D}^\mu \phi]$$

extra suppression from PLR symmetry

- expected sensitivity $c = 2.9 \cdot 10^{-2}$
  - elementary tR, composite tR



4. Sensitivity to CH from the top production

- **Top portal**: dipole

$$\left\{ \frac{g_\star^2}{(4\pi)^2} \frac{g_X}{g_\star} \frac{y_L}{g_\star} \frac{y_R}{g_\star} \right\} \frac{1}{f^2} [\bar{t}_L \sigma_{\mu\nu} \phi q_R] X^{\mu\nu}$$

4. Sensitivity to CH from the top production

- **Top portal**: dipole

$$\left\{ \frac{g_\star^2}{(4\pi)^2} \frac{g_X}{g_\star} \frac{y_L}{g_\star} \frac{y_R}{g_\star} \right\} \frac{1}{f^2} [\bar{t}_L \sigma_{\mu\nu} \phi q_R] X^{\mu\nu}$$

1-loop suppressed

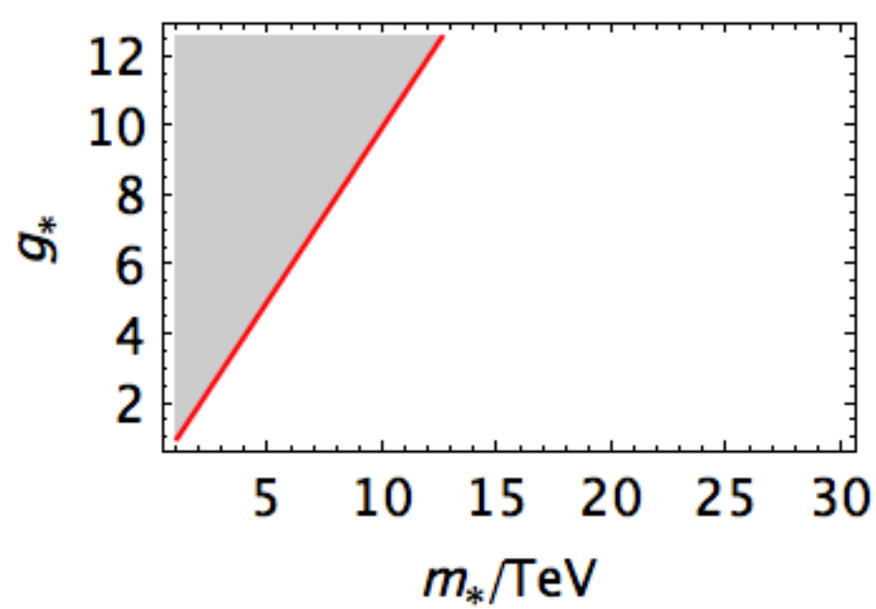
4. Sensitivity to CH from the top production

- **Top portal**: dipole

$$\left\{ \frac{g_\star^2}{(4\pi)^2} \frac{g_X}{g_\star} \frac{y_L}{g_\star} \frac{y_R}{g_\star} \right\} \frac{1}{f^2} [\bar{t}_L \sigma_{\mu\nu} \phi q_R] X^{\mu\nu}$$

1-loop suppressed

- expected sensitivity $c = 2.2 \cdot 10^{-3}$, $3.9 \cdot 10^{-3}$
  - elementary tR, composite tR



4. Sensitivity to CH from the top production

- **Top portal**: momentum-dependent **Ztt** vertex correction

$$\left\{ \frac{g'}{g_\star^2} \frac{y_R^2}{g_\star^2} \right\} \frac{1}{f^2} [\bar{t}_R \gamma_\mu t_R] D_\nu B^{\mu\nu}$$

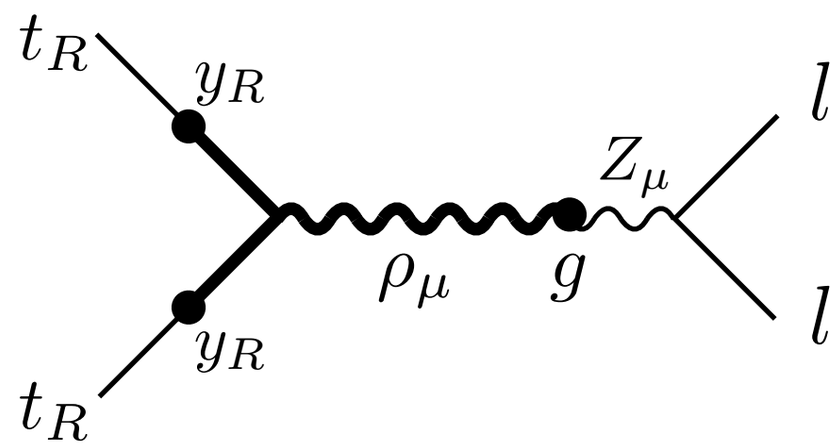
4. Sensitivity to CH from the top production

- **Top portal**: momentum-dependent **Ztt** vertex correction

$$\left\{ \frac{g'}{g_\star^2} \frac{y_R^2}{g_\star^2} \right\} \frac{1}{f^2} [\bar{t}_R \gamma_\mu t_R] D_\nu B^{\mu\nu}$$

- equivalent four-fermion operators

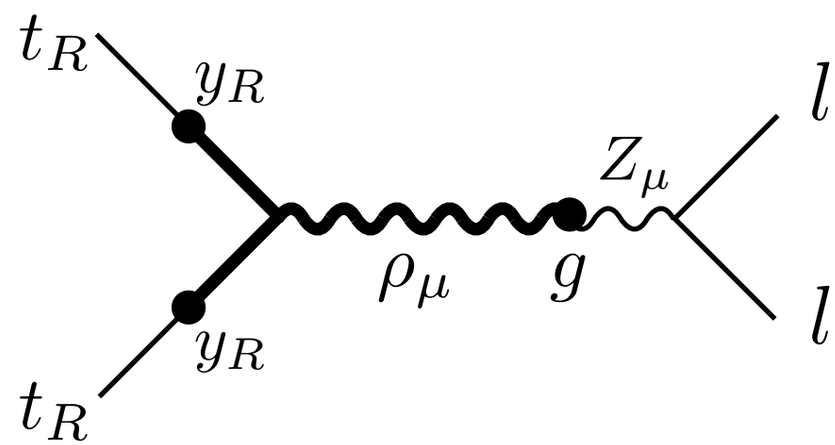
$$\left\{ \frac{g'^2}{g_\star^2} \frac{y_R^2}{g_\star^2} \right\} \frac{1}{f^2} [\bar{t}_R \gamma_\mu t_R][\bar{l} \gamma^\mu l]$$



4. Sensitivity to CH from the top production

- **Top portal**: momentum-dependent **Ztt** vertex correction

$$\left\{ \frac{g'}{g_\star^2} \frac{y_R^2}{g_\star^2} \right\} \frac{1}{f^2} [\bar{t}_R \gamma_\mu t_R] D_\nu B^{\mu\nu}$$

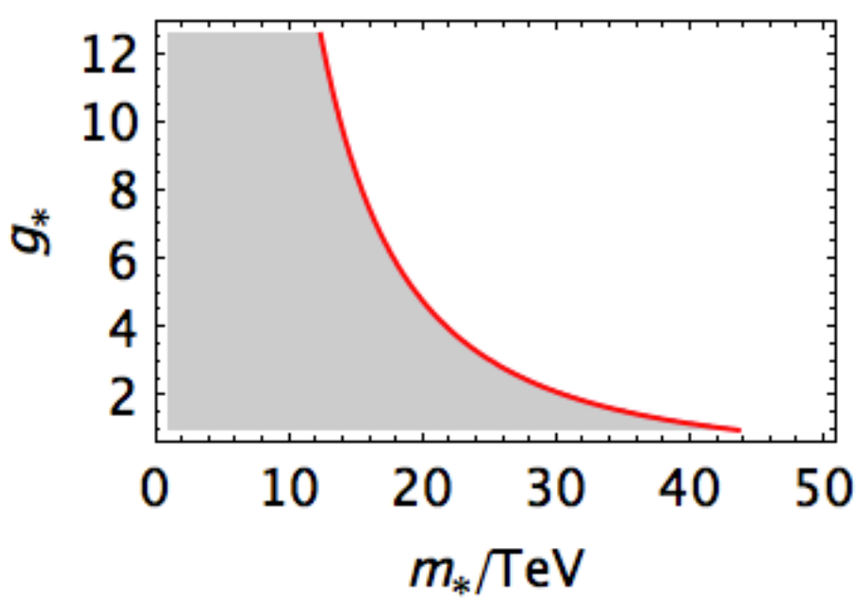


- equivalent four-fermion operators

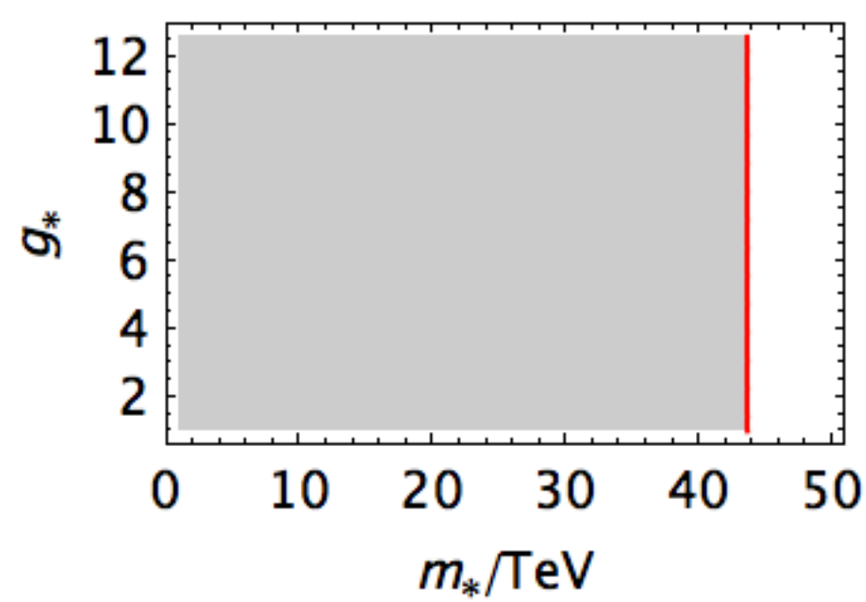
$$\left\{ \frac{g'^2}{g_\star^2} \frac{y_R^2}{g_\star^2} \right\} \frac{1}{f^2} [\bar{t}_R \gamma_\mu t_R][\bar{l} \gamma^\mu l]$$

- expected sensitivity $c = 1.8 \cdot 10^{-4}$

- elementary tR



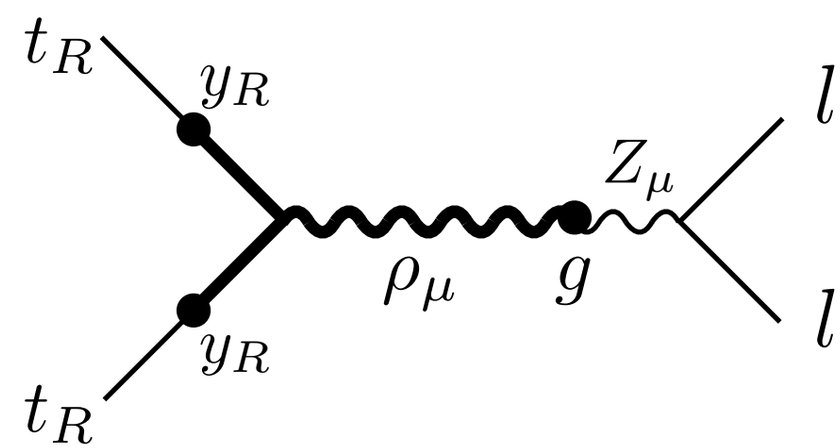
- composite tR



4. Sensitivity to CH from the top production

- **Top portal**: momentum-dependent **Ztt** vertex correction

$$\left\{ \frac{g'}{g_\star^2} \frac{y_R^2}{g_\star^2} \right\} \frac{1}{f^2} [\bar{t}_R \gamma_\mu t_R] D_\nu B^{\mu\nu}$$



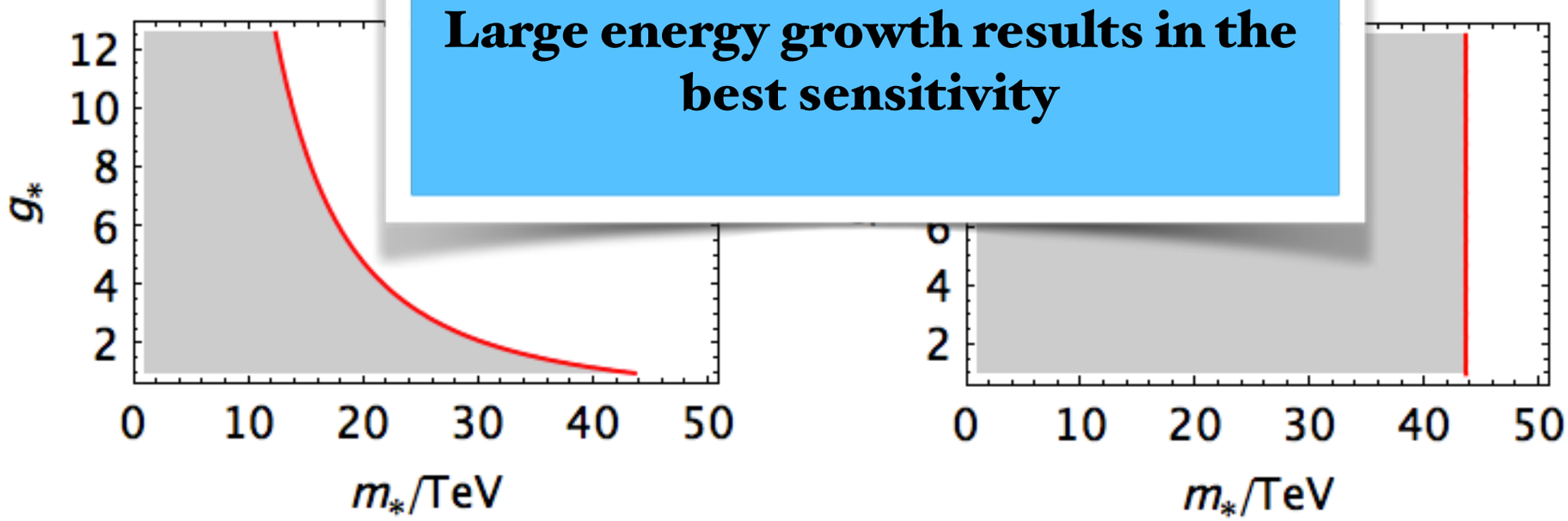
- equivalent four-fermion operators

$$\left\{ \frac{g'^2}{g_\star^2} \frac{y_R^2}{g_\star^2} \right\} \frac{1}{f^2} [\bar{t}_R \gamma_\mu t_R][\bar{l} \gamma^\mu l]$$

- expected sensitivity $c = 1.8 \cdot 10^{-4}$

- eleme tR

Large energy growth results in the best sensitivity



4. Sensitivity to CH from the top production

- There exist operators independent of the top mixings ("universal"), which are also equivalent to the (tt)(ee) operators

$$\mathcal{O}_X = (\partial^\mu X_{\mu\nu})(\partial_\delta X^{\delta\nu})$$

$$(D_\nu W^{\nu\mu})^I = \frac{g}{2}\left(\phi^\dagger i \overleftrightarrow{D}^{\mu I}\phi + \bar{q}\gamma^\mu\tau^I q + \bar{l}\gamma^\mu\tau^I l\right)$$

- **If** they dominate over the top portal for the top physics:

  - sensitivity to top compositeness in t production would be less direct.

  - universal operators may be better constrained from other processes. That would automatically make t physics less relevant for Composite Higgs.

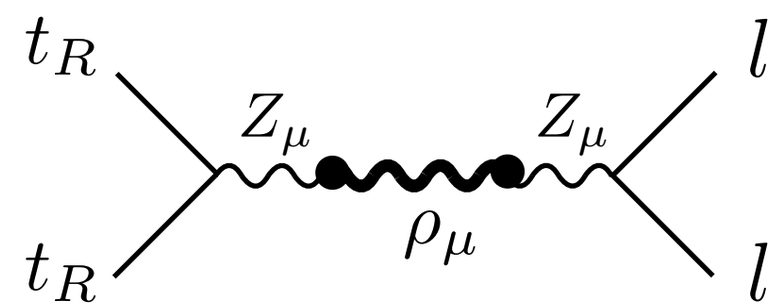
4. Sensitivity to CH from the top production

- **Gauge portal (universal)** operators: only g. b. mixings

$$\frac{g_X^2}{g_\star^2}\frac{1}{g_\star^2}\frac{1}{f^2}(\partial^\mu X_{\mu\nu})(\partial_\delta X^{\delta\nu})$$

- equivalent four-fermion operators

$$\left\{\frac{g_X^4}{g_\star^4}\right\}\frac{1}{f^2}\,[\bar{t}_R\gamma_\mu t_R][\bar{l}\gamma^\mu l]$$



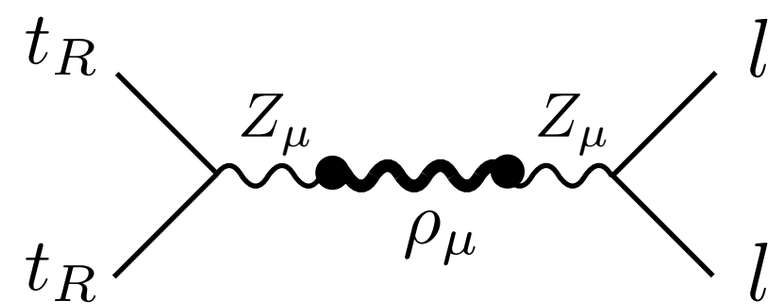
4. Sensitivity to CH from the top production

- **Gauge portal (universal)** operators: only g. b. mixings

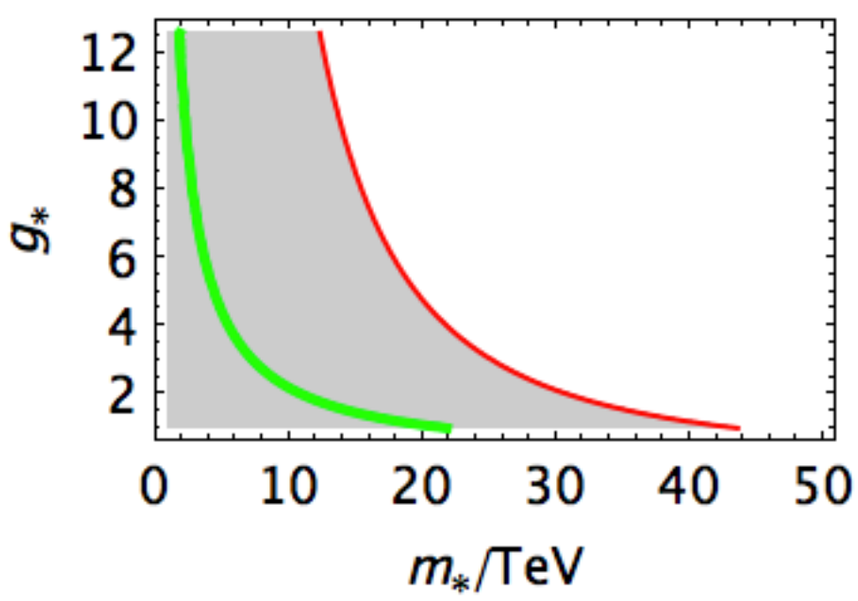
$$\frac{g_X^2}{g_\star^2}\frac{1}{g_\star^2}\frac{1}{f^2}(\partial^\mu X_{\mu\nu})(\partial_\delta X^{\delta\nu})$$

- equivalent four-fermion operators

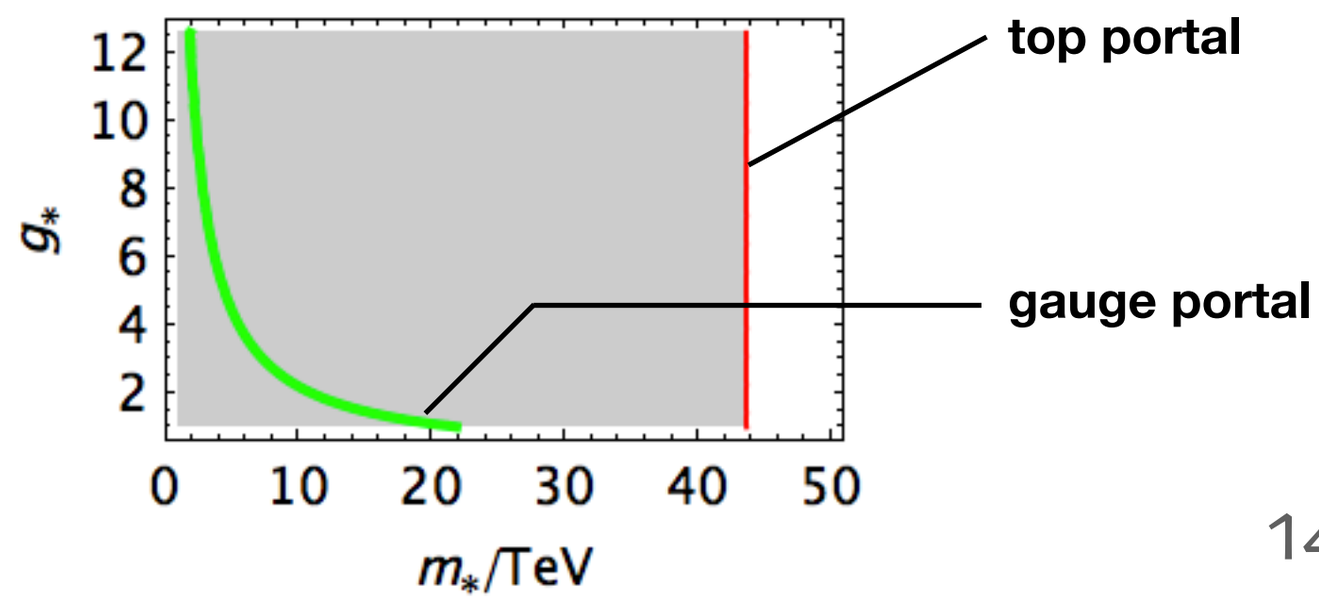
$$\left\{\frac{g_X^4}{g_\star^4}\right\}\frac{1}{f^2}\,[\bar{t}_R\gamma_\mu t_R][\bar{l}\gamma^\mu l]$$



- elementary tR



- composite tR



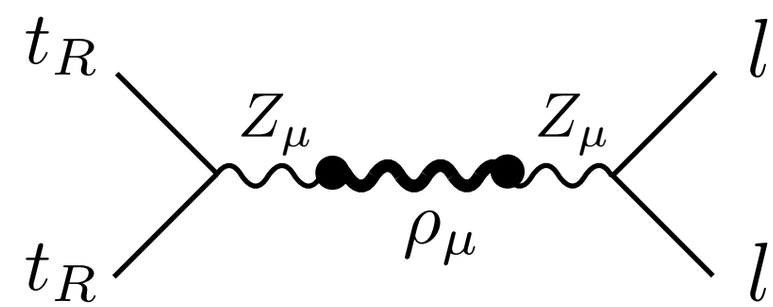
4. Sensitivity to CH from the top production

- **Gauge portal (universal)** operators: only g. b. mixings

$$\frac{g_X^2}{g_\star^2}\frac{1}{g_\star^2}\frac{1}{f^2}(\partial^\mu X_{\mu\nu})(\partial_\delta X^{\delta\nu})$$

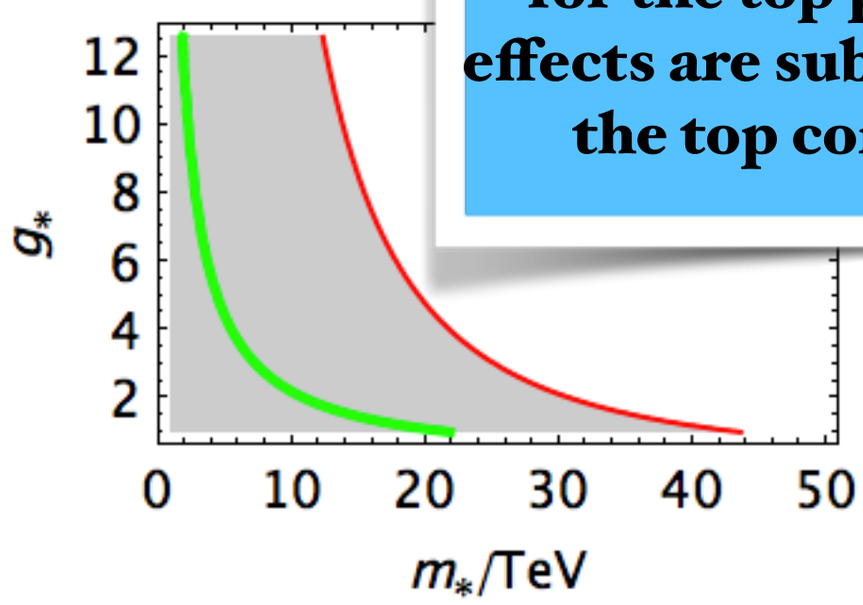
- equivalent four-fermion operators

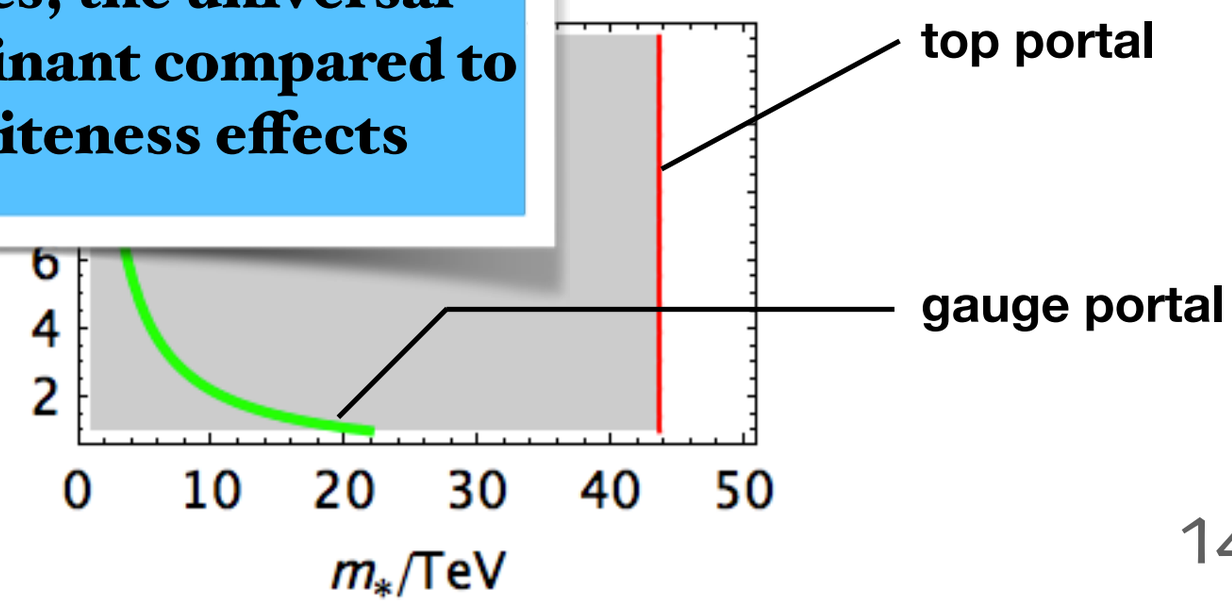
$$\left\{\frac{g_X^4}{g_\star^4}\right\}\frac{1}{f^2}\,[\bar{t}_R\gamma_\mu t_R][\bar{l}\gamma^\mu l]$$



- eleme tR

for the top physics, the universal effects are subdominant compared to the top compositeness effects

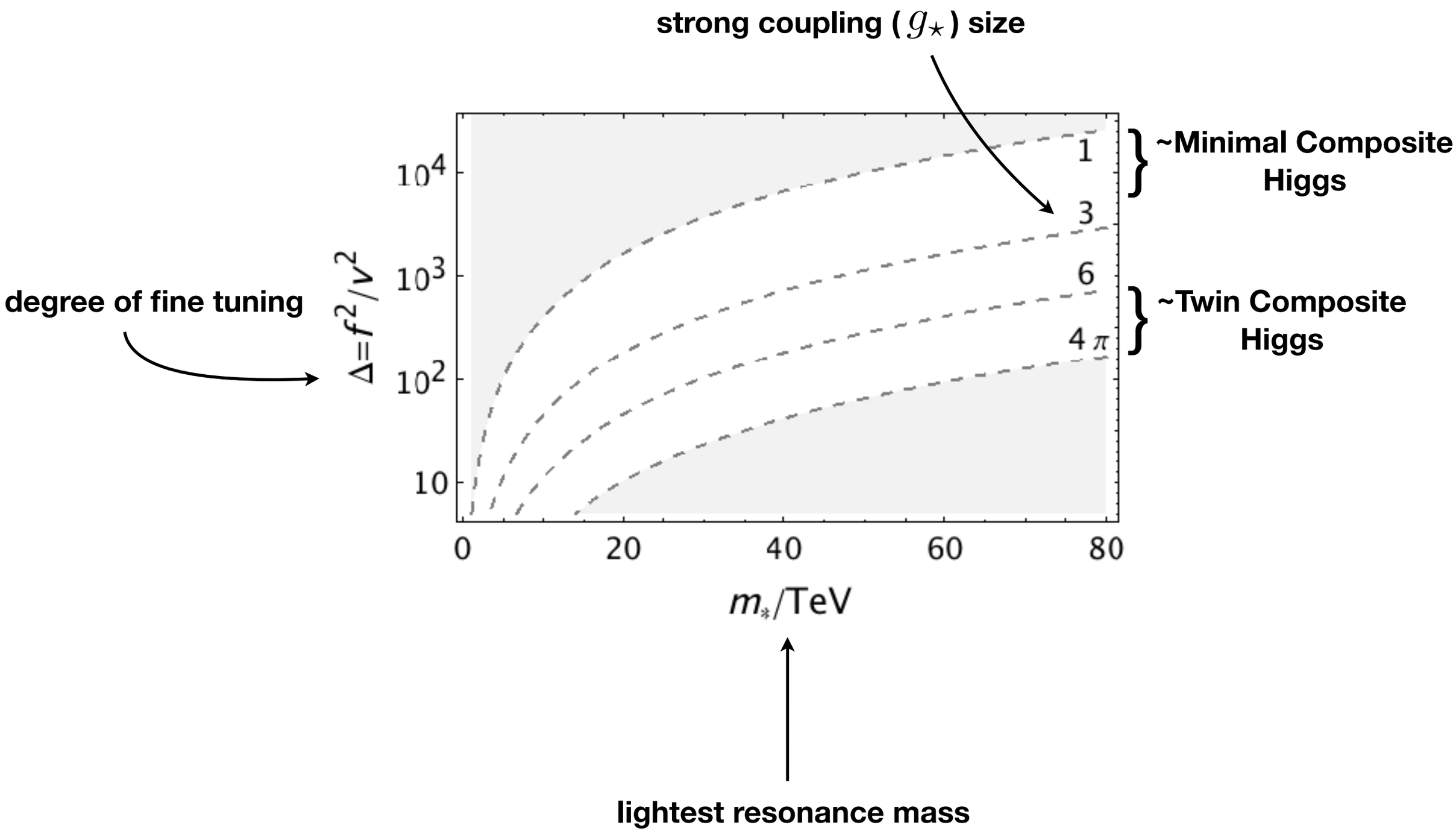




5. Sensitivity to CH from top@CLIC

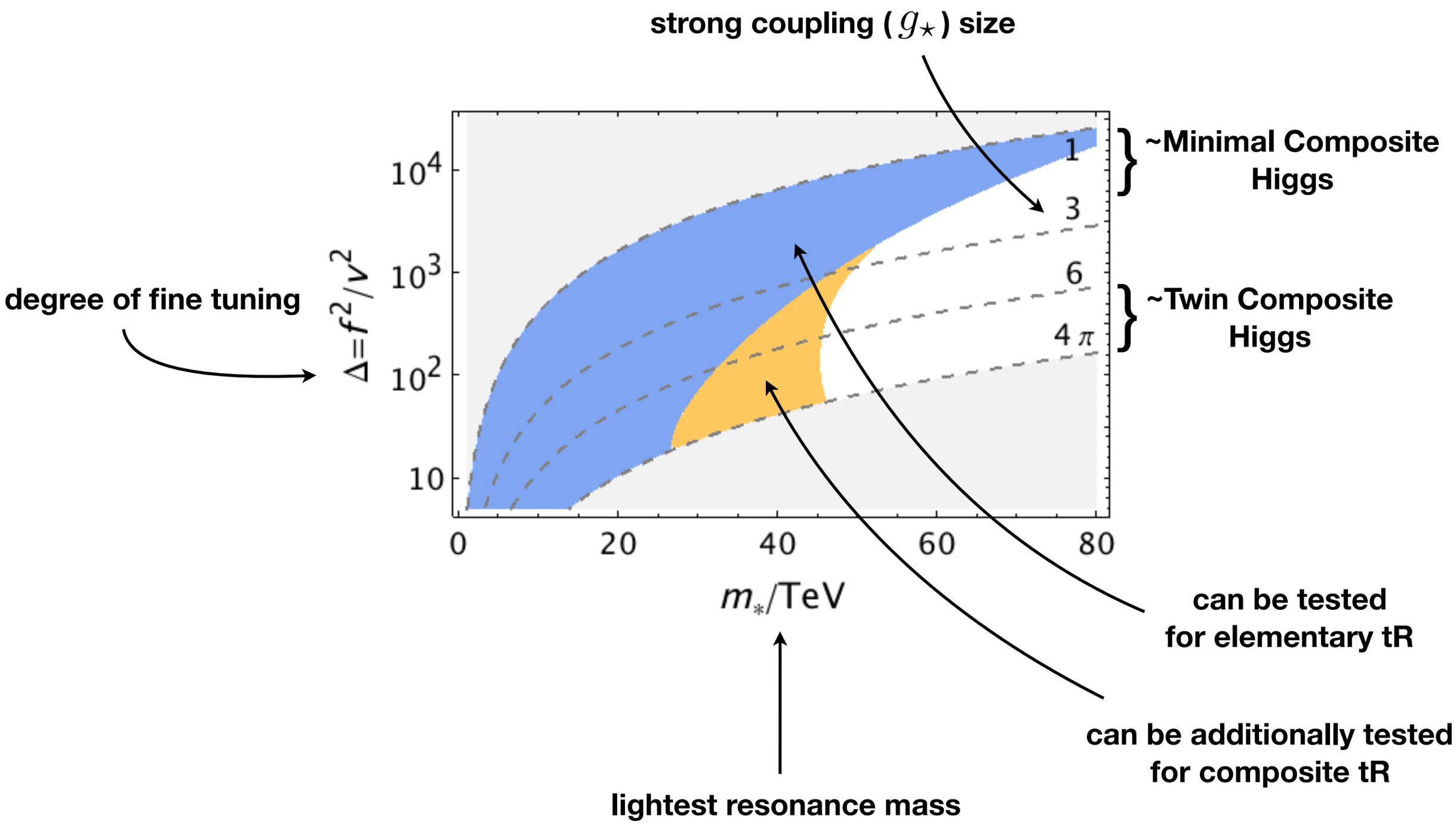
5. Sensitivity to CH from top@CLIC

- constraints on the key CH parameters: typical mass and fine tuning



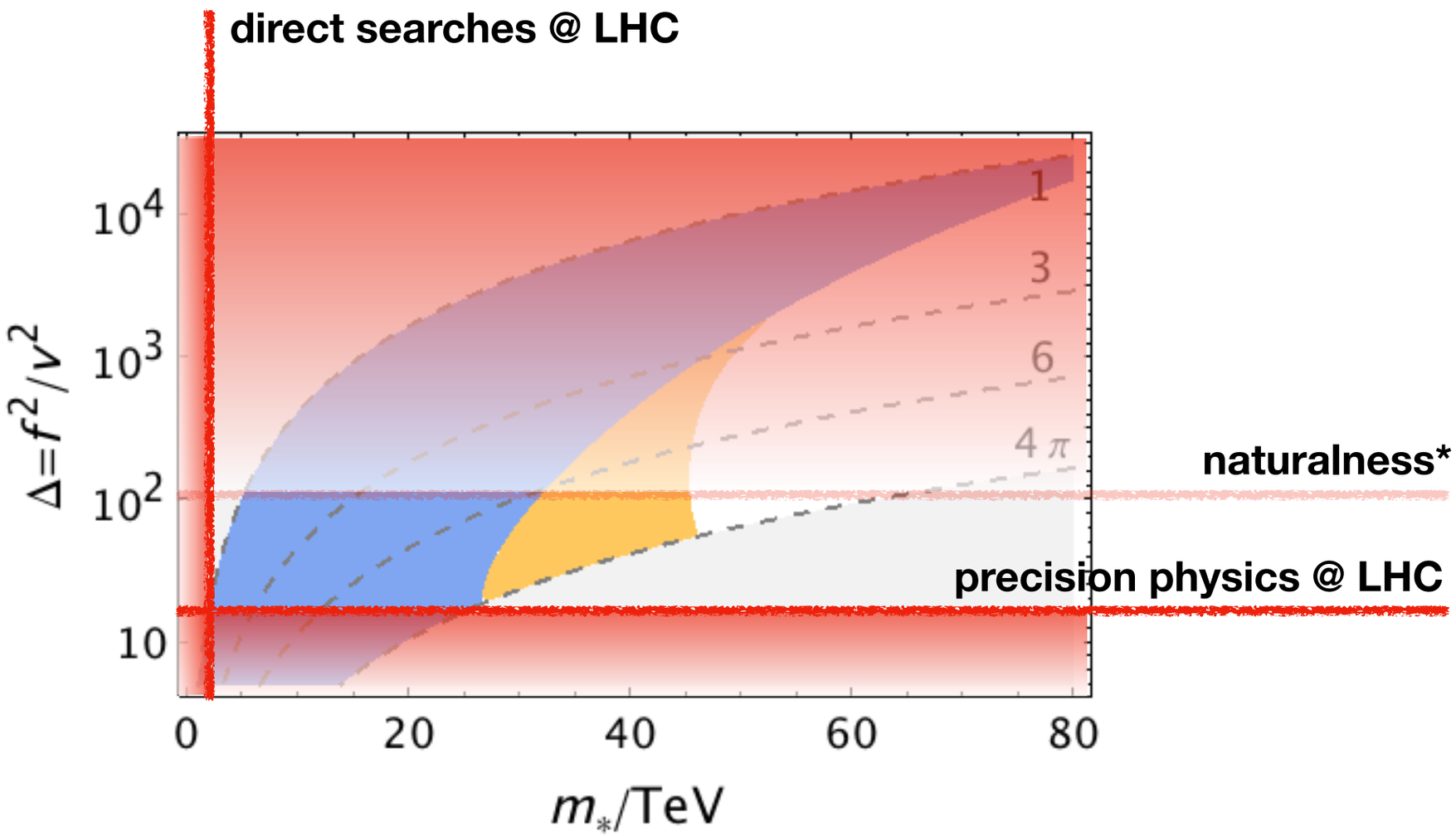
5. Sensitivity to CH from top@CLIC

- constraints on the key CH parameters: typical mass and fine tuning



5. Sensitivity to CH from top@CLIC

- constraints on the key CH parameters: typical mass and fine tuning



Conclusions

- Top physics at CLIC can present a good opportunity to test one of the key CH ingredients - top quark mixings
- Highest sensitivities come from four-fermion operators describing tt production
- Operators sensitive to the top quark mixings dominate in tt production processes
- Large fraction of the natural CH parameter space can be covered by analysing tt physics
- Ultimate test of minimal CH models

back-up slides

3. Top Portal Operators

- A generic EFT can contain all the operators compatible with symmetries.

- Since initial Lagrangian obeys power counting, so will be e.o.m.s of composite fields, and the EFT operator coefficients obtained with their help.

$$y_L q_L + [\text{composite operators}] = 0$$

- Some of these operators are redundant, i.e. they can be expressed through other operators e.g. by using equations of motion of the SM fields

$$c_1 \mathcal{O}_1 \to \delta c_2 \, \mathcal{O}_2 + \delta c_3 \, \mathcal{O}_3$$

- The power counting would hold for a reduced set if

$$\delta c_i \lesssim c_i$$

3. Top Portal Operators

- fermion e.o.m. $\not{D} q = -i(y_L/g_\star)\tilde{\phi}(y_R t)$ $\lambda_t = \frac{y_L y_R}{g_\star}$

does not exceed the power counting estimate

- scalars $(D_\mu D^\mu \phi)^i = m^2 \phi^i - \lambda |\phi|^2 \phi^i + (y_L \bar{q}_L)(y_R t_R)/g_\star$

obeys power counting

- gauge bosons $(D_\nu W^{\nu\mu})^I = \frac{g}{2}\left(\phi^\dagger i \overleftrightarrow{D}^{\mu I} \phi + \bar{q}\gamma^\mu \tau^I q + \bar{l}\gamma^\mu \tau^I l\right)$

breaks power counting

- Redefining away the terms with $D_\mu X^{\mu\nu}$ (as was done e.g. in Warsaw basis) breaks power counting. So, let's keep them.