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Third-generation-philic Naturalness

with Florian Goertz, work in progress

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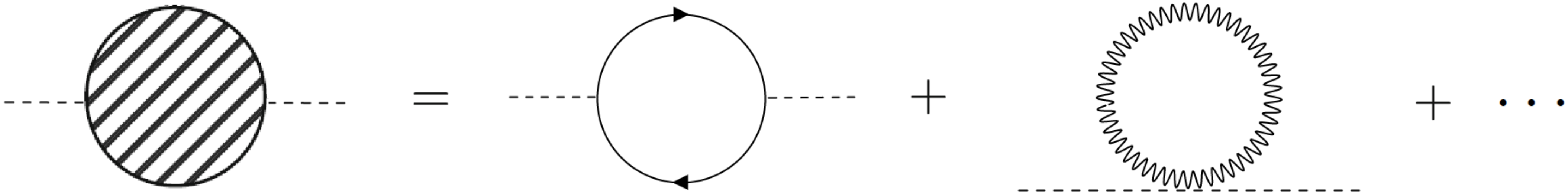
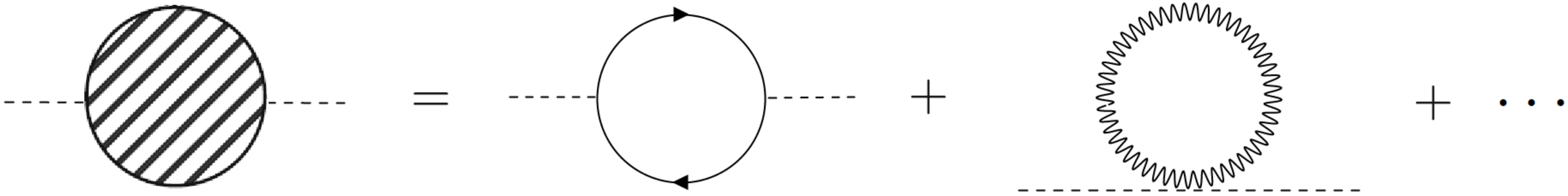
The Hierarchy Problem



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

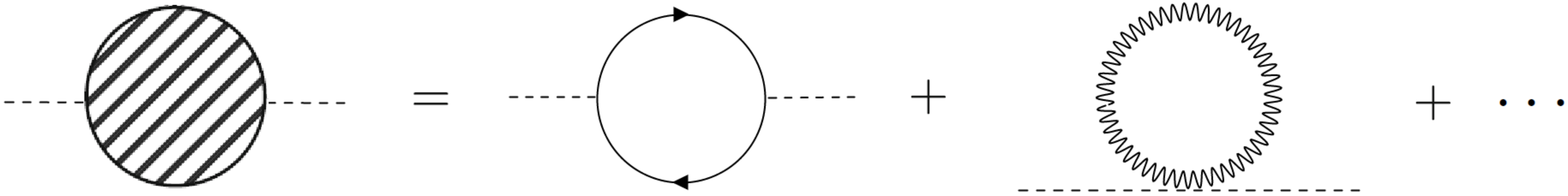
The Naturalness Principle



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

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

The Naturalness Principle

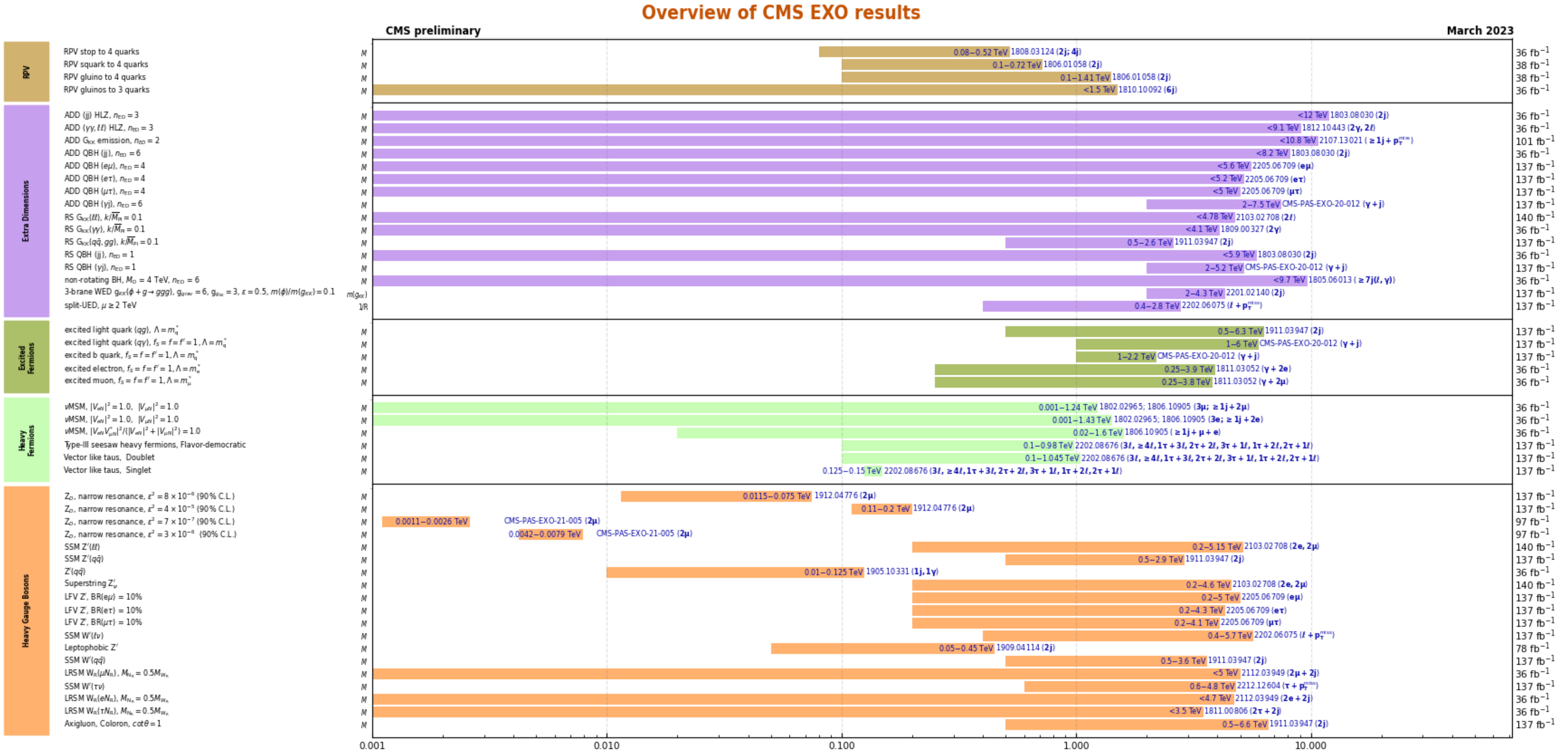


$$\delta m_h^2 = \boxed{-\frac{3}{8\pi^2} y_t^2 \Lambda_t^2 + \frac{9}{64\pi^2} g^2 \Lambda_g^2} + \cdots$$

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

The lightest new d.o.f.!!

Strong constraints on new physics



Selection of observed exclusion limits at 95% C.L. (theory uncertainties are not included).

- However, most searches are based on particles coupled to **“gluons or light quarks”**

Third-generation-philic Naturalness

- What if the new particles only/mainly couple to **"heavy quarks/fermions"**
  1. Lower production rate, ex: $b\bar{b} \rightarrow Z'$
  2. Harder final states, ex: τ instead of e, μ
  3. Accidental $U(2)^5$ global flavor symmetry

  ⇒ Weaker constraints from direct search and flavor observables

- Why a step backward from Neutral Naturalness (hidden sector) ?
  1. Testable solution in visible sector
  2. Explain the heaviness of third-generation fermions
  3. Possible connections with B anomalies

  ⇒ Stronger constraints comparing to NN but **Still worth to explore!**

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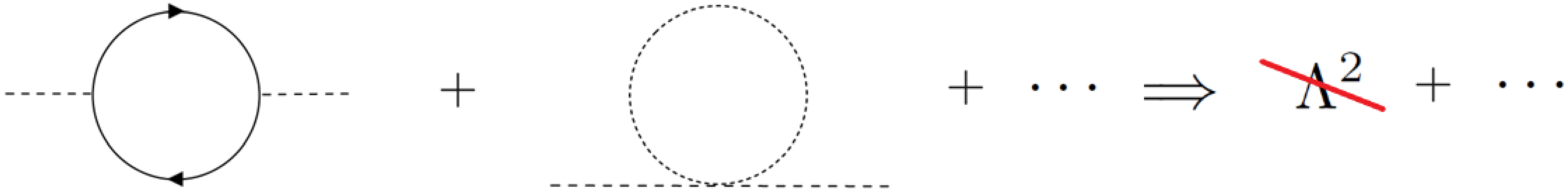
Cutoff of top loop: traditional solutions



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

Top partner solutions

- List of models with top partners of different quantum number

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

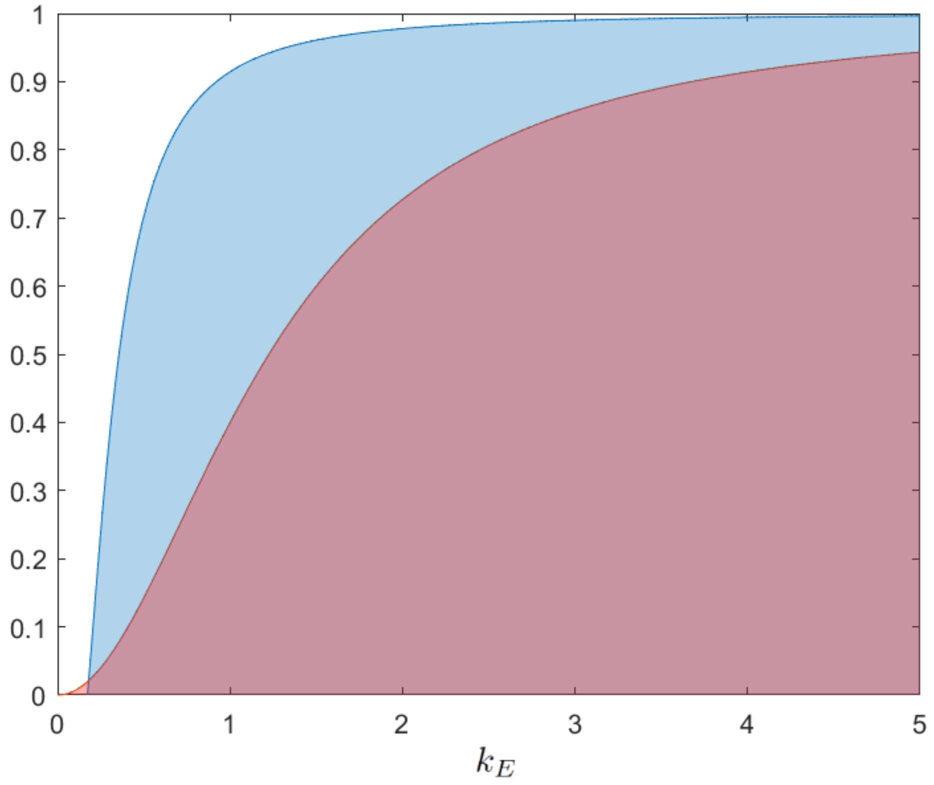
Charged under $SU(3)_C$

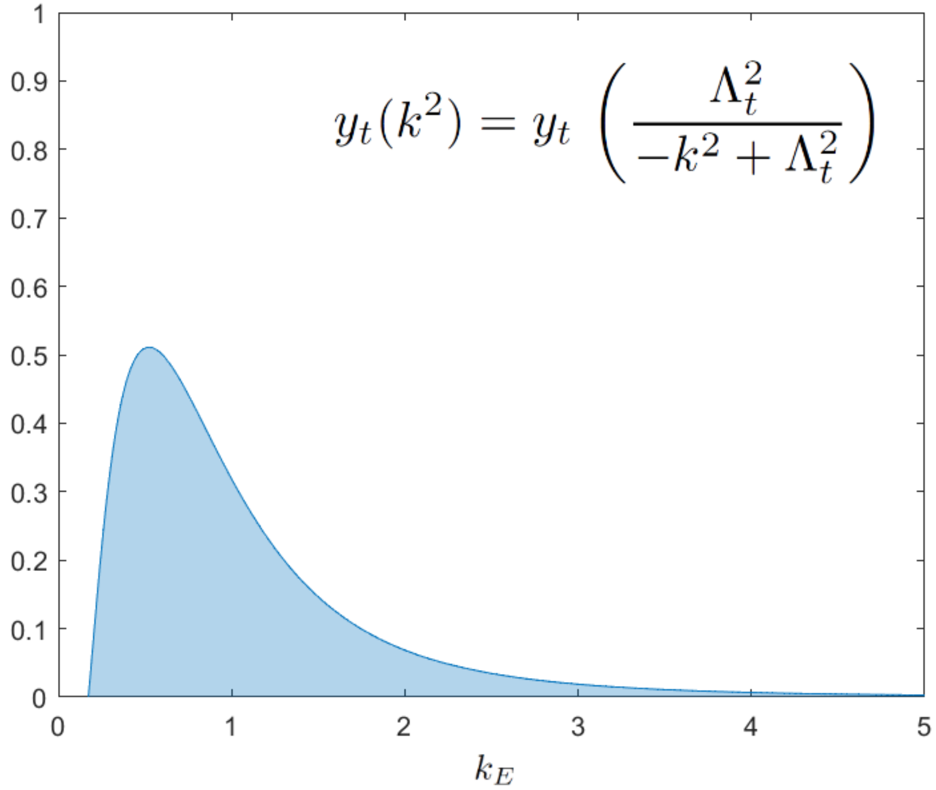
Charged under hidden $SU(3)$

⇒ either colored or hidden

Alternative to Top-partner scenarios

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



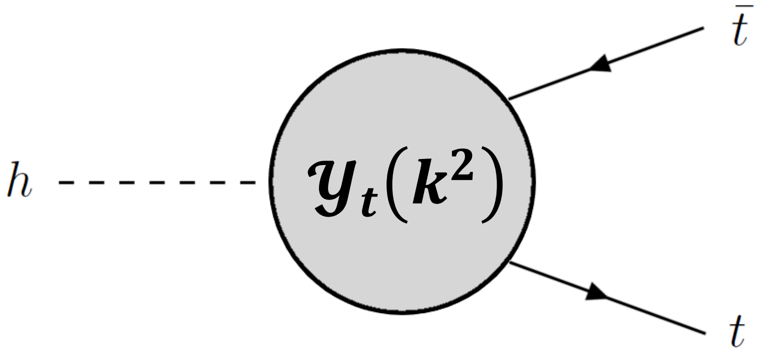


$$\delta m_h^2|_{\text{top}} + \delta m_h^2|_{\text{top partner}} \sim -\frac{3}{8\pi^2} y_t^2 M_T^2 \ln\left(\frac{\Lambda^2}{M_T^2}\right)$$

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

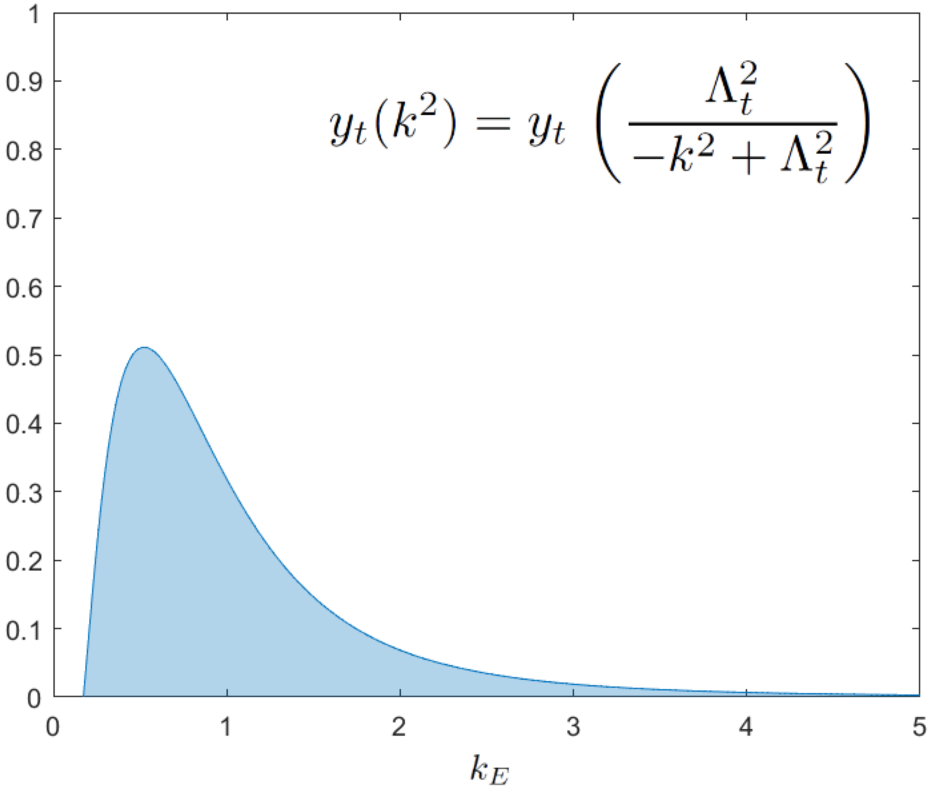
Alternative to Top-partner scenarios

- ➢ Features of the alternative:
- Top Yukawa coupling gets it large value due to large running
- Flavor non-universal (only top)
- Λ_t is determined by top-philic NP



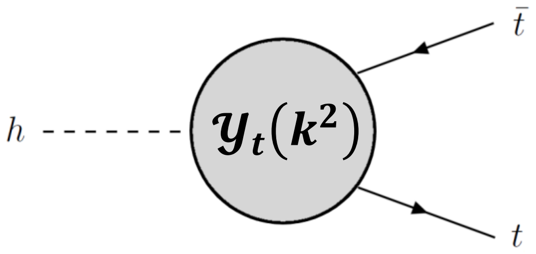
⇒ Zoom in the Top Yukawa vertex

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



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

Zoom in the Top Yukawa vertex



$\Rightarrow$

Elementary Higgs
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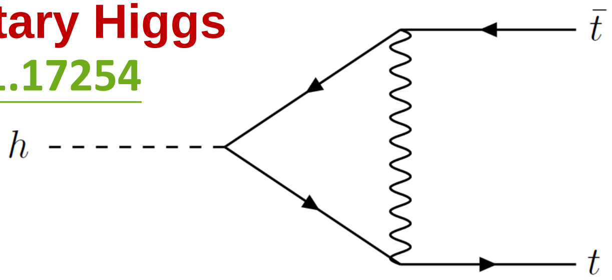
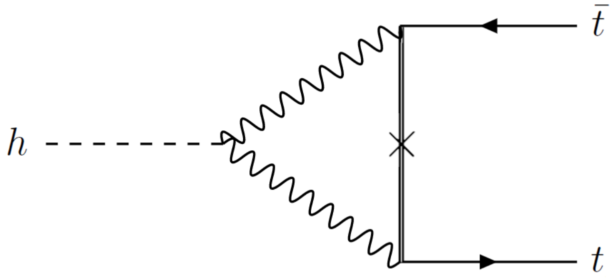
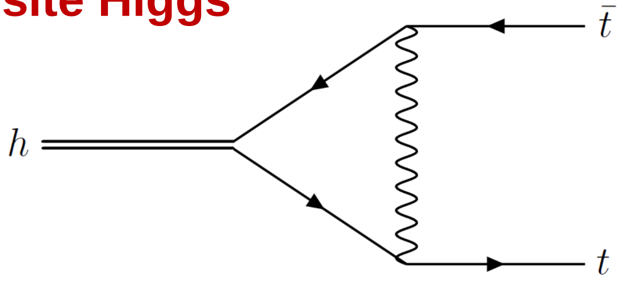


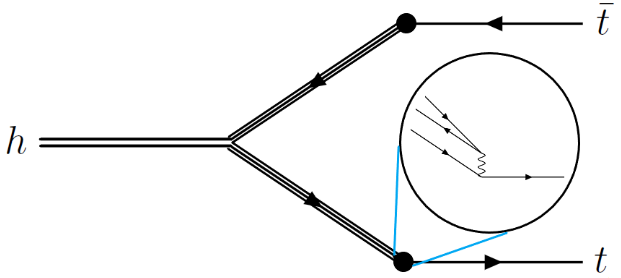


(1) large $\mathcal{Y}_t$ running
new top-philic bosons
with strong coupling

(2) radiative $\mathcal{Y}_t$ generation
bosons and VL fermions
with strong coupling

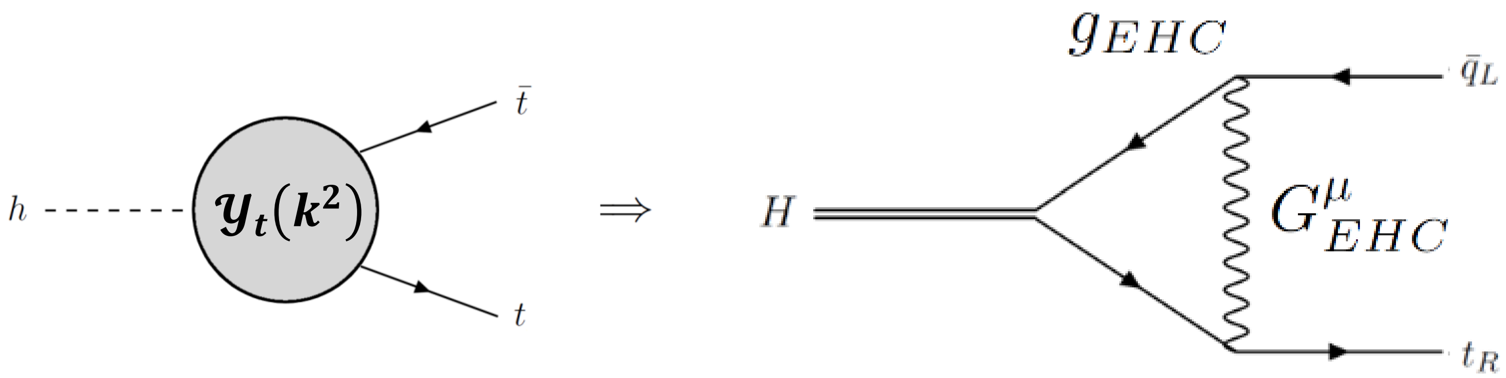
Composite Higgs





(3) $\mathcal{Y}_t$ from four-fermion interations (bilinear / linear)
extended-hypercolor bosons with weak coupling

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

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

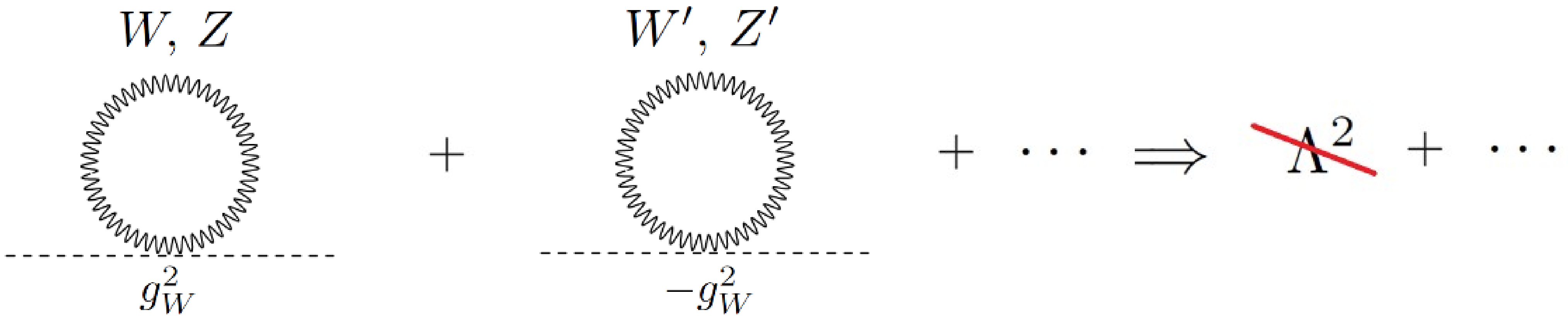
- Naive dimensional analysis in CHM gives $\bar{\psi}_R \psi_L \sim \left(4\pi f^2_{HC}\right) H$ and thus

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

- The top loop is now cut by the top-philic EHC boson and the cutoff scale is determined by $\Lambda_t = M_{EHC} = g_{EHC} f_{EHC}$ which can be light with small g_{EHC}

Cutoff of gauge loop: Heavy gauge bosons

- In little Higgs models, the gauge boson loop is cut by



$SU(2)_W$ gauge loop $SU(2)_{W'}$ gauge loop

- The Higgs quadratic is still generated due to the difference between

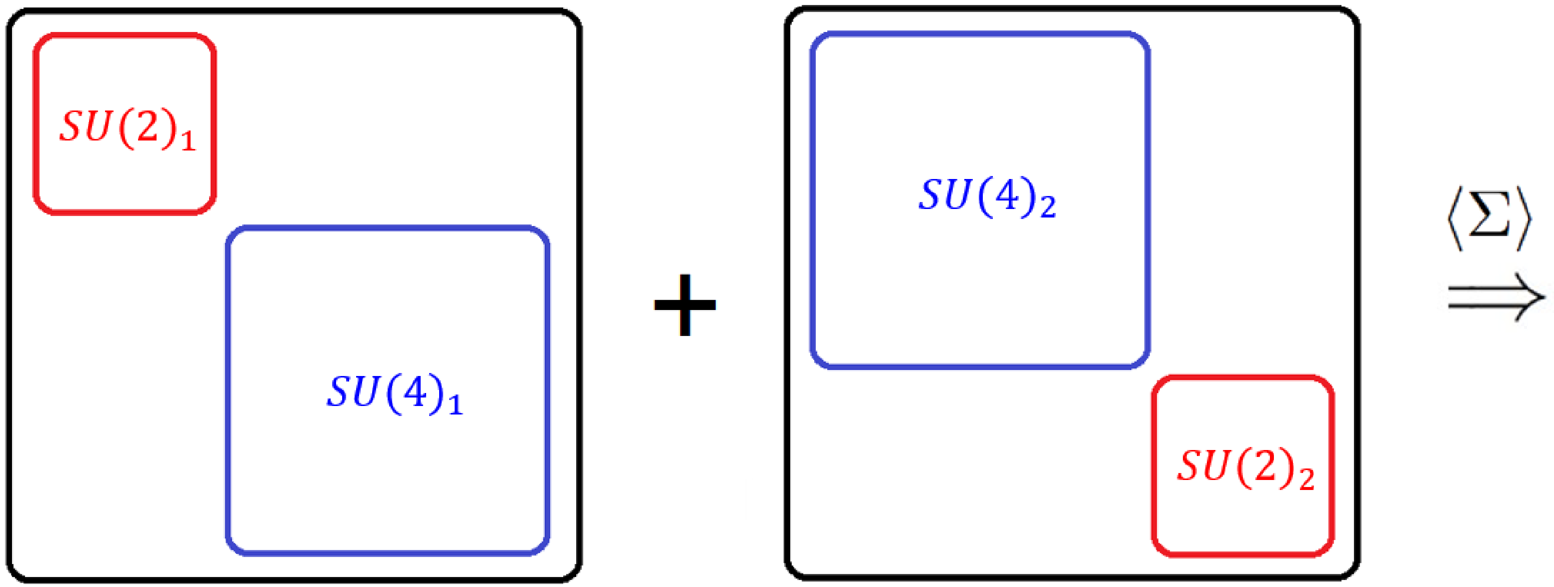
$$\delta m_h^2|_{SU(2)_W} + \delta m_h^2|_{SU(2)_{W'}} \sim \frac{3}{64\pi^2} g_W^2 M_{W'}^2 \ln\left(\frac{\Lambda^2}{M_{W'}^2}\right)$$

- Naturalness principle suggests gauge partners with $\Lambda_g = M_{W'} \approx 1200$ GeV

Collective symmetry breaking

- Take $SU(6)/Sp(6)$ little Higgs model for example: (with gauged $SU(2)_1 \times SU(2)_2$)

I. Low et al
hep-ph/0207243



$g_1 \neq 0, \quad g_2 = 0$ $\qquad$ $g_1 = 0, \quad g_2 \neq 0$

Higgs as pNGB of
coset $SU(6)/Sp(6)$

Unbroken $SU(2)_W$
$SU(2)_1 + SU(2)_2$

Broken $SU(2)_{W'}$
$SU(2)_1 - SU(2)_2$

- The Higgs potential is only generated collectively when both $g_1, g_2 \neq 0$

$$m_h^2 \sim \frac{3}{64\pi^2} g_1^2 g_2^2 f^2 \ln\left(\frac{\Lambda^2}{\mu^2}\right) \to \frac{3}{64\pi^2} g_W^2 M_{W'}^2 \ln\left(\frac{\Lambda^2}{M_{W'}^2}\right)$$

(match the CW potential)

Third-generation-philic version

- Combine Little Higgs with Non-Universal Gauge Interaction

  $SU(2)_1 \rightarrow SU(2)_h$ with coupling g_h for 3rd generation

  $SU(2)_2 \rightarrow SU(2)_\ell$ with coupling g_ℓ for 1st, 2nd generation

- After the symmetry breaking at the scale $f_{HC} \sim 1$ TeV

  $W = \cos\theta_E \cdot W_\ell + \sin\theta_E \cdot W_h$ → SM gauge boson

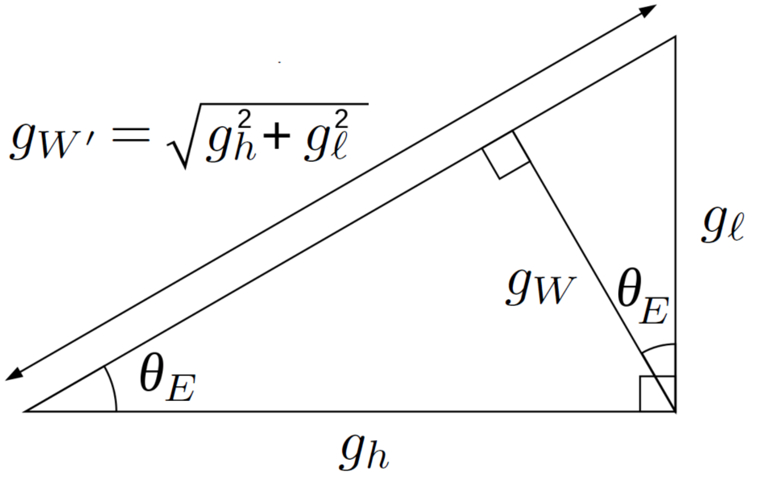
  $W' = \sin\theta_E \cdot W_\ell - \cos\theta_E \cdot W_h$ → Heavy gauge boson

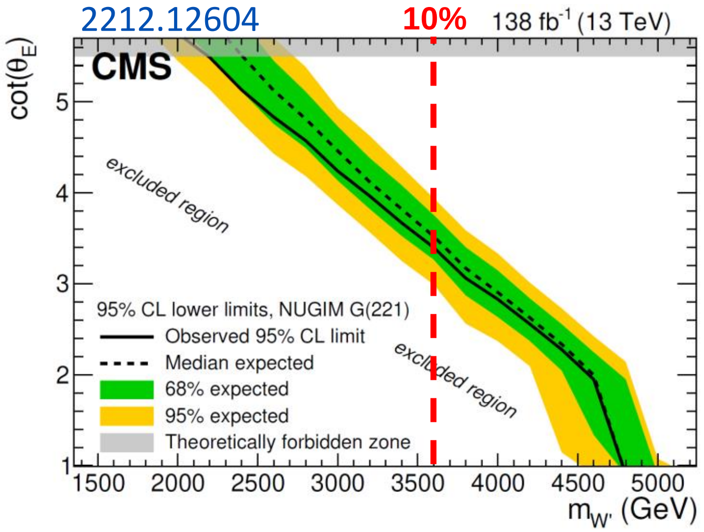
- For $g_h \gg g_\ell$, we get $W \sim W_\ell$ and $W' \sim W_h$, where

  Heavy W' becomes Third-generation-philic !!

- Main direct search from the $\tau\nu$ final state :

✓ Some parameter space is still allowed for 10% fine-tuning or even better considering broad W' with $g_h > 3.6$





Combine two ideas: $\boldsymbol{SU(6)/Sp(6)}$ FCHM

➢ CHM with extended hypercolor (fundamental) and collective symmetry (large coset)

Ex: $\boldsymbol{SU(6)/Sp(6)}$ fundamental composite Higgs model with $SU(2)_h \times SU(2)_\ell \times U(1)$

- 6 Weyl hyperfermions in the fundamental representation of the $Sp(NHC)$ hypercolor group

$$\begin{array}{ll} (T_L, B_L) = (2,1,0), & T_R = (1,1,1/2), \\ (C_L, S_L) = (1,2,0), & B_R = (1,1,-1/2) \end{array} \quad \Longrightarrow \quad \psi = (T_L, B_L, T_R^C, B_R^C, C_L, S_L)^T$$

- Once the hypercolor becomes strongly coupled, hyperfermions form a condensate and breaks $SU(6) \to Sp(6)$, which can be described by a nonlinear Sigma model

$$\langle\Sigma\rangle = \begin{pmatrix} 0 & 0 & -\mathbb{I}_{2\times2} \\ 0 & i\sigma_2 & 0 \\ \mathbb{I}_{2\times2} & 0 & 0 \end{pmatrix} \Longrightarrow i\pi_a X_a \cdot \Sigma_0 = \begin{pmatrix} \epsilon s & (H_1\, H_2) & -\frac{\phi_a}{\sqrt{2}}\sigma^a + \frac{\eta}{\sqrt{6}}\mathbf{1} \\ -(H_1\, H_2)^T & 2\frac{\eta}{\sqrt{6}}\epsilon & -(-H_2\, H_1)^\dagger \\ \frac{\phi_a}{\sqrt{2}}\sigma^{a*} - \frac{\eta}{\sqrt{6}}\mathbf{1} & (-H_2\, H_1)^* & -\epsilon^T s^* \end{pmatrix}$$

- The coset $SU(6)/Sp(6)$ contains 14 pNGBs, including a complex singlet s, a real singlet η, a real triplet ϕ_a (will be eaten by the broken $SU(2)_{W'}$) and two Higgs doublets H_1 and H_2

Higgs potential

- For simplicity, we consider the inert 2HDM and the SM Higgs $H = H_1$
- The Higgs potential is generated mainly from the top loop and gauge loop given as

Top-philic EHC boson

Third-gen.-philic Heavy SU(2) boson

$$V_H = \left(-\frac{3}{8\pi^2} y_t^2 \boxed{M_{EHC}^2} + \frac{9}{64\pi^2} g_W^2 \boxed{M_{W'}^2} \ln\frac{\Lambda^2}{M_{W'}^2}\right)|H|^2 = -(\,89\ \text{GeV}\,)^2\,|H|^2$$

$$+\left(\frac{3}{16\pi^2} y_t^4 \ln\frac{M_{EHC}^2}{m_t^2} + \frac{9}{64\pi^2} g_W^2 g_{W'}^2 \ln\frac{\Lambda^2}{M_{W'}^2}\right)|H|^4 \quad +(\ \ 0.13\ \ )\ \ |H|^4$$

~0.06 when $M_{EHC} = 800$ GeV

~0.06 when $g_{W'} = 5$ (broad W')

Summary

- **Motivation**
  - Naturalness requires light new physics responsible of top loop and gauge loop
  - Absence of new particles so far can be explained if NP is third-generation-philic
- **Model Building**
  - Cutoff of top loop: EHC boson (top-philic)
  - Cutoff of gauge loop: Heavy SU(2) boson (third-generation-philic)
  - A concrete model based on SU(6)/Sp(6) fundamental composite Higgs modol
- **Future prospect**
  - Constraints from direct searches and indirect searches
  - Concrete setups for extended hypercolor mechanism
  - Connect to the heaviness of the third generation fermions

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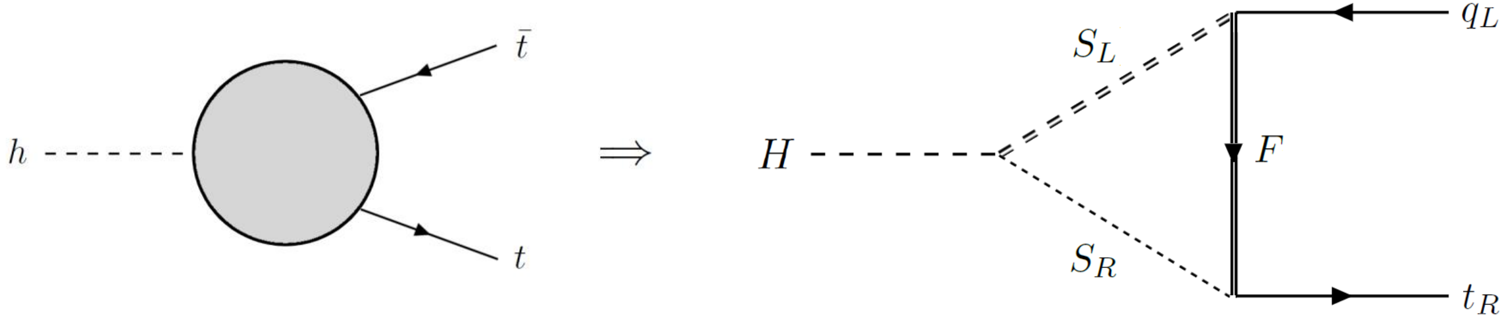
Back up

Radiative y_t generation



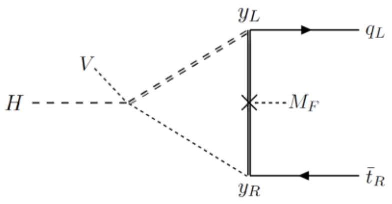
Minimal setup:

EW doublet scalar S_L

EW singlet scalar S_R

EW singlet fermion F

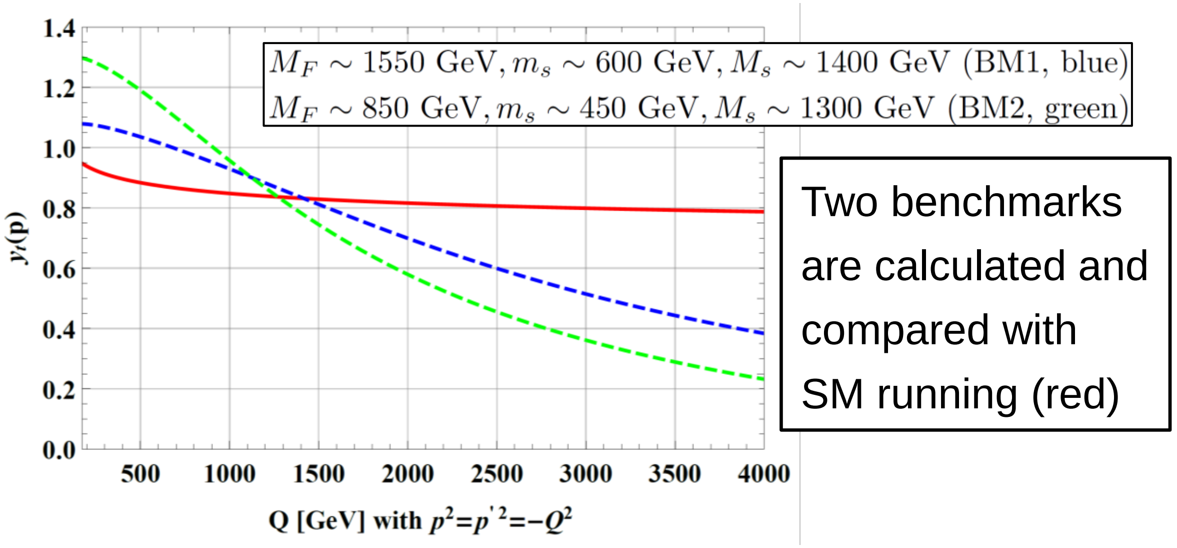
- The diagram introduces a dim-6 operator



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

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

$$= y_t$$



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

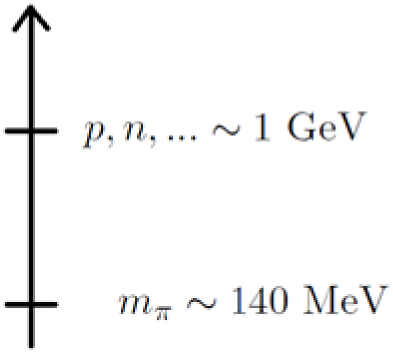
Fundamental Composite Higgs Models

- 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.



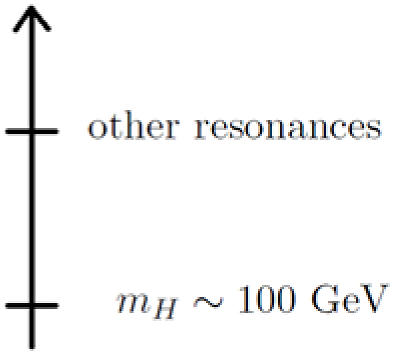
Quark with QCD

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

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

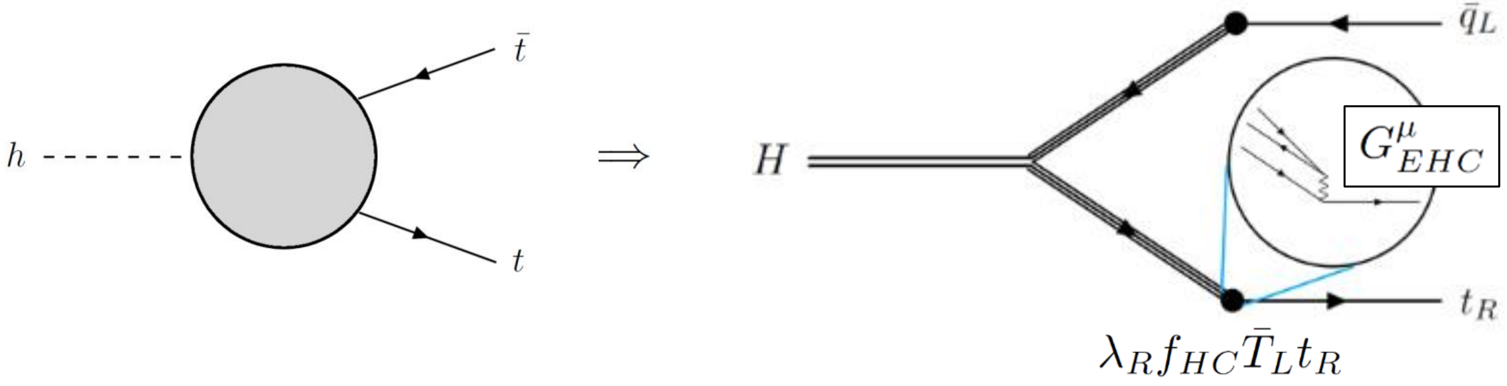
which gives (at least) four NG bosons as **Higgs doublet!!**

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)

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)

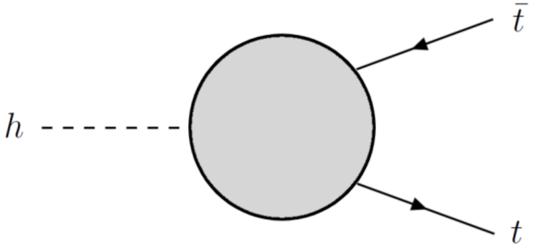
$$\mathcal{L}_{\rm EHC} = g_{EHC} G^{\mu}_{EHC} (\bar{\psi}_1 \gamma_\mu \psi_2 + \bar{\psi}_3 \gamma_\mu t_R) \quad \rightarrow \quad \mathcal{L}_{\rm eff} \supset \frac{g^2_{EHC}}{M^2_{EHC}} (\bar{\psi}_1 \bar{\psi}_2 \bar{\psi}_3)\,(t_R)$$

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

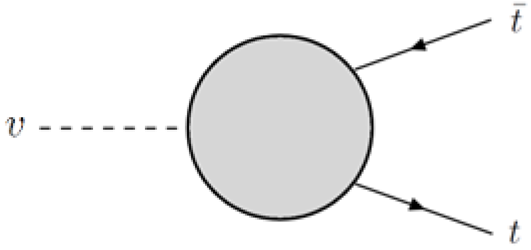
$$\mathcal{L}_{\rm PC} = \lambda_L \bar{q}_L H T_R + g_T f_{HC} \bar{T}_R T_L + \lambda_R f_{HC} \bar{T}_L t_R \Rightarrow \boxed{y_t \sim \frac{\lambda_L \lambda_R}{g_T} \propto \lambda_R = \frac{g^2_{EHC}}{M^2_{EHC}} \cdot 4\pi f^2_{HC}}$$

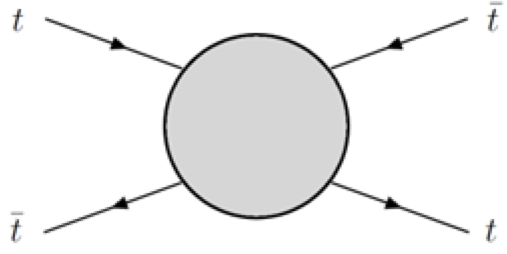
- Again, the top loop is cut off at the mass scale of $M_{EHC} = g_{EHC} f_{EHC}$

Indirect searches (Direct test of the idea!)



$\Rightarrow$





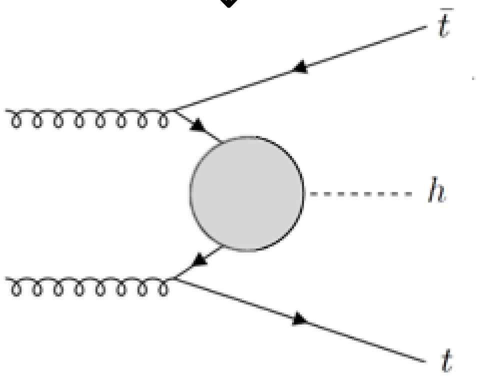
$y_t = y_t(k^2)$

$m_t = m_t(k^2)$

$\sim C/\Lambda_t^2$

Top Yukawa at high scale

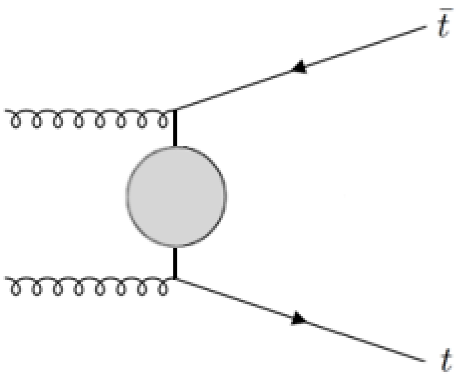
↓



$t\bar{t}h$ differential xs

Top mass at high scale

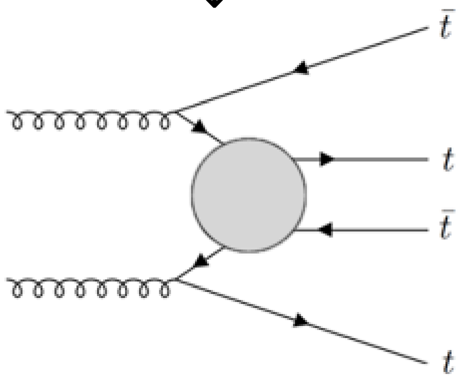
↓



$t\bar{t}$ differential xs

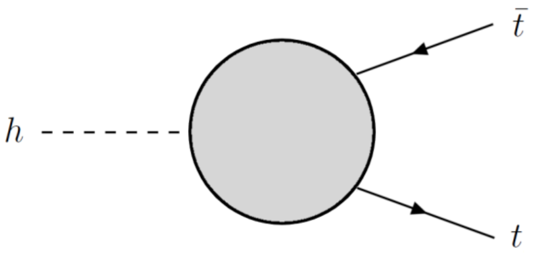
Top-philic new interactions

↓



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

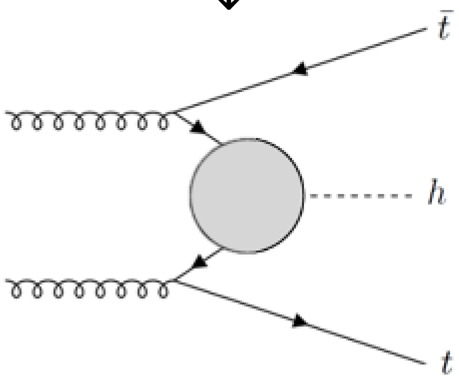
Running of the top Yukawa coupling



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

Top Yukawa at high scale

↓



$t\bar{t}h$ **differential xs**

T. Han et al
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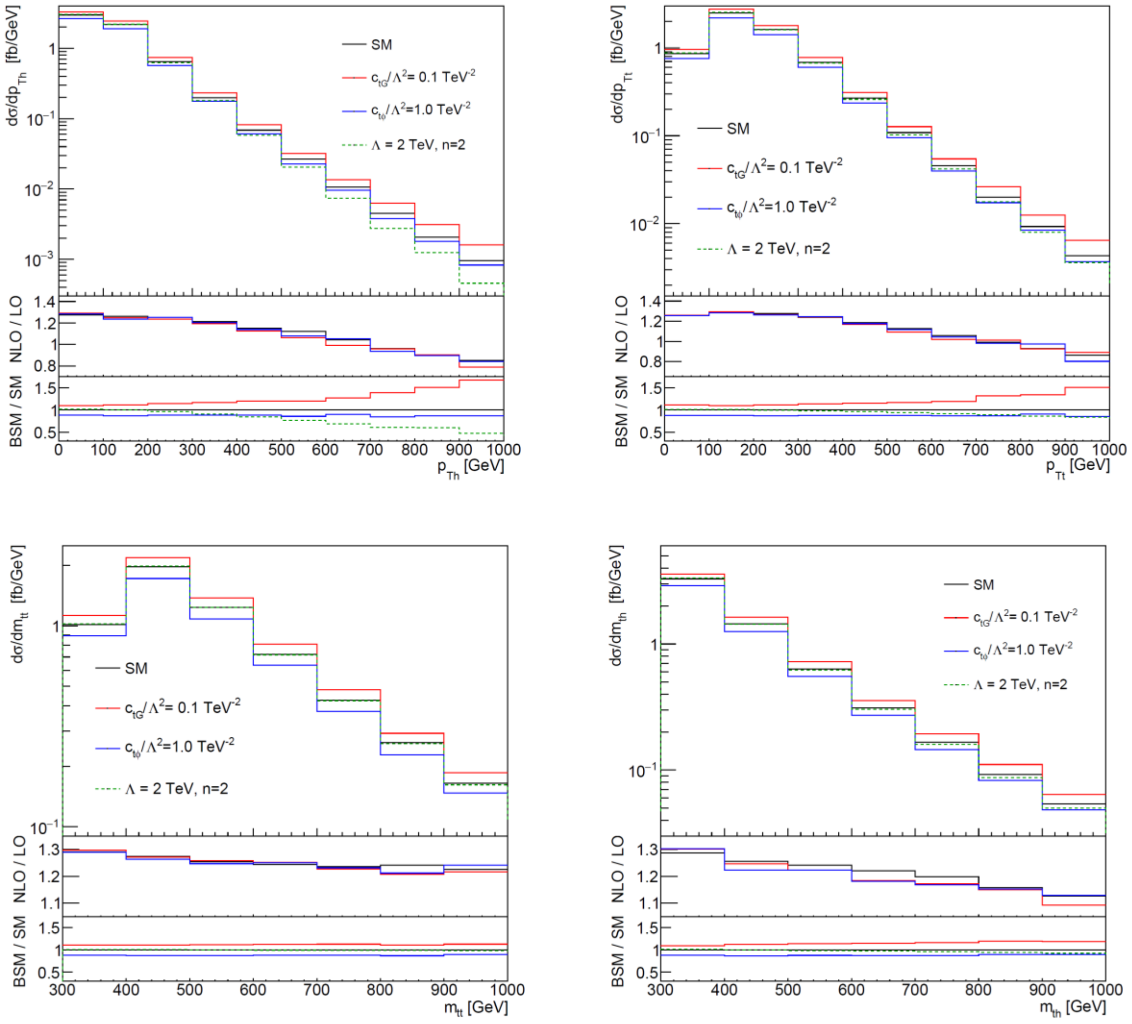
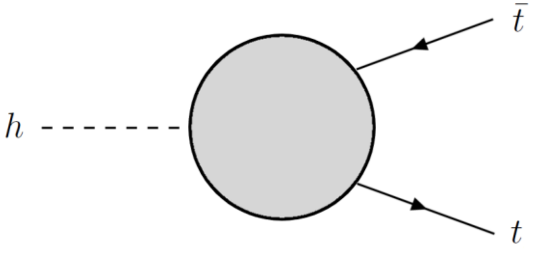
⇒



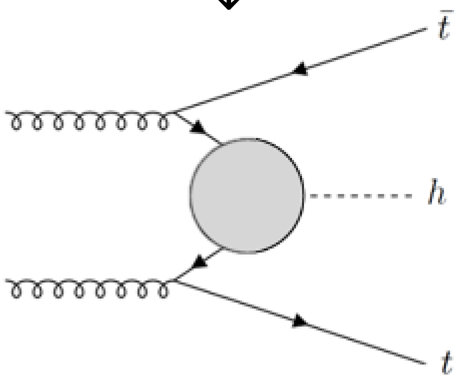
Running of the top Yukawa coupling



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

Top Yukawa at high scale

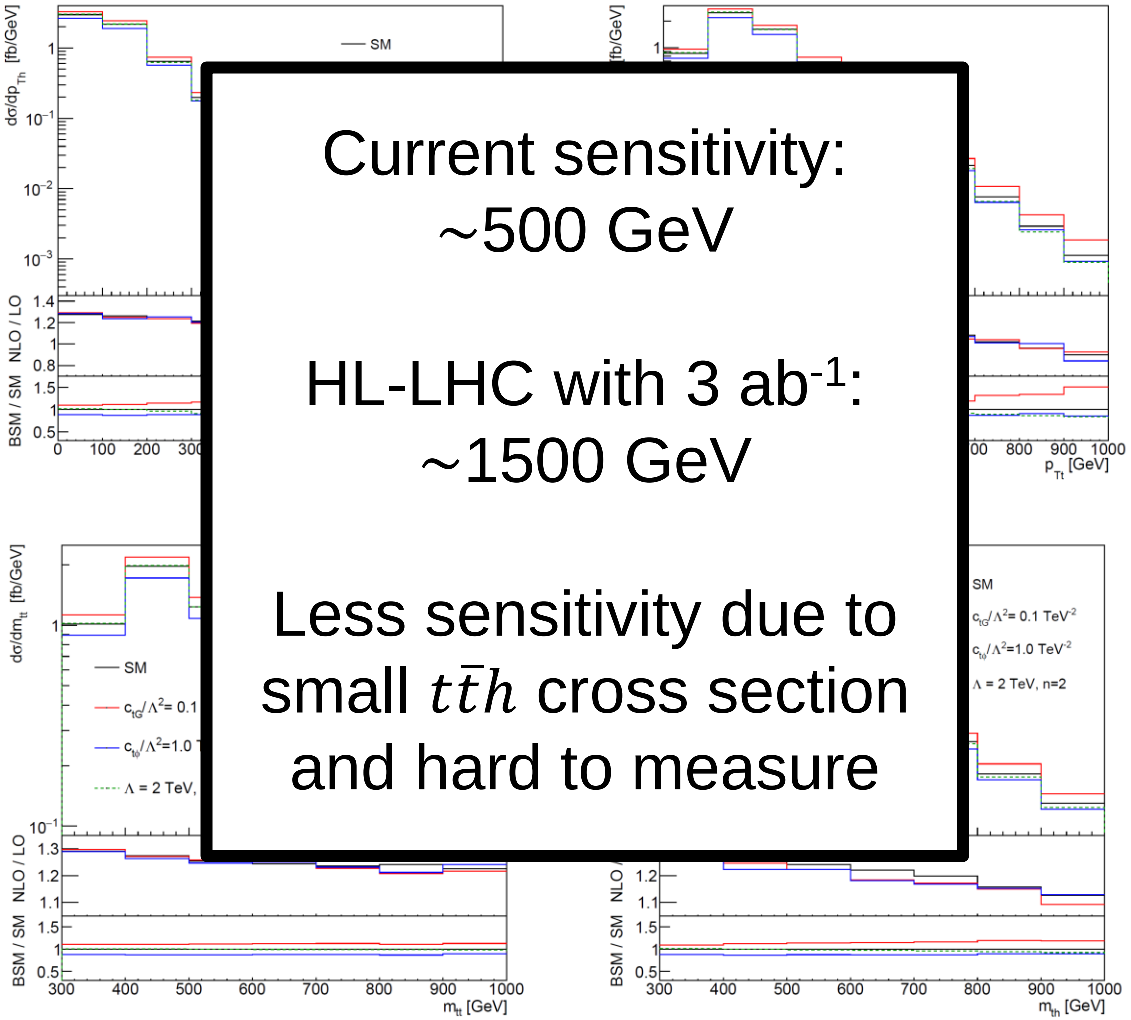
↓



$t\bar{t}h$ differential xs

T. Han et al
2106.00018

⇒



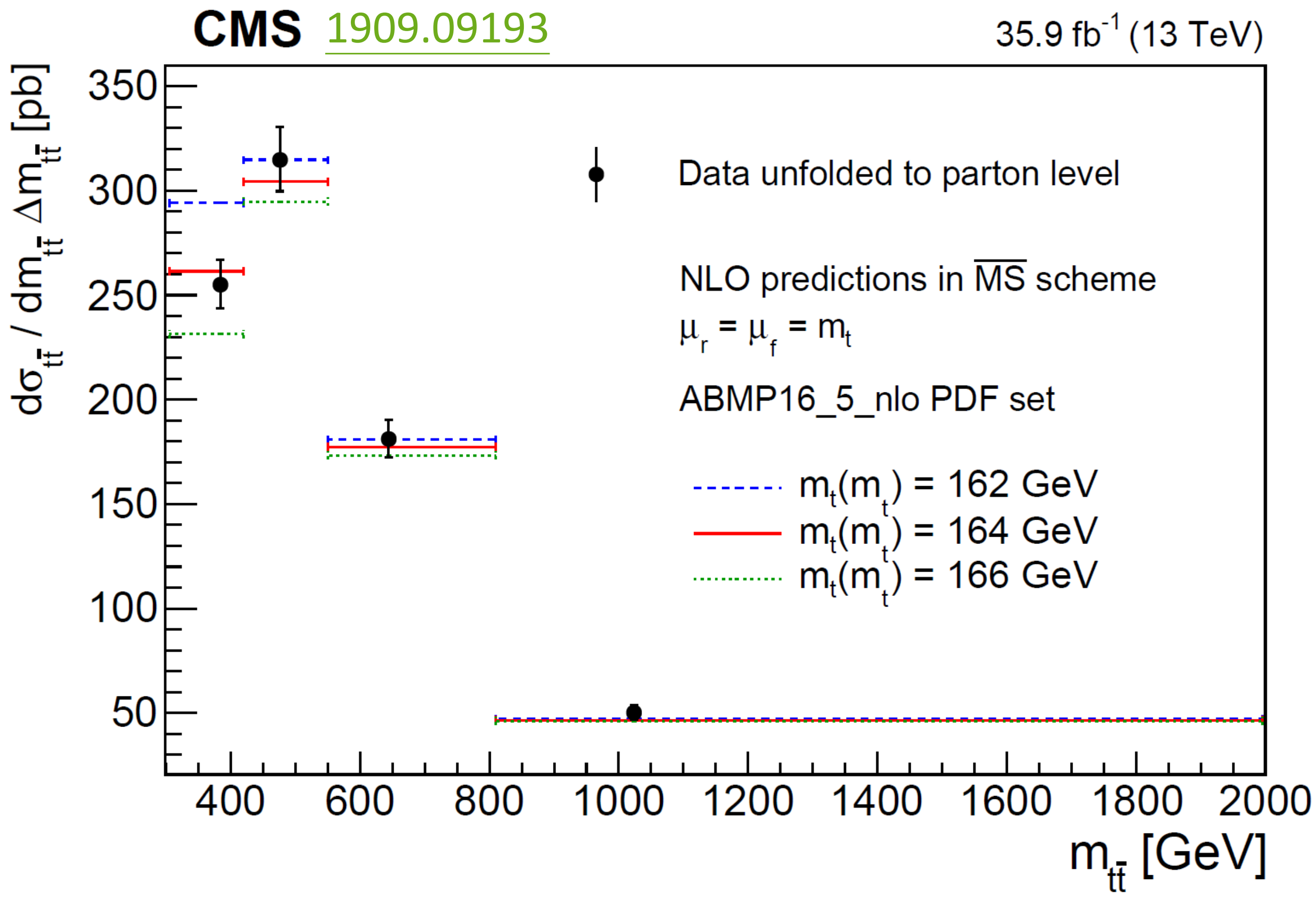
Current sensitivity:
~500 GeV

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

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

Running of the top quark mass

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

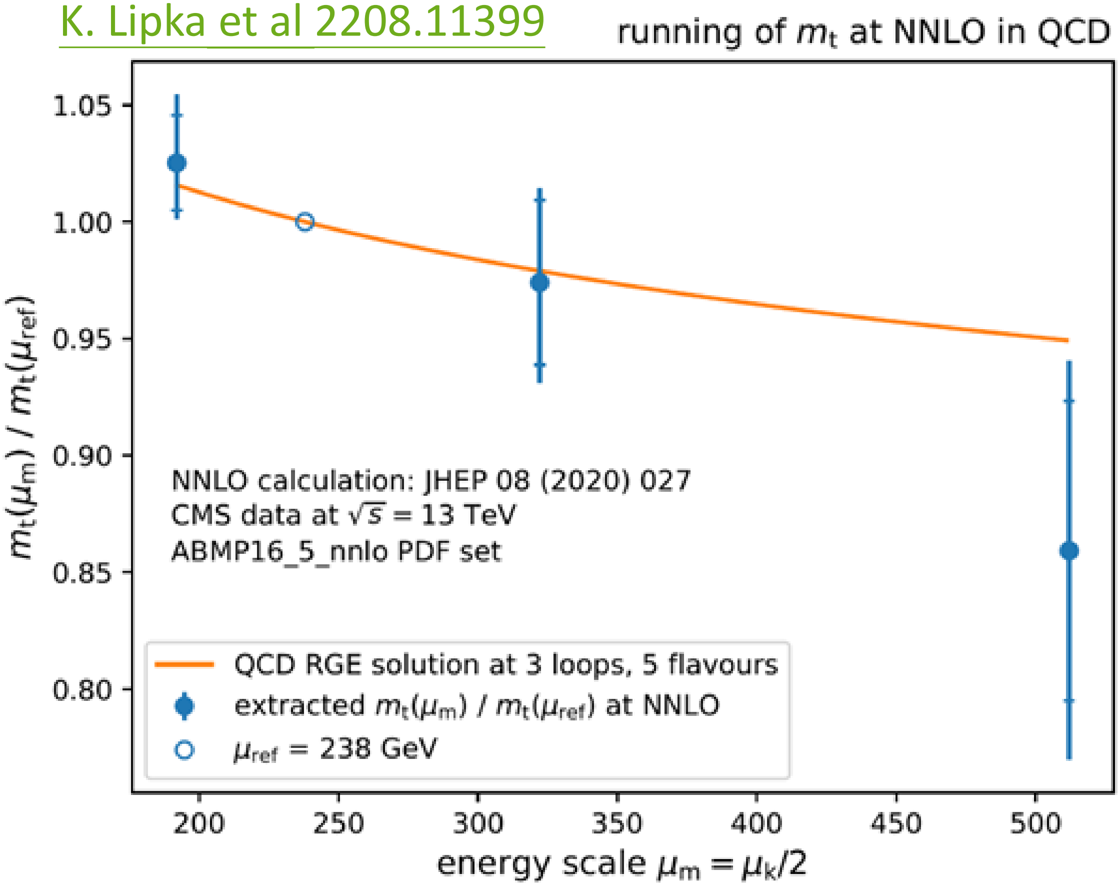


First measurement of top mass at the high scales !
(using only 2016 Run 2 data)

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

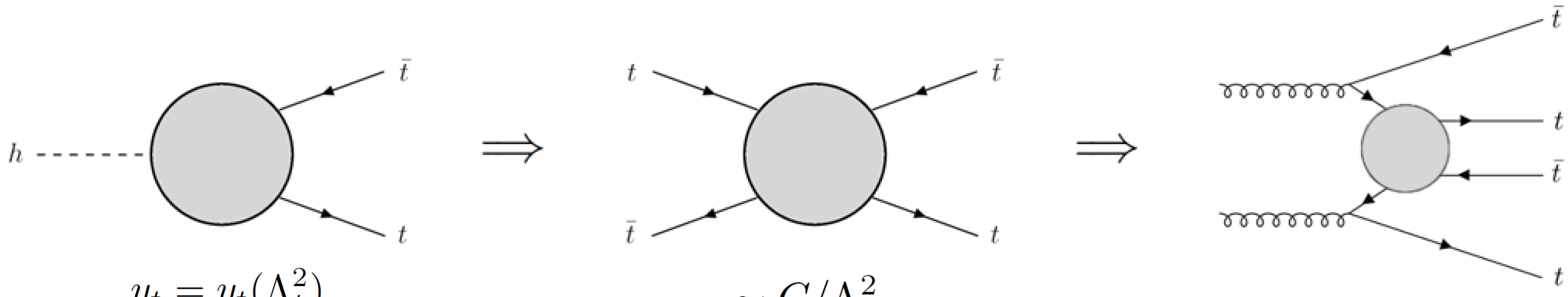
We can already put the constraint on Λ_t as

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

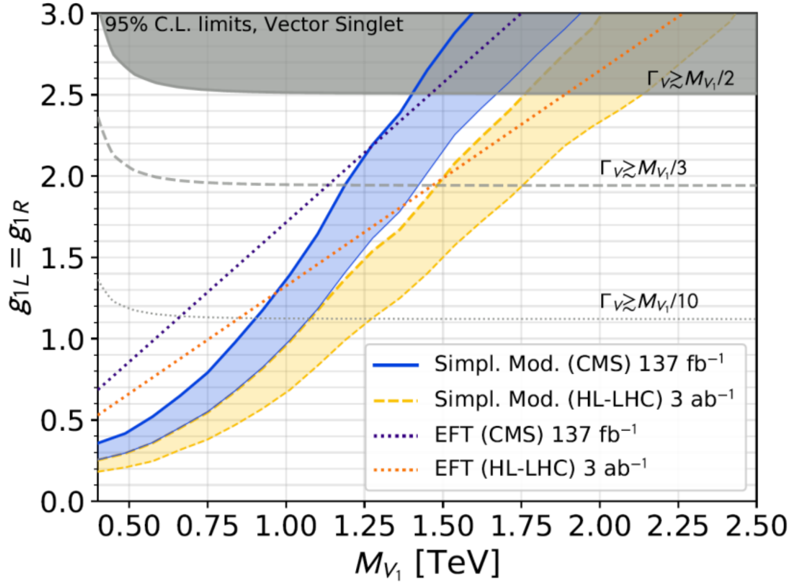
→ $\sigma_{t\bar{t}t\bar{t}} < 36\ (27)$ fb at 95% C.L.

Both are NEW! (Moriond 2023)

F. Maltoni et al 2104.09512

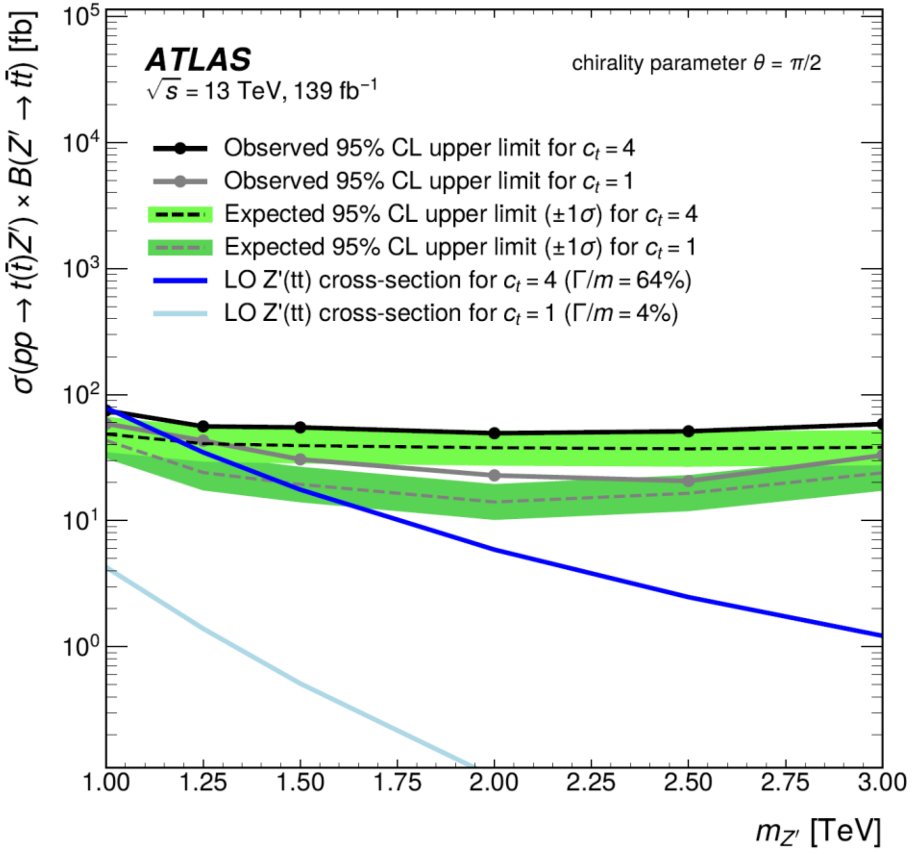
$\Rightarrow$

old analysis but based on a stronger constraint

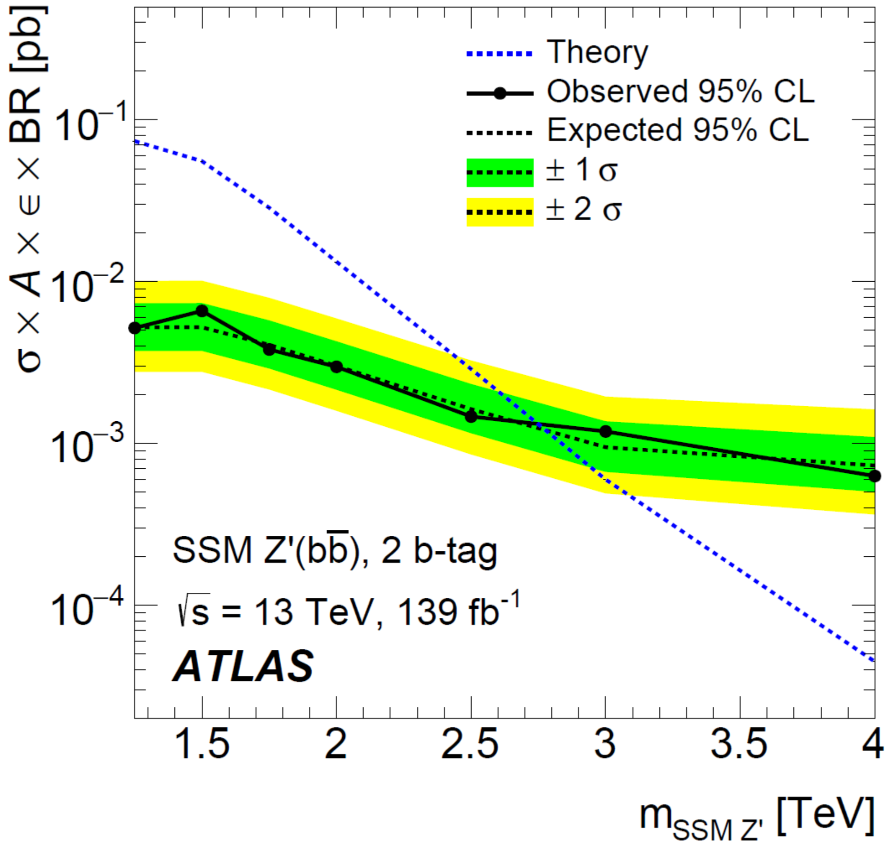


Direct searches – top-philic Z' boson

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

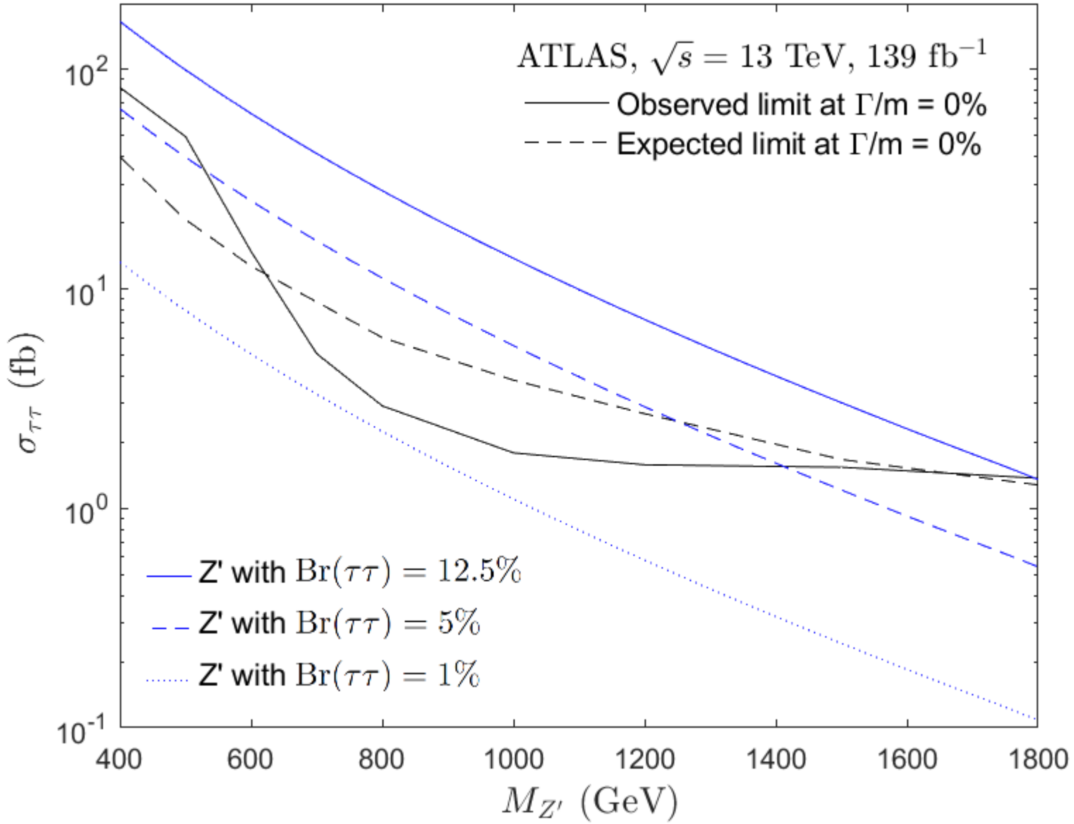


- Couple to $q_L = (t_L, b_L)$ (in bilinear case)
- Process: $b_L\bar{b}_L \to Z' \to b_L\bar{b}_L$ 1910.08447



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