MAX-PLANCK-INSTITUT FÜR KERNPHYSIK HEIDELBERG

The Hierarchy Problem and the Top Yukawa: An Alternative to Top Partner Solutions

with Andreas Bally, Florian Goertz, based on arXiv:2211.17254 ...

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Max-Planck-Institut für Kernphysik, Heidelberg

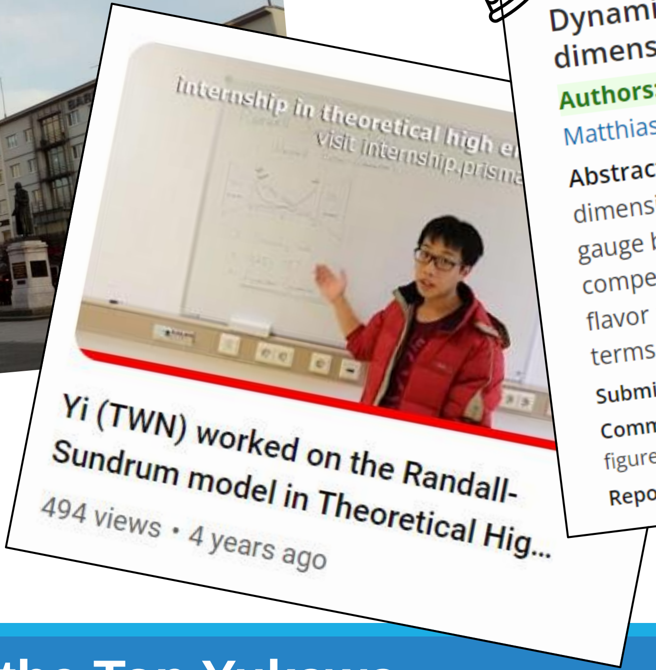
May 10th, 2023

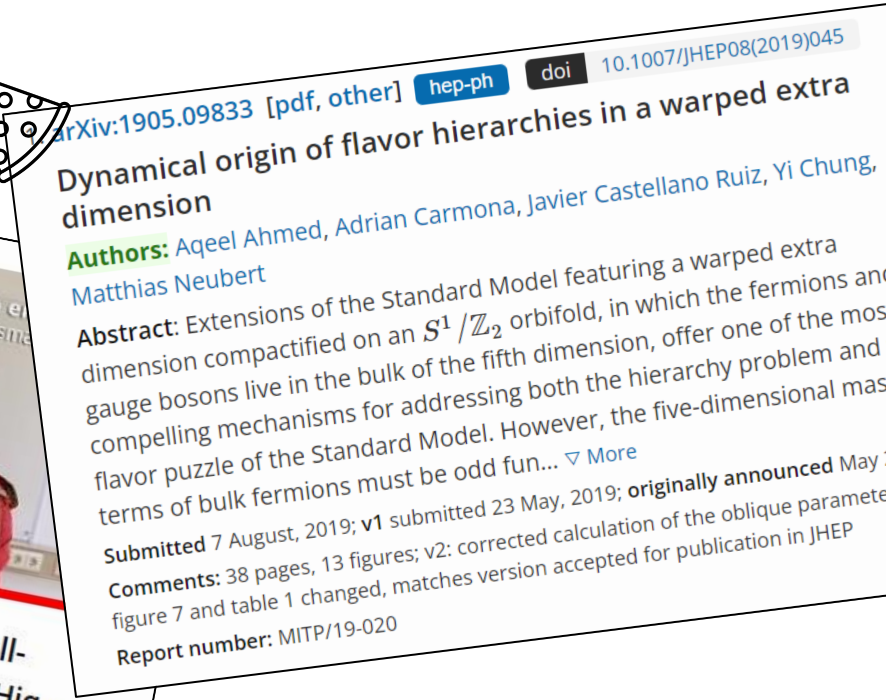
Pushing the Limits of Theoretical Physics , MITP, JGU Mainz

MITP, Matthias and Me

Congratulations and Great Thanks!!

10th anniversary of MITP and 60th birthday of Matthias




arXiv:1905.09833 [pdf, other] hep-ph doi 10.1007/JHEP08(2019)045

Dynamical origin of flavor hierarchies in a warped extra dimension

Authors: Aqeel Ahmed, Adrian Carmona, Javier Castellano Ruiz, Yi Chung, Matthias Neubert

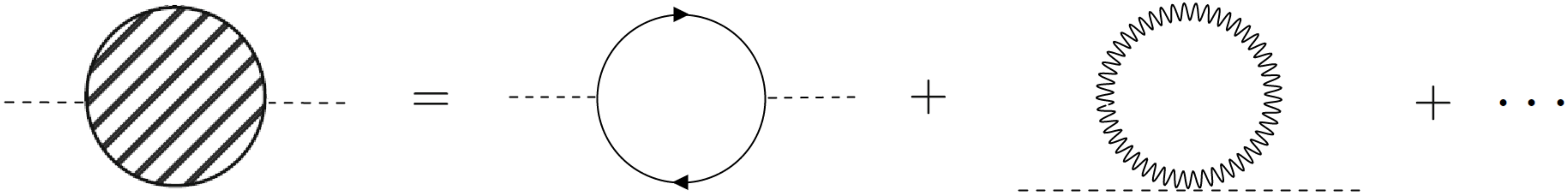
Abstract: Extensions of the Standard Model featuring a warped extra dimension compactified on an $S^1/\mathbb{Z}_2$ orbifold, in which the fermions and gauge bosons live in the bulk of the fifth dimension, offer one of the most compelling mechanisms for addressing both the hierarchy problem and the flavor puzzle of the Standard Model. However, the five-dimensional mass terms of bulk fermions must be odd fun... ▽ More

Submitted 7 August, 2019; v1 submitted 23 May, 2019; originally announced May

Comments: 38 pages, 13 figures; v2: corrected calculation of the oblique paramete figure 7 and table 1 changed, matches version accepted for publication in JHEP

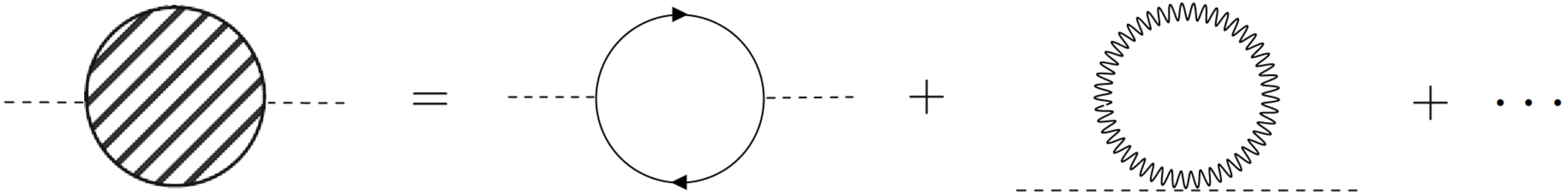
Report number: MITP/19-020

The Hierarchy Problem



$$\delta m_h^2 = -\frac{3}{8\pi^2} y_t^2 \Lambda_t^2 + \frac{9}{64\pi^2} g^2 \Lambda_g^2 + \cdots$$

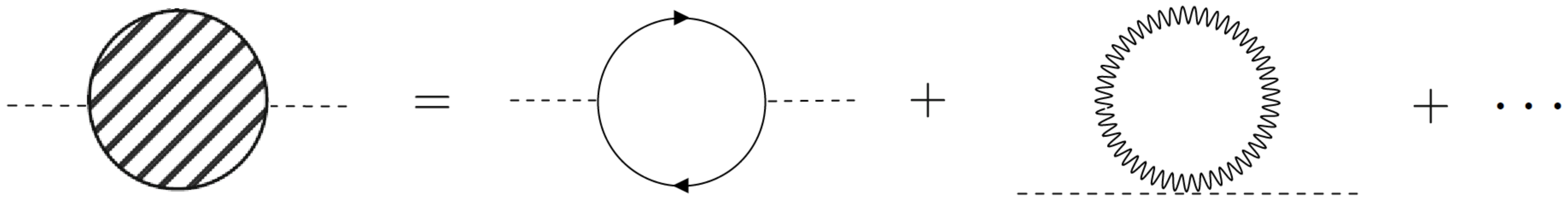
The Naturalness Principle



$$\delta m_h^2 = -\frac{3}{8\pi^2} y_t^2 \Lambda_t^2 + \frac{9}{64\pi^2} g^2 \Lambda_g^2 + \cdots$$

New Physics at $\Lambda_t \sim 500$ GeV $\Lambda_g \sim 1200$ GeV

The Naturalness Principle

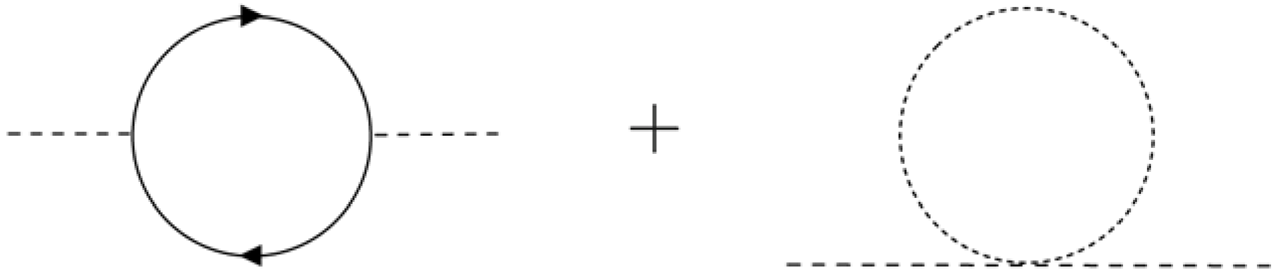


$$\delta m_h^2 = \boxed{-\frac{3}{8\pi^2} y_t^2 \Lambda_t^2} + \frac{9}{64\pi^2} g^2 \Lambda_g^2 + \cdots$$

New Physics at $\boxed{\Lambda_t \sim 500\ \mathrm{GeV}}$ $\Lambda_g \sim 1200\ \mathrm{GeV}$

The lightest new d.o.f.!!

Top partner solutions



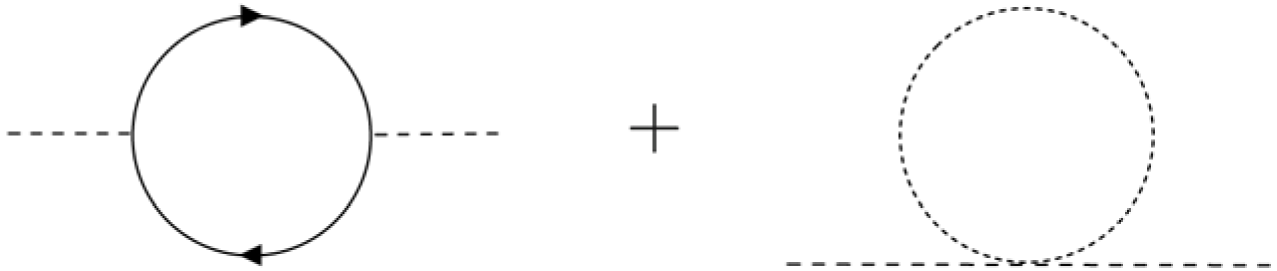
Top loop

Top-partner loop

$$+ \cdots \Longrightarrow \cancel{\Lambda^2} + \cdots$$

- The cancellation is guaranteed by Symmetry (ex: SUSY, shift symmetry …)

Top partner solutions



$$+ \cdots \Longrightarrow \cancel{\Lambda^2} + \cdots$$

Top loop   Top-partner loop

- The cancellation is guaranteed by Symmetry (ex: SUSY, shift symmetry …)
- The Higgs quadratic is still generated due to the difference between

$$\delta m_h^2|_{\text{top}} + \delta m_h^2|_{\text{top partner}} \sim -\frac{3}{8\pi^2} y_t^2 M_T^2 \ln\left(\frac{\Lambda^2}{M_T^2}\right)$$

- Naturalness principle suggests top partners with $\Lambda_t = M_T \approx 500$ GeV

Problems with Colored top partners

- Absence of colored top partners up to 1.2 TeV

  $\Rightarrow\ \sim 10\%$ fine tuning (even worse for large log factor)

Quantum #	Scalar	Fermion
QCD x EW	SUSY	CHM / RS

$\Rightarrow$ Colored top partners

Alternative to Colored top partners

- Absence of colored top partners up to 1.2 TeV

  $\Rightarrow$ $\sim 10\%$ fine tuning (even worse for large log factor)

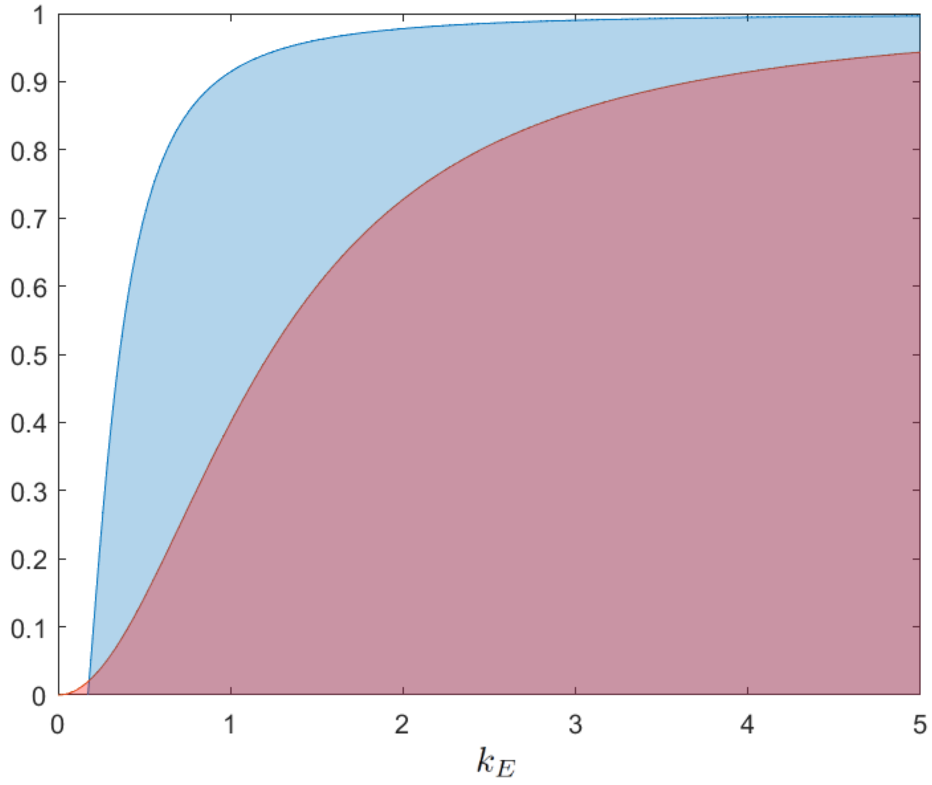
Quantum #	Scalar	Fermion
QCD x EW	SUSY	CHM / RS
Neutral x EW	Folded SUSY	Quirky Little Higgs
Neutral x Neutral	Tripled Top Hyperbolic Higgs	Twin Higgs

$\Rightarrow$ Uncolored top partners

Table borrowed from Chris Verhaaren

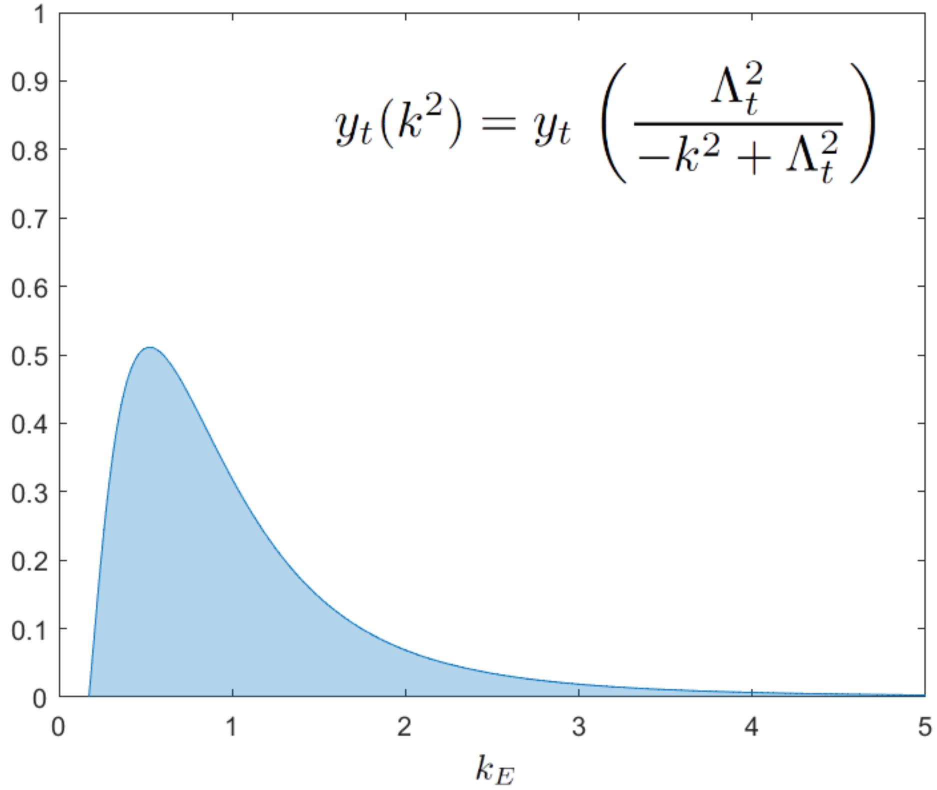
Alternative to Top-partner scenarios

- Cancellation (take $M_T = 1.2$ TeV)



$$\delta m_h^2|_{\text{top}} + \delta m_h^2|_{\text{top partner}} \sim -\frac{3}{8\pi^2} y_t^2 M_T^2 \ln\left(\frac{\Lambda^2}{M_T^2}\right)$$

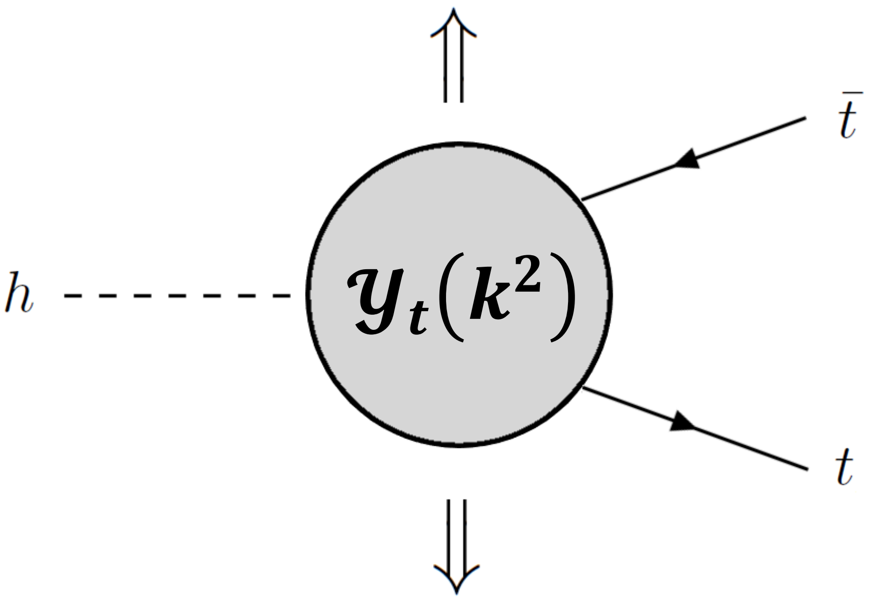
- Reduction (take $\Lambda_T = 1.2$ TeV)



$$\delta m_h^2|_{\text{top}} \sim -i\, 2N_c \int \frac{d^4k}{(2\pi)^4} y_t^2(k^2) \frac{k^2+m_t^2}{(k^2-m_t^2)^2} \sim -\frac{3}{8\pi^2} y_t^2 \Lambda_t^2$$

Modify the Top Yukawa vertex

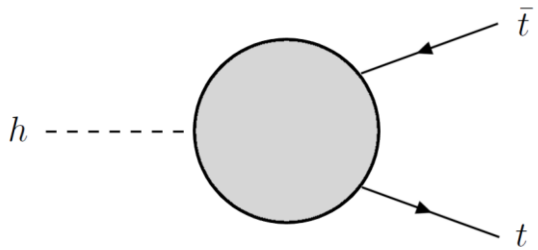
Model Building



Phenomenology

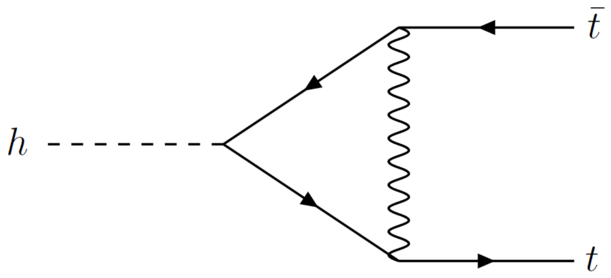
Go Up: Model Building

Zoom in the Top Yukawa vertex

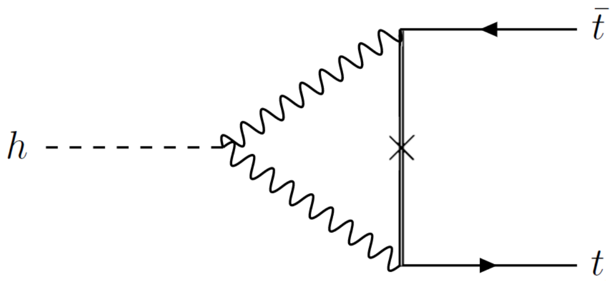


$$y_t = y_t(k^2)$$

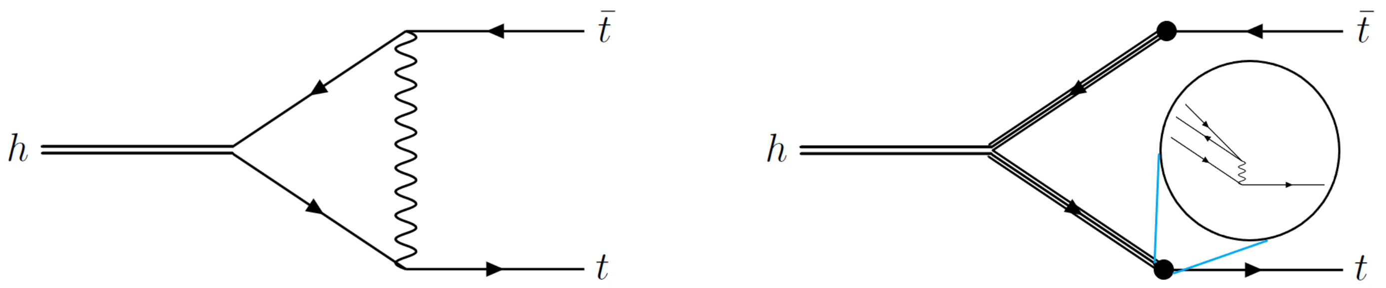
$\Rightarrow$



(1) large y_t running
new top-philic bosons
with strong coupling

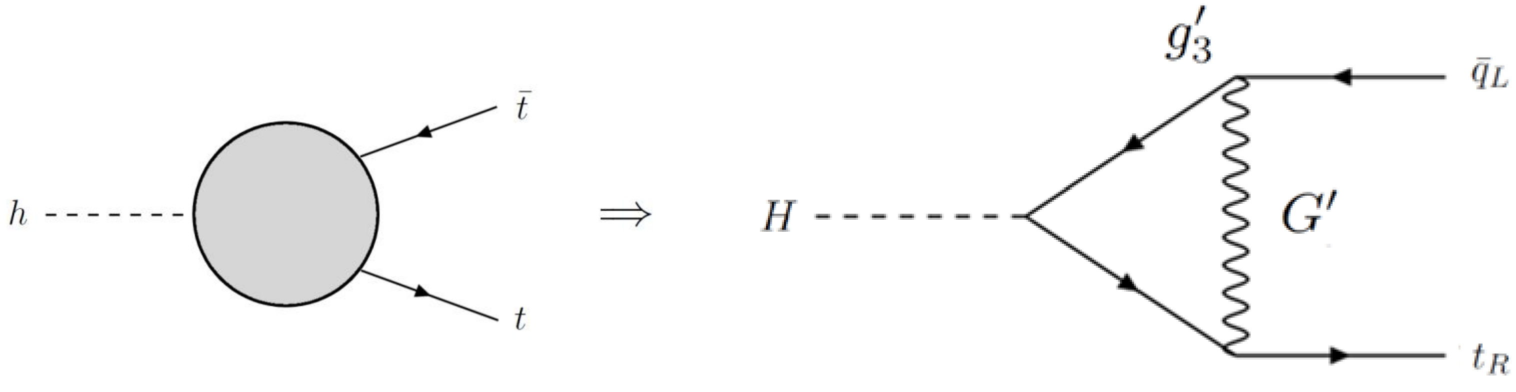


(2) radiative y_t generation
bosons and VL fermions
with strong coupling



(3) y_t from 4-fermi int. (for composite higgs)
extended-hypercolor bosons with weak coupling

Large y_t running



New top-philic bosons

Example:

Heavy gluons (Coloron)

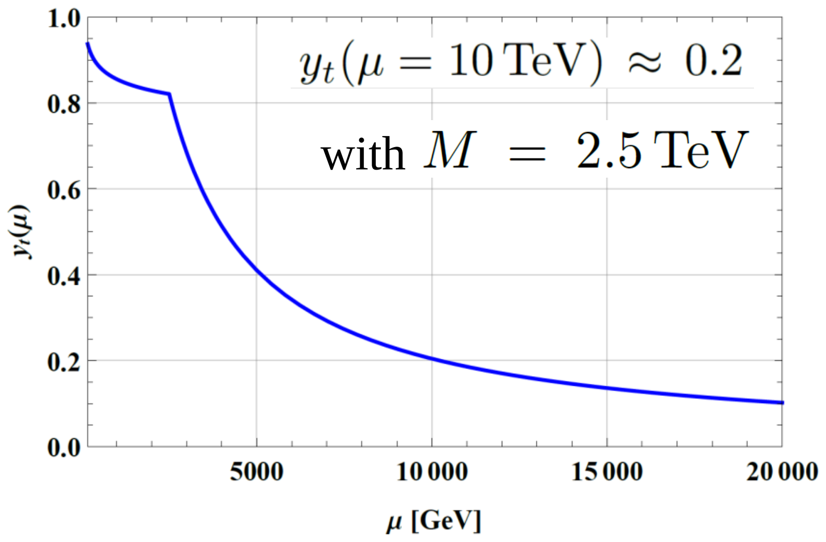
with the coupling $g_3' \sim 4.5$

- Large coupling can introduce large running

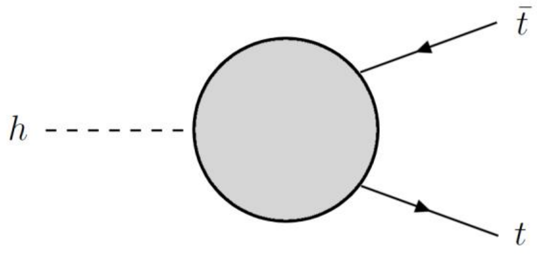
$$\frac{d\, y_t(\mu)}{d\, \ln\, \mu} = \frac{y_t(\mu)}{16\pi^2}\left(\frac{9}{2}\, y_t^2(\mu) - \frac{3(N^2-1)}{N} g_N^2\right)$$

need to be strong enough but not too strong

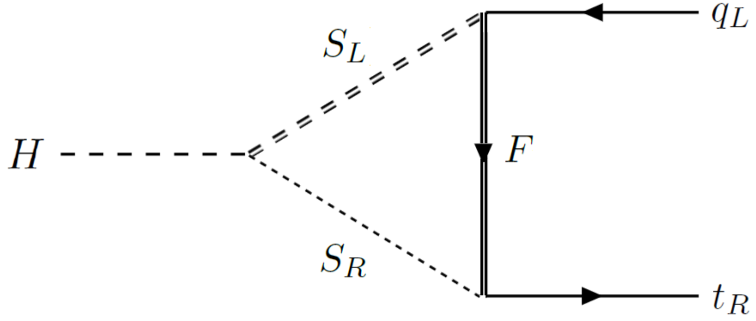
to avoid top condensate (topcolor)



Radiative y_t generation



$\Rightarrow$



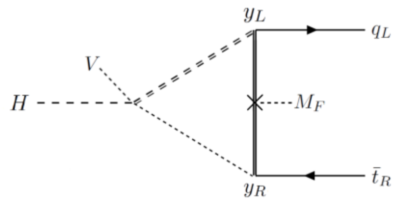
Minimal setup:

EW doublet scalar S_L

EW singlet scalar S_R

EW singlet fermion F

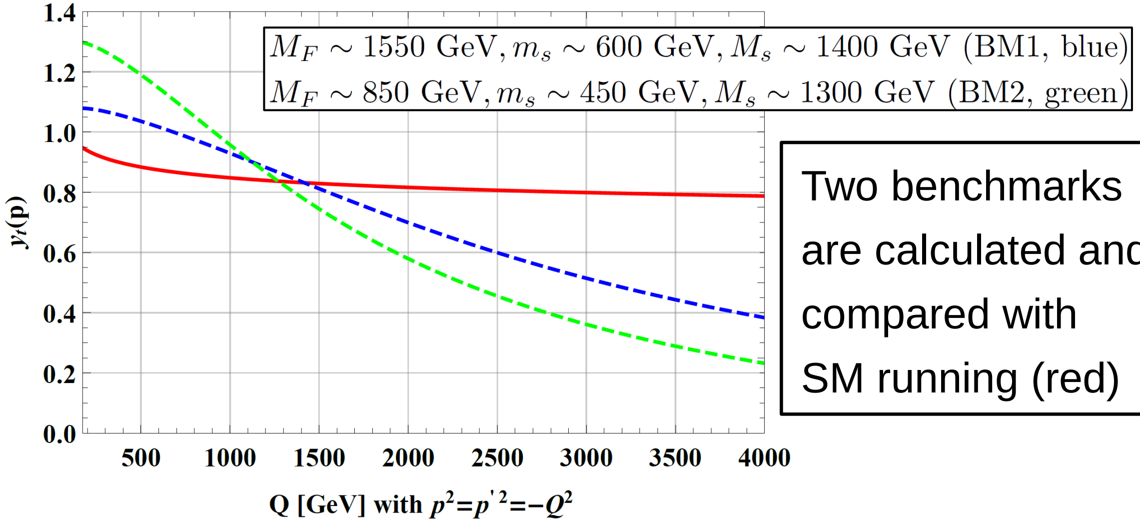
- The diagram introduces a dim-6 operator



$$\sim \frac{y_L y_R}{16\pi^2}\frac{(H S_V \bar{q}_L S_F t_R)}{M^2}$$

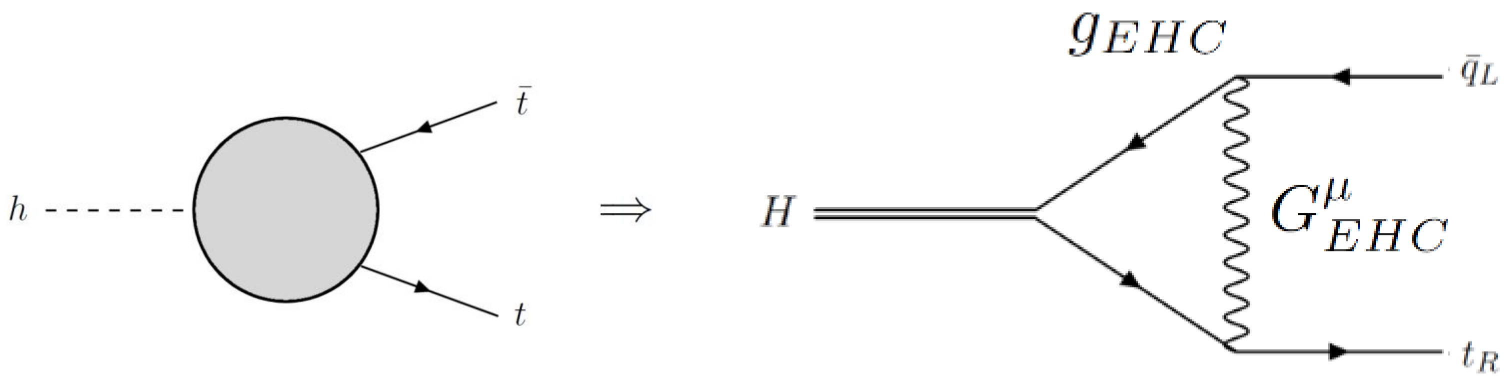
$$\Rightarrow \boxed{\frac{y_L y_R}{16\pi^2}\frac{V M_F}{M^2}}(\bar{q}_L H t_R)$$

$$= y_t$$



Two benchmarks are calculated and compared with SM running (red)

y_t from four-fermion int. (bilinear)



Composite Higgs with

Extended Hypercolor

$\boldsymbol{M_{EHC} = g_{EHC} f_{EHC}}$

f_{EHC} : the scale of EHC

- Top Yukawa in CHM can originate from connecting the strong sector to a SM bilinear

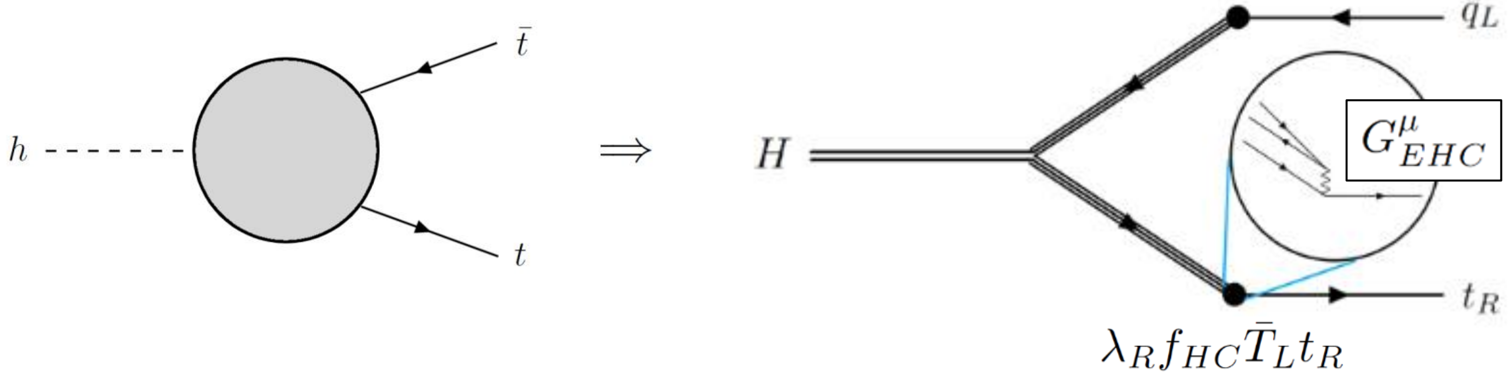
$$\mathcal{L}_{\text{EHC}} = g_{EHC} G^{\mu}_{EHC} (\bar{q}_L \gamma_\mu \psi_L + \bar{\psi}_R \gamma_\mu t_R) \quad \rightarrow \quad \mathcal{L}_{\text{eff}} \supset \frac{g^2_{EHC}}{M^2_{EHC}} \left(\bar{\psi}_R \psi_L\right) \left(\bar{q}_L t_R\right)$$

- Naive dimensional analysis in CHM gives $\bar{\psi}_R \psi_L \sim (4\pi f^2_{HC})\, H$ and thus

$$\boxed{y_t \sim \frac{g^2_{EHC}}{M^2_{EHC}} \cdot 4\pi f^2_{HC}} \sim 4\pi \left(\frac{f_{HC}}{f_{EHC}}\right)^2 \sim 1 \quad \Rightarrow \quad f_{EHC} \sim 3.5 \times f_{HC} \gtrsim 3 \text{ TeV}$$

- The cutoff of top loop is determined by $M_{EHC} = g_{EHC} f_{EHC}$, which requires weak g_{EHC}

y_t from four-fermion int. (linear)



Composite Higgs with
Extended Hypercolor
$\boldsymbol{M_{EHC} = g_{EHC} f_{EHC}}$
f_{EHC} : the scale of EHC

- Top Yukawa in CHM can also come linear connection (i.e. partial compositeness)

$$\mathcal{L}_{\rm EHC} = g_{EHC} G^\mu_{EHC} (\bar{\psi}_1 \gamma_\mu \psi_2 + \bar{\psi}_3 \gamma_\mu t_R) \quad \rightarrow \quad \mathcal{L}_{\rm eff} \supset \frac{g^2_{EHC}}{M^2_{EHC}} (\bar{\psi}_1 \bar{\psi}_2 \bar{\psi}_3)(t_R)$$

- Naive dimensional analysis in CHM gives $\psi_1 \psi_1 \psi_3 \sim (4\pi f^3_{HC}) T_L$ and thus

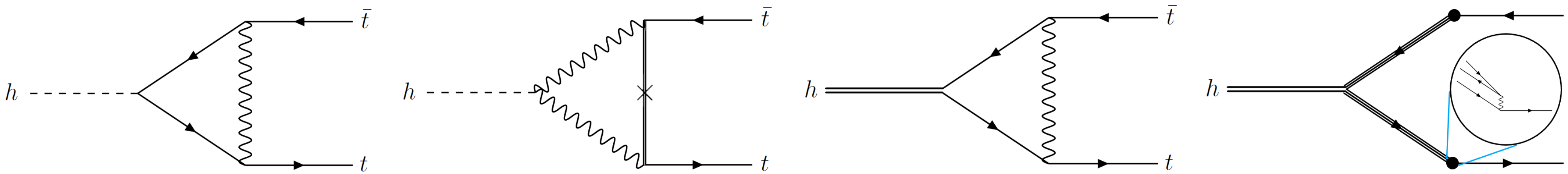
$$\mathcal{L}_{\rm PC} = \lambda_L \bar{q}_L H T_R + g_T f_{HC} \bar{T}_R T_L + \lambda_R f_{HC} \bar{T}_L t_R \Rightarrow \boxed{y_t \sim \frac{\lambda_L \lambda_R}{g_T} \propto \lambda_R = \frac{g^2_{EHC}}{M^2_{EHC}} \cdot 4\pi f^2_{HC}}$$

- Again, the top loop is cut off at the mass scale of $M_{EHC} = g_{EHC} f_{EHC}$

Go Down: Phenomenology

Direct searches

- First, we need to select a model



- For each theory, there comes different d.o.f. and difficulties

  (1) **top-philic bosons** with strong coupling : broad resonances with $\Gamma/M \gg 10\%$

  (2) **bosons and VL fermions** with strong coupling, diverse quantum number and spectrum

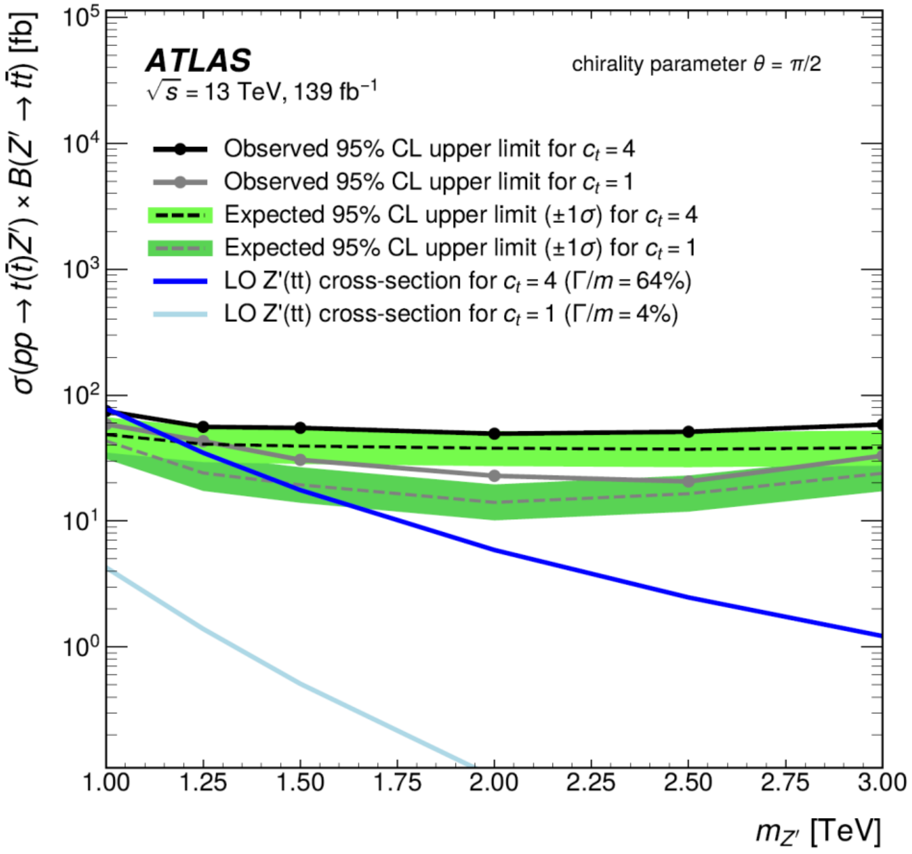
  (3) **extended-hypercolor bosons** with diverse quantum number including hypercolor

  $\Rightarrow$ **Hard to perform, suffer from strong couplings and model-dependence**

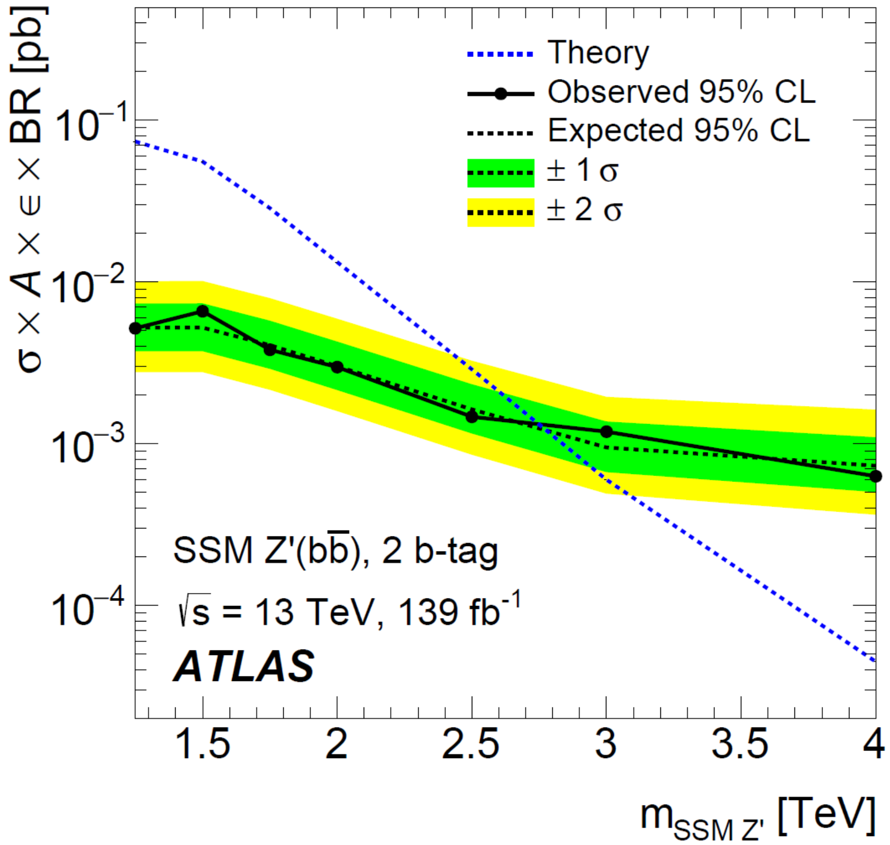
- The only exception is the *top-philic* Z' *boson* in the extended hypercolor models?

Direct searches – top-philic Z' boson

- Only couple to t_R (in linear case)
- Process: $t_R \bar{t}_R \to Z' \to t_R \bar{t}_R$ 2304.01678

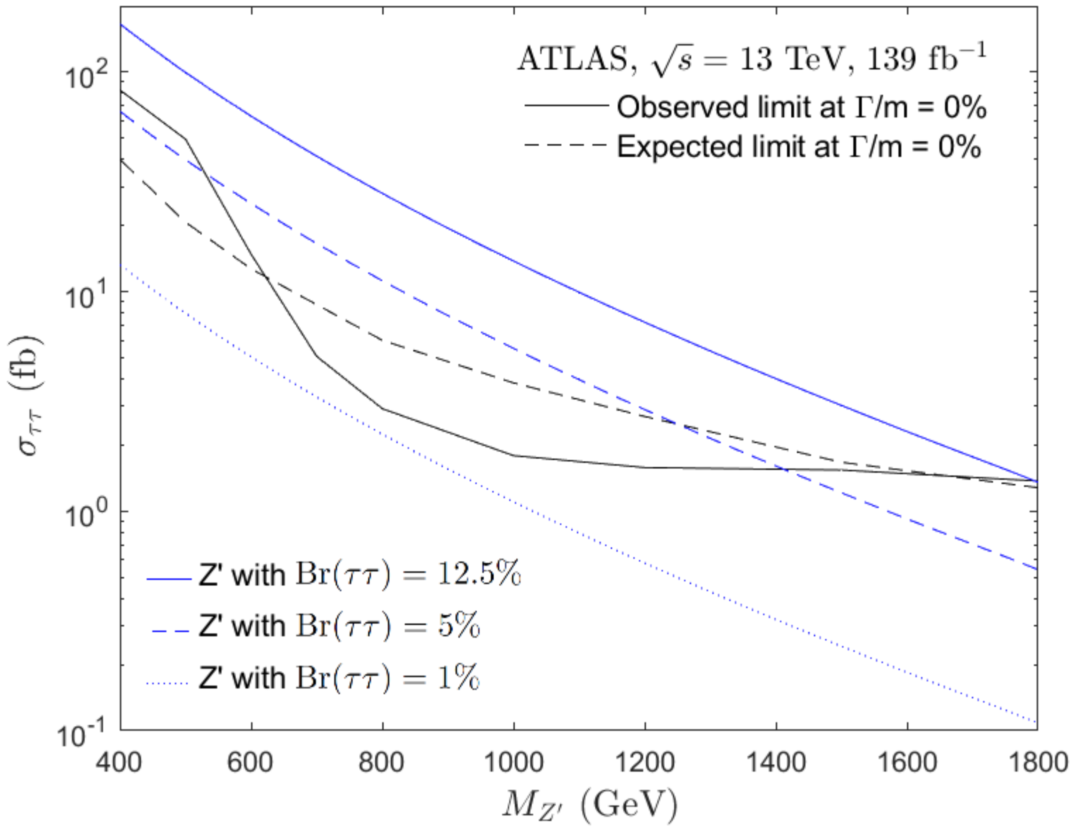


- Couple to $q_L = (t_L, b_L)$ (in bilinear case)
- Process: $b_L \bar{b}_L \to Z' \to b_L \bar{b}_L$ 1910.08447



Direct searches – 3rd-philic Z' boson

- Also couple to the third generation leptons, including tau leptons.
- Process: $b\bar{b} \to Z' \to \tau\tau$ with $g = M/(3\ \mathrm{TeV})$, $\mathrm{Br}(\tau\tau) = 12.5\%,\ 5\%,\ 1\%$ 2002.12223

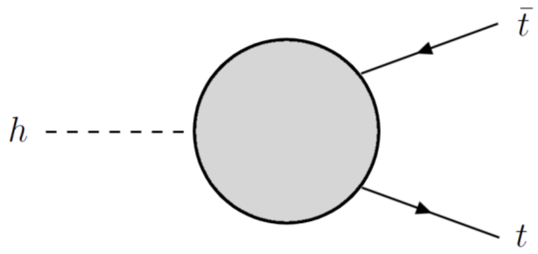


The only way to access the natural parameter space

EHC $\boldsymbol{Z'}$ with $Q(\tau) \neq 0$

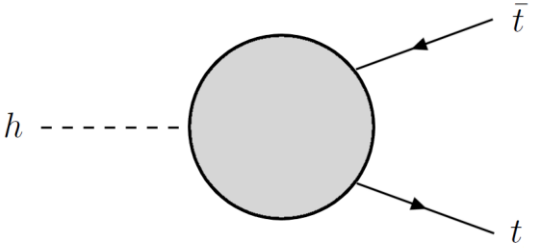
The constraint depends on the detailed $U(1)'$ charge

Direct test of the idea?

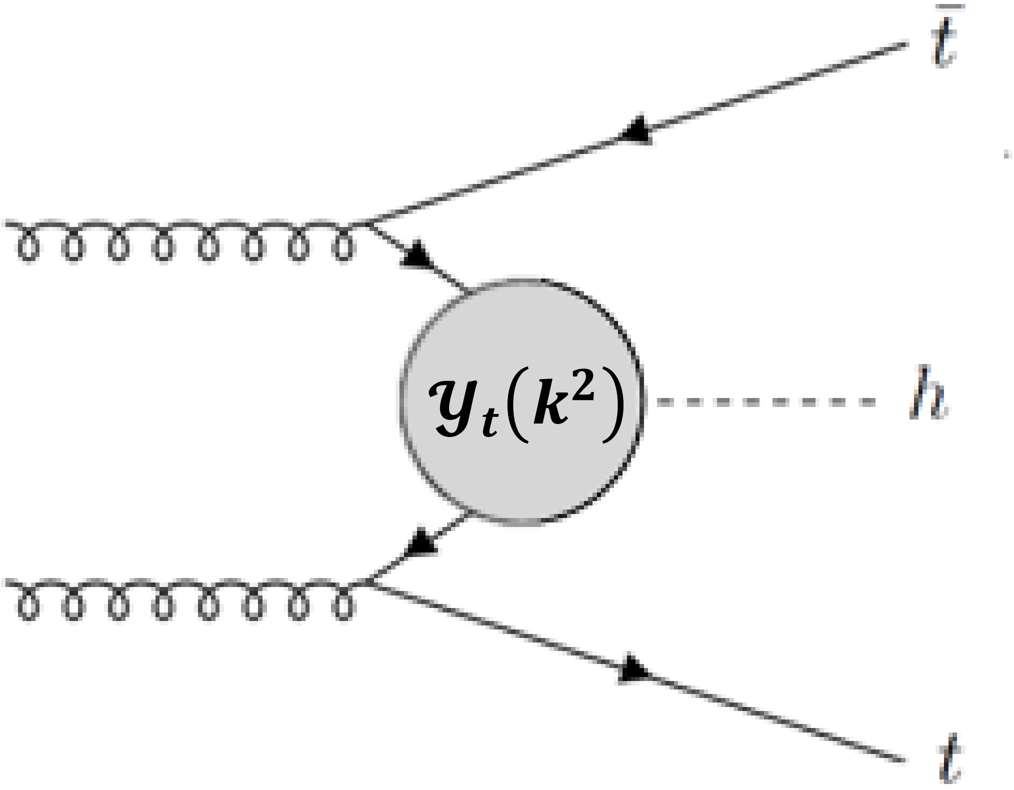


$$y_t = y_t(k^2)$$

Direct test of the idea!



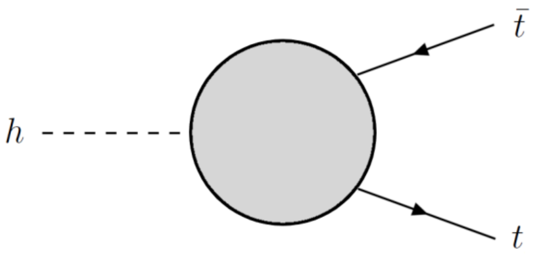
$\Rightarrow$



$$y_t = y_t(k^2)$$

$t\bar{t}h$ differential cross section

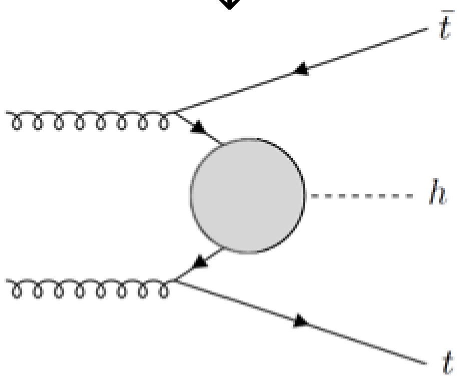
Running of the top Yukawa coupling



$$y_t = y_t(k^2)$$

Top Yukawa at high scale

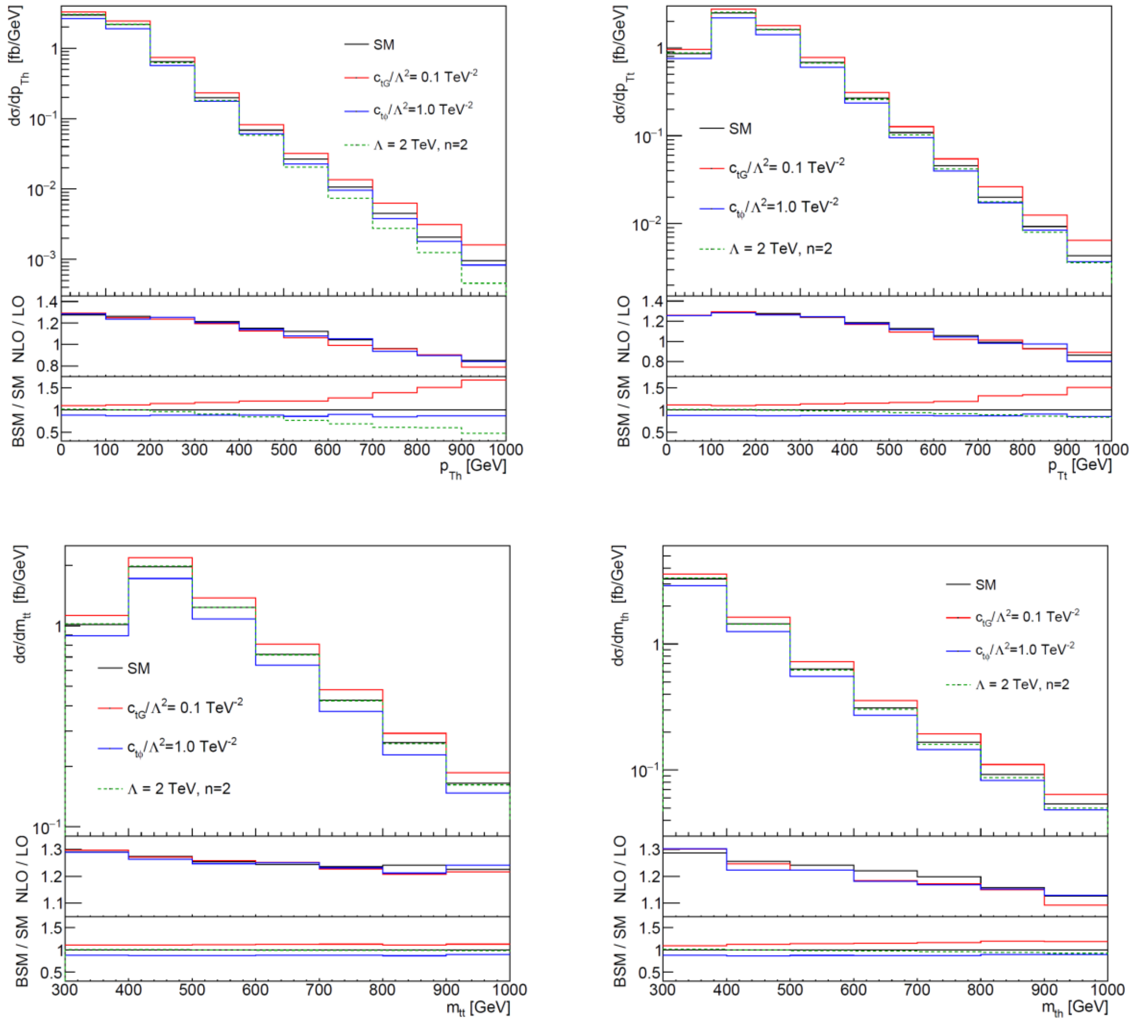
↓



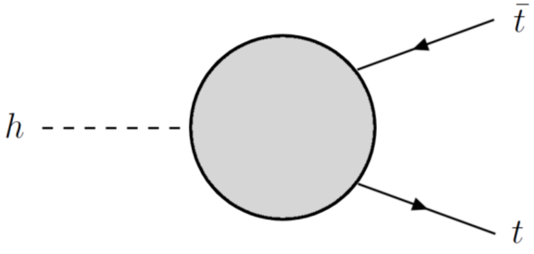
$t\bar{t}h$ differential xs

T. Han et al
2106.00018

$\Rightarrow$



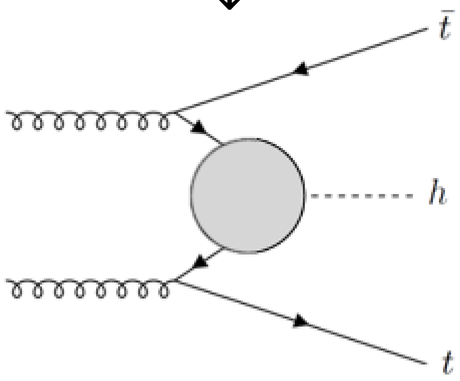
Running of the top Yukawa coupling



$$y_t = y_t(k^2)$$

Top Yukawa at high scale

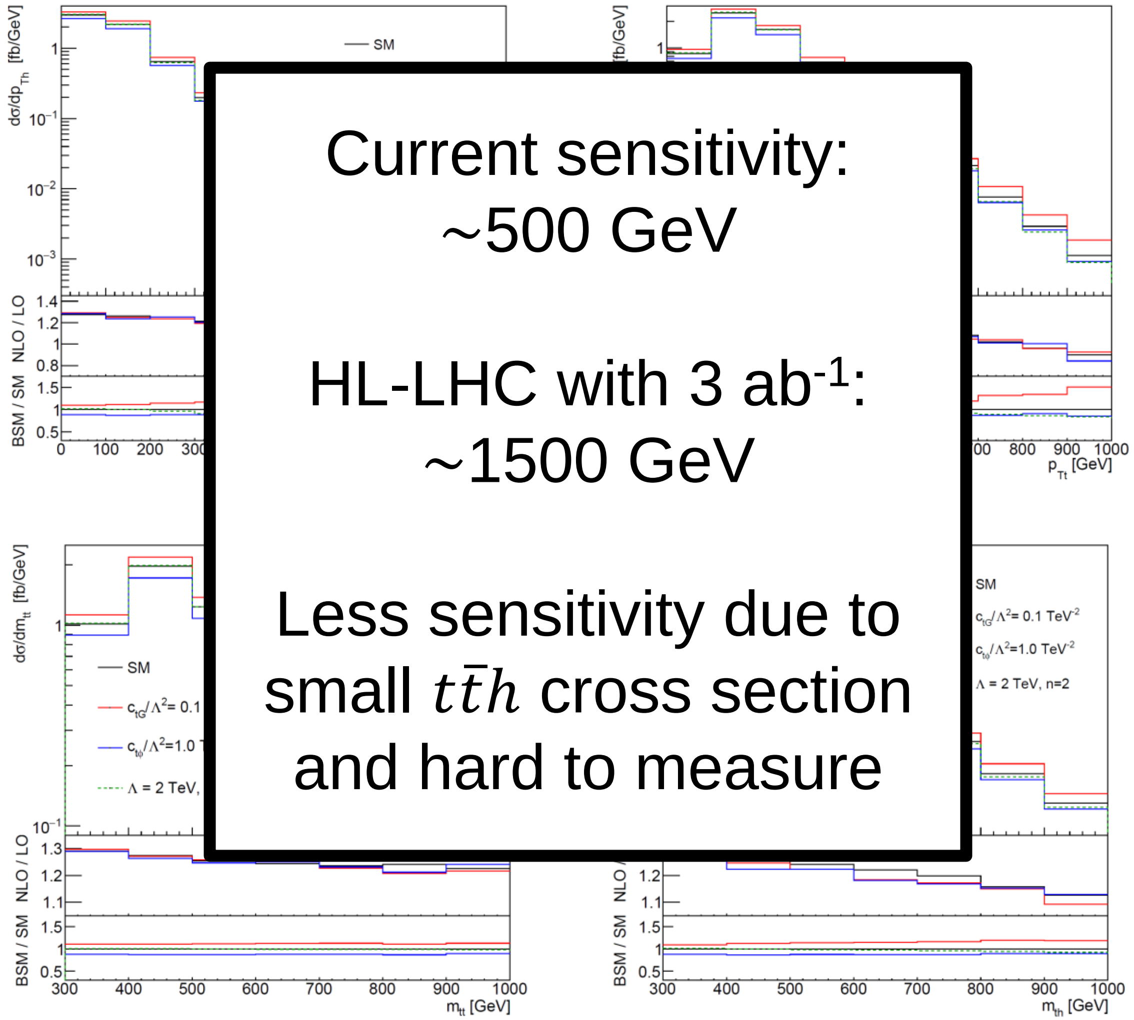
↓



$t\bar{t}h$ differential xs

T. Han et al
2106.00018

⇒

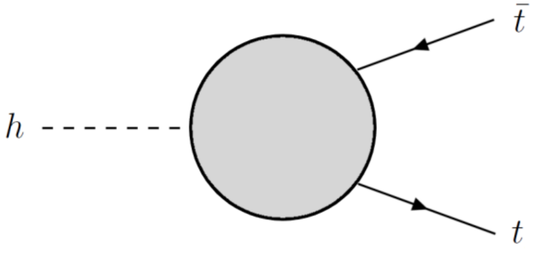


Current sensitivity:
~500 GeV

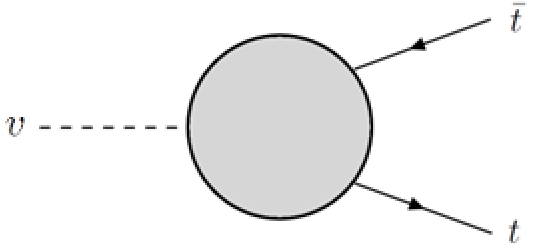
HL-LHC with 3 ab^{-1}:
~1500 GeV

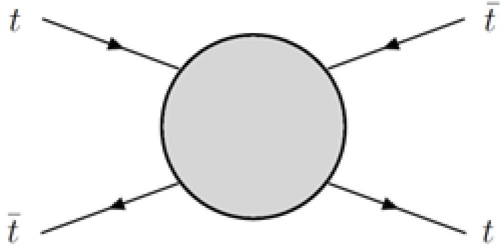
Less sensitivity due to small $t\bar{t}h$ cross section and hard to measure

Indirect searches (Direct test of the idea!)



$\Rightarrow$





$$y_t = y_t(k^2)$$

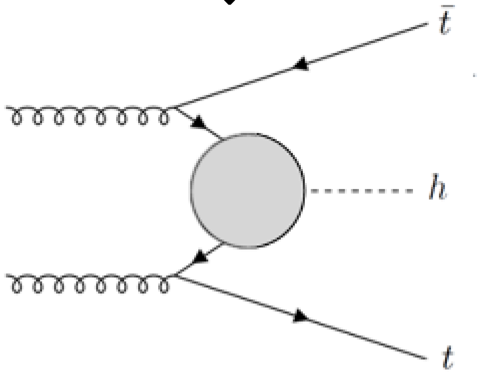
$$m_t = m_t(k^2)$$

$$\sim C/\Lambda_t^2$$

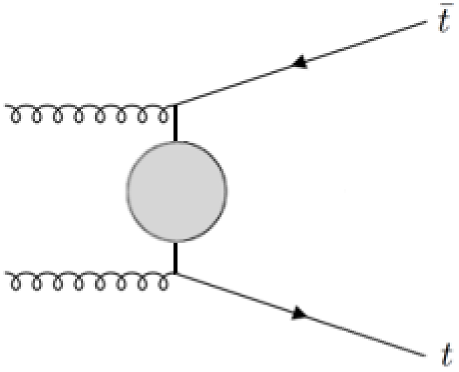
Top Yukawa at high scale ↓

Top mass at high scale ↓

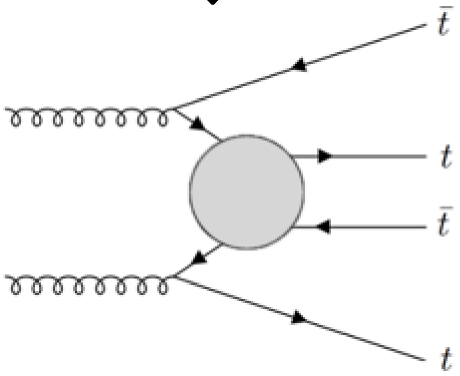
Top-philic new interactions ↓



$t\bar{t}h$ differential xs



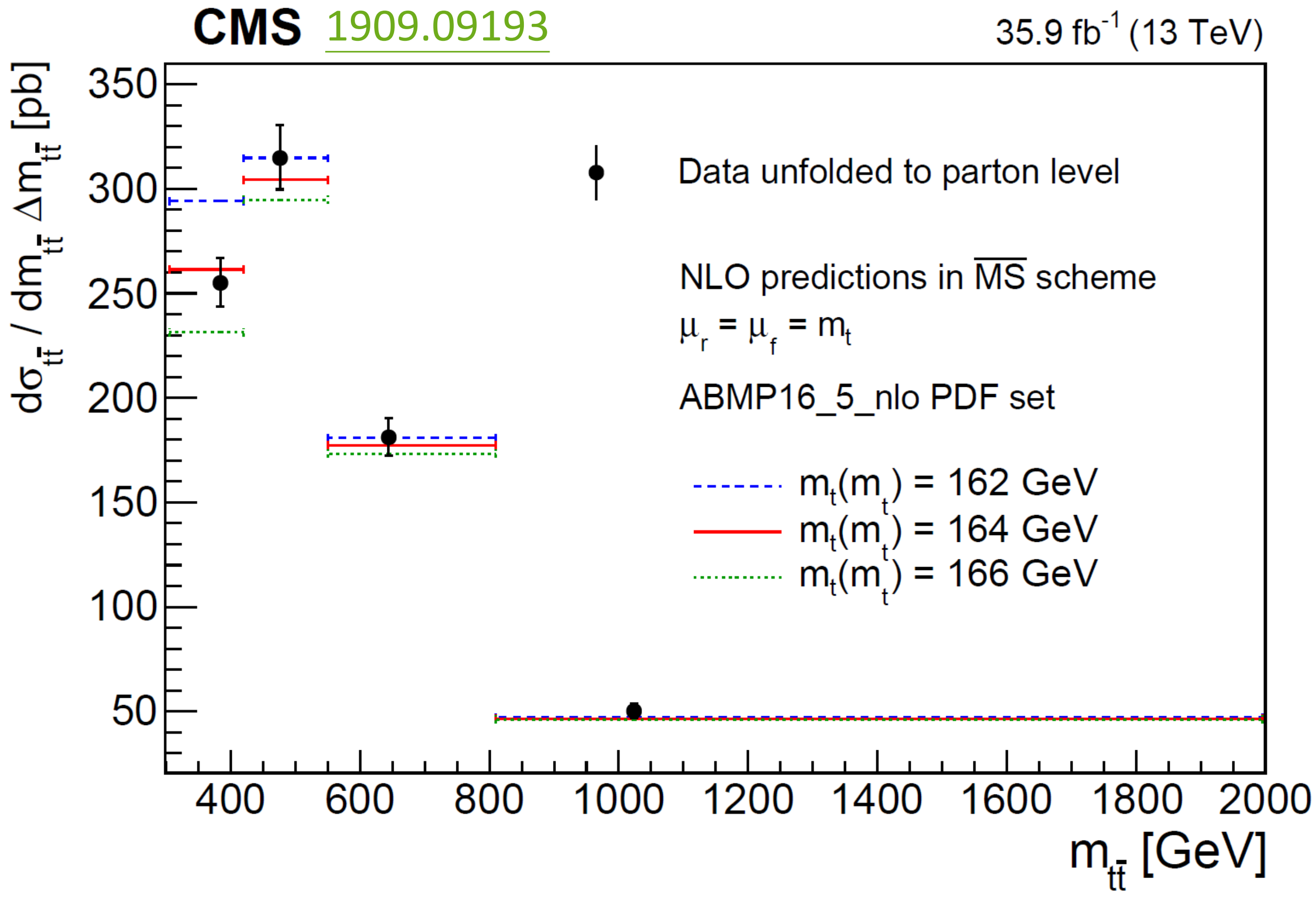
$t\bar{t}$ differential xs



$t\bar{t}t\bar{t}$ (4top) xs

Running of the top quark mass

- Nontrivial running m_t at the high scale will affect the $t\bar{t}$ differential cross section

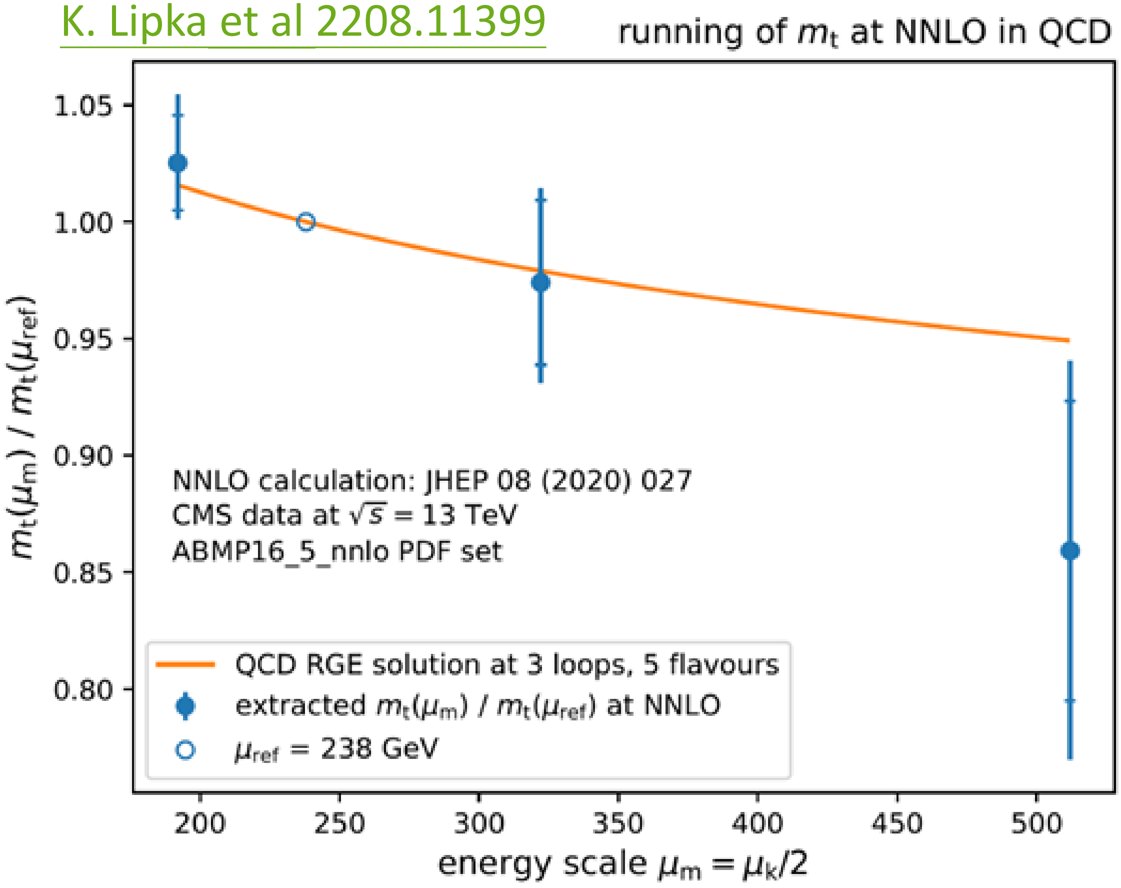


First measurement of top mass at the high scales !
(using only 2016 Run 2 data)

Running of the top quark mass

- Nontrivial running m_t at the high scale will affect the $t\bar{t}$ differential cross section

K. Lipka et al 2208.11399



Assuming $m_t(\mu_m) = m_{t,\mathrm{SM}}(\mu_m)\left(\frac{\Lambda_t^2}{\mu_m^2+\Lambda_t^2}\right)$

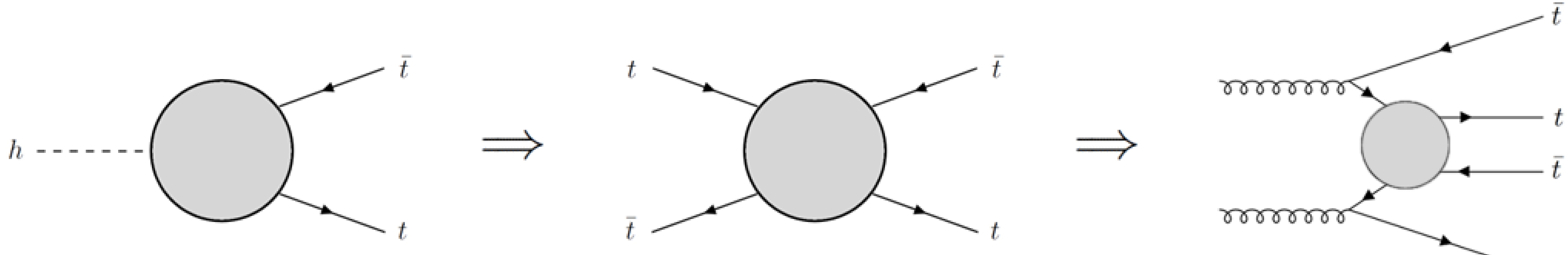
We can already put the constraint on Λ_t as

95% CL bound : $\Lambda_t \gtrsim 700$ GeV

68% CL bound : $\Lambda_t \gtrsim 900$ GeV

Interesting parameter spaces will be tested in **LHC Run 3** !

Four top quarks cross section



$y_t = y_t(\Lambda_t^2)$ $\sim C/\Lambda_t^2$

- Standard Model prediction: $13.4^{+1.0}_{-1.8}$ fb including NLL' (arXiv: 2212.03259)
- ATLAS with 139 fb^{-1} : $22.5^{+6.6}_{-5.6}$ fb
- CMS with 138 fb^{-1} : $17.9^{+4.4}_{-4.1}$ fb

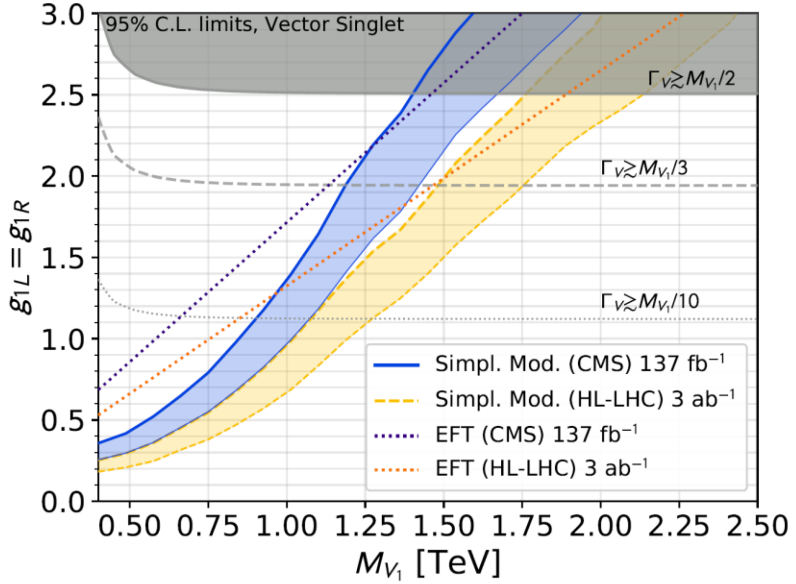
  $\rightarrow$ $\sigma_{t\bar{t}t\bar{t}} < 36\ (27)$ fb at 95% C.L.

  Both are NEW! (Moriond 2023)

F. Maltoni et al 2104.09512

$\Rightarrow$

old analysis but based on a stronger constraint



Summary

- **The top quark loop is the most important part of the Hierarchy Problem / Naturalness**
  - Traditionally, top partners are introduced to **cancel** the top-loop contribution
  - Alternative: **modify the running** of y_t to lower the top-loop contribution
  - What should show up at $\Lambda_t \approx 500$ GeV : **Top partner** → **New top-philic d.o.f.**

- **Go Up: Model building**
  - Elementary Higgs with strongly coupled top-philic new physics
  - Composite Higgs with weakly coupled extended hypercolor bosons

- **Go Down: Phenomenology**
  - Hard to perform direct searches due to strong couplings and model-dependence
  - Direct test of idea through Top physics, including $\boldsymbol{t\bar{t}h}$, $\boldsymbol{t\bar{t}}$, and $\boldsymbol{t\bar{t}t\bar{t}}$ cross section

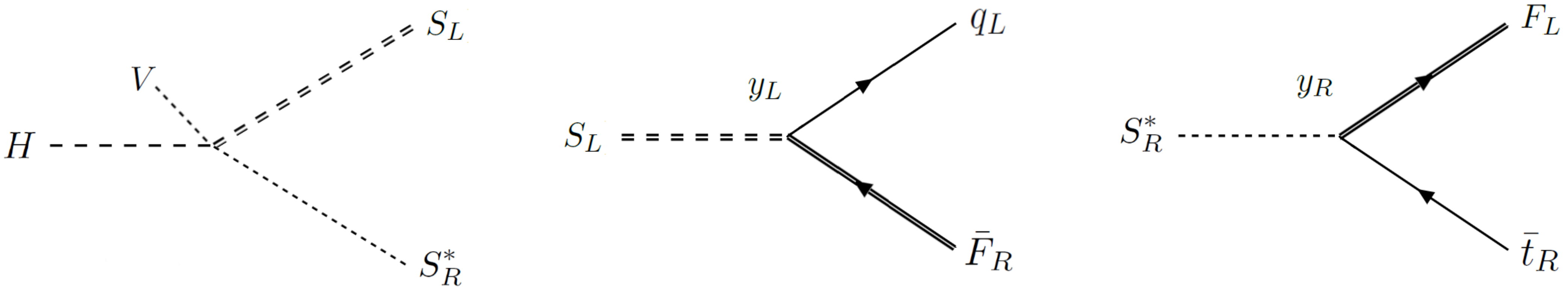
Before giving up on Naturalness, let's make sure no stone is left unturned!

Back up

Radiative y_t generation

Simplified Scalar Model

- At least three vertices are required



or written in Lagrangian

$$\mathcal{L}_{\text{int}} = -V S_R S_L^\dagger H - y_L \bar{q}_L S_L F_R - y_R \bar{t}_R S_R F_L + \text{h.c.} \ ,$$

where S_L is a doublet, S_R is a singlet, and F is a singlet vector-like fermion.

- Mass terms are also required

$$\mathcal{L}_{\text{mass}} = -M_L^2 |S_L|^2 - M_R^2 |S_R|^2 - M_F \bar{F}_L F_R + \text{h.c.} \ .$$

Simplified Scalar Model

- Focus on the neutral scalar components

$$\mathcal{L}_{\text{neutral}} = |\partial s_L|^2 + |\partial s_R|^2 - M_L^2|s_L|^2 - M_R^2|s_R|^2 - V\langle H\rangle(s_L^* s_R + s_R^* s_L)$$
$$= |\partial s_h|^2 + |\partial s_\ell|^2 - M_s^2|s_h|^2 - m_s^2|s_\ell|^2$$

where the mass eigenstates are given by

$$\begin{pmatrix} s_L \\ s_R \end{pmatrix} = \begin{pmatrix} \cos\beta & -\sin\beta \\ \sin\beta & \cos\beta \end{pmatrix} \begin{pmatrix} s_{\text{heavy}} \\ s_{\text{light}} \end{pmatrix} = \begin{pmatrix} c_\beta & -s_\beta \\ s_\beta & c_\beta \end{pmatrix} \begin{pmatrix} s_h \\ s_\ell \end{pmatrix}$$

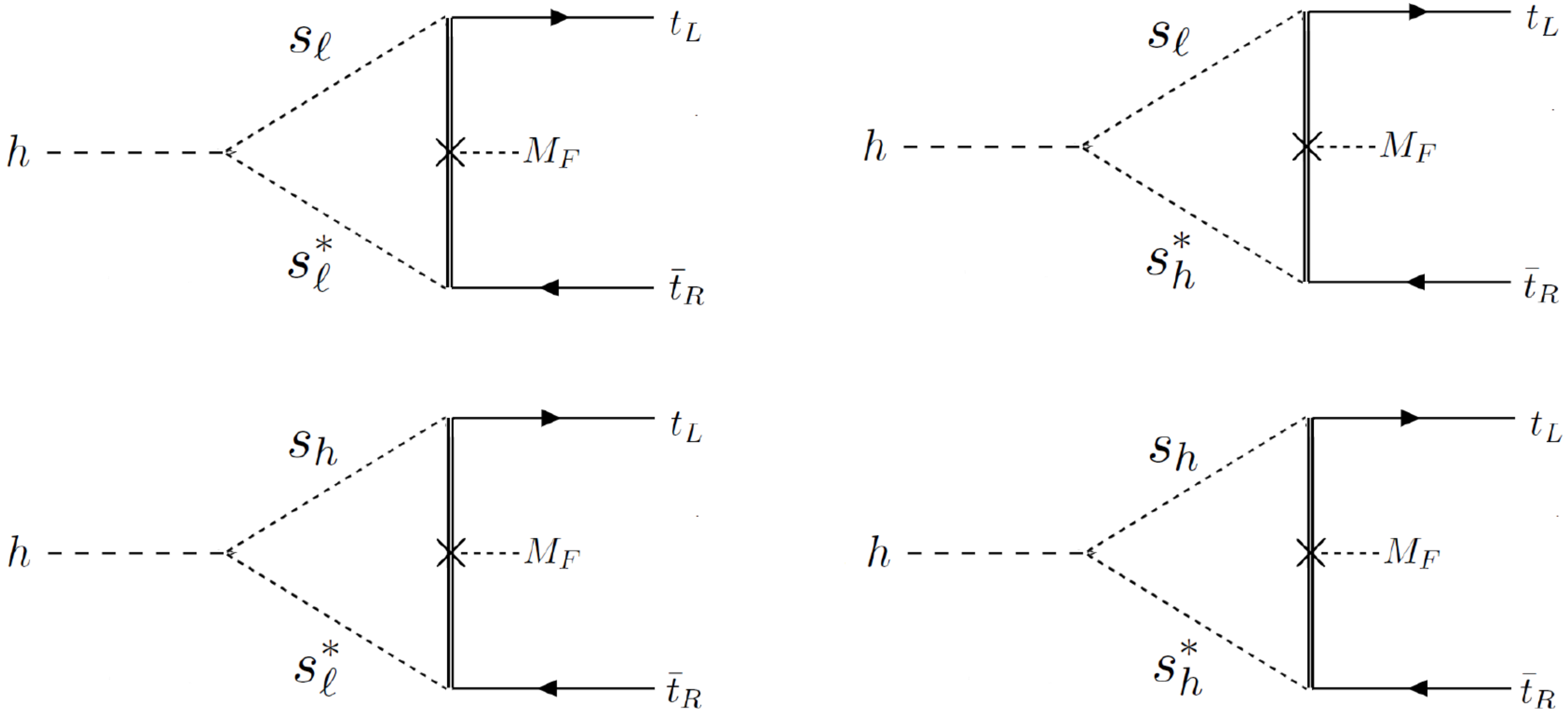
- The interaction terms also become

$$\mathcal{L}_{\text{trilinear}} = -\sqrt{2}\,V c_\beta s_\beta\, h|s_h|^2 + \sqrt{2}\,V c_\beta s_\beta\, h|s_\ell|^2 - \frac{V(c_\beta^2 - s_\beta^2)}{\sqrt{2}}\, h s_h^* s_\ell + \text{h.c.}$$

$$\mathcal{L}_{\text{fermion}} = -(y_L c_\beta\, \bar{t}_L s_h F_R + y_R s_\beta\, \bar{t}_R s_h F_L) - (-y_L s_\beta\, \bar{t}_L s_\ell F_R + y_R c_\beta\, \bar{t}_R s_\ell F_L) + \text{h.c.}$$

Generate the Top Yukawa coupling

- The original one-loop diagram is decomposed to the four diagrams below



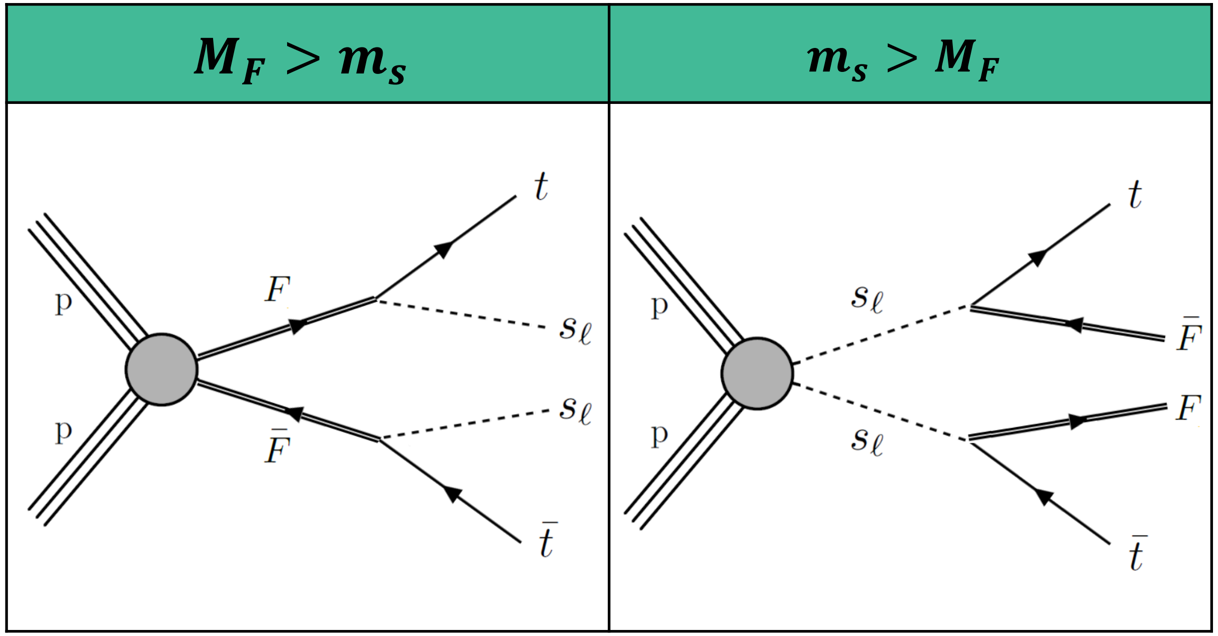
$$\Longrightarrow \quad y_t = V y_L y_R \left((c_\beta^2 - s_\beta^2)^2 \int [s_\ell, s_h, F] + 2\, c_\beta^2 s_\beta^2 \int [s_\ell, s_\ell, F] + 2\, c_\beta^2 s_\beta^2 \int [s_h, s_h, F] \right)$$

Diverse phenomenology

- Phenomenology are determined by the lightest scalar s_ℓ and vector-like fermion F
- The quantum number and the spectrum of the new d.o.f. are not determined
- They can have diverse **"Quantum number"** and **"Spectrum"**

Scalar	Fermion
$(1, 0)$	$(3, +2/3)$
$(1, -1)$	$(3, -1/3)$
$(3, -1/3)$	$(1, -1)$
$(3, +2/3)$	$(1, 0)$

$\Longrightarrow$

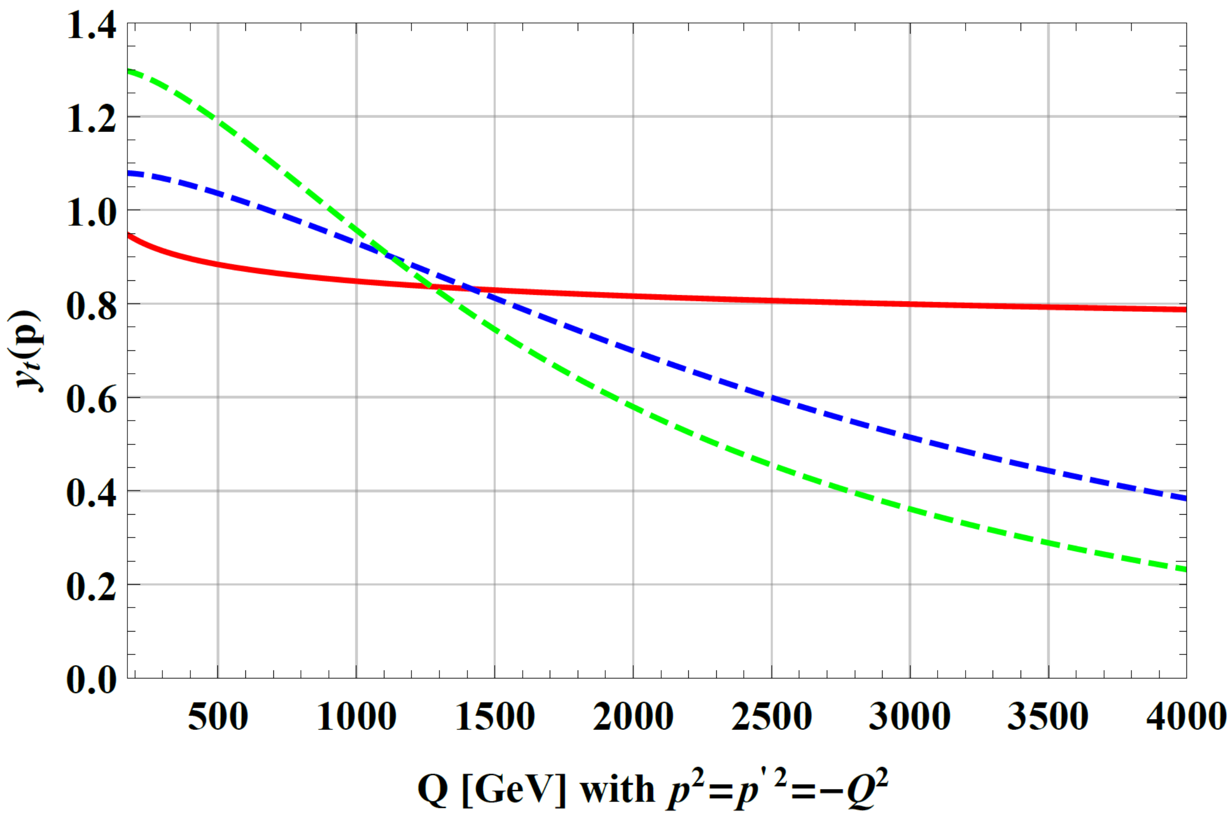


Warning: they might be broad resonances which are not under current search strategy.

Top Yukawa from low scale to high scale

$$M_F \sim 1550\ \text{GeV}, m_s \sim 600\ \text{GeV}, M_s \sim 1400\ \text{GeV}\ (\text{BM1, blue})$$
$$M_F \sim 850\ \text{GeV}, m_s \sim 450\ \text{GeV}, M_s \sim 1300\ \text{GeV}\ (\text{BM2, green})$$

Two benchmarks are calculated and compared with SM running (red)



- The value of y_t is normalized according to the correct top mass
- Larger y_t due to additional diagrams with extra Higgs insertion, which lead to

$$\mathcal{L}_{\text{top}} = c_6 \left(\bar{q}_L H t_R\right) + c_{6+4n} \left(H^\dagger H\right)^n \left(\bar{q}_L H t_R\right)$$

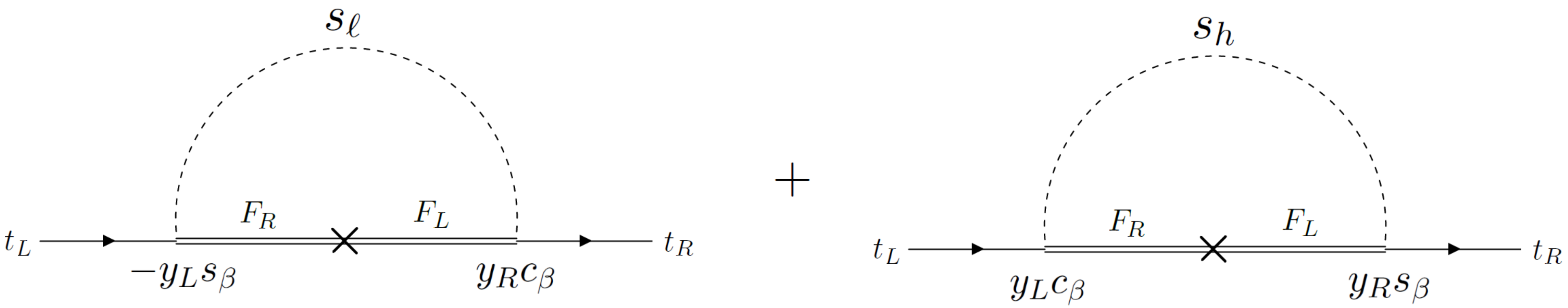
- Main Constraint: top Yukawa measurement

$$\kappa_t \equiv \frac{y_t}{y_t^{\text{SM}}} = 1 + \mathcal{O}\left(\frac{V^2 v^2}{M^4}\right)$$

with current bound $\mathbf{0.7} < \boldsymbol{\kappa_t} < \mathbf{1.1}$ at 95% CL (likely be weaker considering off-shell effect)

Running of the top quark mass

- The top quark mass is generated through



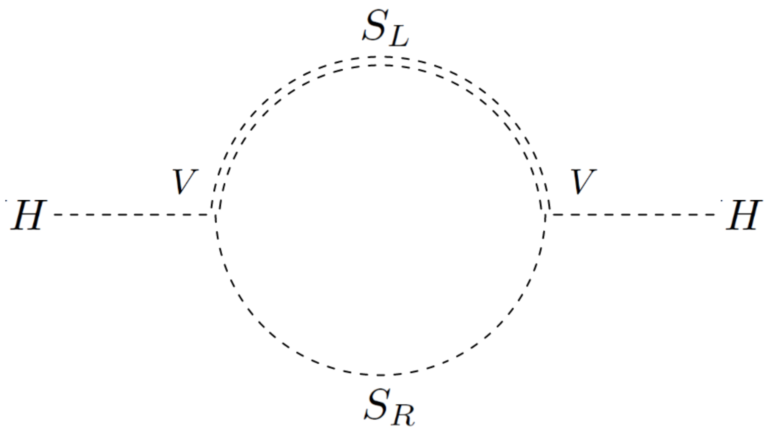
$$-\,y_L y_R c_\beta s_\beta \int [s_\ell, F] \qquad\qquad y_L y_R c_\beta s_\beta \int [s_h, F]$$

- The top quark mass m_t is radiatively generated in the intermediate scale

  $\rightarrow$ Nontrivial running m_t at the high scale which will affect the $t\bar{t}$ cross section

Additional contribution

- The trilinear couplings between the Higgs and scalars will introduce a new loop

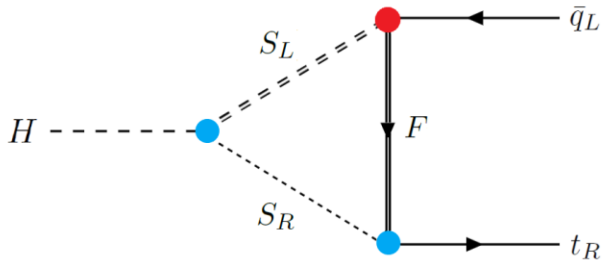


$$\Longrightarrow \quad \Delta m_H^2|_{\text{scalar}} \sim \frac{1}{16\pi^2} V^2 \ln\left(\frac{\Lambda_{\text{NP}}^2}{M^2}\right)$$

- ➢ This loop is however logarithmically sensitive to NP and will not reintroduce a HP
- ➢ Assuming a low-scale UV completion, the correction leads to 7% tuning in both benchmarks, which is at the same order as the top-quark tuning. Therefore, the new scalar loops do not worsen the tuning.

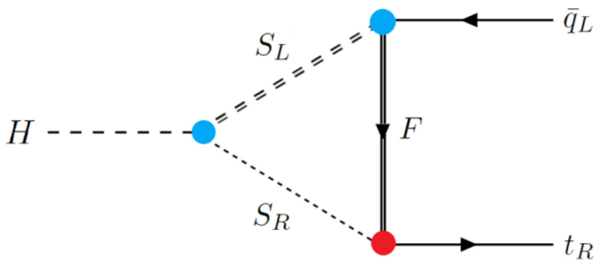
Top Yukawa from strong dynamics

- If y_t comes from pure strong dynamics, then even at one-loop level we expect $y_t \sim 4\pi$
- A suppression $\boldsymbol{\varepsilon}$ is required between the strong and weak sector to get $y_t \sim 1$
- Three possibilities



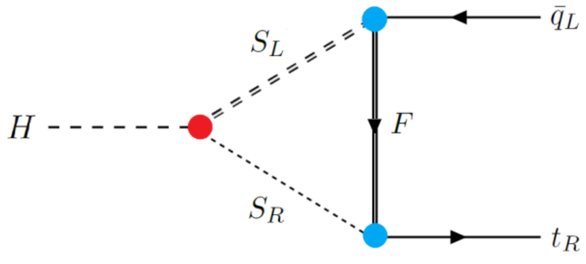
Strong sec.
S_L, S_R, F
H, t_R

Weak sec.
q_L



Strong sec.
S_L, S_R, F
H, q_L

Weak sec.
t_R



Strong sec.
S_L, S_R, F
q_L, t_R

Weak sec.
H

small M without large κ_t

Strongly coupled UV theory

- A Top seesaw-like model based on $SU(3)_L \times SU(2)_R$ global symmetry with bound states

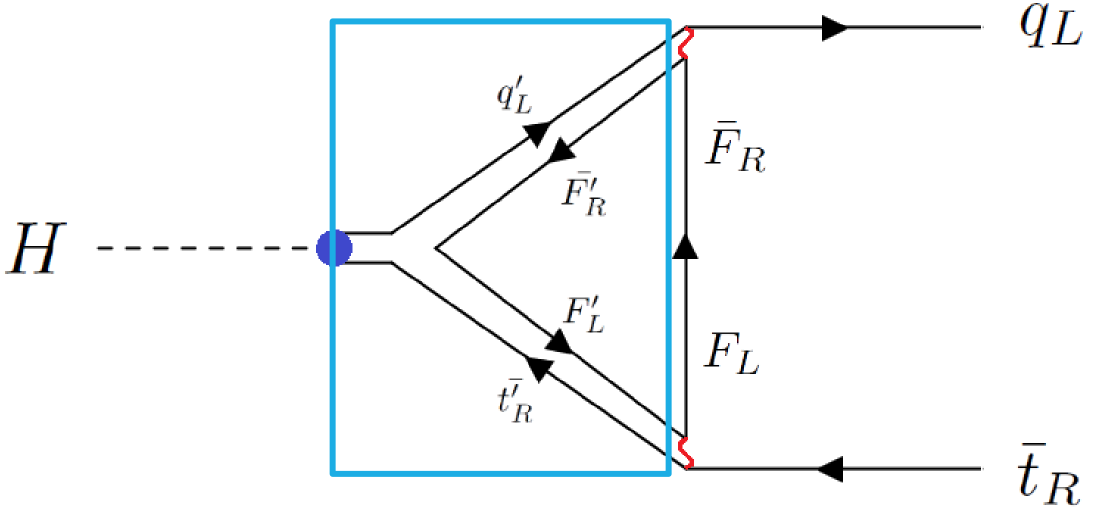
Weak sector:

$$H,\, Q_L = \begin{pmatrix} F_L \\ t_L \\ b_L \end{pmatrix}, \quad Q_R = \begin{pmatrix} F_R \\ t_R \end{pmatrix}$$

Strong sector:

$$\Phi,\, Q'_L = \begin{pmatrix} F'_L \\ t'_L \\ b'_L \end{pmatrix}, \quad Q'_R = \begin{pmatrix} F'_R \\ t'_R \end{pmatrix}$$

$$\Phi = \bar{Q}'_R Q'_L = \begin{pmatrix} S_V^* & S_R^* \\ S_L & S_H \end{pmatrix}$$



$\Longrightarrow$

$$\mathcal{L}_\Phi = |\partial\Phi|^2 - \tilde{M}(\mu)^2|\Phi|^2 - \tilde{\lambda}(\mu)|\Phi|^4 - \tilde{y}(\mu)\,\bar{Q}'_L\,\Phi\,Q'_R$$

$$\supset\; 2\,\tilde{\lambda}\,\langle S_V\rangle\,(S_R S_L^\dagger S_H) - \tilde{y}\,\bar{q}'_L S_L F'_R - \tilde{y}\,\bar{t}'_R S_R F'_L$$

$$\tilde{\lambda}(\mu) = \frac{16\pi^2}{NC},\; \tilde{y}(\mu) = \frac{4\pi}{\sqrt{NC}},\; C = \ln\left(\frac{M'^2}{\mu^2}\right)$$