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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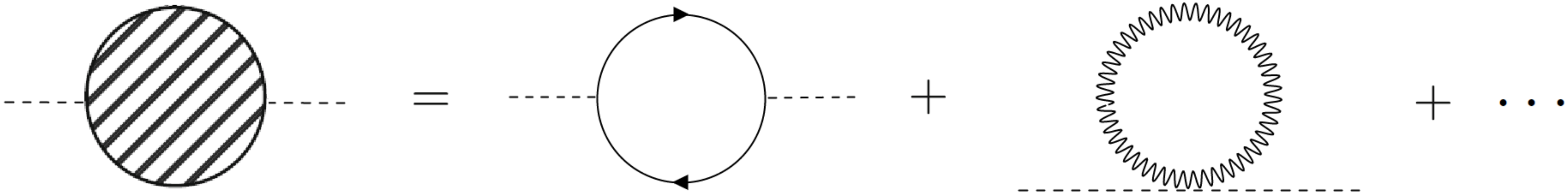
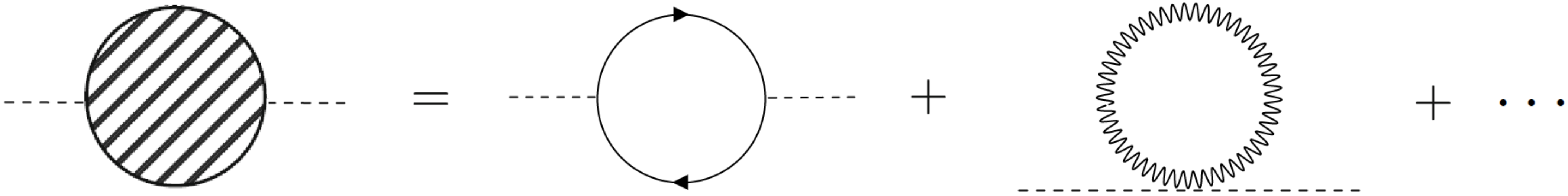
December 29th, 2022
Mini-Workshop on Highlights of 2022, NCTS

The Hierarchy Problem



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

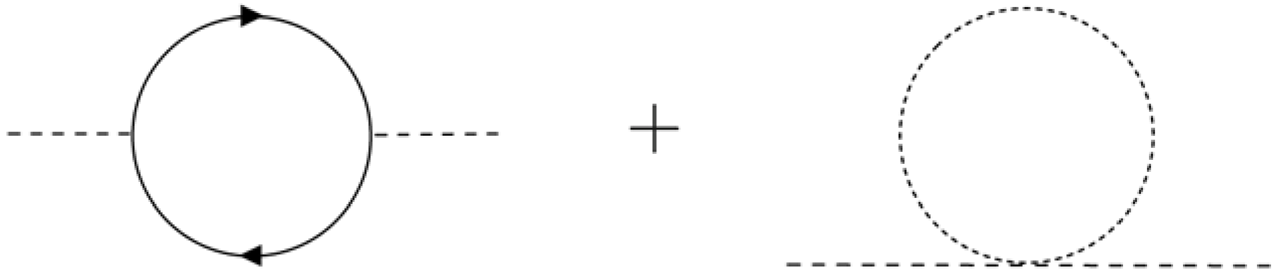
The Hierarchy Problem



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

The largest contribution!!

Top partner solutions



Top loop   Top-partner loop

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

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

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

Problems with Colored top partner

- 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)

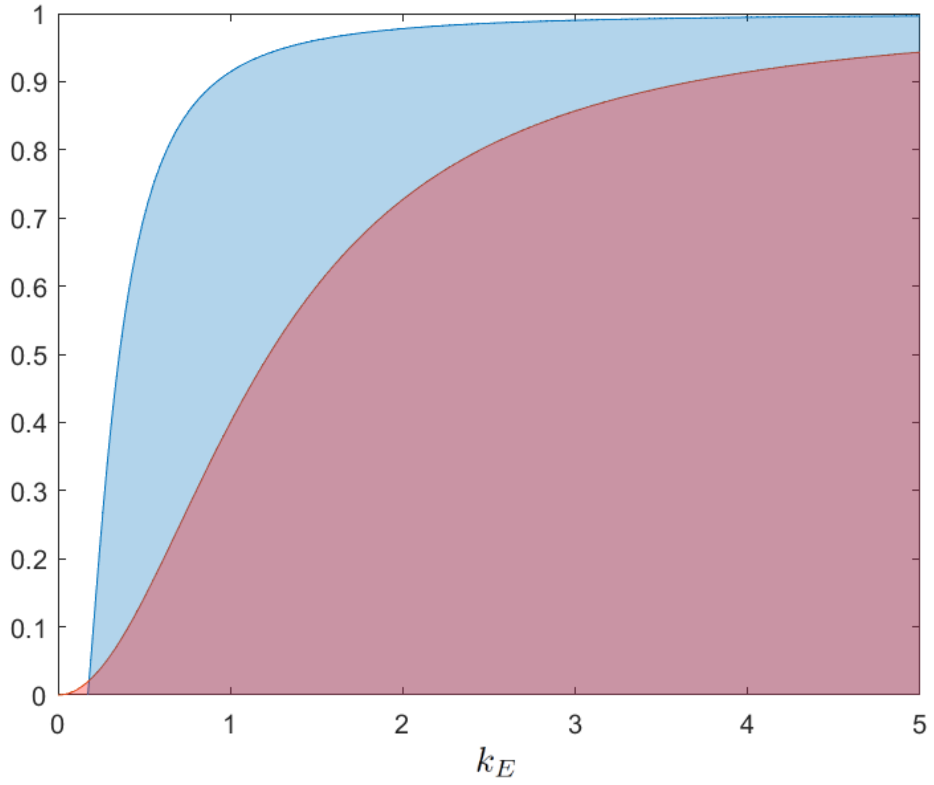
Quantum #	Scalar	Fermion
QCD x EW	SUSY	CHM / RS
Neutral x EW	Folded SUSY	Quirky Little Higgs
Neutral x Neutral	Tripled Top Hyperbolic Higgs	Twin Higgs

$\Rightarrow$ Uncolored top partners

Table borrowed from Chris Verhaaren

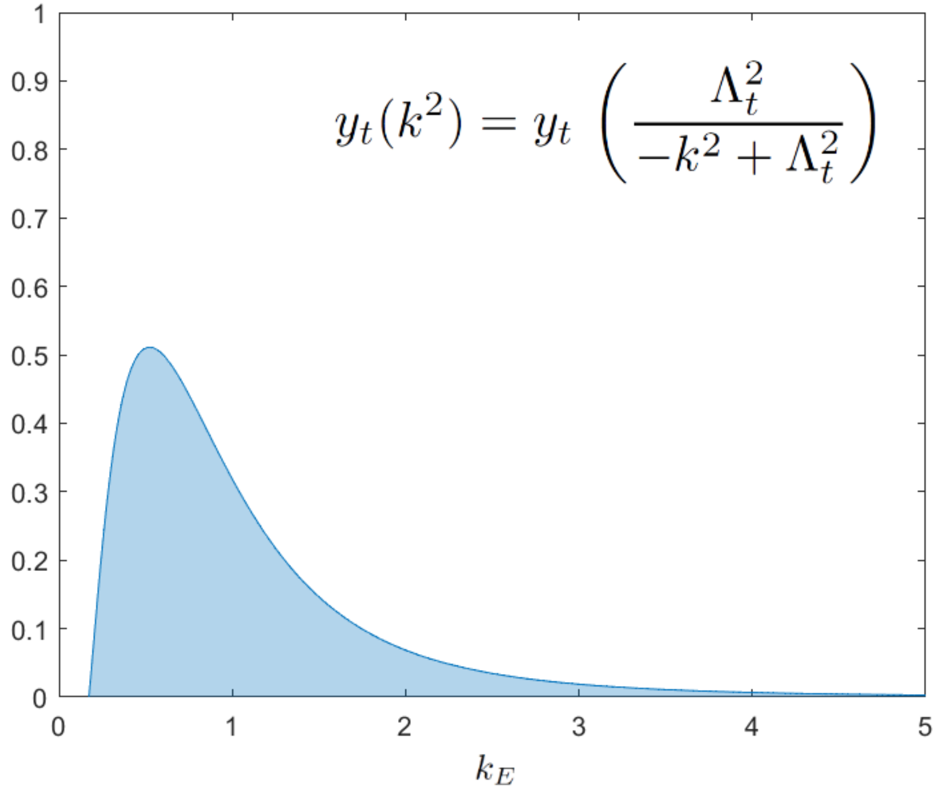
Alternative to Top-partner scenarios

- Cancellation (take $M_T = 1.2$ TeV)



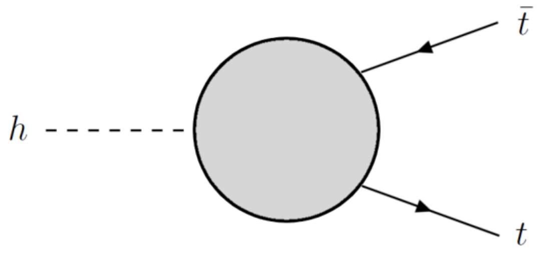
$$\delta m_h^2|_{\text{top}} + \delta m_h^2|_{\text{top partner}} \sim -\frac{3}{8\pi^2} y_t^2 M_T^2 \ln\left(\frac{\Lambda^2}{M_T^2}\right)$$

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



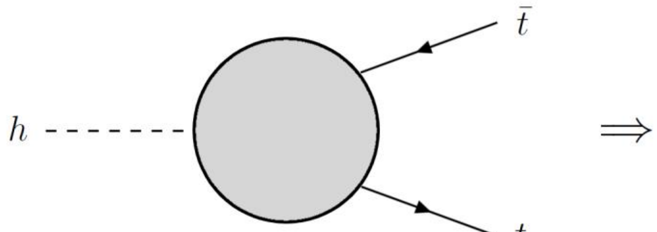
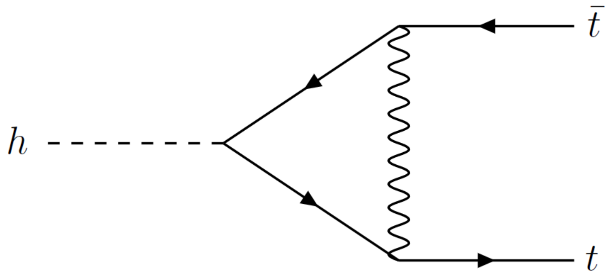
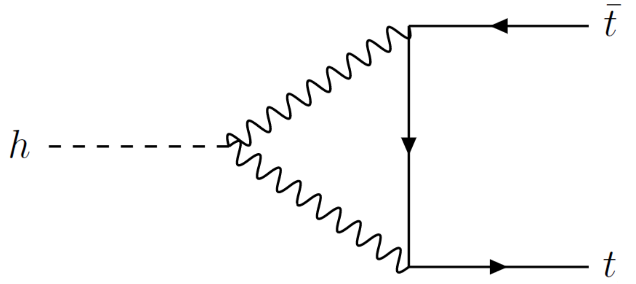
$$\delta m_h^2|_{\text{top}} \sim -i\,2N_c \int \frac{d^4k}{(2\pi)^4} y_t^2(k^2) \frac{k^2 + m_t^2}{(k^2 - m_t^2)^2} \sim -\frac{3}{8\pi^2} y_t^2 \Lambda_t^2$$

Zoom in the Top Yukawa vertex



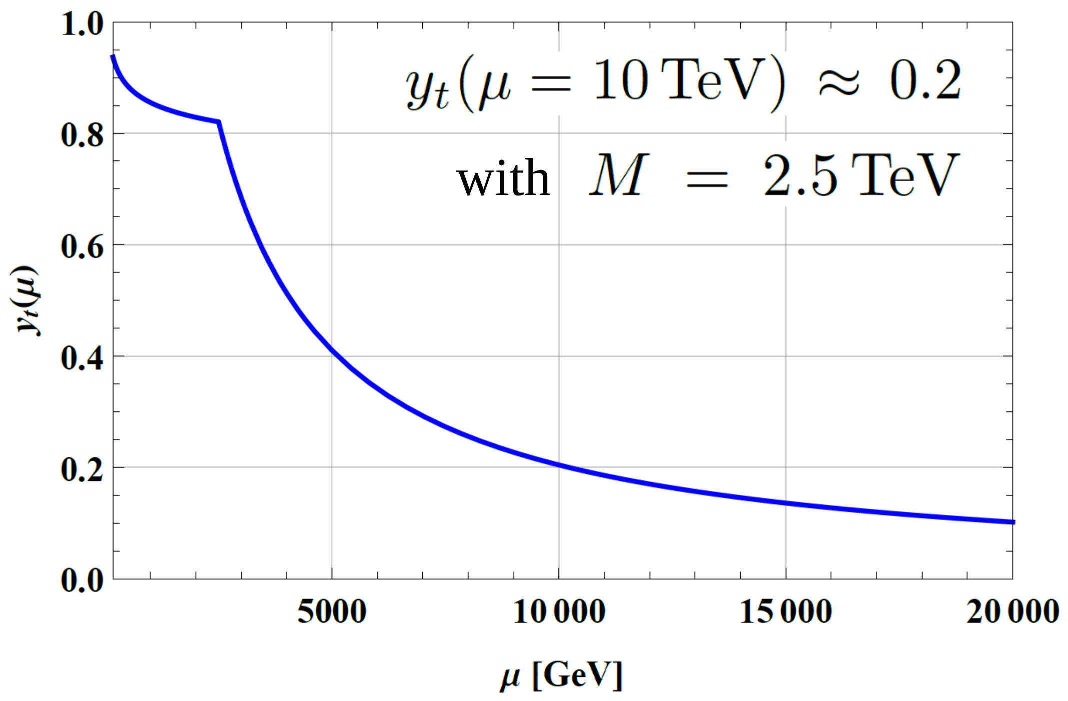
$$y_t = y_t(k^2)$$

Zoom in the Top Yukawa vertex

		
Modification	**Large y_t running**	**y_t from dim-6 op.**
New degrees of freedom	Top-philic bosons	New bosons and fermions

Large y_t running

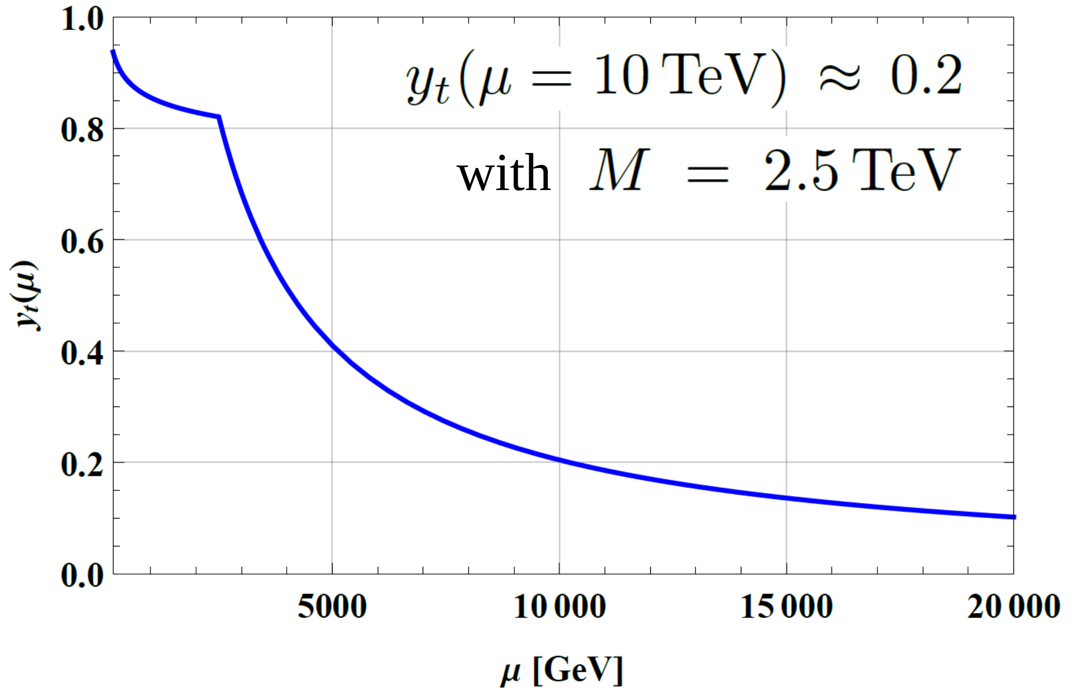
Strongly interacting top-philic boson



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

Top-loop becomes subleading with $\Lambda_{\mathrm{NP}} = 10\ \mathrm{TeV}$

Strongly interacting top-philic boson

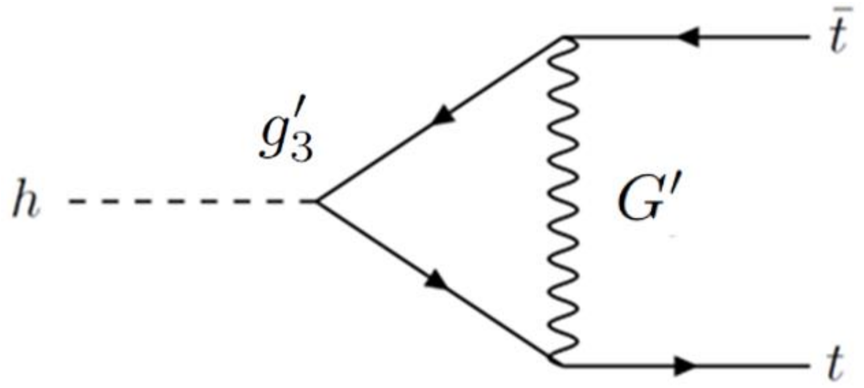


$$\frac{d\, y_t(\mu)}{d\,\ln\,\mu} = \frac{y_t(\mu)}{16\pi^2}\left(\frac{9}{2}\, y_t^2(\mu) - \frac{3(N^2-1)}{N} g_N^2\right)$$

Top-loop becomes subleading with $\Lambda_{\rm NP} = 10$ TeV

$\Longrightarrow$

Ex: Heavy gluons (Coloron)



with the $SU(3)$ coupling $g_3' \sim 4.5$

Direct consequences:

- Bound state of top-anti-top with the mass around $M = 2.5$ TeV
- Enhancement in 4t cross section!!

Four top quarks cross section

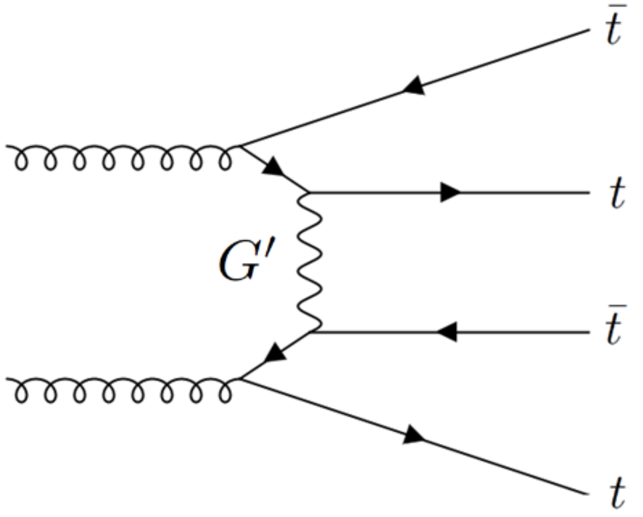
- Broad resonances (G' and H_t) with $\Gamma/M \gg 10\%$

  → hard to perform resonance search

- Inclusive measurement of rare SM processes such as 4t

  → final state with two leptons of the same electric charge

  or with more than two leptons



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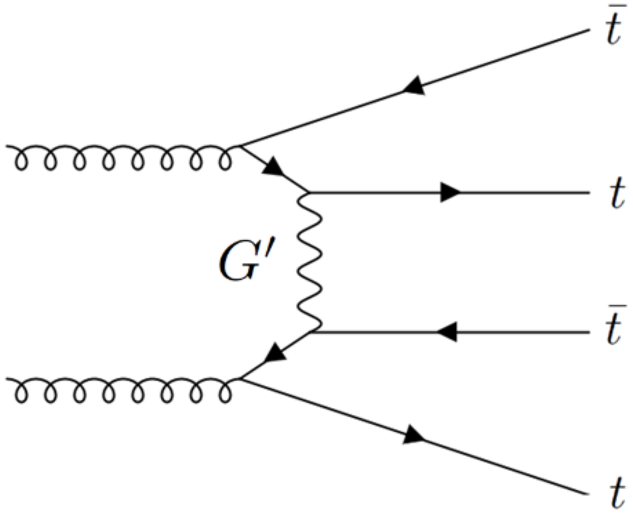


- Standard Model prediction: 12.0 ± 2.4 fb
- ATLAS with 139 fb^{-1} : 24^{+7}_{-6} fb & CMS with 137 fb^{-1} : 17^{+5}_{-5} fb

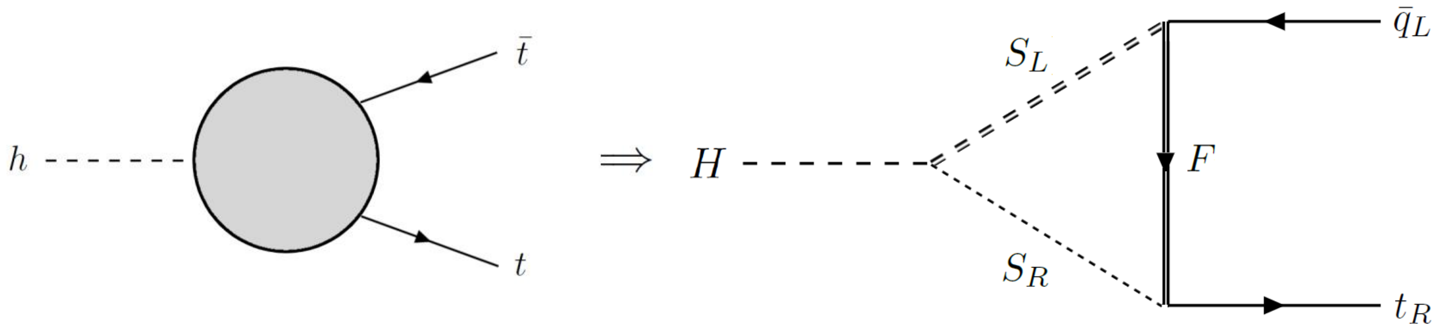
  → $\sigma_{t\bar{t}t\bar{t}} < 38\ (27)$ fb at 95% CL level from ATLAS (CMS)

- The bound can be reinterpreted as the bound on a vector color octet G'

  $\frac{g_3'}{M_{G'}} < 2.9\,(2.5)$ with $M_{G'} > 2$ TeV ⇒ **Main constraints for large top Yukawa running**

y_t from dim-6 operator

Top Yukawa arise from Dim-six operator



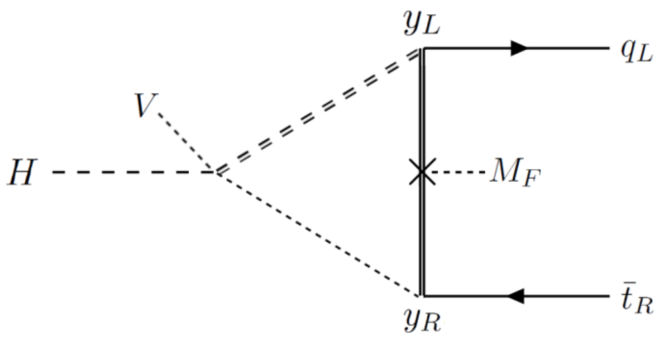
Minimal setup:

EW doublet scalar S_L

EW singlet scalar S_R

EW singlet fermion F

- The diagram introduces a dim-6 operator



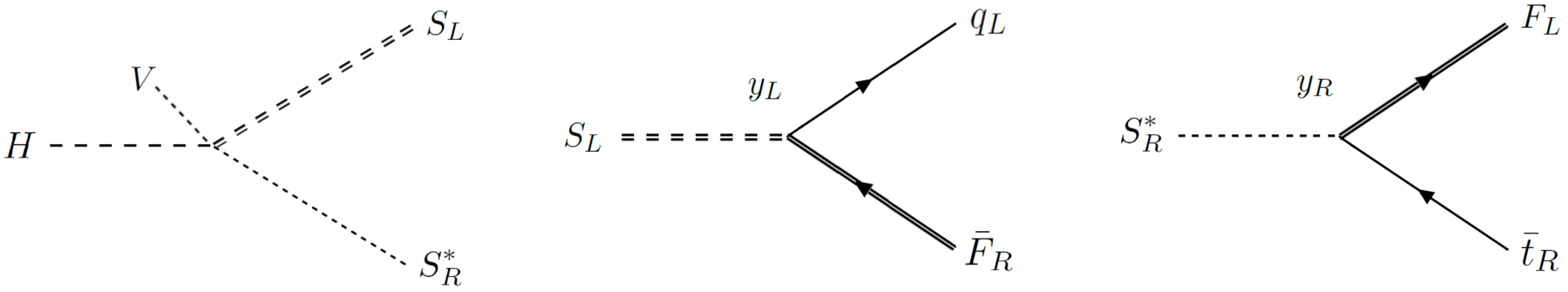
$$\sim \frac{y_L y_R}{16\pi^2}\frac{(H S_V \bar{q}_L S_F t_R)}{M^2} \Longrightarrow \boxed{\frac{y_L y_R}{16\pi^2}\frac{V M_F}{M^2}}(\bar{q}_L H t_R)$$

$$= y_t \sim 1$$

from strong dynamics!!

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

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

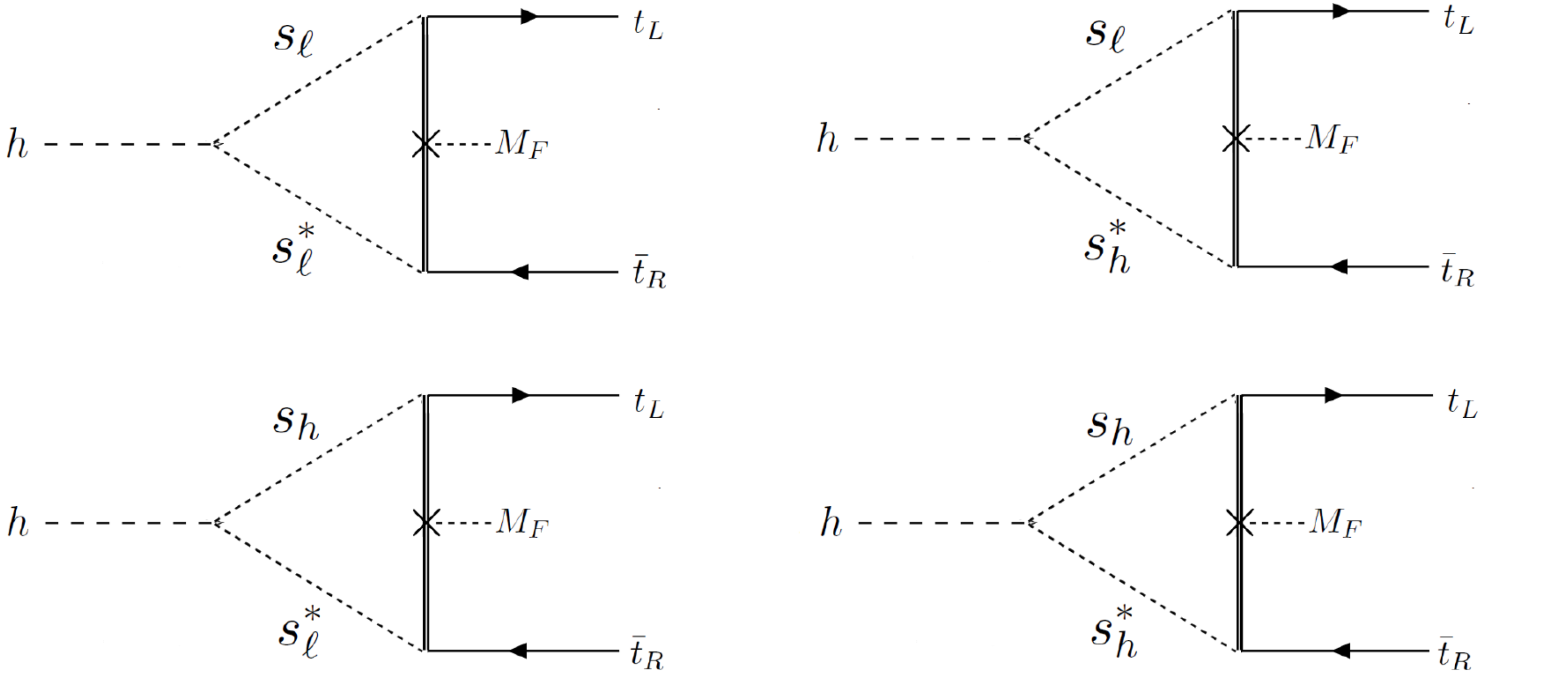
- The interaction terms also become

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

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

Generate the Top Yukawa coupling

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

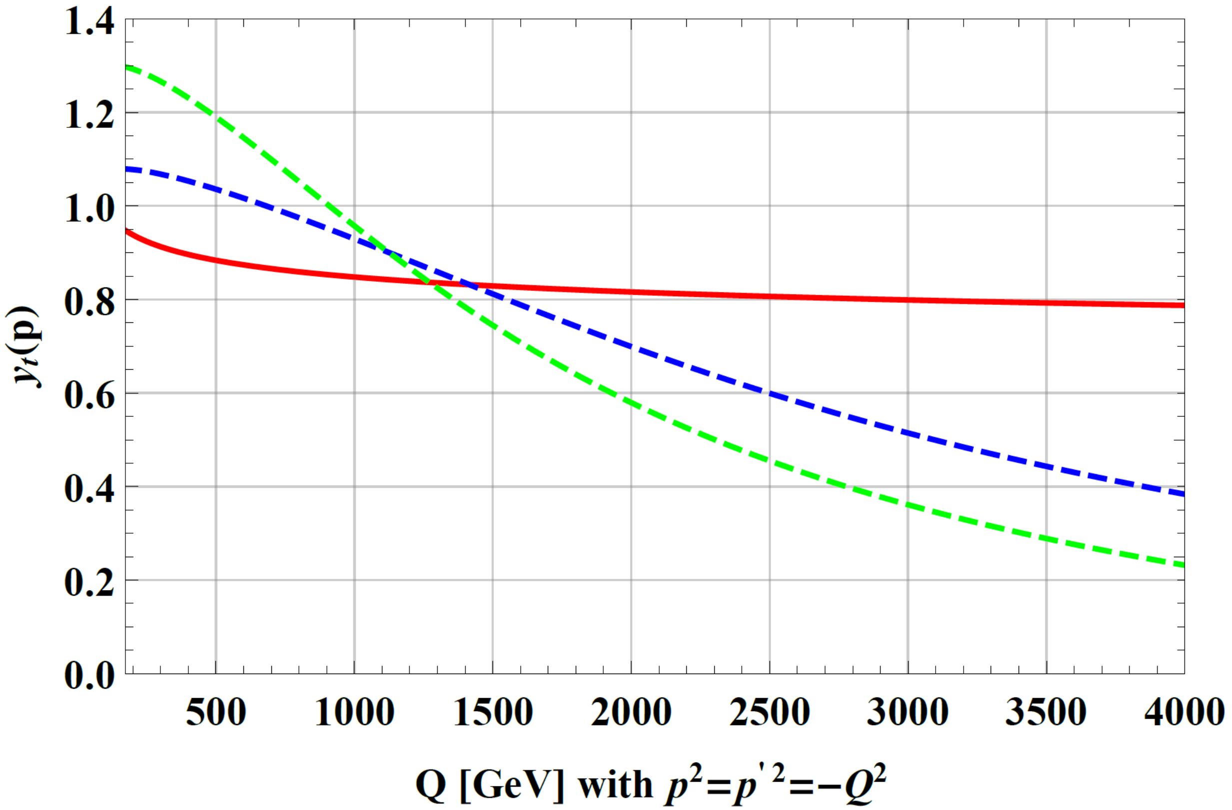


$$\Longrightarrow \quad y_t = V y_L y_R \left((c_\beta^2 - s_\beta^2)^2 \int [s_\ell, s_h, F] + 2\, c_\beta^2 s_\beta^2 \int [s_\ell, s_\ell, F] + 2\, c_\beta^2 s_\beta^2 \int [s_h, s_h, F] \right)$$

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)



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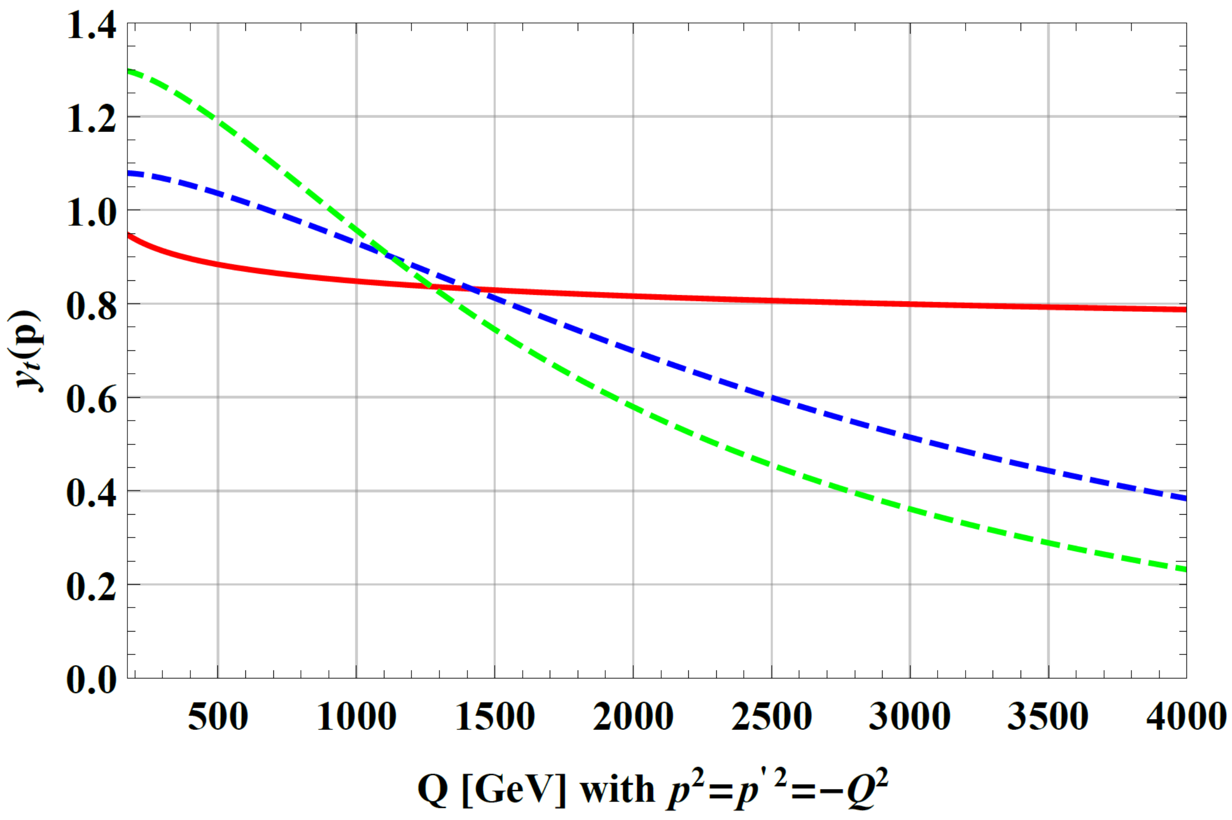


- The value of y_t is normalized according to the correct top mass
- Larger y_t due to additional diagrams with extra Higgs insertion, which lead to

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

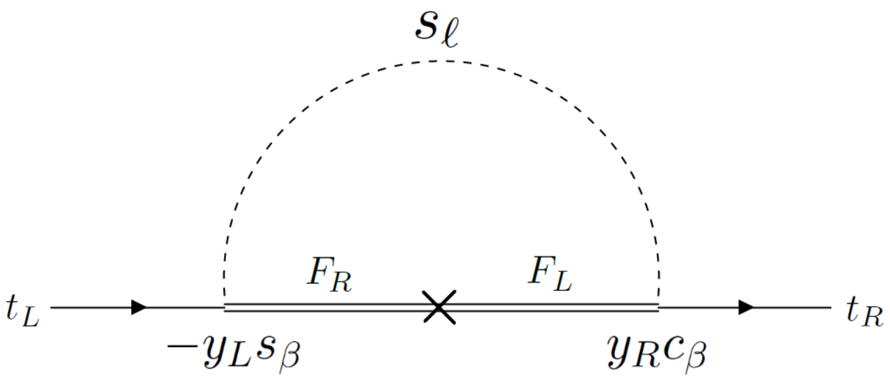
- Main Constraint: top Yukawa measurement

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

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

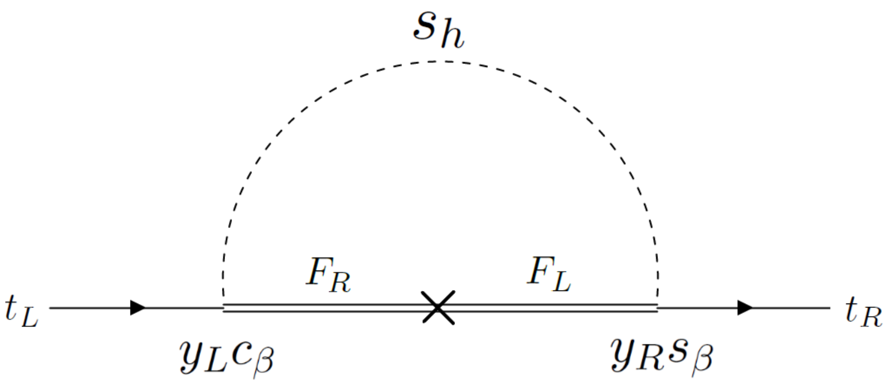
Running of the top quark mass

- The top quark mass is generated through



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

$+$

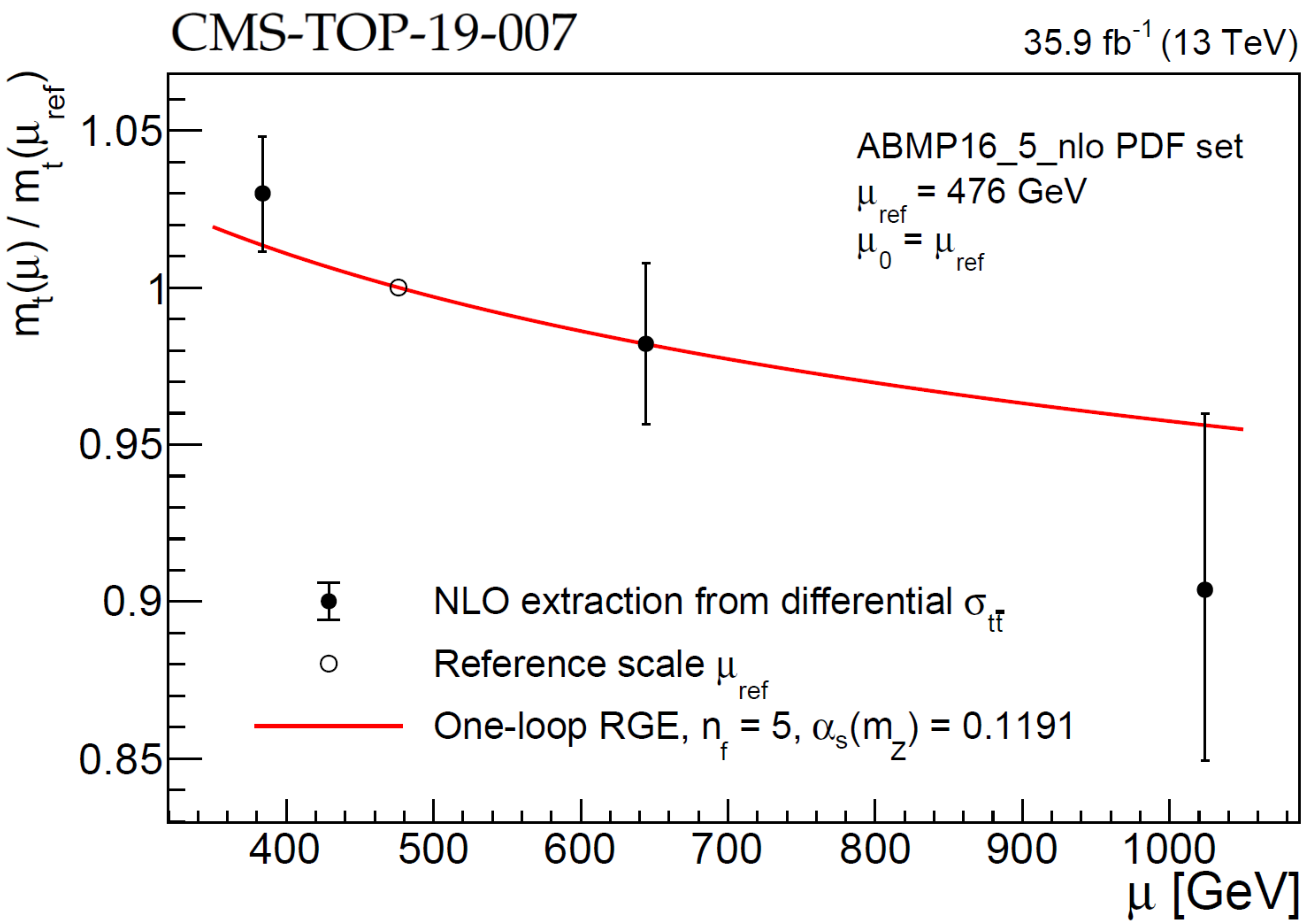


$$y_L y_R c_\beta s_\beta \int [s_h, F]$$

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

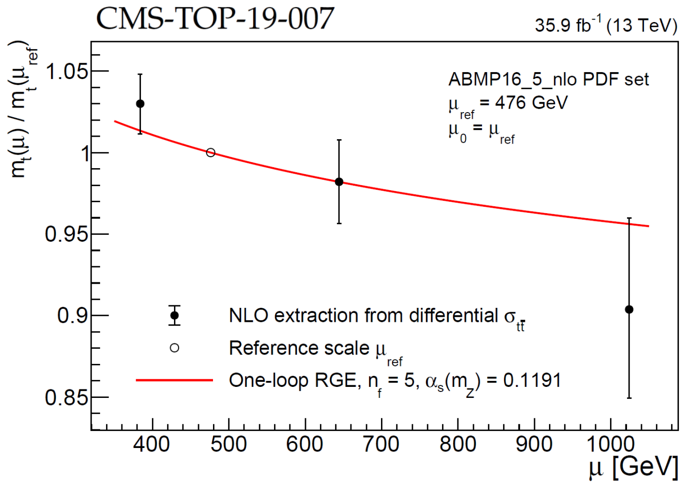
  $\rightarrow$ Nontrivial running m_t at the high scale which will affect the $t\bar{t}$ cross section

Running of the top quark mass

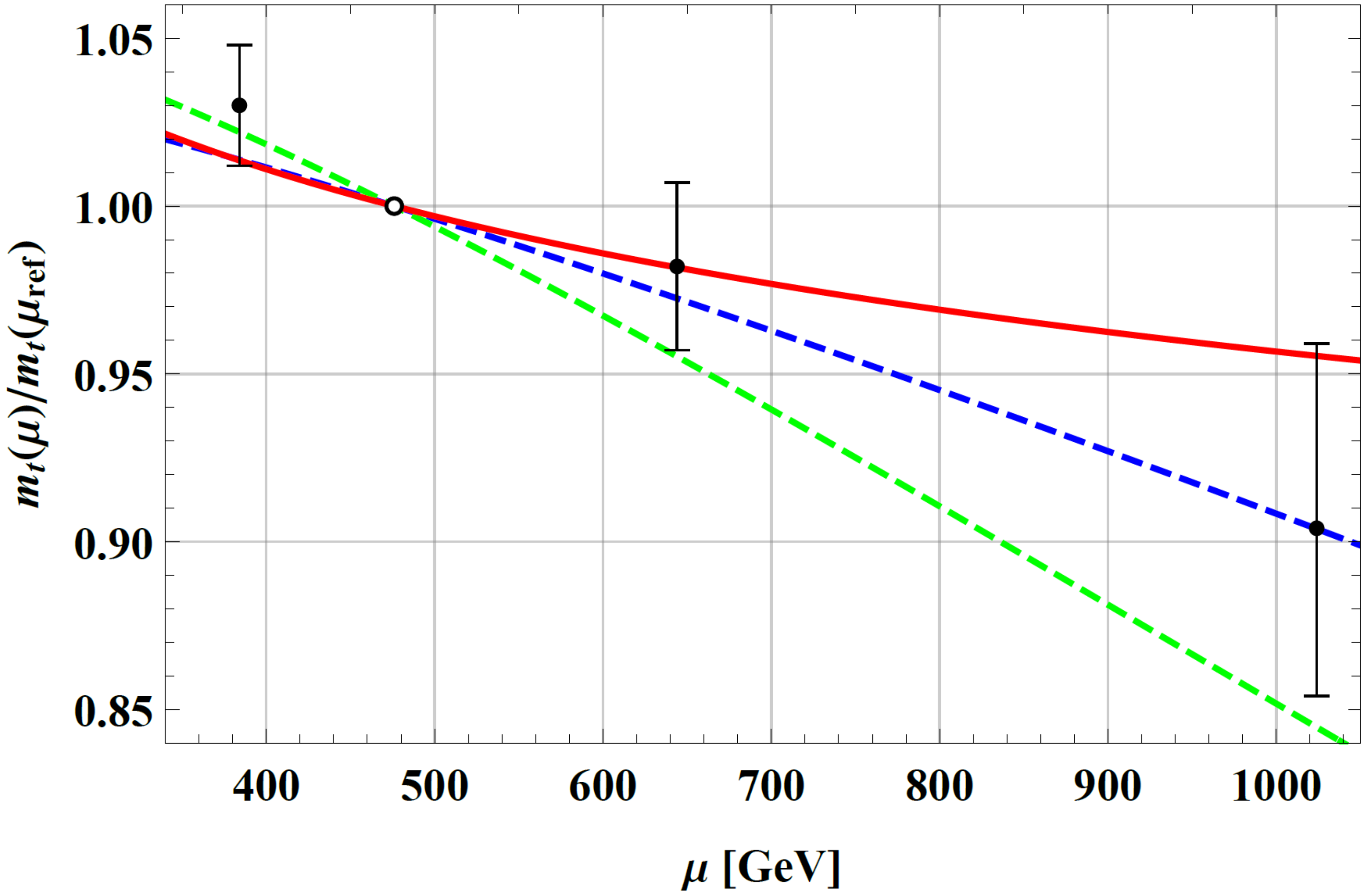


The first measurement from CMS !!

Running of the top quark mass



$\Longrightarrow$



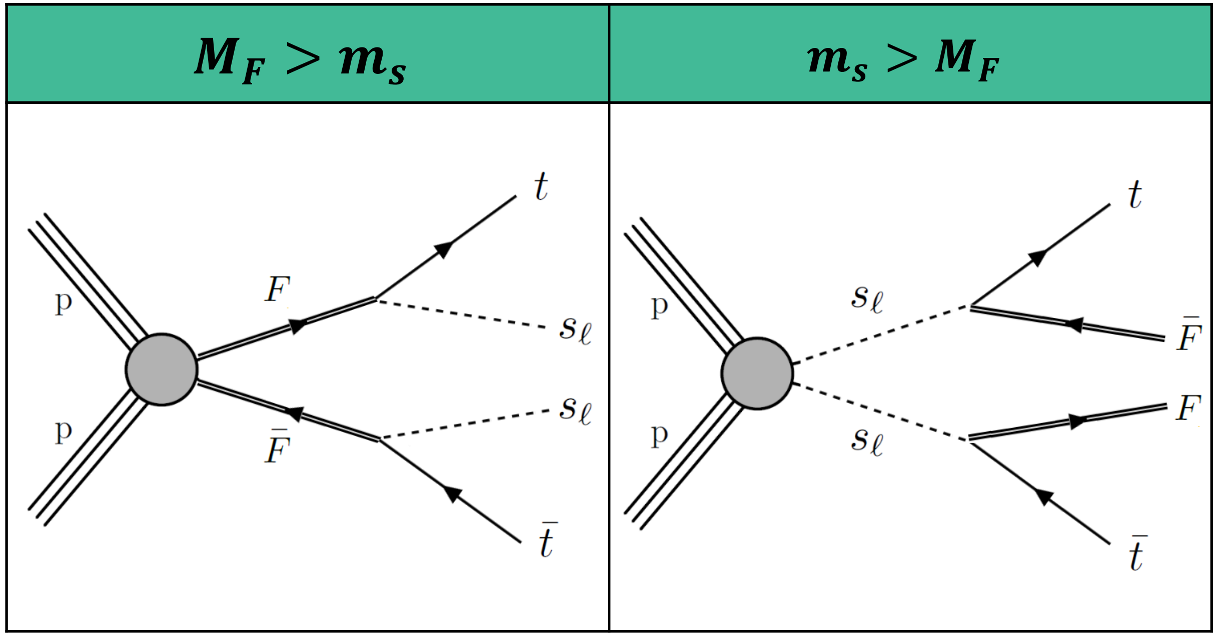
Direct test of the idea!!

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.

Conclusion

- Top quark is the most important part of the hierarchy problem
- 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 Λ_t : **Top partner** → **New d.o.f.** related to the top quark

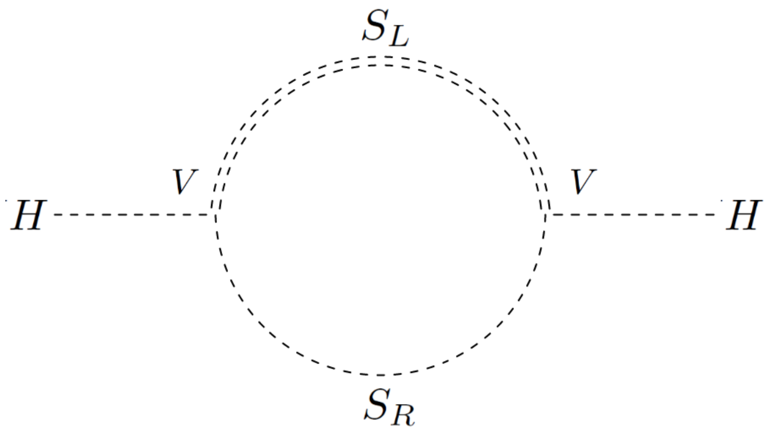
- Features of the alternative scenario (y_t from dim-6 operator)
- **New bosons and VL fermions** accompanied with **strong interaction** are required
- Direct impact on the **top Yukawa coupling** and **running of the top quark mass**
- **Diverse phenomenology** to be explored (new methods for broad resonances required)
- Even more diverse taking (1) scalar bosons → vector bosons (2) singlet → multiplet

Warning: It can NOT solve the hierarchy problem on its own but assist existing models.

Back up

Additional contribution

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

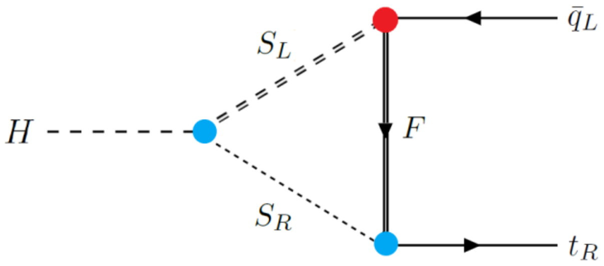


$$\Longrightarrow \quad \Delta m_H^2|_{\text{scalar}} \sim \frac{1}{16\pi^2} V^2 \ln\left(\frac{\Lambda_{\text{NP}}^2}{M^2}\right)$$

- ➢ 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.

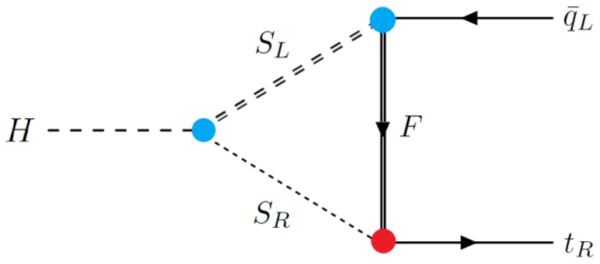
Top Yukawa from strong dynamics

- 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



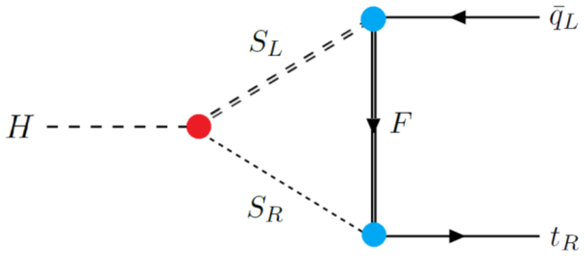
Strong sec. S_L, S_R, F H, t_R

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

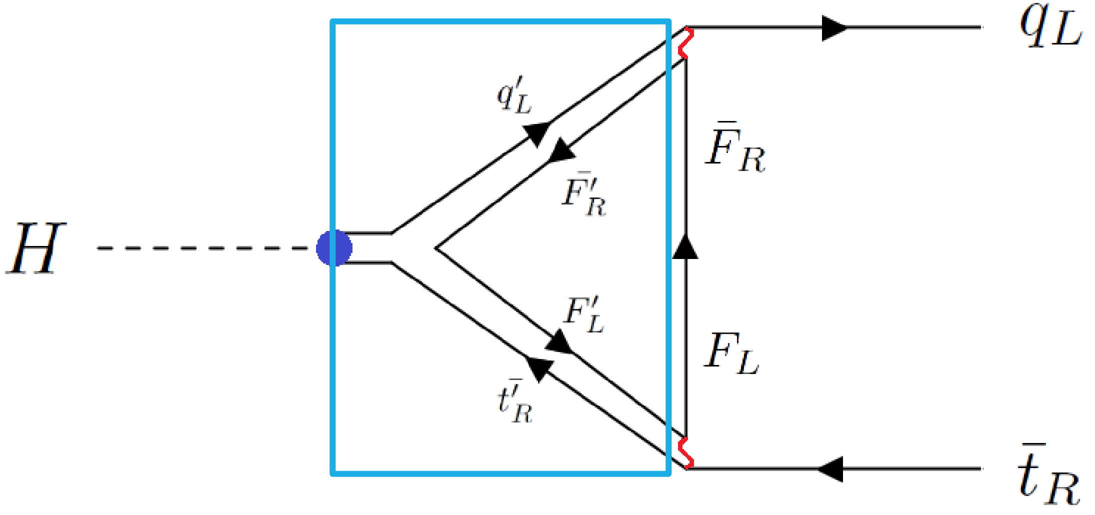
Weak sector:

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

Strong sector:

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

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



$\Longrightarrow$

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

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

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