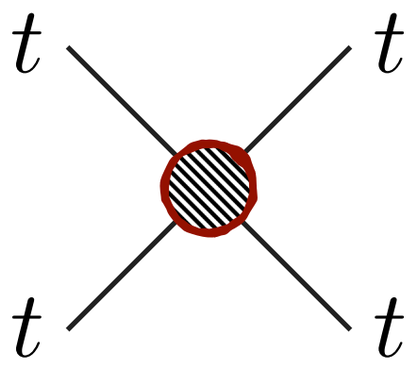
The Present and Future of 4-Tops



HIGGS AND EFFECTIVE FIELD THEORY 2021

Javi Serra

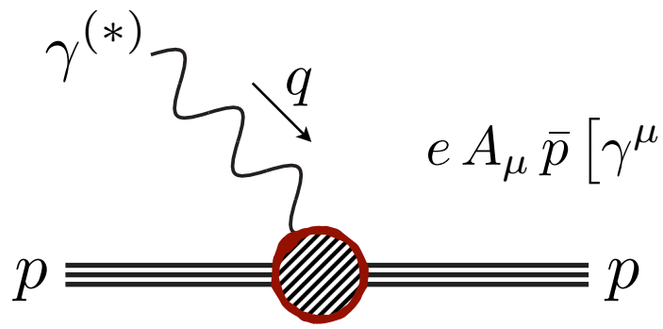
Technische Universität München

arXiv:2010.05915

w/ G. Banelli, E. Salvioni, T. Theil and A. Weiler

Strongly-interacting, a.k.a. composite, top quark

Since its discovery (CDF, D0 '95) we know the top is not a composite like e.g. the proton.



$$e\,A_\mu\,\bar{p}\left[\gamma^\mu F_1(q^2) + i\,\sigma^{\mu\nu} q_\nu F_2(q^2)\right] p$$

$$F_1(q^2 \simeq -m_p^2) - 1 = O(1)$$

↓

Compositeness scale of order of the particle's mass.

$$m_* \sim m_p$$

chiral Top effective compositeness

$$t_R \to e^{i\alpha} t_R$$
$$q_L \to e^{-i\alpha} q_L$$

$$m_t \ll m_*$$

Effective Field Theory (EFT) approach best suited to describe top compositeness.

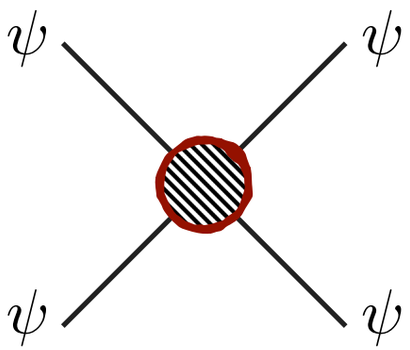
(Georgi et al. '94)

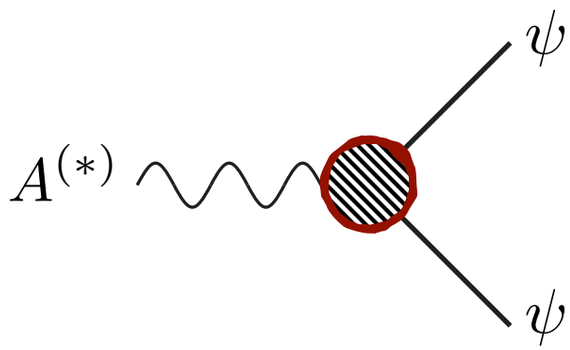
$$\psi = t_R,\, q_L$$

$$\frac{c_{\psi\psi}}{m_*^2}\,(\bar{\psi}\gamma_\mu\psi)^2$$

$$\frac{c_{\psi D}}{m_*^2}\,\bar{\psi} D_\mu^3 \gamma^\mu \psi$$

$$D_\mu^3 \sim D^2 D_\mu,\, D_\nu D_\mu D^\nu,\, g F_{\mu\nu} D^\nu$$





Two distinct types of non-standard effects.

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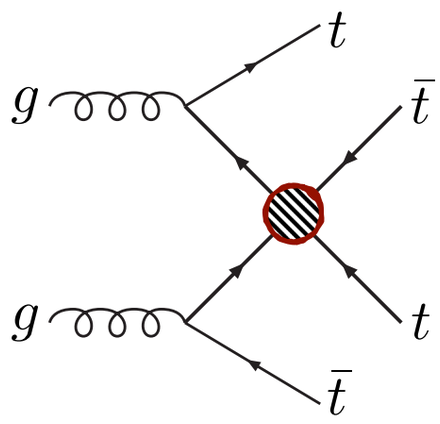
$$\frac{c_{\psi D}}{m_*^2}\,\bar{\psi} D_\mu^3 \gamma^\mu \psi$$

Most genuine consequence of top compositeness: strong 4-top scattering.

(Pomarol, JS '08)

$$c_{\psi\psi} \sim g_*^2$$



$$\mathcal{M}_{\psi\psi} \sim \frac{g_*^2}{m_*^2}\, s$$

Enhanced in strongly-coupled theories $g_* \gg 1$; energy growing effects.

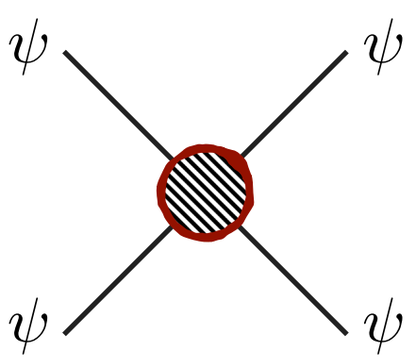
Goldstino effective compositeness

(Liu, Pomarol, Rattazzi, Riva '16)

$$\psi \to \psi + \xi + i(\psi^\dagger \bar{\sigma} \xi - \xi^\dagger \bar{\sigma} \psi)\partial\psi$$

$$m_\psi \ll m_*$$

$$\frac{\hat{c}_{\psi\psi}}{m_*^4}\,(\partial_\nu \bar{\psi}\gamma^\mu\psi)(\bar{\psi}\gamma_\mu\partial^\nu\psi)$$



$$\hat{\mathcal{M}}_{\psi\psi} \sim \frac{\hat{c}_{\psi\psi}}{m_*^4} s^2$$

Coefficients theoretically constrained by unitarity, locality and causality of UV completion.

(Bellazzini, Riva, JS, Sgarlata '17)

$$\hat{c}_{\psi\psi} > 0$$

chiral Top effective compositeness

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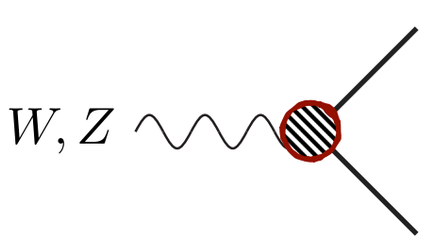
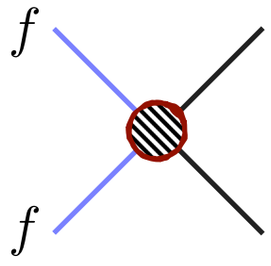
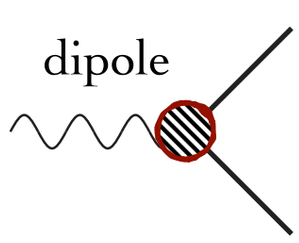
$$\boxed{\frac{c_{\psi D}}{m_*^2}\,\bar{\psi} D_\mu^3 \gamma^\mu \psi} \qquad c_{\psi D} \sim 1$$

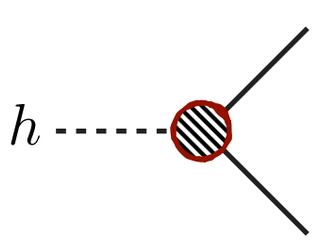
In physical processes, always involve other SM particles (equations of motion).

$g^2 (H^\dagger D_\mu H)(\bar{\psi}\gamma^\mu\psi)$ $\quad$ $g^2 (\bar{f}\gamma_\mu f)(\bar{\psi}\gamma^\mu\psi)$ $\quad$ $g y_t\, \bar{q}_L H \sigma_{\mu\nu} F^{\mu\nu} t_R$ $\quad$ $y_t \lambda_H\, |H|^2 \bar{q}_L H t_R$









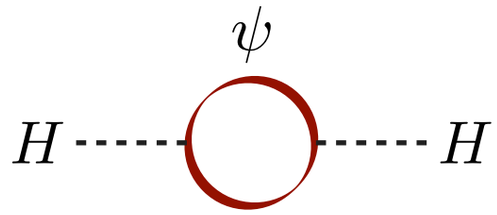
Not enhanced at strong coupling; other fields complicate top-compositeness interpretation.

Why/Where top compositeness

- Search for inner structure of particles currently viewed as fundamental.
- Part of solution to the flavor puzzle of the Standard Model.
- …

However, none of these single out per se the top quark nor TeV energies.

☑ Origin of the electroweak scale and the electroweak hierarchy problem.



$$m_H^2 \sim y_\psi^2 m_*^2$$

Large Yukawa indicates top quark plays key role in theories explaining EWSB.

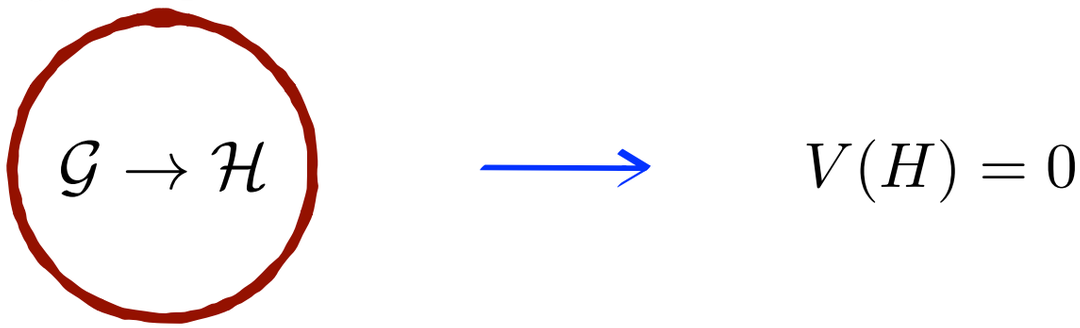
Composite pseudo-Goldstone Higgs

New strong dynamics gives rise to the Higgs field from global symmetry breaking.

(Kaplan, Georgi '83)

$$H \to H + \Theta$$

strongly-coupled sector



Provides rationale why Higgs is lighter than compositeness scale.

$$m_H \ll m_*$$

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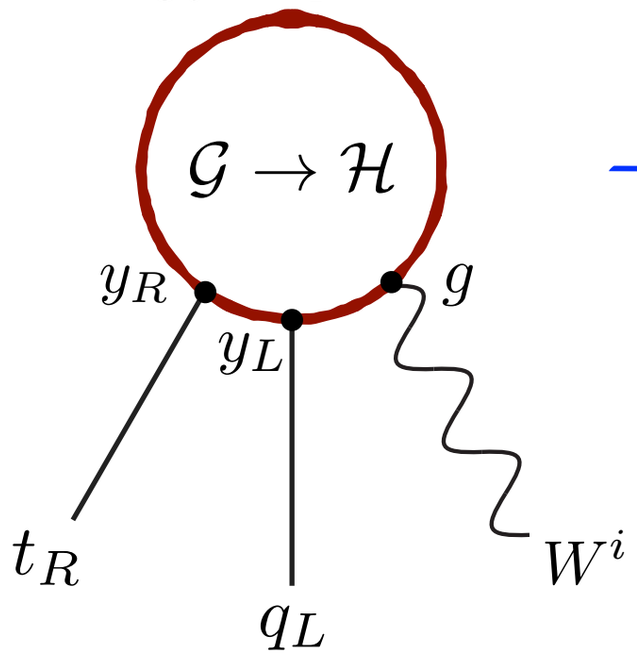

$$V(H) = m_H^2 |H|^2 + \lambda_H |H|^4 \neq 0$$

$$m_H^2 \sim \frac{m_*^2}{16\pi^2}\left(-y_t^2 + g^2\right) < 0$$

The top quark is crucial to break the electroweak symmetry.

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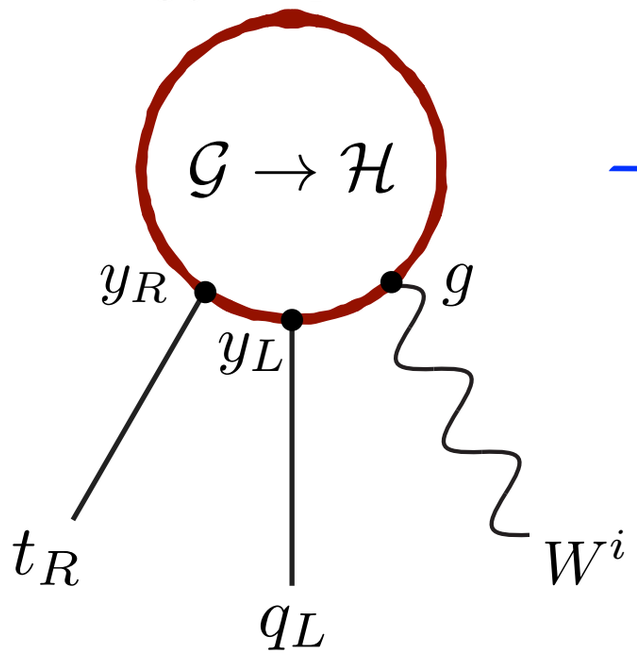

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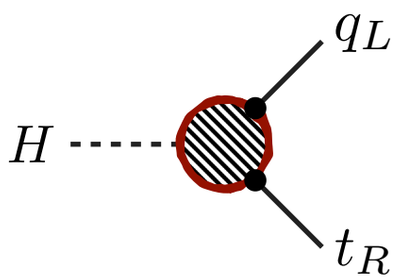
The large top Yukawa requires a large degree of top compositeness.



$$y_t \sim \frac{y_L y_R}{g_*} \sim 1$$

Top and Higgs compositeness

Let us consider* limit of **maximally strongly-coupled right-handed top**: $y_R \to g_*$, $y_L \to y_t$

- *4*-top contact int.: $\frac{g_*^2}{m_*^2}(\bar{t}_R\gamma_\mu t_R)^2 \xrightarrow{\text{LHC}} \frac{m_*}{g_*} \gtrsim 0.7\,\text{TeV}$
- *Ztt* coupling: $\frac{g_*^2}{m_*^2}(H^\dagger D_\mu H)(\bar{t}_R\gamma^\mu t_R) \xrightarrow{\text{LHC}} \frac{\delta g_t}{g_t} \lesssim 0.1$
- *htt* coupling: $\frac{y_t g_*^2}{m_*^2}|H|^2\bar{q}_L H t_R \xrightarrow{\text{LHC}} \frac{\delta y_t}{y_t} \lesssim 0.3$

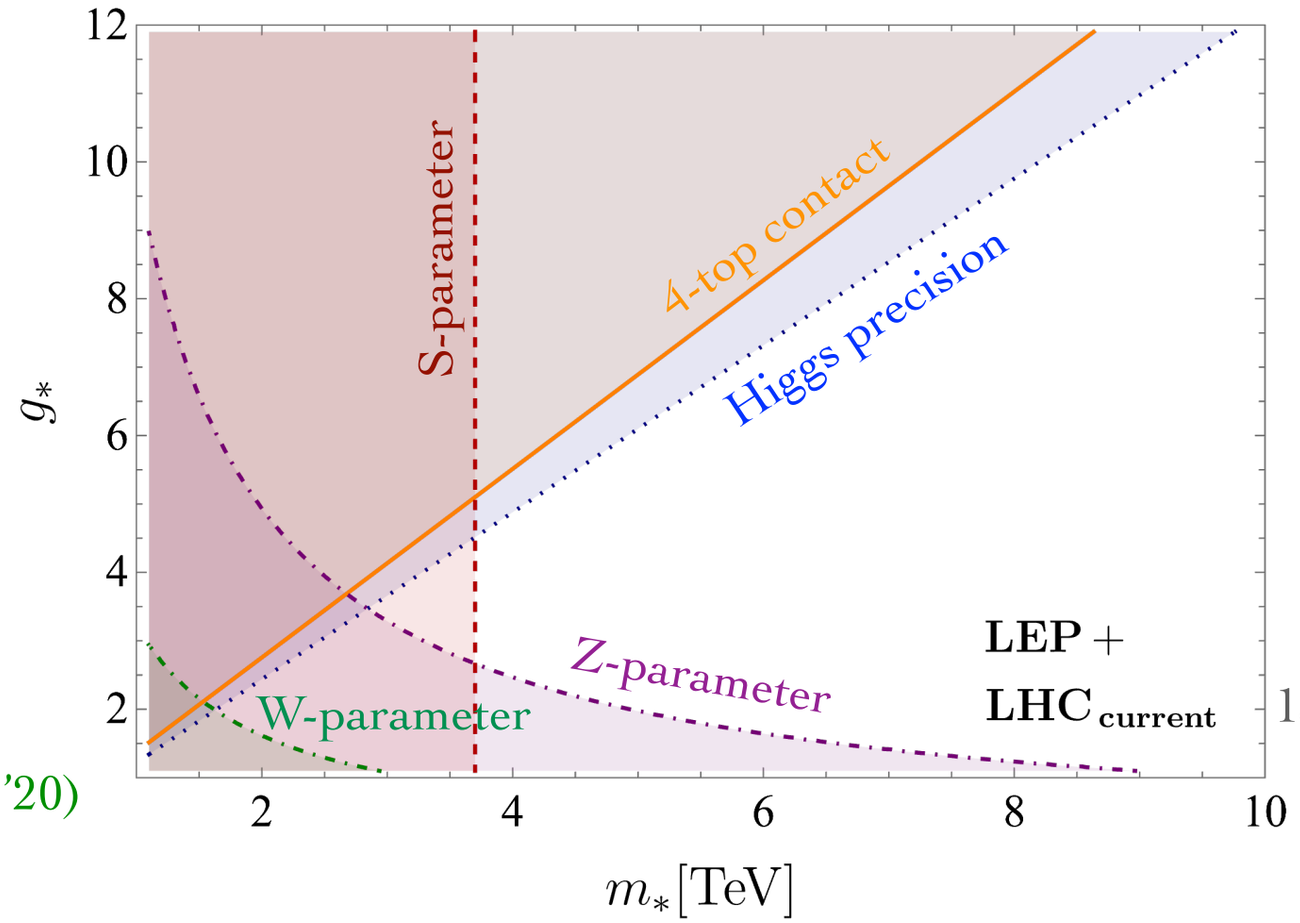
⋁

- *Wtb* coupling: $\frac{y_t^2}{m_*^2}(H^\dagger\sigma^a D_\mu H)(\bar{q}_L\sigma^a\gamma^\mu q_L) \xrightarrow{\text{LHC}} \frac{\delta g_{Wtb}}{g_{Wtb}} \lesssim 3\times 10^{-2}$
- top-dipole coupling: $\frac{y_t g_s}{m_*^2}\bar{q}_L H\sigma_{\mu\nu}G^{\mu\nu}t_R \xrightarrow{\text{LHC}} m_* \gtrsim 1\,\text{TeV}$
- light-top contact int.: $\frac{g_s^2}{m_*^2}(\bar{u}_R\gamma_\mu u_R)(\bar{t}_R\gamma^\mu t_R) \xrightarrow{\text{LHC}} m_* \gtrsim 1.5\,\text{TeV}$

* Experimental consistency and fine-tuning.

Current status

Most top-physics constraints are weaker than Higgs-physics, except 4-top production.



(Banelli et al. '20)

$$\frac{m_*}{g_*} \gtrsim 0.73\,\text{TeV}$$

(ATLAS '18)

$$\frac{m_*}{g_*} \gtrsim 0.82\,\text{TeV}$$

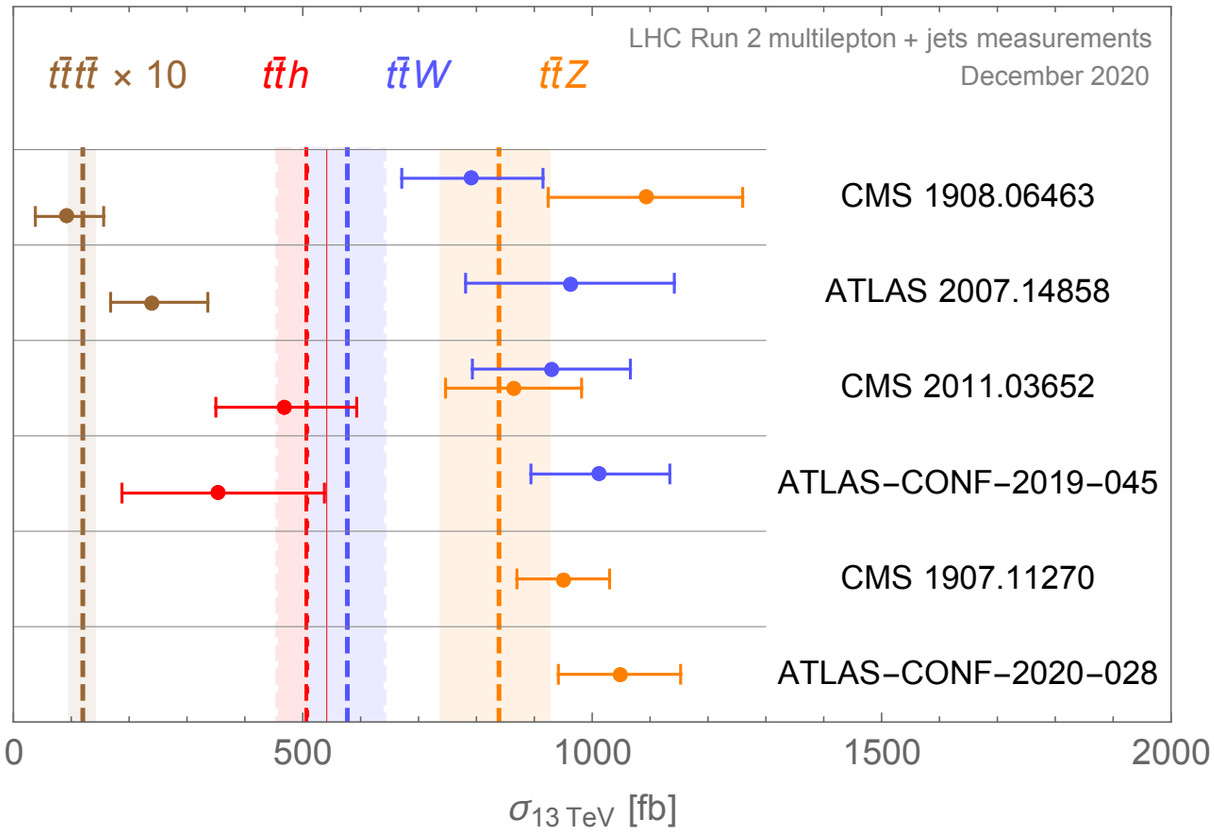
(de Blas et al. '19)

Power counting approach: exclusions derived from dominant effect in given observable; complementary to global fits.

- Higgs precision: $\frac{g_*^2}{m_*^2}\partial_\mu|H|^2\partial^\mu|H|^2$
- S-parameter: $\frac{gg'}{m_*^2}H^\dagger W_{\mu\nu}HB^{\mu\nu}$
- Z-parameter: $\frac{g_s^2}{g_*^2m_*^2}(D_\rho G_{\mu\nu})^2$
- W-parameter: $\frac{g^2}{g_*^2m_*^2}(D_\rho W_{\mu\nu})^2$

LHC multilepton + jets "excesses"

Run-2 ATLAS and CMS analyses show mild yet coherent excesses over the SM.



(Banelli et al. '20)

Most theory activity focussed on improving SM predictions, in particular top-pair + W.

(arXiv:1907.04343, 2001.03031, 2004.09552, 2005.09427, 2012.01363, 2007.12089, 2009.0003, 2101.11808, …)

↓

Interesting to explore in the context of new physics in the top/Higgs sector.

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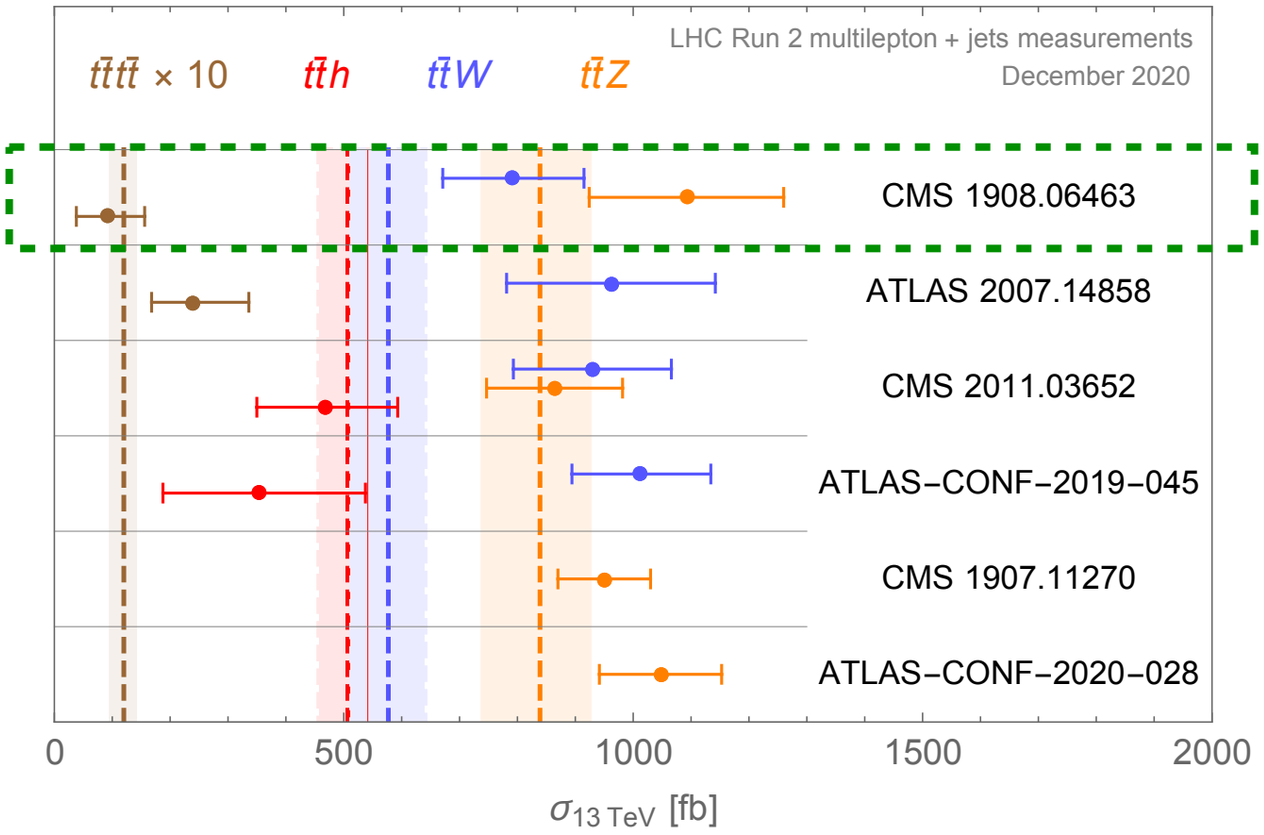

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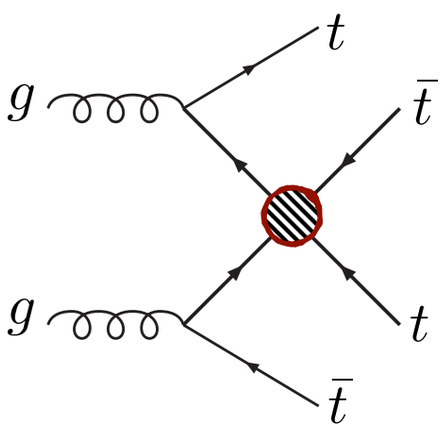
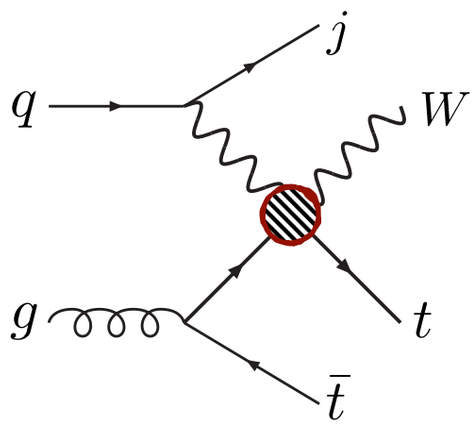
LHC multilepton + jets "excesses"

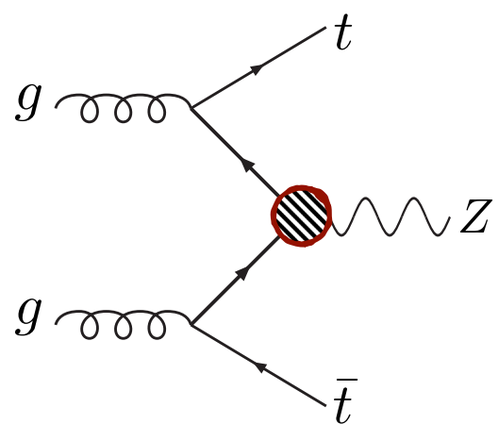
Reinterpretation of cut-and-count CMS (1908.06463) 4-top search.

$$\frac{c_{tt}}{v^2}\left(\bar{t}_R\gamma_\mu t_R\right)^2$$



$$\frac{c_{Ht}}{v^2} i\left(H^\dagger D^\mu H\right)\left(\bar{t}_R\gamma_\mu t_R\right)$$

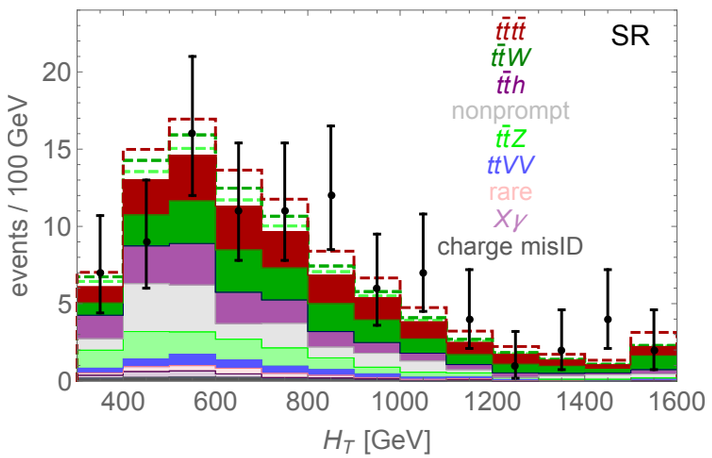


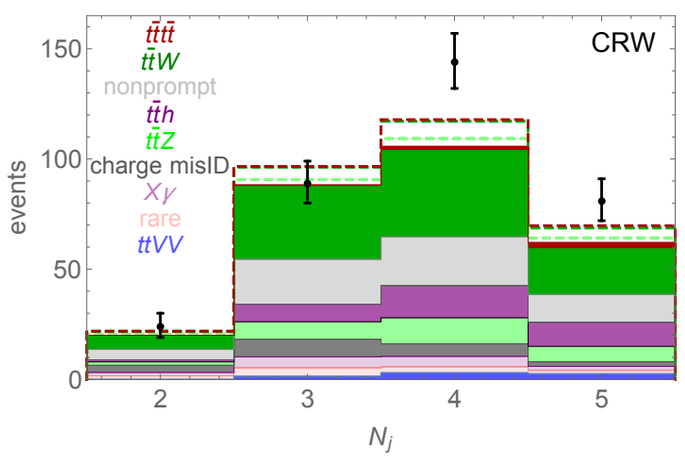


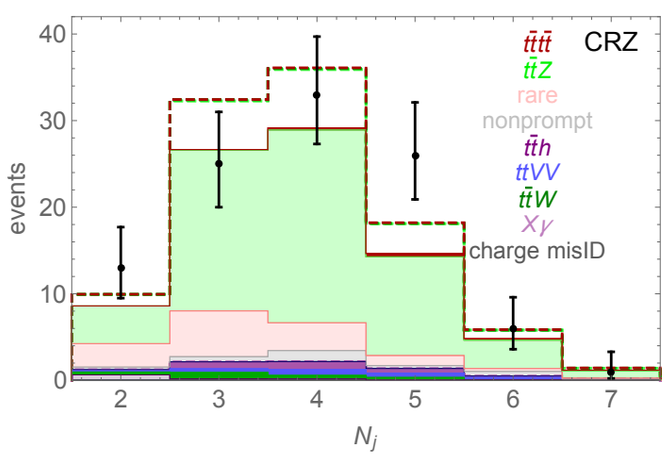
(Dror et al. '15, Frederix et al. '17, Maltoni et al. '19)

(missing) tW-scattering contribution

Joint fit to signal region (SR), ttW control region (CRW) and ttZ control region (CRZ).







13 TeV, 139 /fb

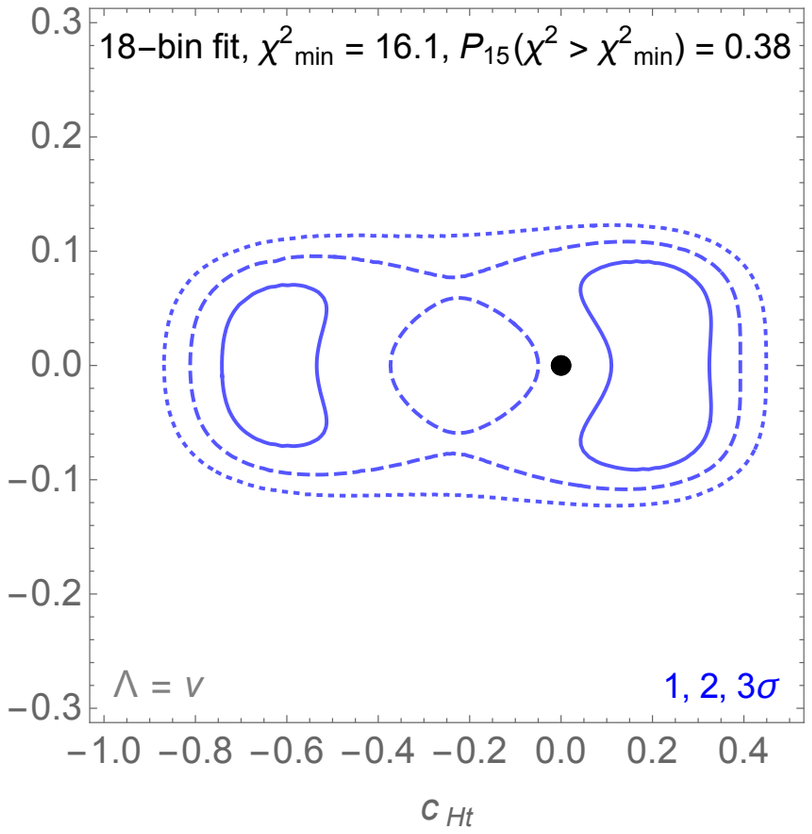
(Banelli et al. '20)

LHC multilepton + jets "excesses"

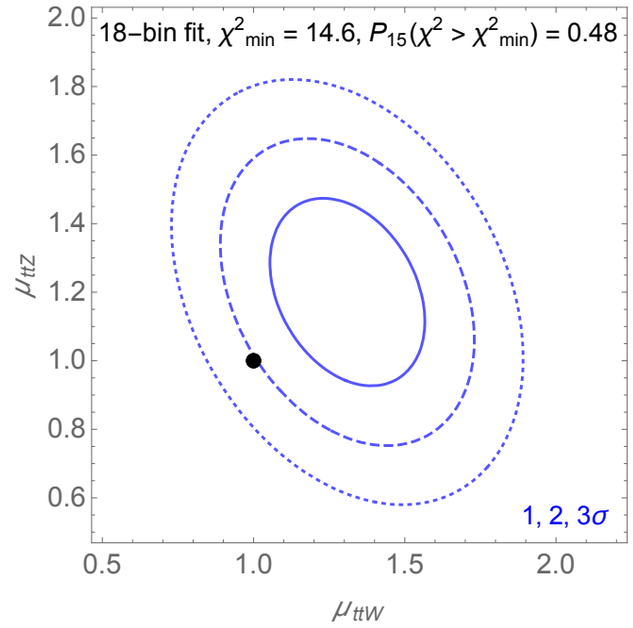
Fit points to sensible values of $m_*/g_* \sim 0.75\,\mathrm{TeV}$.

Best fit point:

$(c_{Ht},\, c_{tt}) \approx (0.2,\, \pm 0.05)$



13 TeV, 139 /fb



Goodness of fit similar to signal-strength rescaling.

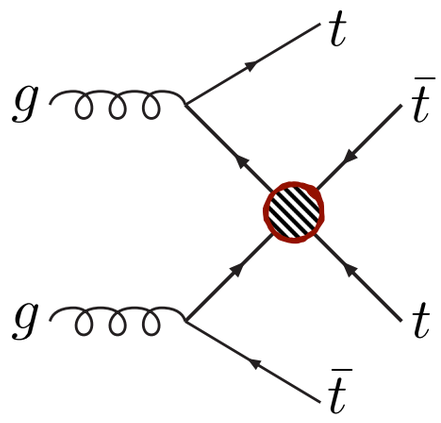
↓

Additional motivation to explore a strongly-interacting top quark at future colliders.

Future hadron colliders: FCC-hh

Energy growth in strongly-coupled scenarios leads to clear enhancement of sensitivity.

$$\frac{c_{tt}}{m_*^2}\left(\bar{t}_R\gamma_\mu t_R\right)^2$$



$$\mathcal{M}_{tt} \sim \frac{g_*^2}{m_*^2}s$$

$$c_{tt} = g_*^2$$

- **Same-sign di-lepton** (BR = 4.1%) and **tri-lepton** final states (BR = 2.6%) to suppress backgrounds.
- Main irreducible backgrounds: 4-top (SM), top-pair + W, Z, h.
- Larger relative SM 4-top rate than main backgrounds: $\left.\frac{\sigma_{100\,\mathrm{TeV}}}{\sigma_{13\,\mathrm{TeV}}}\right|_{t\bar{t}t\bar{t}} \approx 350$ $\left.\frac{\sigma_{100\,\mathrm{TeV}}}{\sigma_{13\,\mathrm{TeV}}}\right|_{t\bar{t}W} \approx 40$

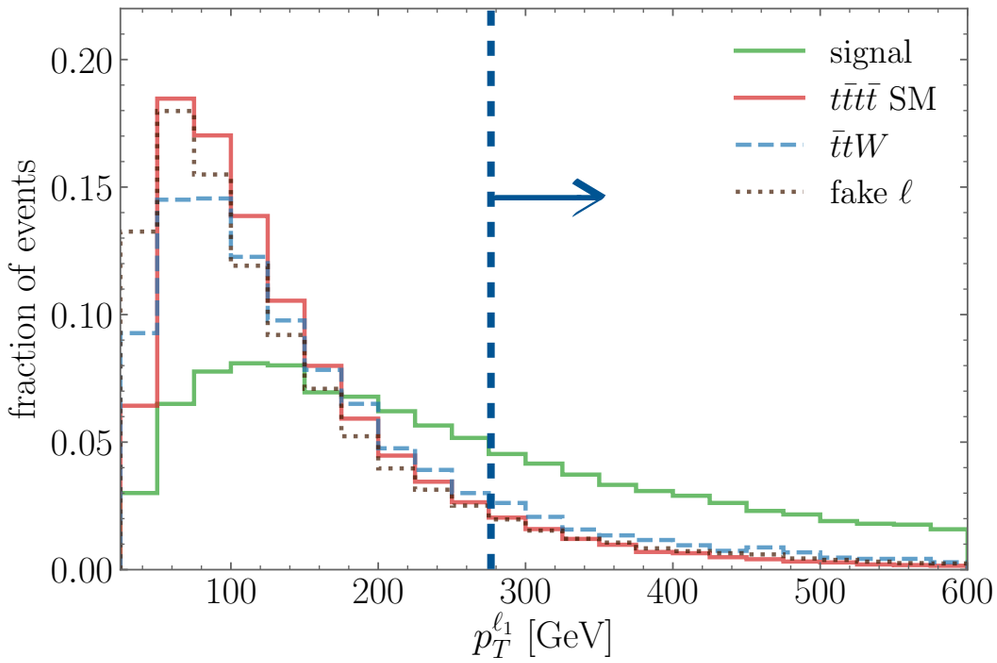
(Frederix, Pagani, Zaro '17)

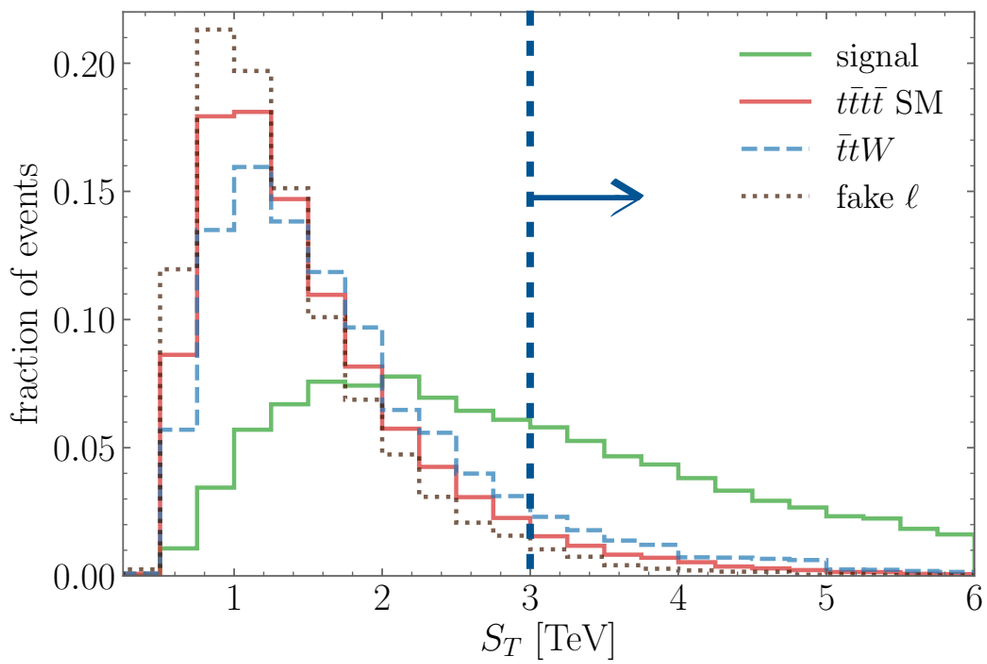
- Fake-lepton/charge-flip reducible backgrounds estimated/validated with top-pair + jets LHC data.
- Builds on ATLAS (1811.02305), CMS (1908.06463) and SM-theory 4-top analyses (Alvarez et al '16).

Future hadron colliders: FCC-hh

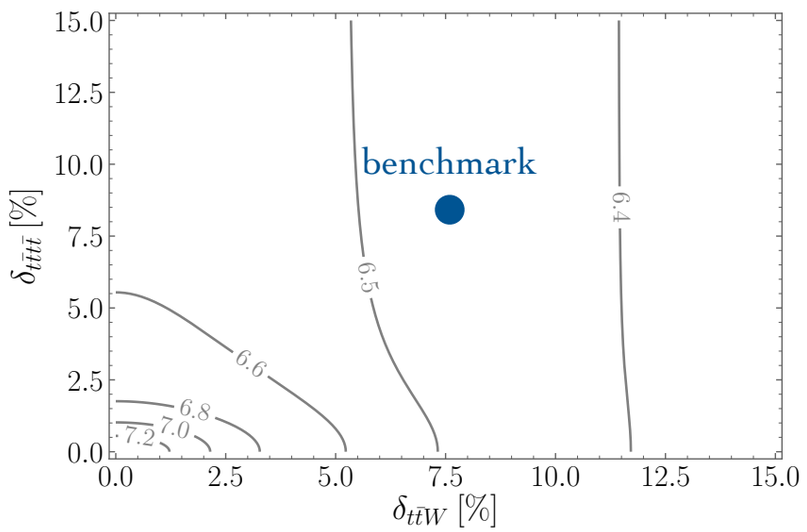
Similar sensitivity for **same-sign di-lepton** and tri-lepton.

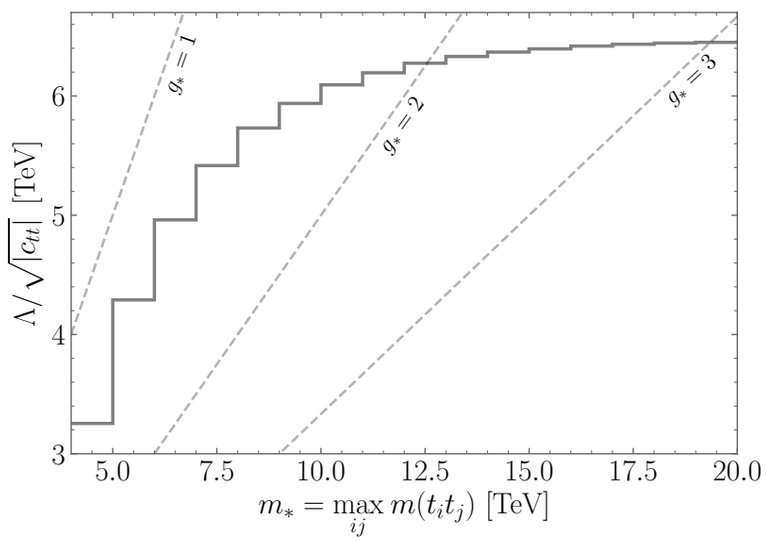
Baseline selection: exactly two SSL with $p_T^{\ell_1,\ell_2} > 40,\ 25\,\text{GeV}$, ≥ 5 jets (≥ 3 b-tagged), $H_T > 400\,\text{GeV}$.





Checked dependence on background systematics, fake-lepton prob., EFT regime of validity.

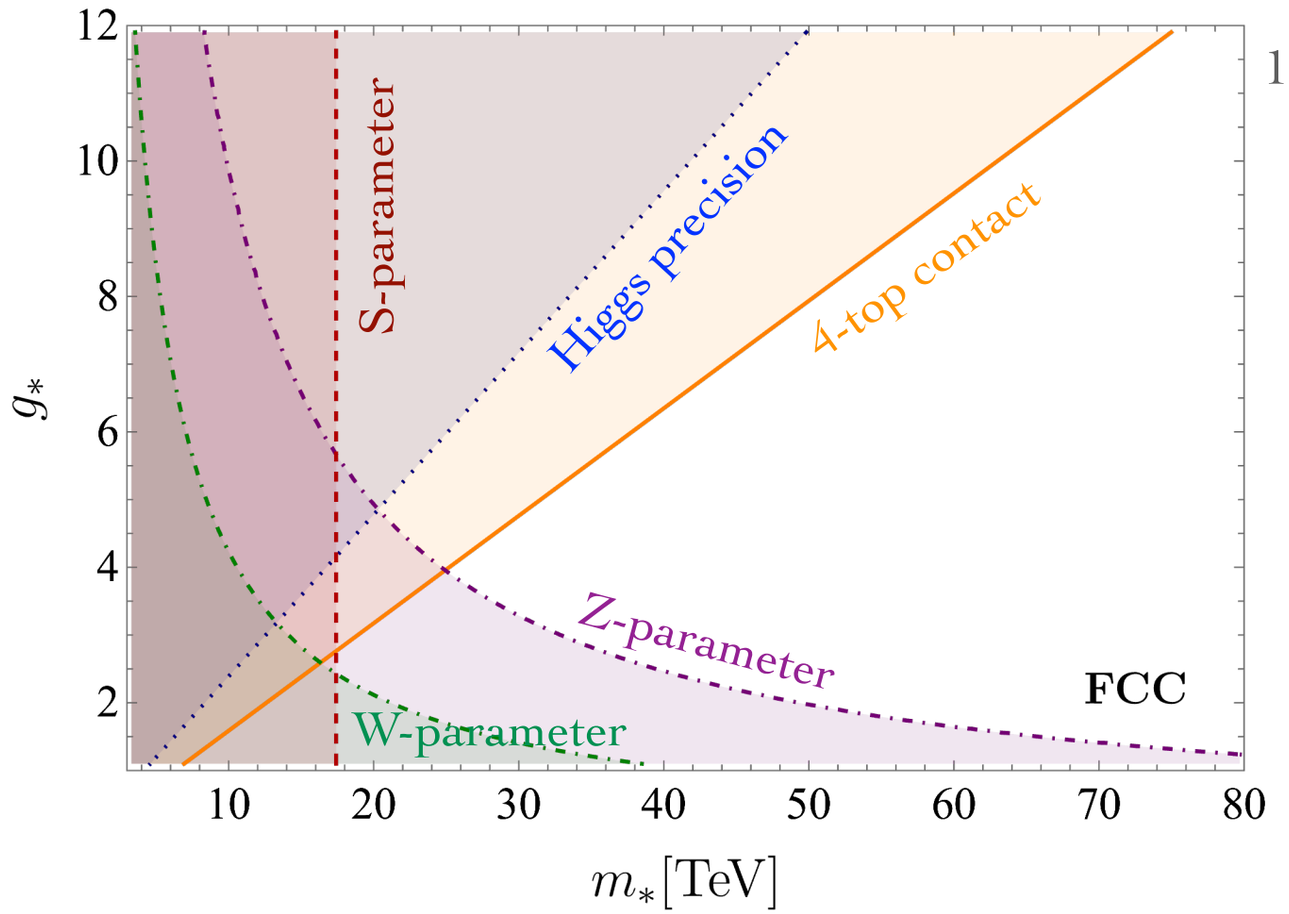




Top and Higgs compositeness: FCC

Dominant sensitivity to large compositeness scale/coupling via 4-top contact interactions;

$$c_{tt} = g_*^2$$



100 TeV, 30 /ab

$$\frac{m_*}{g_*} > 6.5\,\text{TeV}$$

(Banelli et al. '20)

$$\frac{m_*}{g_*} > 4.2\,\text{TeV}$$

(de Blas et al. '19)

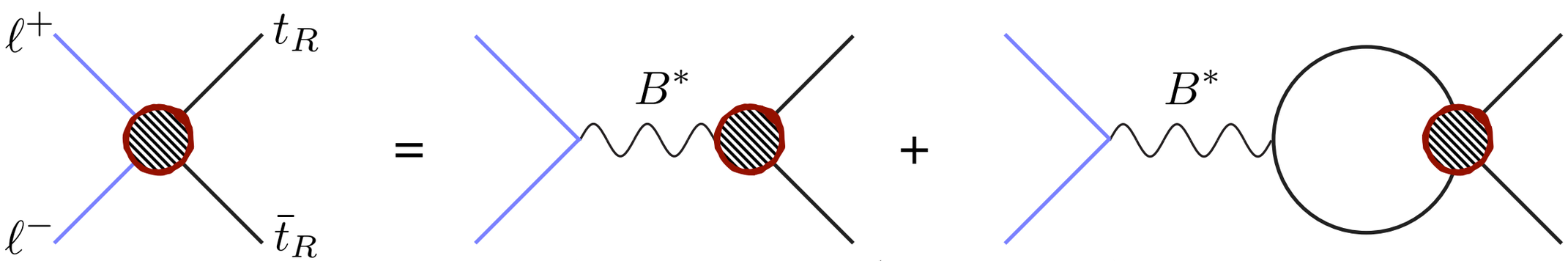
higher than Higgs couplings even if these are from full FCC (-ee/-hh) program.

- Higgs precision: $\frac{g_*^2}{m_*^2}\partial_\mu|H|^2\partial^\mu|H|^2$
- Z-parameter: $\frac{g_s^2}{g_*^2 m_*^2}(D_\rho G_{\mu\nu})^2$

Future lepton colliders

Not feasible to directly probe 4-top contact interactions at lepton colliders.

renormalization group evolution



$$\frac{c_{tD}}{m_*^2}(\partial^\mu B_{\mu\nu})(\bar{t}_R\gamma^\nu t_R)$$

$$\frac{c_{tD}}{m_*^2}(\mu) = \frac{c_{tD}}{m_*^2}(m_*) + \frac{c_{tt}}{m_*^2}(m_*)\frac{32}{9}\frac{g'}{16\pi^2}\log\left(\frac{m_*^2}{\mu^2}\right)$$

e.o.m.

$$\frac{c_{te}}{m_*^2}(\bar{e}_R\gamma_\mu e_R)(\bar{t}_R\gamma^\mu t_R)$$
$$\frac{c_{t\ell}}{m_*^2}(\bar{\ell}_L\gamma_\mu \ell_L)(\bar{t}_R\gamma^\mu t_R)$$

$$\frac{c_{te}}{m_*^2} = 2\frac{c_{t\ell}}{m_*^2} = \frac{g'^2}{m_*^2}\left(\frac{32}{9}\frac{g_*^2}{16\pi^2}\log + \text{finite}\right)$$

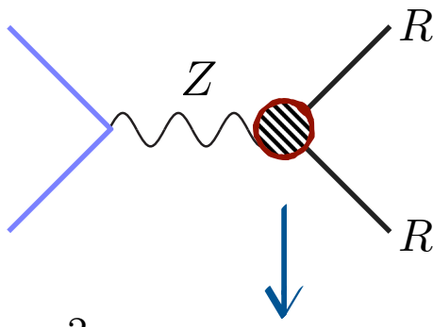
For strongly-coupled theories $g_* \gg 1$, RGE term leading contribution.

(Banelli et al. '20)

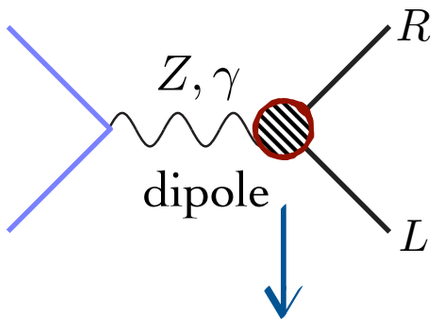
Future lepton colliders

- Several c.o.m. energies and polarized beams is crucial to probe different operators.

$\mathcal{M}_{\ell^+\ell^-\to t\bar{t}} \sim$



$+$



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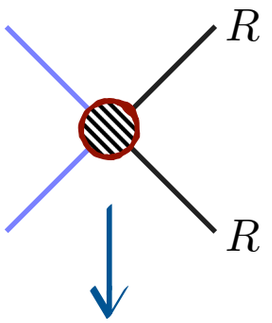


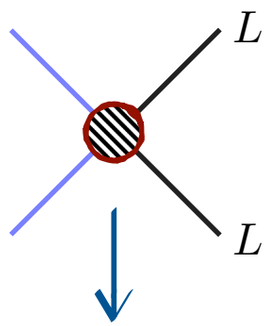
$$\frac{g_*^2}{m_*^2}(H^\dagger D_\mu H)(\bar{t}_R\gamma^\mu t_R) \qquad \frac{y_t g}{m_*^2}\bar{q}_L H\sigma_{\mu\nu}W^{\mu\nu}t_R \qquad \frac{c_{te}}{m_*^2}(\bar{e}_R\gamma_\mu e_R)(\bar{t}_R\gamma^\mu t_R)$$

$$\sim \frac{g_*^2}{m_*^2}m_W^2 \qquad \sim \frac{g^2}{m_*^2}m_t\sqrt{s} \qquad \sim \frac{g_*^2}{m_*^2}s$$

Contact interactions at high-energy colliders dominate the sensitivity to g_*/m_*.

- Bottom pair-production provides sensitivity to the weakly coupled regime $g_* \sim 1$.

$\mathcal{M}_{\ell^+\ell^-\to b\bar{b}} \sim$

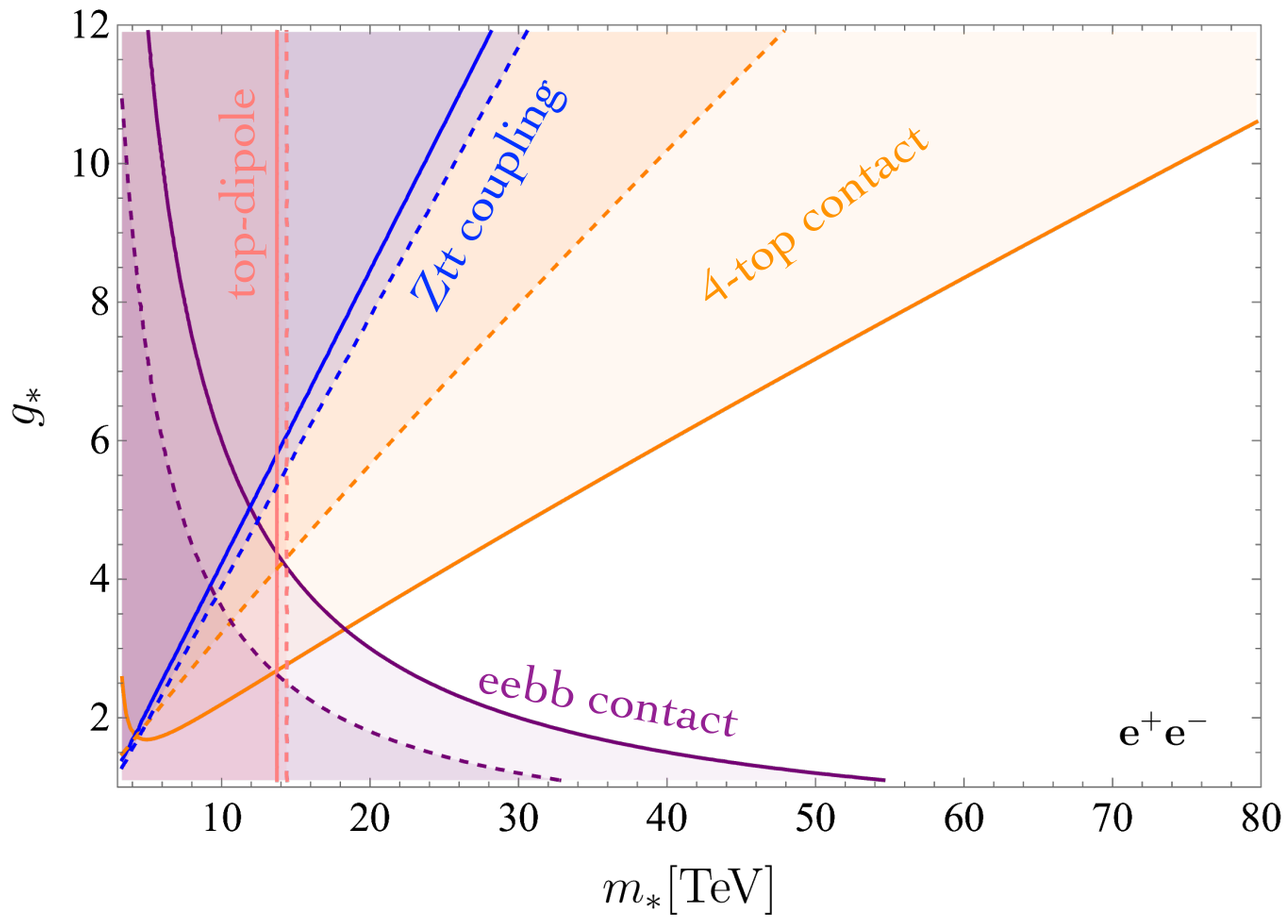


$$\sim \frac{y_t^2 g^2}{g_*^2 m_*^2}s$$

$$\frac{y_t^2 g^2}{g_*^2 m_*^2}(\bar{\ell}_L\gamma_\mu\ell_L)(\bar{q}_L\gamma^\mu q_L)$$

Future lepton colliders: ILC vs CLIC

High c.o.m. energies great advantage in (indirectly) probing most of parameter space.



—— CLIC
$\sqrt{s} = 0.38,\ 1.4,\ 3$ TeV
$L = 0.5,\ 1.5,\ 3$ /ab

------- ILC
$\sqrt{s} = 0.5,\ 1$ TeV
$L = 0.5,\ 1$ /ab

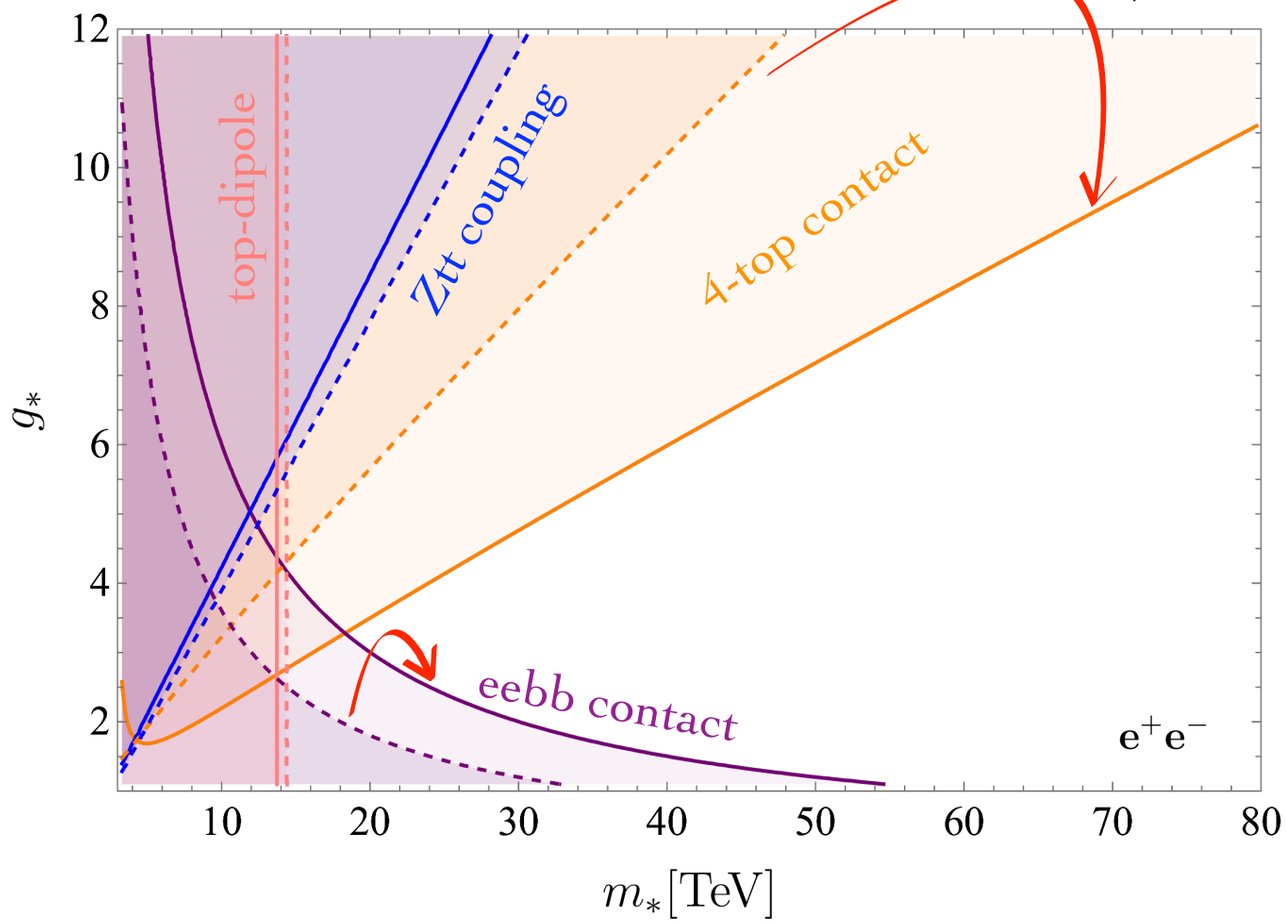
Based on reinterpretation of results for sensitivity to the individual operators: Durieux, Perelló, Vos, Zhang '18.
See also Durieux, Matsedonskyi '18.

Contact interactions and highest-energy runs dominate the sensitivity.

Future lepton colliders: ILC vs CLIC

High c.o.m. energies great advantage in (indirectly) probing most of parameter space.

$$\times\sqrt{\frac{s_{\rm ILC}}{s_{\rm CLIC}}}\sqrt{\frac{L_{\rm ILC}}{L_{\rm CLIC}}}$$ (statistically dominated errors)



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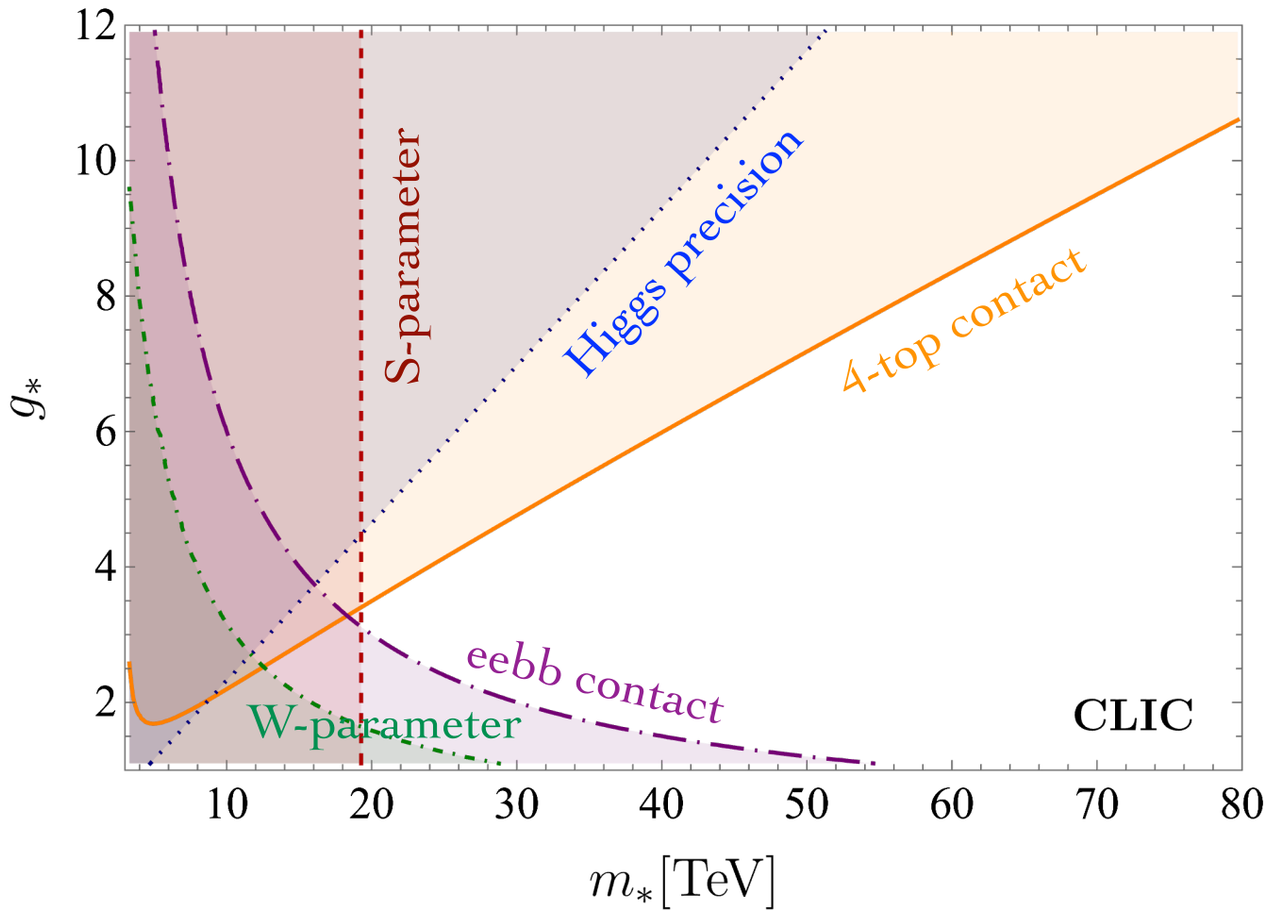
Based on reinterpretation of results for sensitivity to the individual operators: Durieux, Perelló, Vos, Zhang '18. See also Durieux, Matsedonskyi '18.

Contact interactions and highest-energy runs dominate the sensitivity.

Top and Higgs compositeness: CLIC

Dominant sensitivity to large compositeness scale/coupling via 4-top contact interactions.

$$c_{tt} = g_*^2$$



$$\frac{m_*}{g_*} > 7.7 \text{ TeV}$$

(Banelli et al. '20)

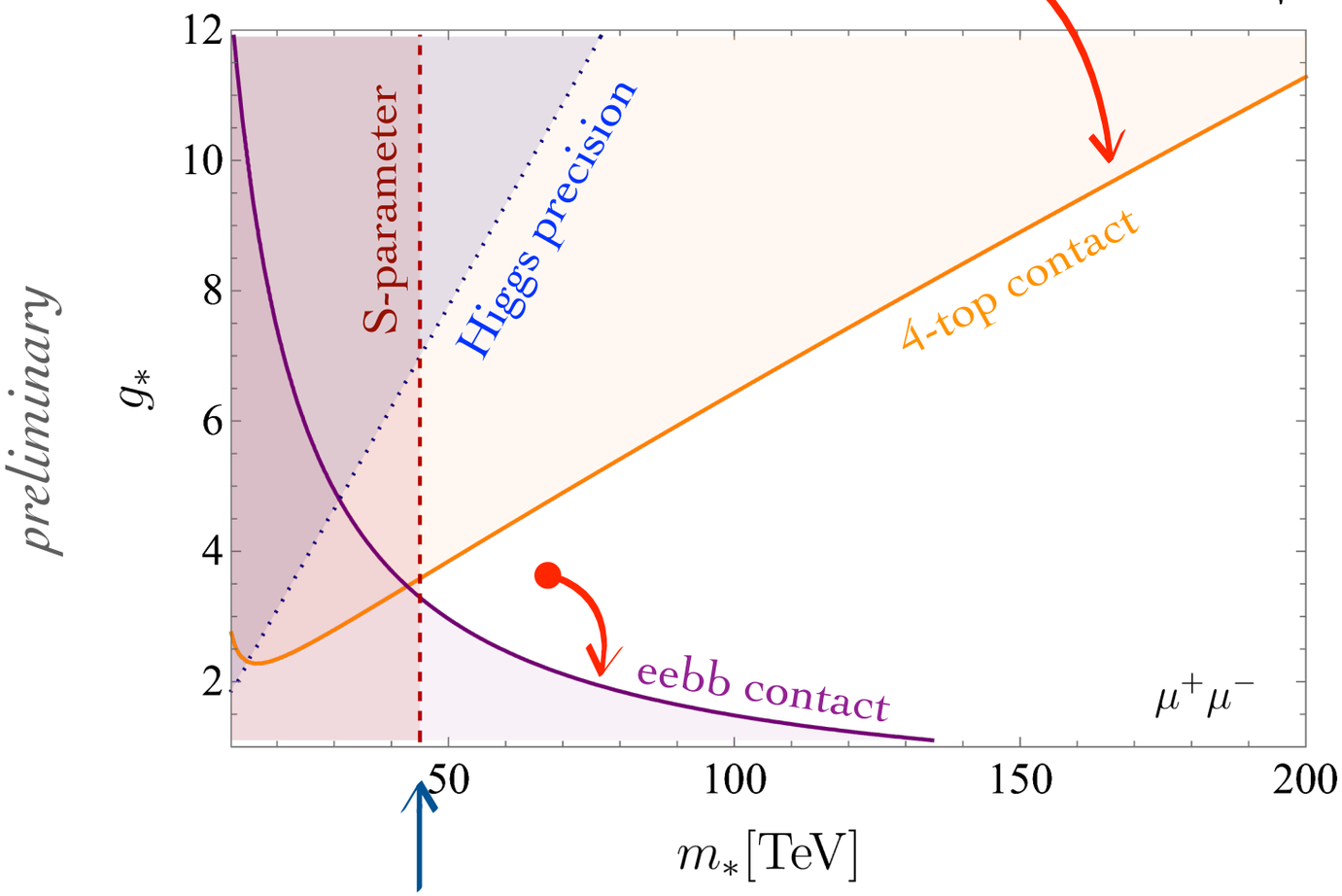
$$\frac{m_*}{g_*} > 4.3 \text{ TeV}$$

(de Blas et al. '19)

Top and Higgs compositeness: muon collider

Same conclusion at a high-energy muon collider, with larger reach!

$\sqrt{s_{\mu^+\mu^-}} = 10\,\text{TeV} \quad L_{\mu^+\mu^-} = 10\,/\text{ab}$ $\times \sqrt{\frac{s_{\text{CLIC}}}{s_{\mu^+\mu^-}}} \sqrt{\frac{L_{\text{CLIC}}}{L_{\mu^+\mu^-}}}$ (statistically dominated errors)



(Buttazzo et al. '20)

$\frac{m_*}{g_*} \gtrsim 18\,\text{TeV}$

$\frac{m_*}{g_*} \gtrsim 6.4\,\text{TeV}$

(Han et al. '20)

Main assumption is that uncertainty remains statistically dominated.

Conclusions/Outlook

- Top (effective) compositeness is a very motivated target for high-energy colliders.

  In particular because of its connection to the origin of the electroweak scale.

- Current LHC measurements are already (intriguingly) interesting.

  Probes of genuine strong 4-top production competitive with Higgs precision.

  Pattern of mild excesses in multi-lepton + jets deserve closer inspection.

- Future colliders would provide very powerful tests of a strongly-interacting top.

  Hadron colliders, directly via strong *tt*-scattering in 4-top production.

  Lepton colliders, indirectly via RGE effects in top-pair production.

$$\left.\frac{m_*}{g_*}\right|^{4t}_{\text{LHC, 36/fb}} \gtrsim 0.73\,\text{TeV} \qquad \left.\frac{m_*}{g_*}\right|^{4t}_{\text{FCC}-\text{hh}} \gtrsim 6.5\,\text{TeV} \qquad \left.\frac{m_*}{g_*}\right|^{t\bar{t}}_{\text{CLIC 3}} \gtrsim 7.7\,\text{TeV} \qquad \left.\frac{m_*}{g_*}\right|^{t\bar{t}}_{\text{muon 10}} \gtrsim 18\,\text{TeV}$$

Exploring levels of electroweak-scale fine-tuning below the per-mille level.

Thank you.