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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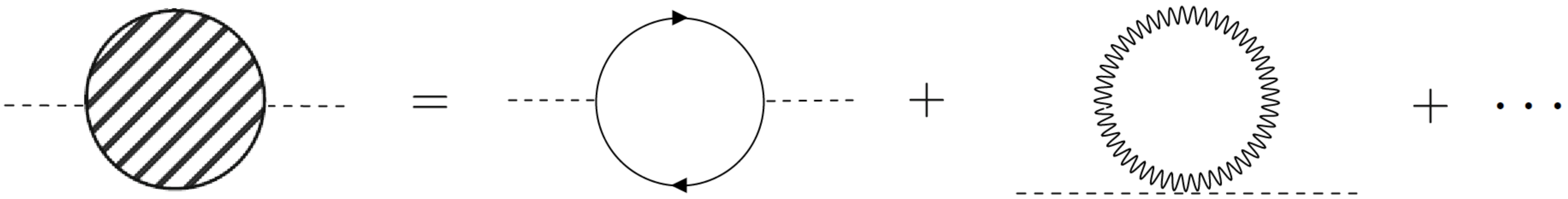
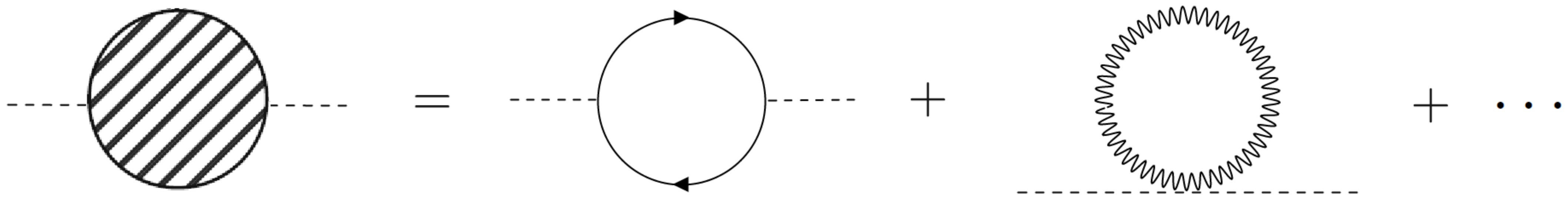
The Hierarchy Problem



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

The Naturalness Principle



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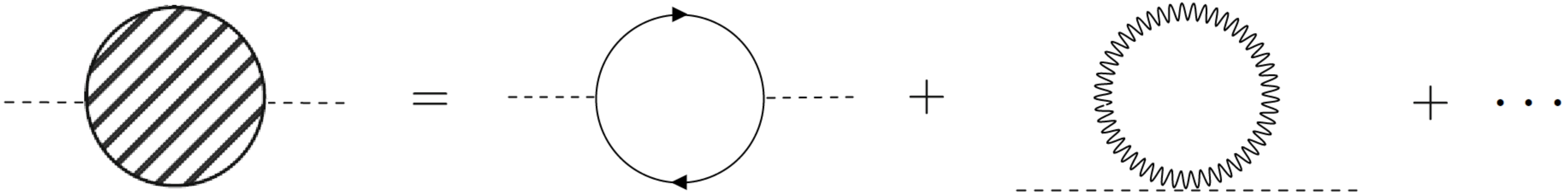
New Physics at $\Lambda_t \sim 500$ GeV $\Lambda_g \sim 1200$ GeV

The Naturalness Principle

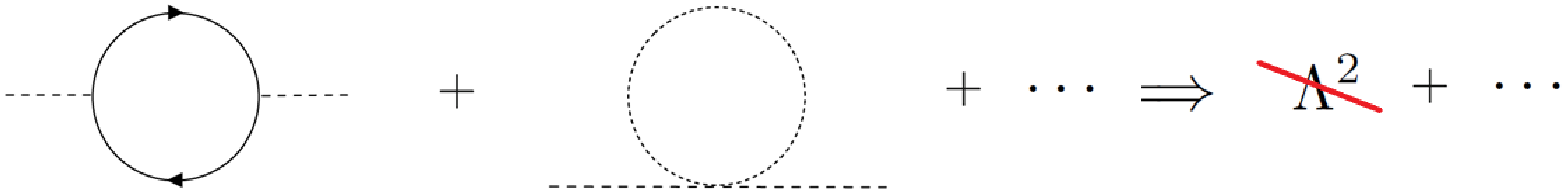


$$\delta m_h^2 = -\frac{3}{8\pi^2} y_t^2 \Lambda_t^2 + \frac{9}{64\pi^2} g^2 \Lambda_g^2 + \cdots$$

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

The lightest new d.o.f.!!

Top partner solutions

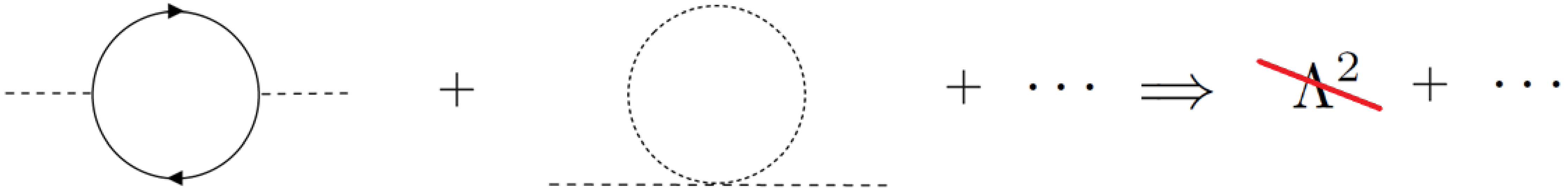


Top loop

Top-partner loop

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

Top partner solutions



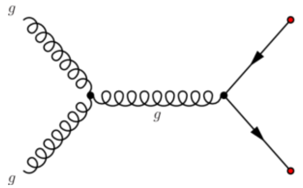
Top loop Top-partner loop

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

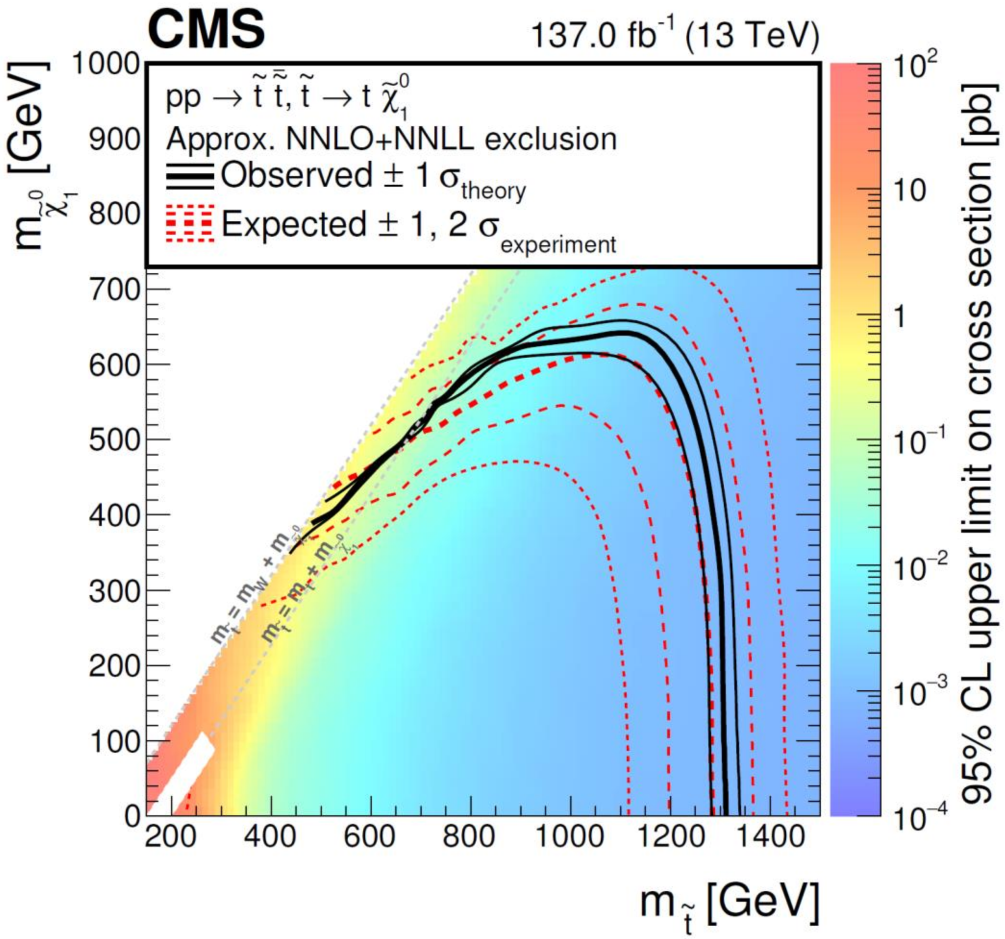
$$\delta m_h^2|_{\text{top}} + \delta m_h^2|_{\text{top partner}} \sim -\frac{3}{8\pi^2} y_t^2 M_T^2 \ln\left(\frac{\Lambda^2}{M_T^2}\right)$$

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

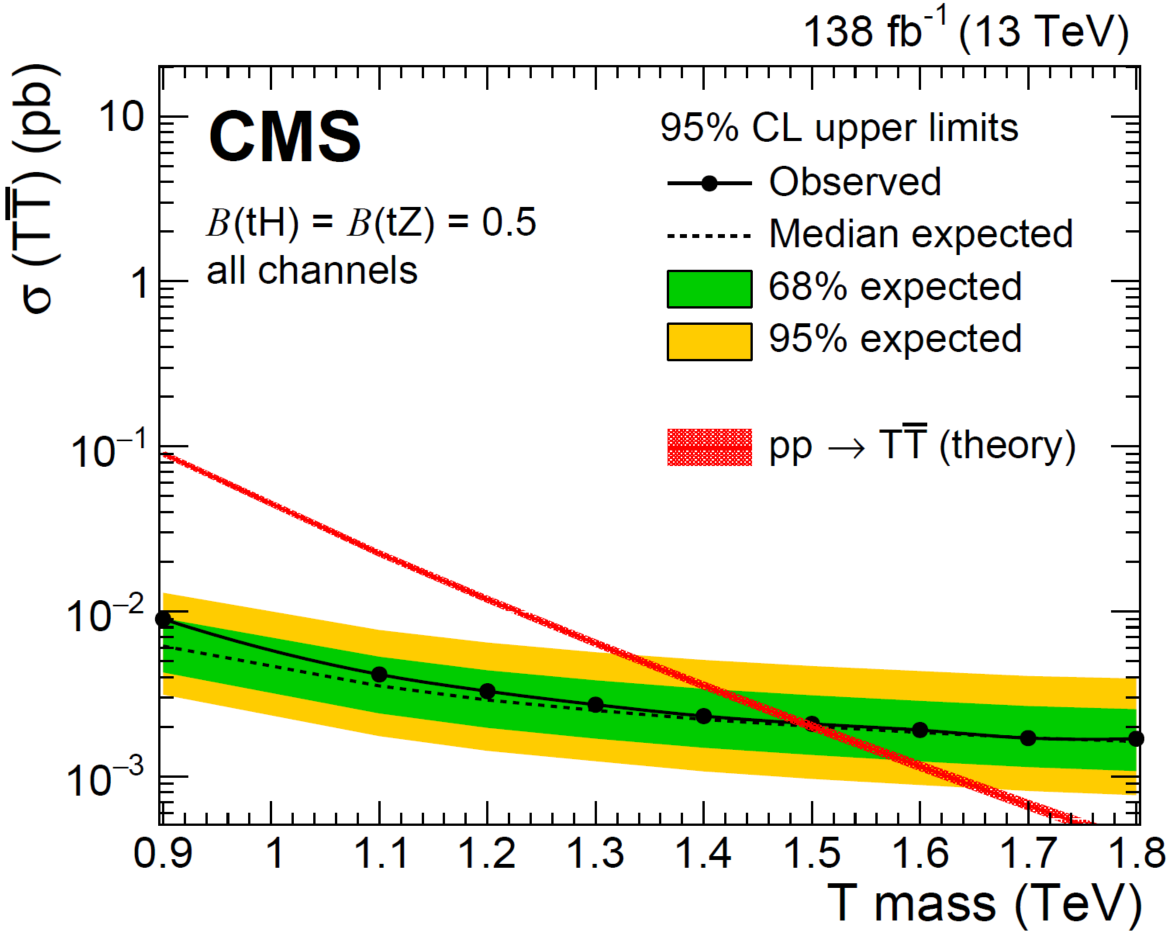
Colored top partner searches



- Scalar top partner $\tilde{t}$ search (2103.01290)



- Fermionic top partner T search (2209.07327)



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)

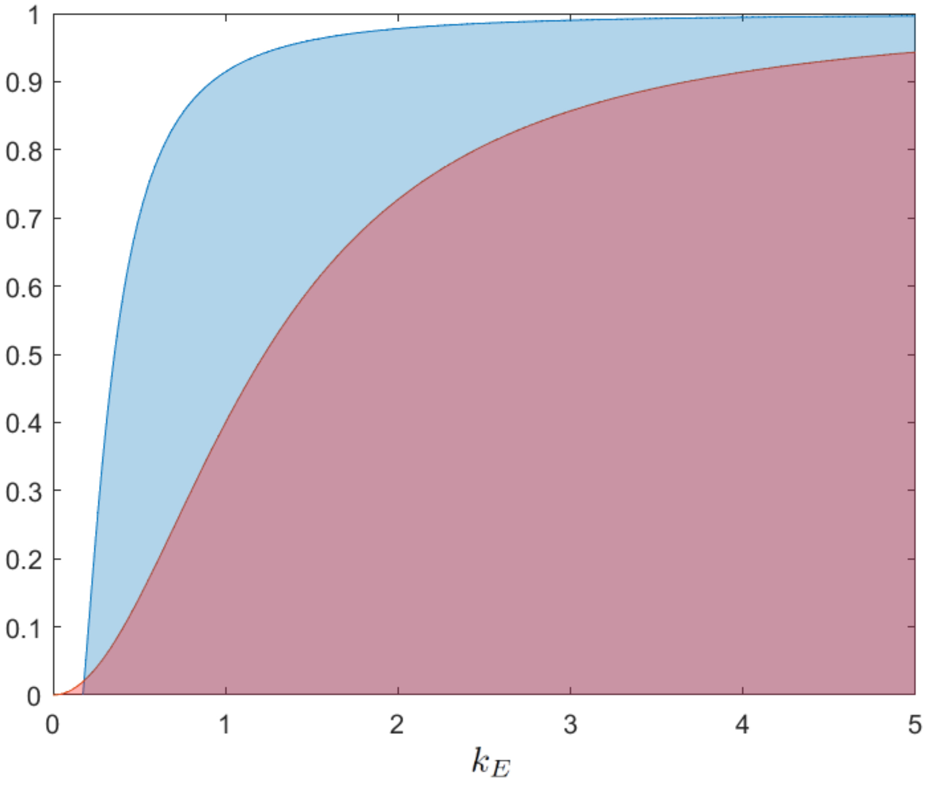
Quantum #	Scalar	Fermion
QCD x EW	SUSY	CHM / RS
Neutral x EW	Folded SUSY	Quirky Little Higgs
Neutral x Neutral	Tripled Top Hyperbolic Higgs	Twin Higgs

Table borrowed from Chris Verhaaren

$\Rightarrow$ Uncolored top partners

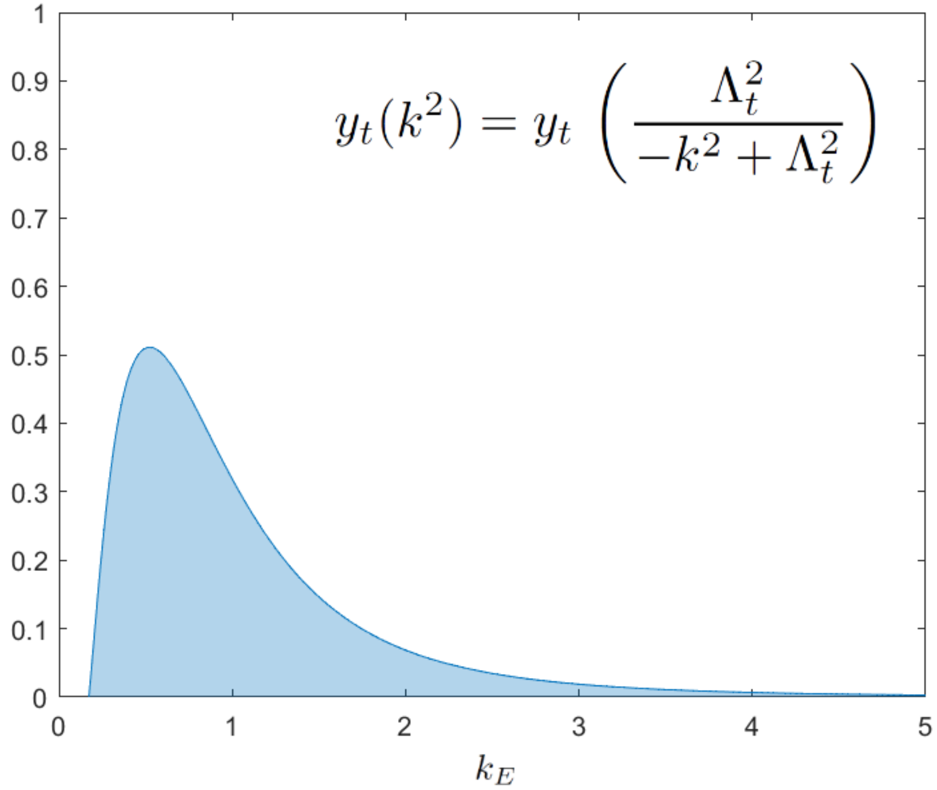
Alternative to Top-partner scenarios

- Cancellation (take $M_T = 1.2$ TeV)



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

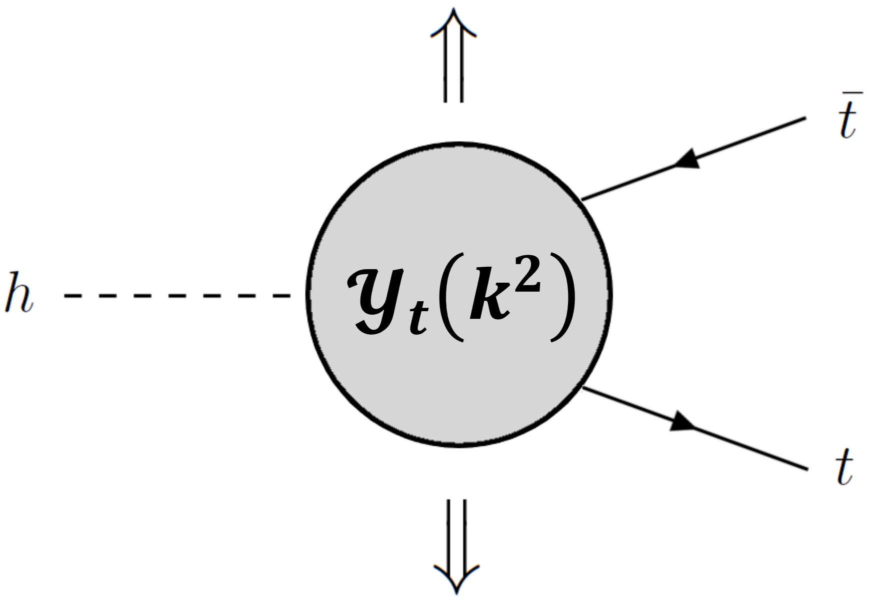
- Reduction (take $\Lambda_T = 1.2$ TeV)



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

Modify the Top Yukawa vertex

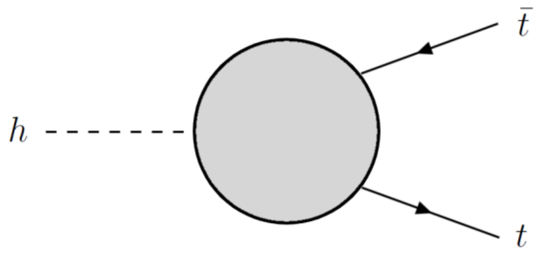
Model Building



Phenomenology

Go Up: Model Building

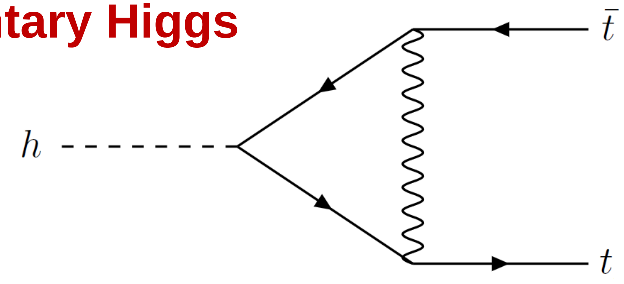
Zoom in the Top Yukawa vertex



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

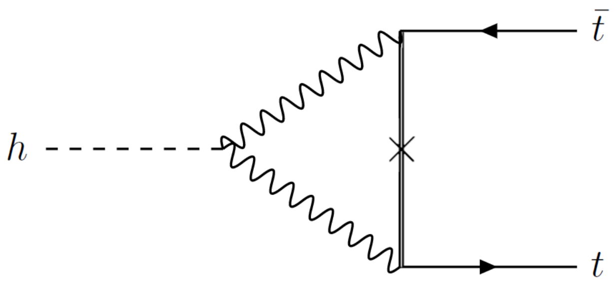
$\Rightarrow$

Elementary Higgs



(1) large y_t running

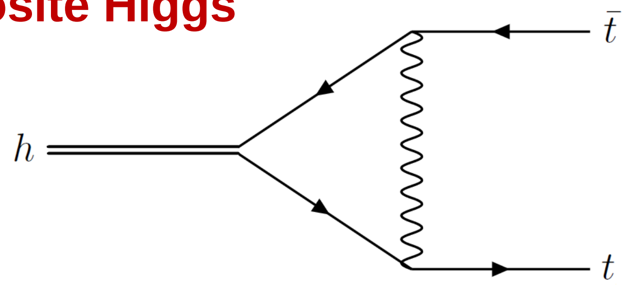
new top-philic bosons
with strong coupling

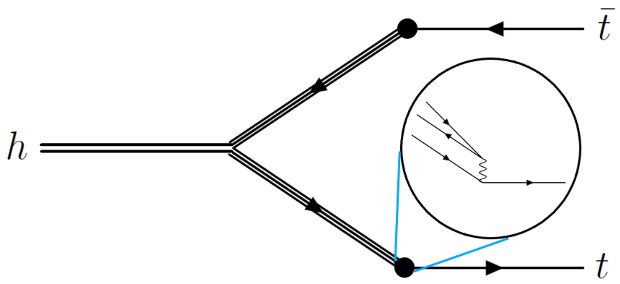


(2) radiative y_t generation

bosons and VL fermions
with strong coupling

Composite Higgs

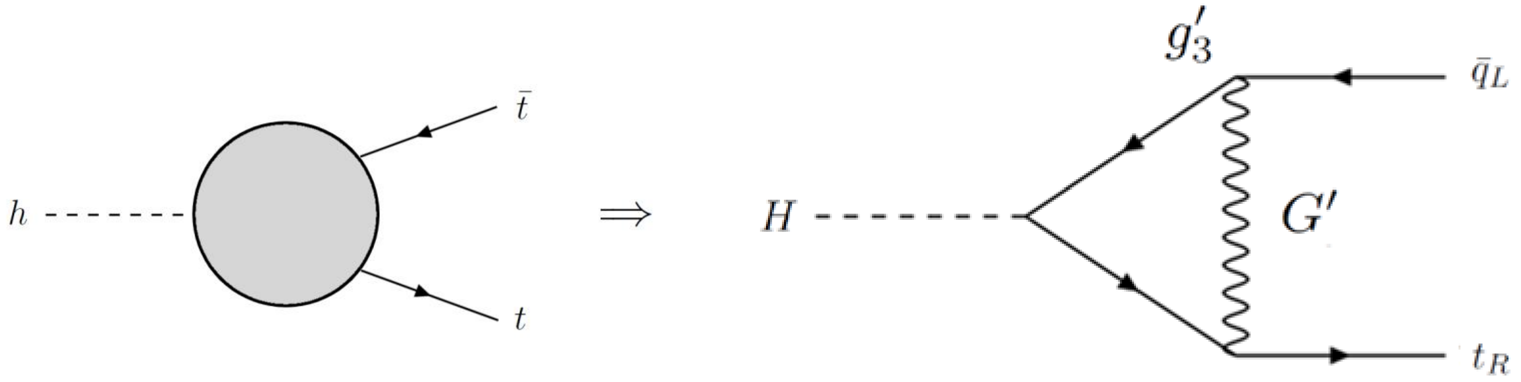




(3) y_t from from four-fermion interations

extended-hypercolor bosons with weak coupling

Large y_t running



New top-philic bosons

Example:

Heavy gluons (Coloron)

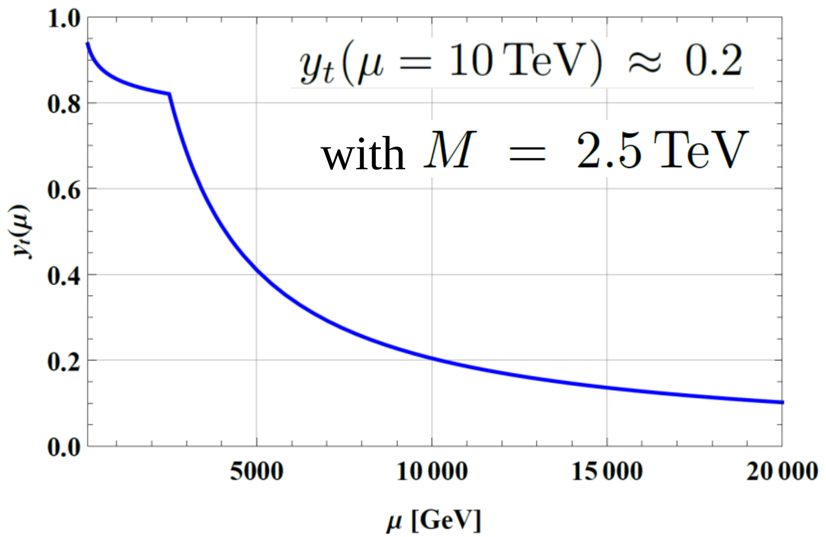
with the coupling $g_3' \sim 4.5$

- Large coupling can introduce large running

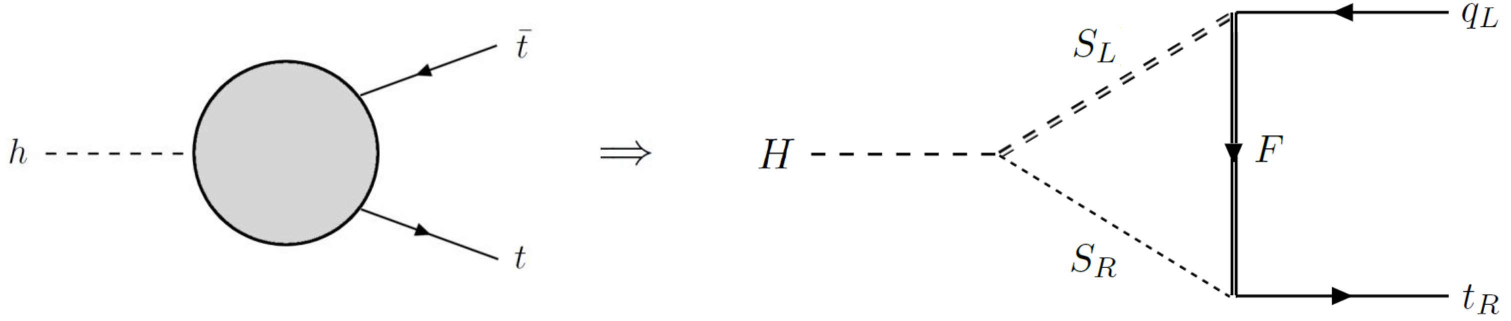
$$\frac{d\,y_t(\mu)}{d\,\ln\,\mu} = \frac{y_t(\mu)}{16\pi^2}\Big(\frac{9}{2}\,y_t^2(\mu) - \frac{3(N^2-1)}{N} g_N^2\Big)$$

need to be strong enough but not too strong

to avoid top condensate (topcolor)



Radiative y_t generation



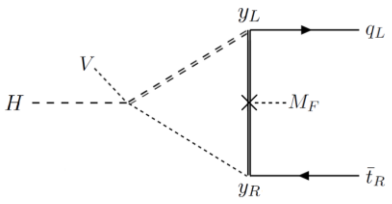
Minimal setup:

EW doublet scalar S_L

EW singlet scalar S_R

EW singlet fermion F

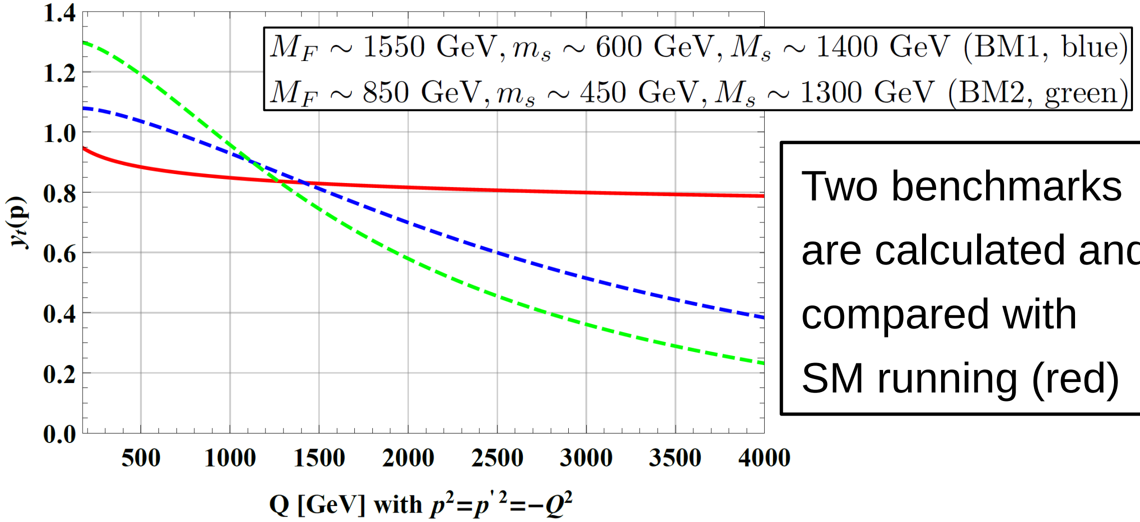
- The diagram introduces a dim-6 operator



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

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

$$= y_t$$



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

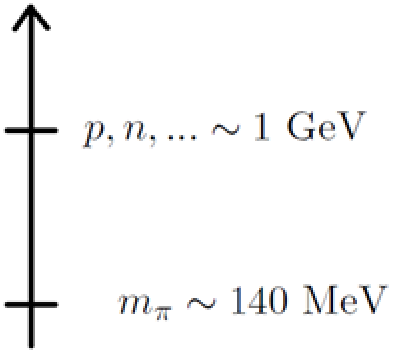
Fundamental Composite Higgs Models

- Chiral symmetry breaking

$$SU(2)_L \times SU(2)_R \rightarrow SU(2)_V$$

which gives three massless NG bosons, i.e. pions!!

However, the symmetry is broken by quark masses and EM interactions, and we get massive pions.



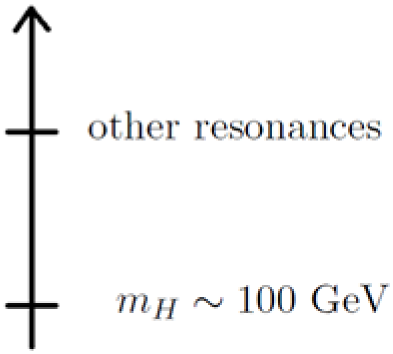
Quark with QCD

- (Some global) symmetry breaking with a scale $f_{HC} \sim 1\,\mathrm{TeV}$

$$\mathcal{G} \rightarrow \mathcal{H} \ni SU(2)_L \times U(1)_Y$$

which gives (at least) four NG bosons as **Higgs doublet!!**

The symmetry can be broken by different interactions (usually by electroweak interaction and Yukawa interaction) and give us the nontrivial Higgs potential.



Hyperfermion with Hypercolor (HC)

Fundamental Composite Higgs Models

- Chiral symmetry breaking

$$SU(2)_L \times SU(2)_R \to SU(2)_V$$

which gives three massless NG bosons, i.e. pions!!

However, the symmetry is b ... s, and we get massive pions.

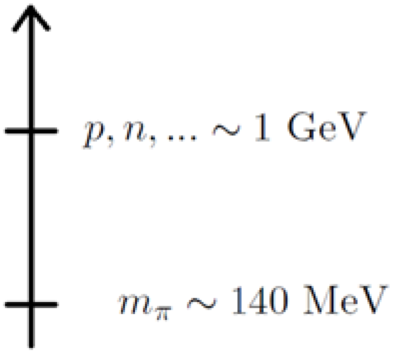
$$H = \bar{\psi}\psi$$

- (Some global) symmetry

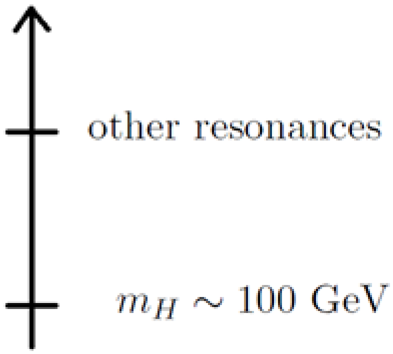
$$\mathcal{G} \to \mathcal{H} \ni SU(2)_L \times U(1)_Y$$

which gives (at least) four NG bosons as **Higgs doublet!!**

The symmetry can be broken by different interactions (usually by electroweak interaction and Yukawa interaction) and give us the nontrivial Higgs potential.

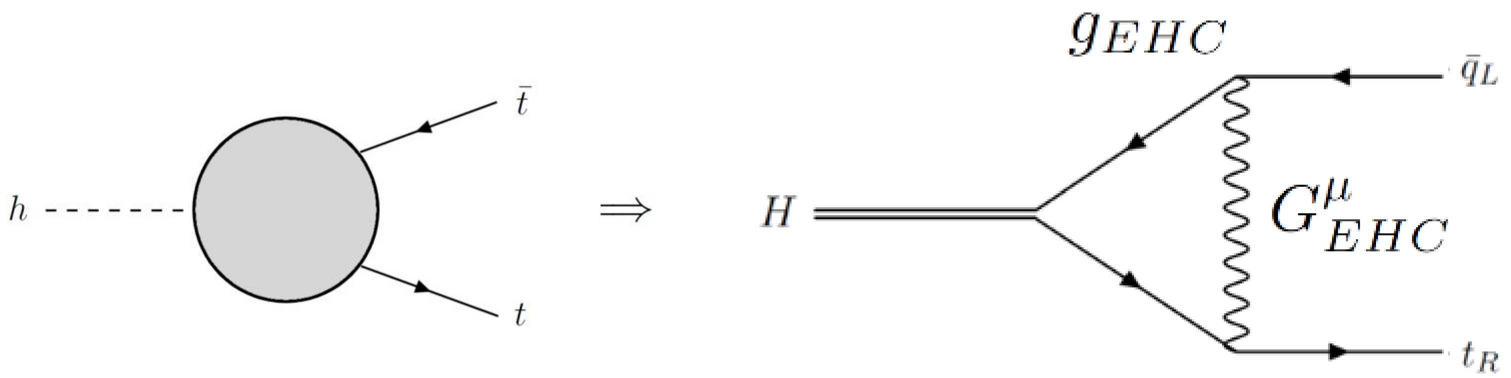


Quark with QCD



Hyperfermion with Hypercolor (HC)

y_t from four-fermion int. (bilinear)



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

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

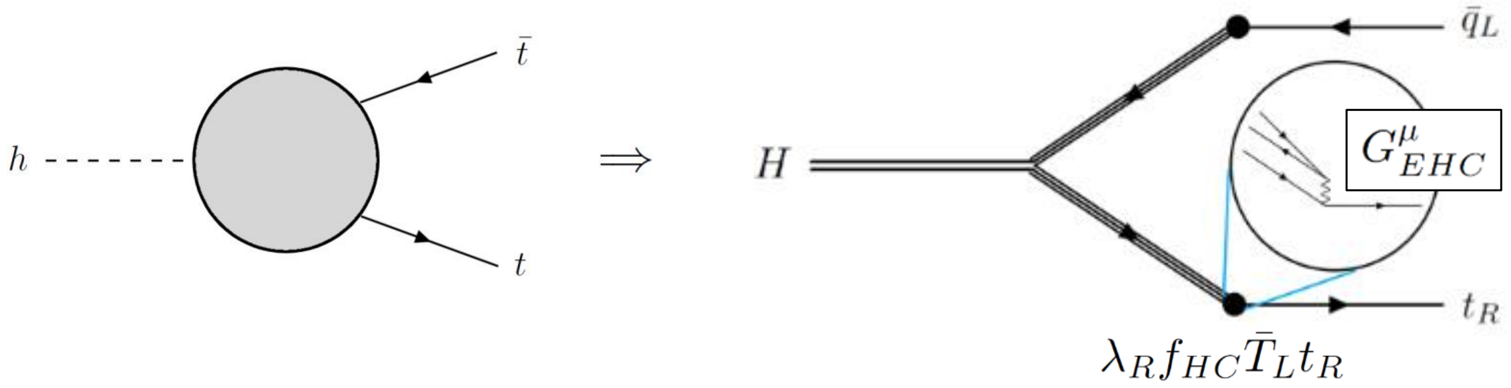
$$\mathcal{L}_{\text{EHC}} = g_{EHC} G^{\mu}_{EHC} (\bar{q}_L \gamma_\mu \psi_L + \bar{\psi}_R \gamma_\mu t_R) \;\rightarrow\; \mathcal{L}_{\text{eff}} \supset \frac{g^2_{EHC}}{M^2_{EHC}} (\bar{\psi}_R \psi_L)(\bar{q}_L t_R)$$

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

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

- 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
$M_{EHC} = g_{EHC} f_{EHC}$
f_{EHC} : the scale of EHC

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

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

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

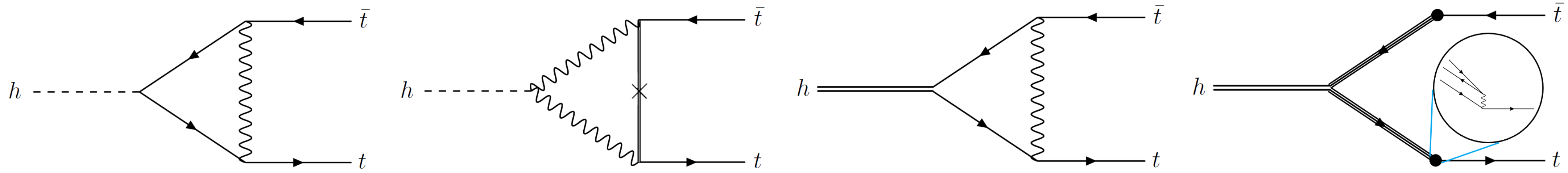
$$\mathcal{L}_{\text{PC}} = \lambda_L \bar{q}_L H T_R + g_T f_{HC} \bar{T}_R T_L + \lambda_R f_{HC} \bar{T}_L t_R \Rightarrow \boxed{y_t \sim \frac{\lambda_L \lambda_R}{g_T} \propto \lambda_R = \frac{g^2_{EHC}}{M^2_{EHC}} \cdot 4\pi f^2_{HC}}$$

- 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

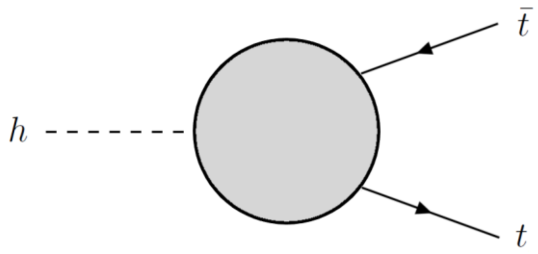
  (1) **top-philic bosons** with strong coupling : broad resonances with $\Gamma/M \gg 10\%$

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

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

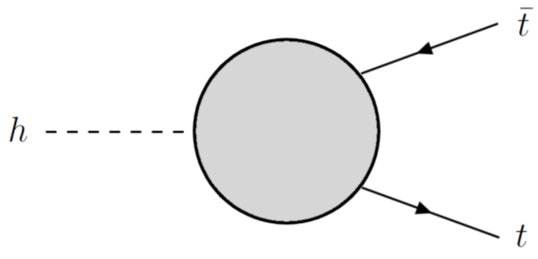
$\Rightarrow$ **Hard to perform, suffer from strong couplings and model-dependence**

Direct test of the idea?



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

Direct test of the idea!



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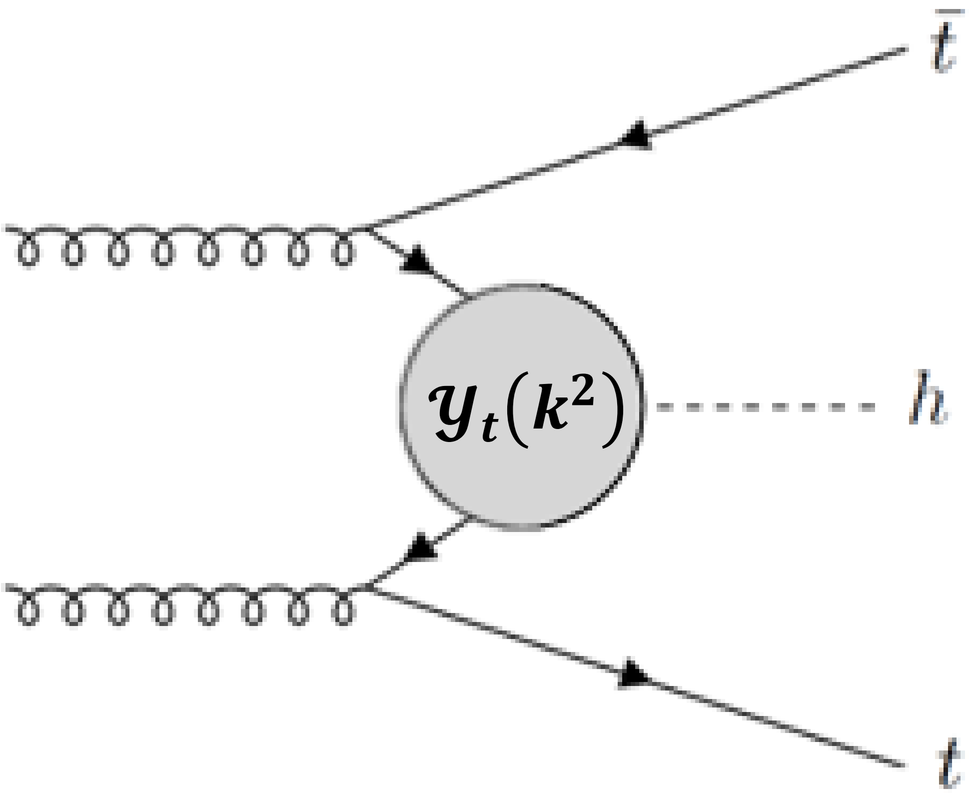
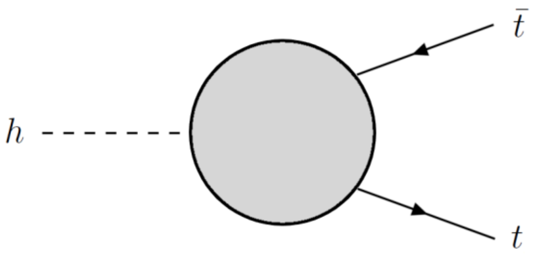
$\Rightarrow$



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

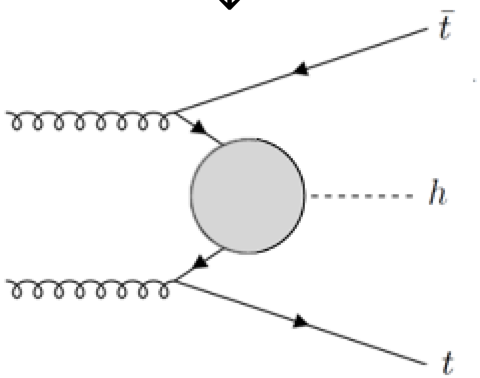
Running of the top Yukawa coupling



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

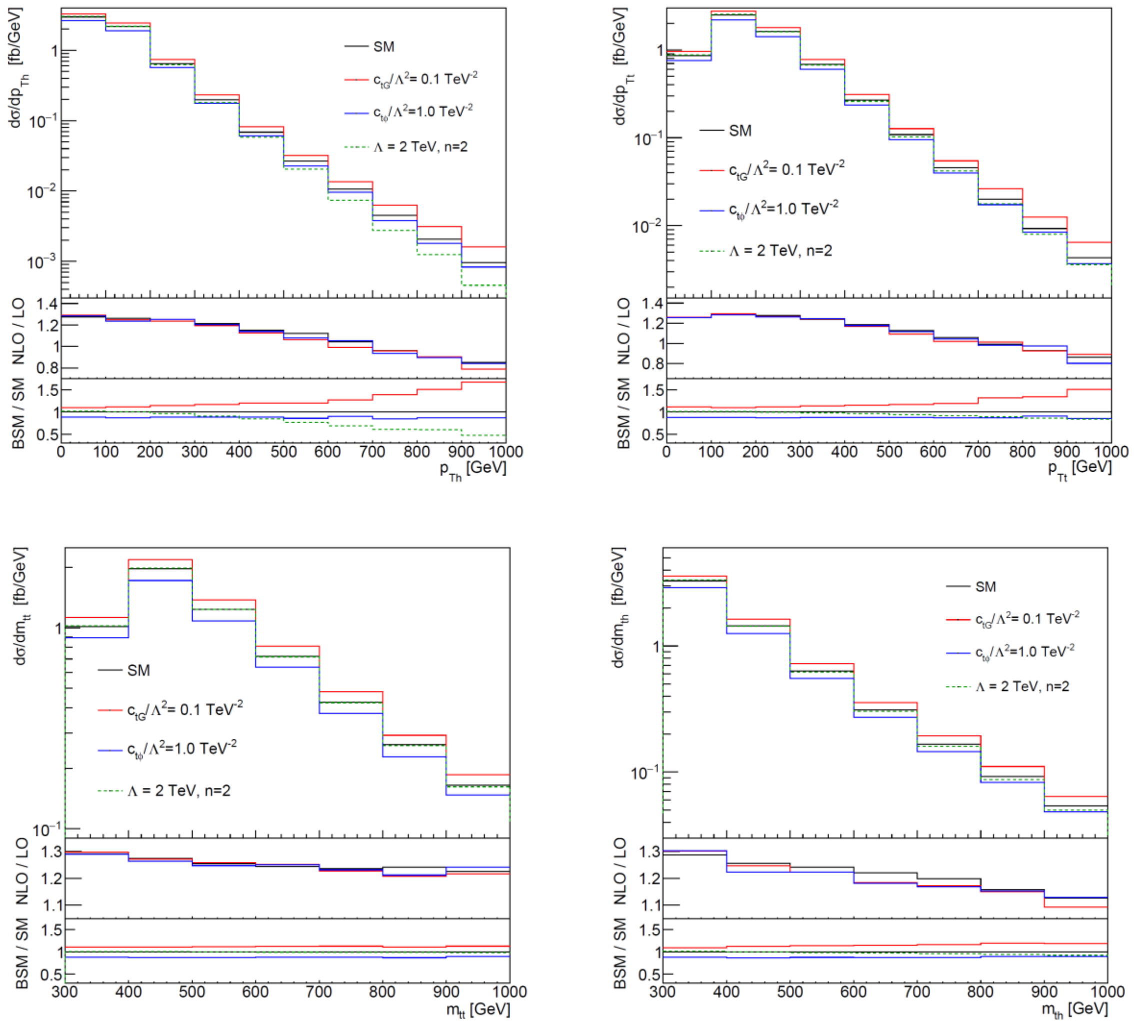
Top Yukawa at high scale

↓

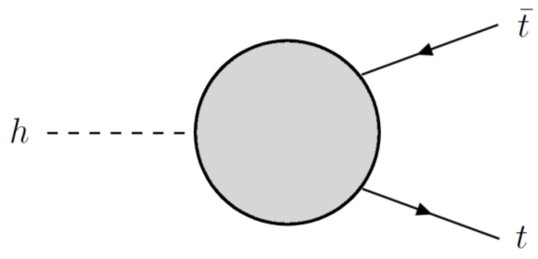


$t\bar{t}h$ differential xs

T. Han et al
2106.00018
⇒



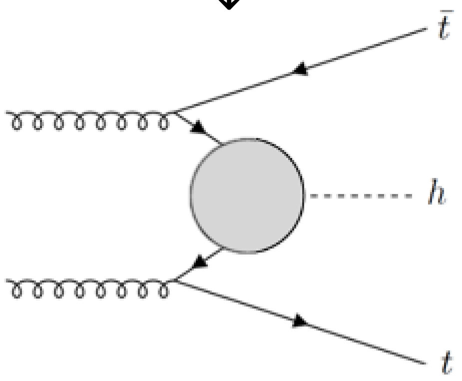
Running of the top Yukawa coupling



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

Top Yukawa at high scale

↓



$t\bar{t}h$ differential xs

T. Han et al
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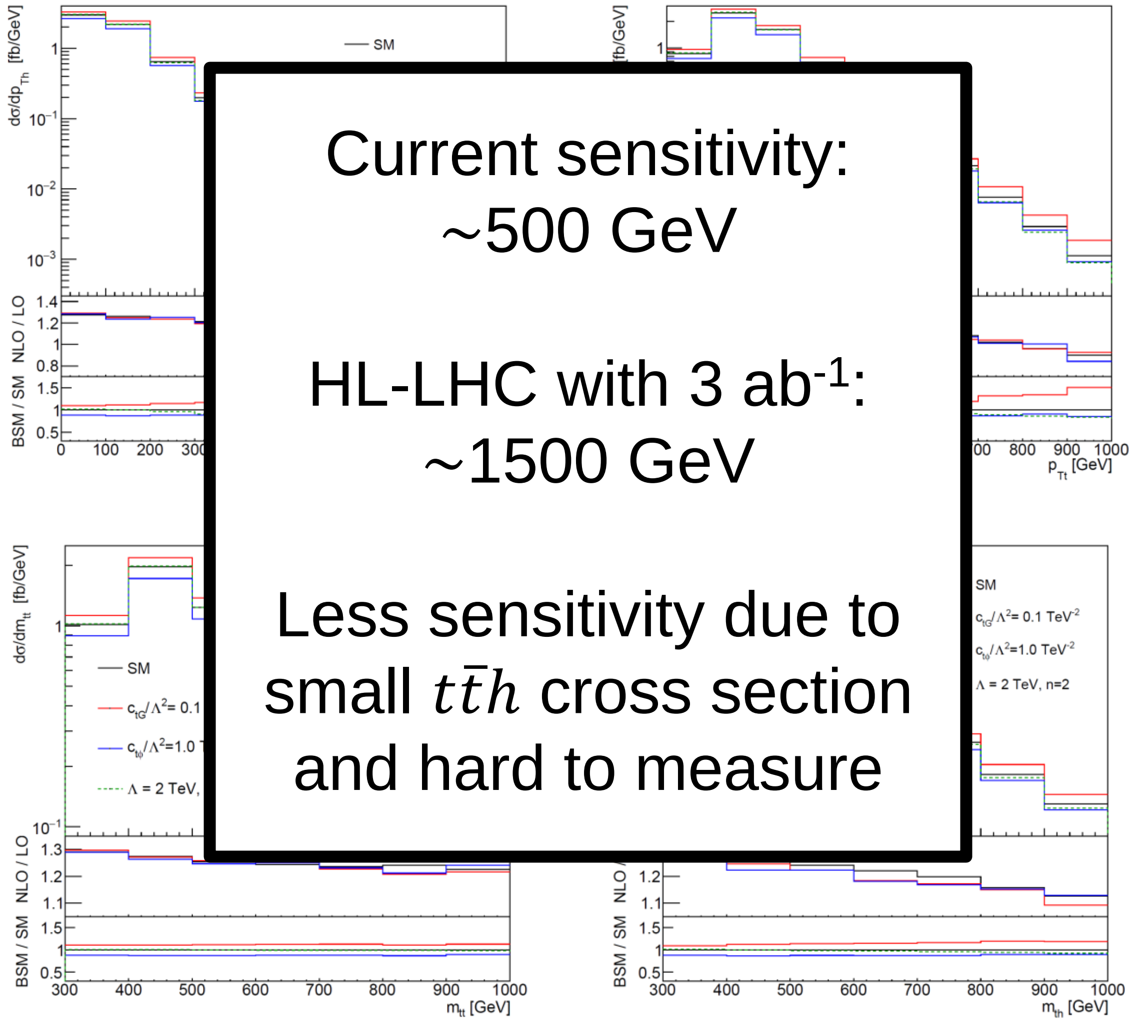
⇒

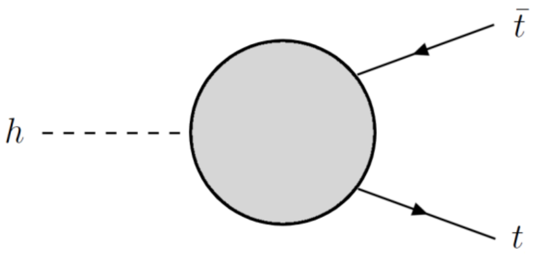


Current sensitivity:
~500 GeV

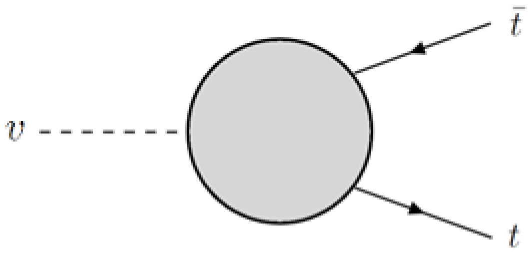
HL-LHC with 3 ab^{-1}:
~1500 GeV

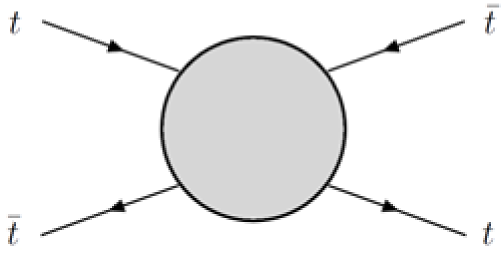
Less sensitivity due to small $t\bar{t}h$ cross section and hard to measure

Indirect searches (Direct test of the idea!)



$\Rightarrow$

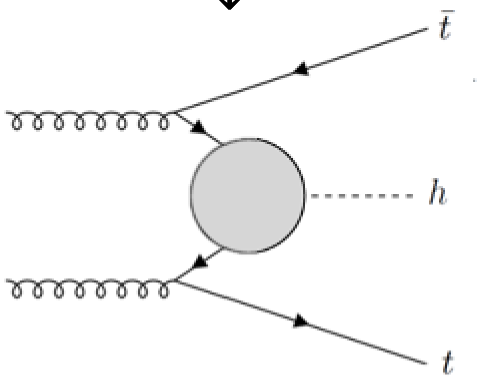




$y_t = y_t(k^2)$ | $m_t = m_t(k^2)$ | $\sim C/\Lambda_t^2$

Top Yukawa at high scale

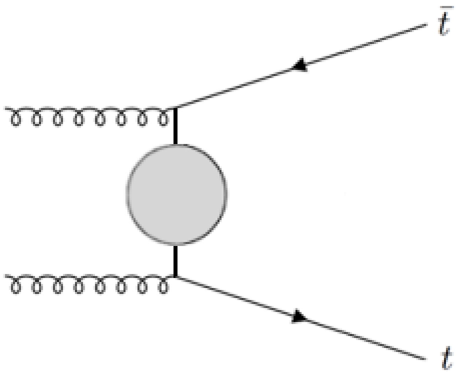
$\downarrow$



$t\bar{t}h$ differential xs

Top mass at high scale

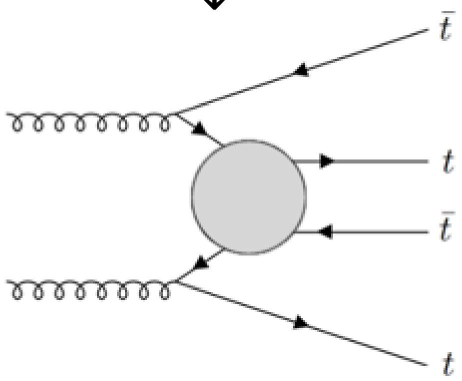
$\downarrow$



$t\bar{t}$ differential xs

Top-philic new interactions

$\downarrow$

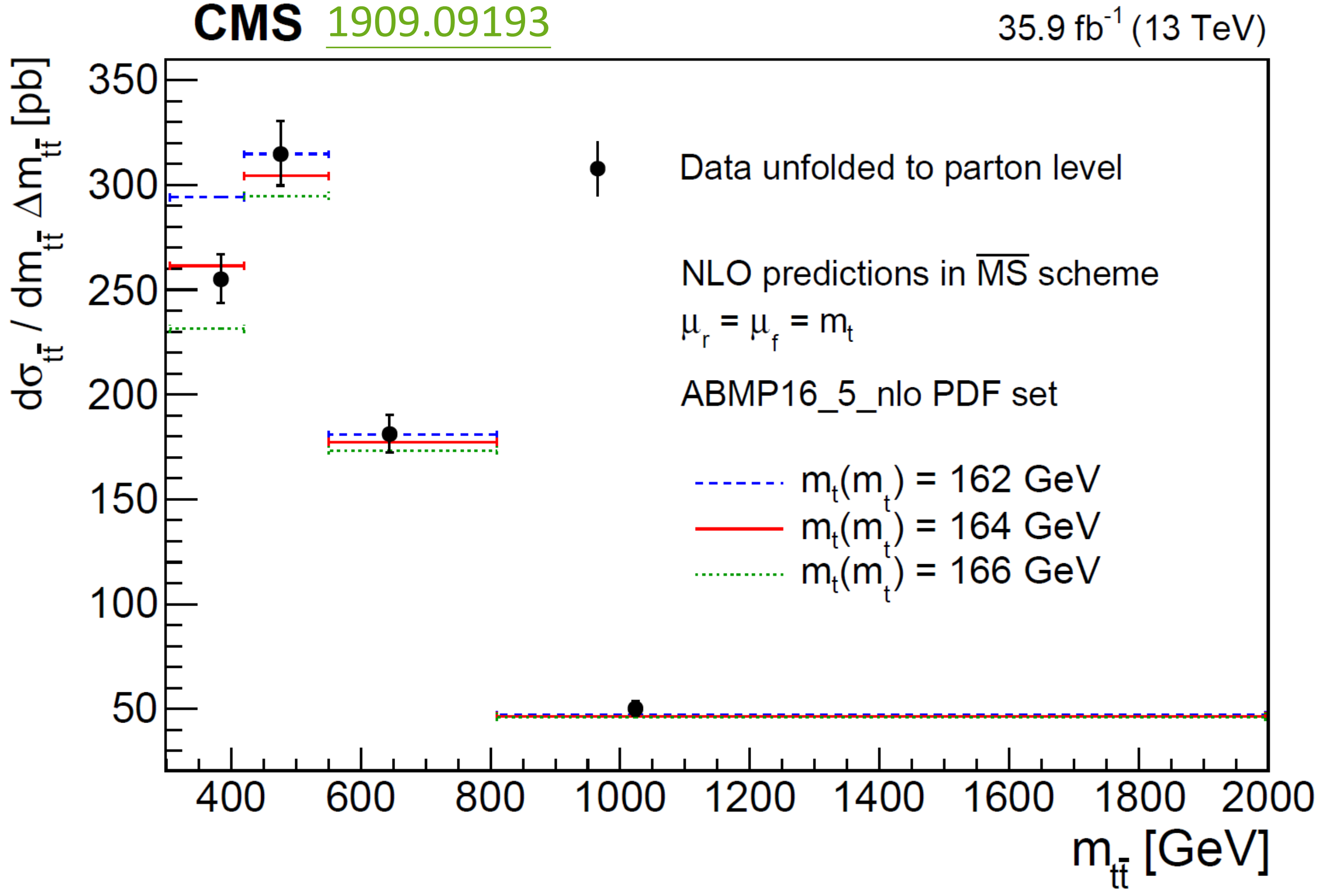


$t\bar{t}t\bar{t}$ (4top) xs

Running of the top quark mass

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

CMS 1909.09193

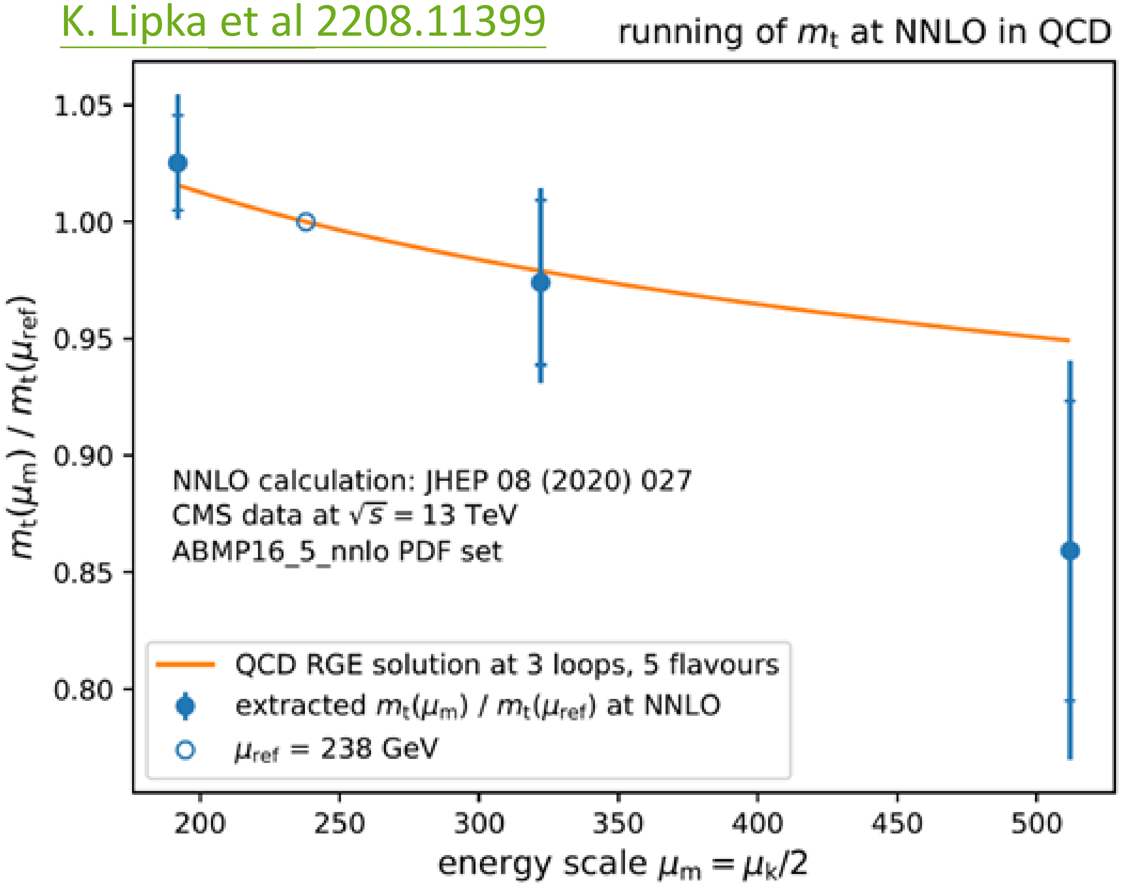


First measurement of top mass at the high scales ! (using only 2016 Run 2 data)

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

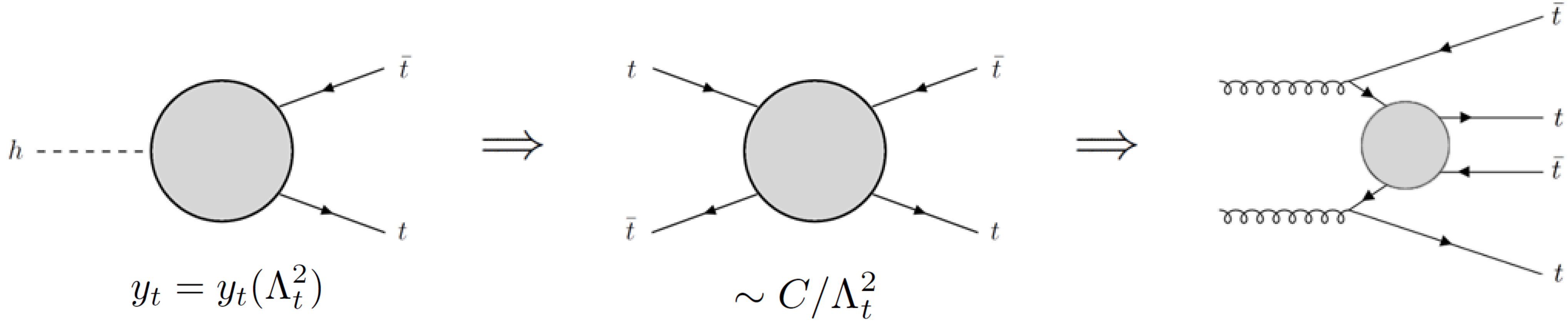
We can already put the constraint on Λ_t as

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



- 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} : $17.7^{+4.4}_{-4.0}$ fb

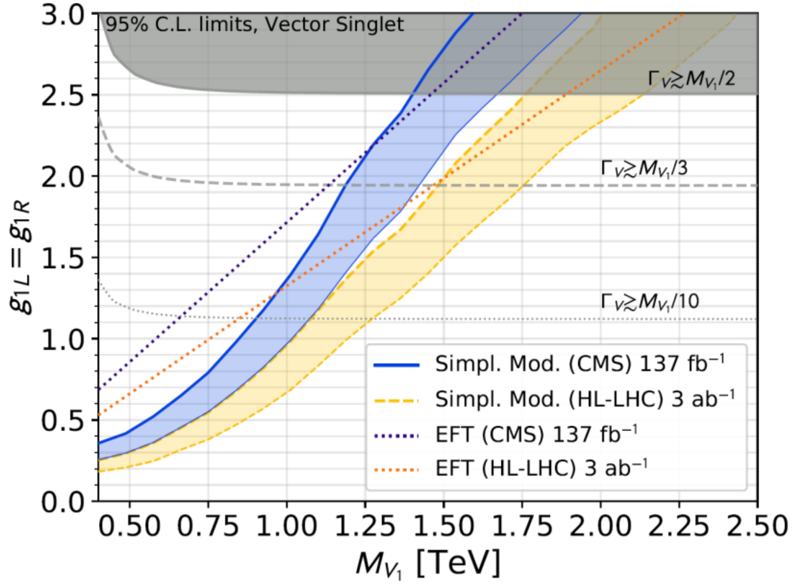
→ $\sigma_{t\bar{t}t\bar{t}} < 36\ (27)$ fb at 95% C.L.

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

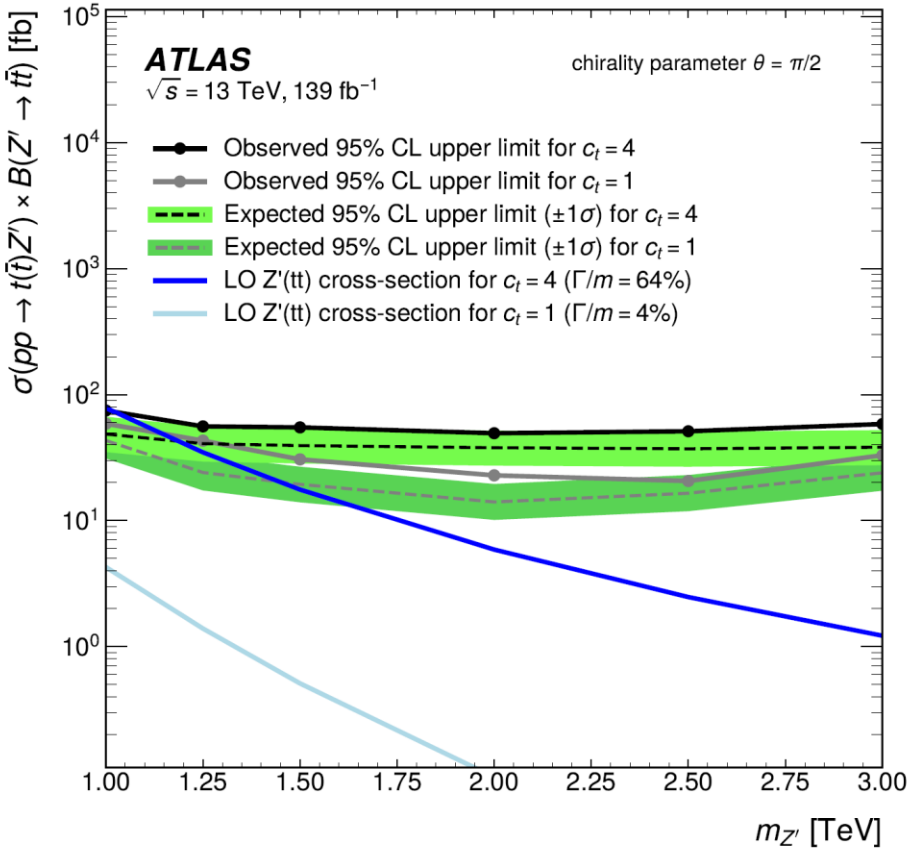
- **Go Down: Phenomenology**
- Hard to perform direct searches due to strong couplings and model-dependence
- Direct test of idea through Top physics, including $t\bar{t}h$, $t\bar{t}$, and $t\bar{t}t\bar{t}$ cross section

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

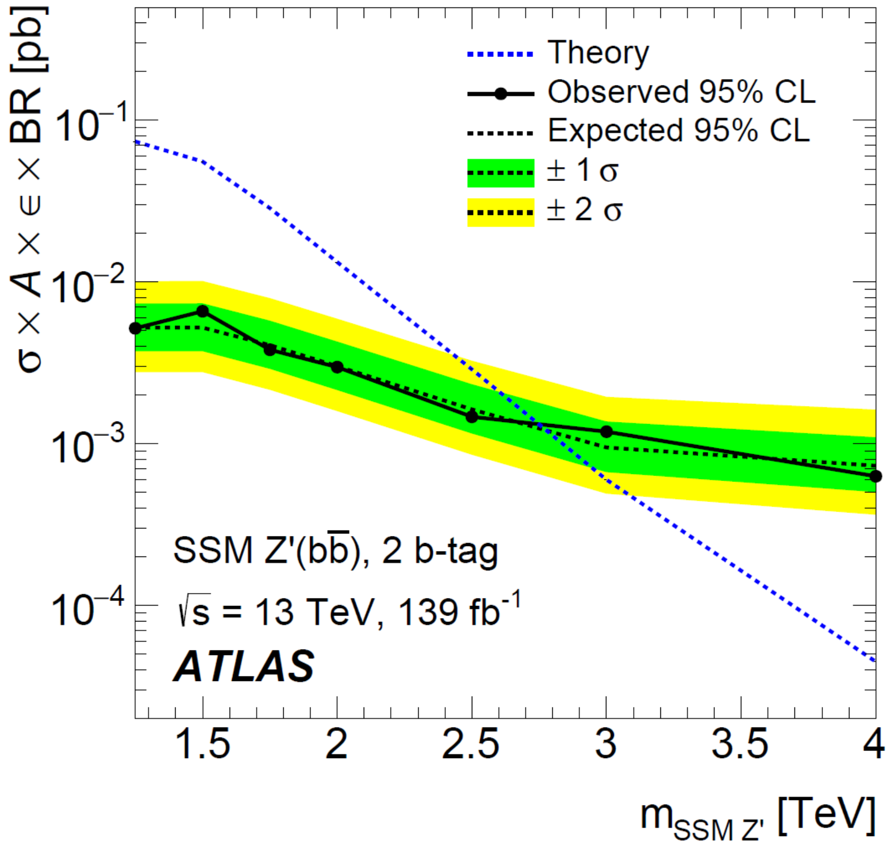
Back up

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

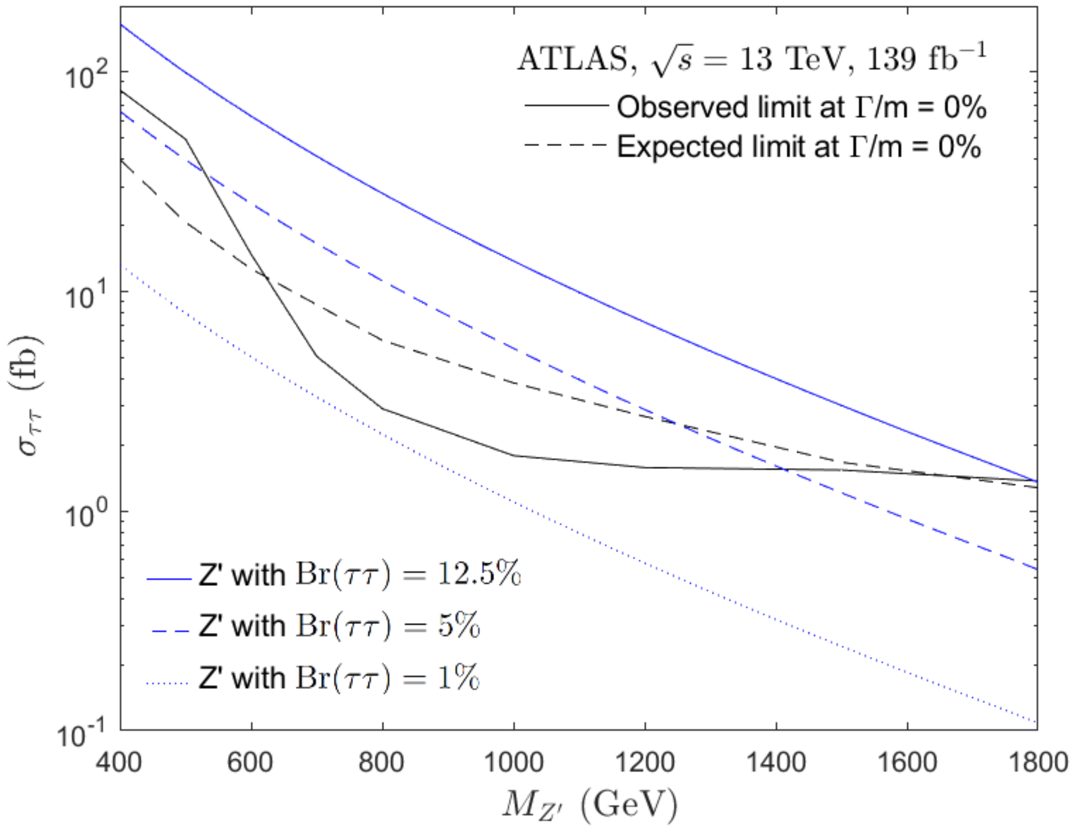


- Couple to $q_L = (t_L, b_L)$ (in bilinear case)
- Process: $b_L\bar{b}_L \to Z' \to b_L\bar{b}_L$ 1910.08447



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

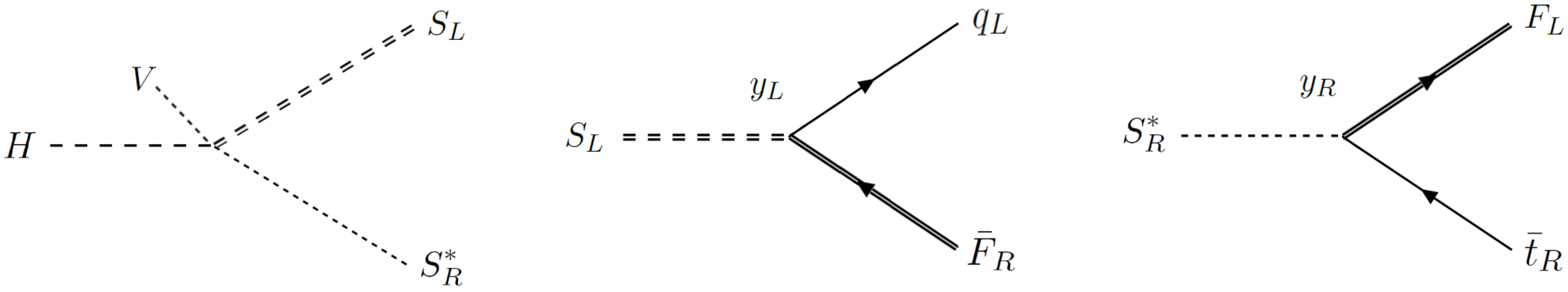
EHC Z' with $Q(\tau) \neq 0$

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

Radiative y_t generation

Simplified Scalar Model

- At least three vertices are required



or written in Lagrangian

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

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

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

where the mass eigenstates are given by

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

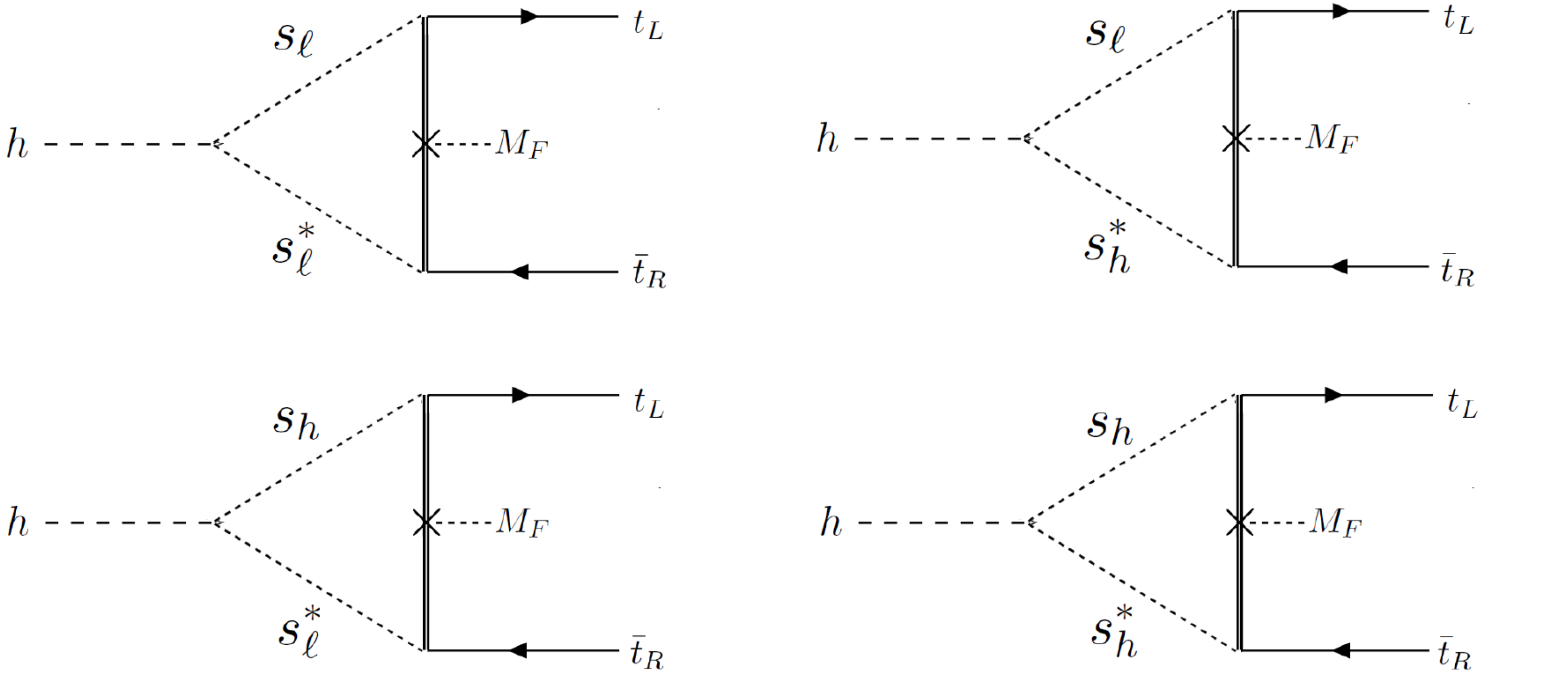
- The interaction terms also become

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

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

Generate the Top Yukawa coupling

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



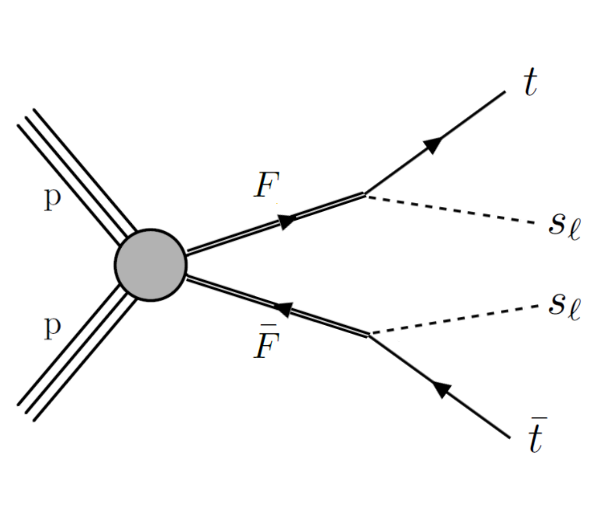
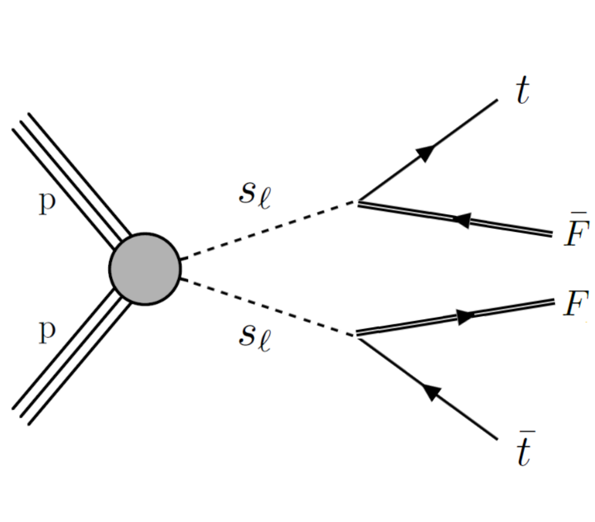
$$\Longrightarrow \quad y_t = V y_L y_R \left((c_\beta^2 - s_\beta^2)^2 \int [s_\ell, s_h, F] + 2\, c_\beta^2 s_\beta^2 \int [s_\ell, s_\ell, F] + 2\, c_\beta^2 s_\beta^2 \int [s_h, s_h, F] \right)$$

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

$\Longrightarrow$

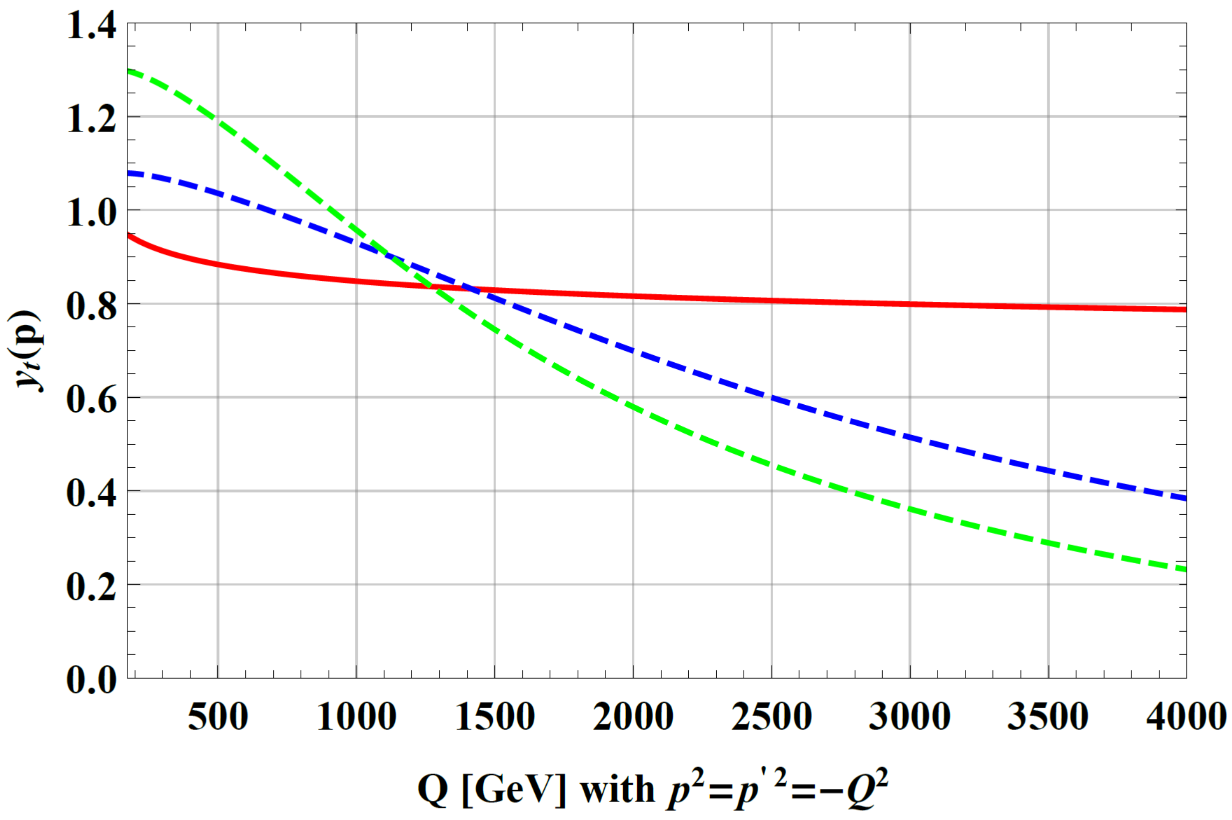
$M_F > m_s$	$m_s > M_F$
	

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

Top Yukawa from low scale to high scale

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

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

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

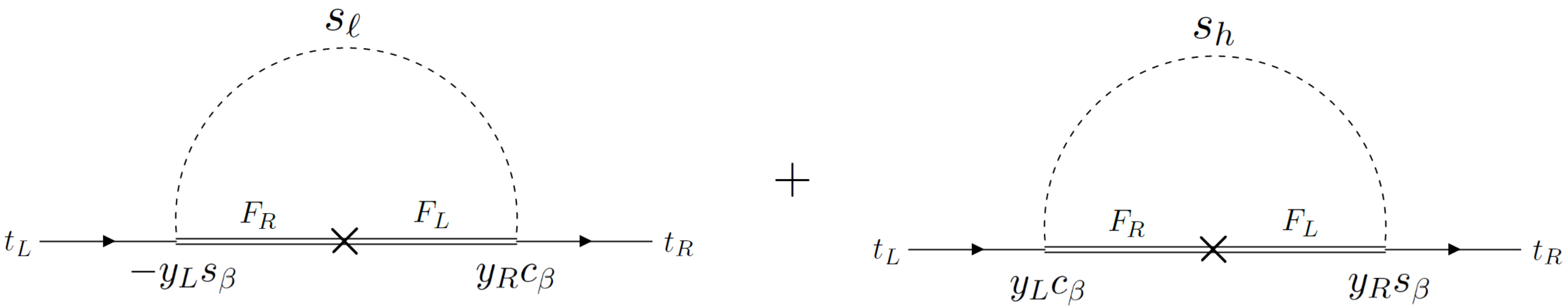
- Main Constraint: top Yukawa measurement

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

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



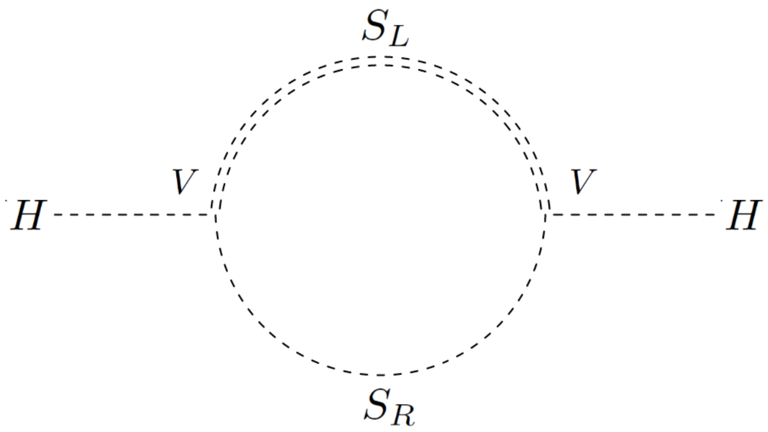
$$-\,y_L y_R c_\beta s_\beta \int [s_\ell, F] \qquad\qquad y_L y_R c_\beta s_\beta \int [s_h, F]$$

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

  → 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

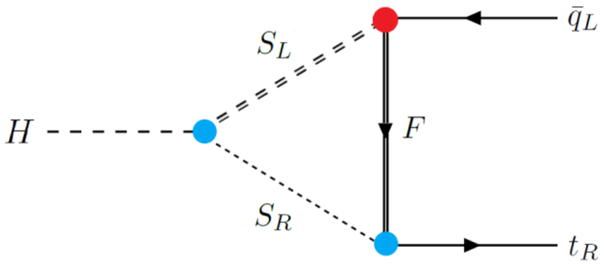


$$\Longrightarrow \quad \Delta m_H^2|_{\text{scalar}} \sim \frac{1}{16\pi^2} V^2 \ln\left(\frac{\Lambda_{\text{NP}}^2}{M^2}\right)$$

- ➢ 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.

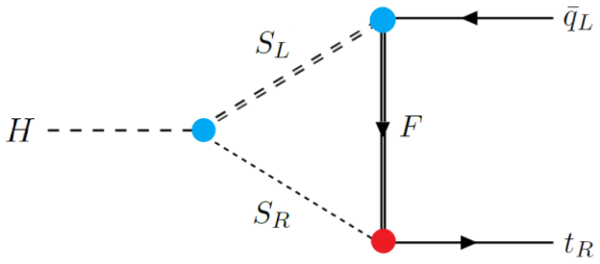
Top Yukawa from strong dynamics

- 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



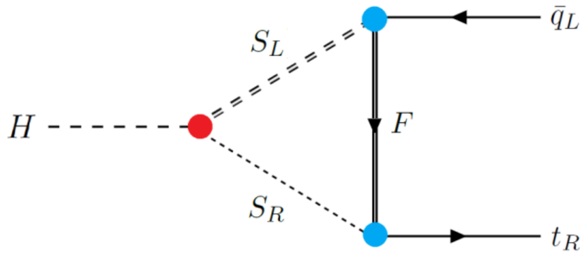
Strong sec.
S_L, S_R, F
H, t_R

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

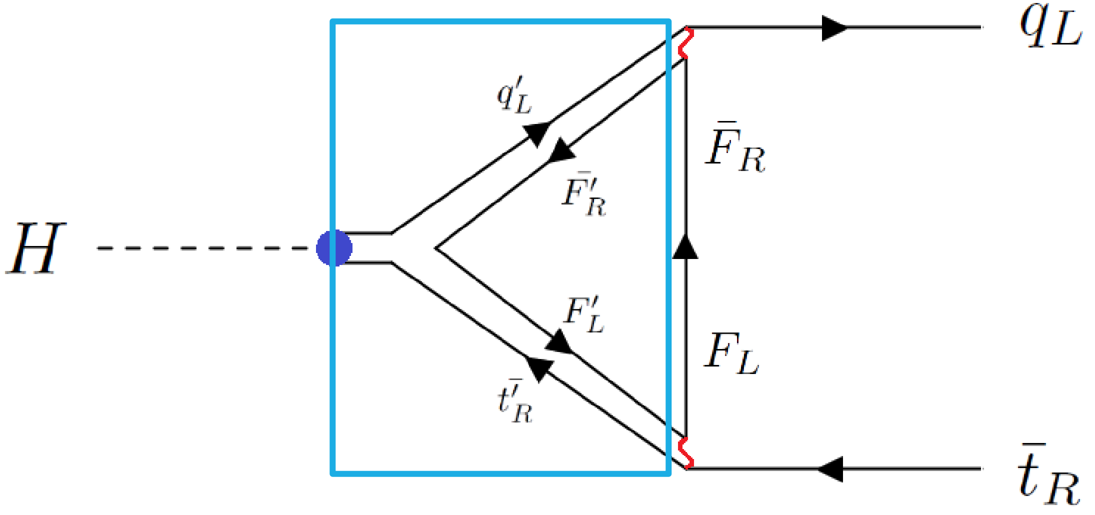
Weak sector:

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

Strong sector:

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

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



$\Longrightarrow$

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

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

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