Top-BSM Physics at Future multi-TeV Colliders

TOP2021

14th International Workshop on Top Quark Physics

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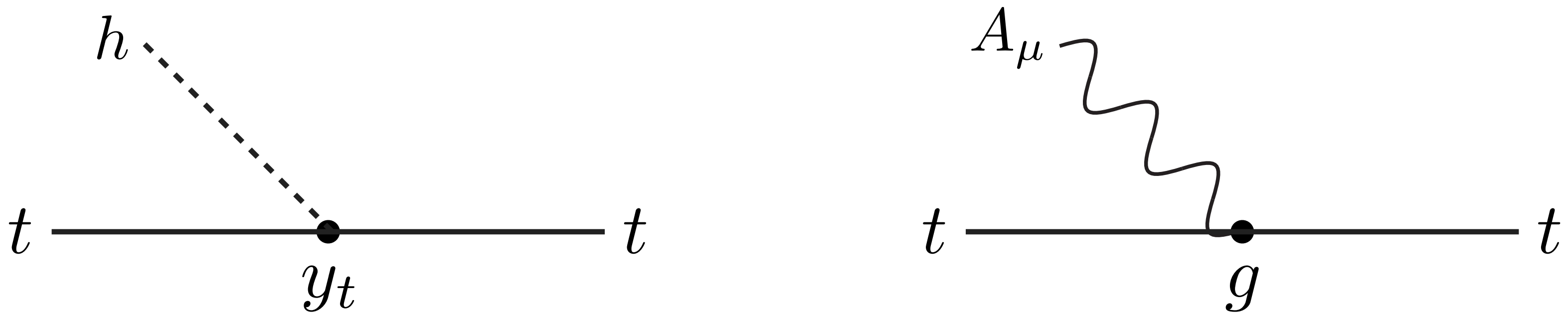
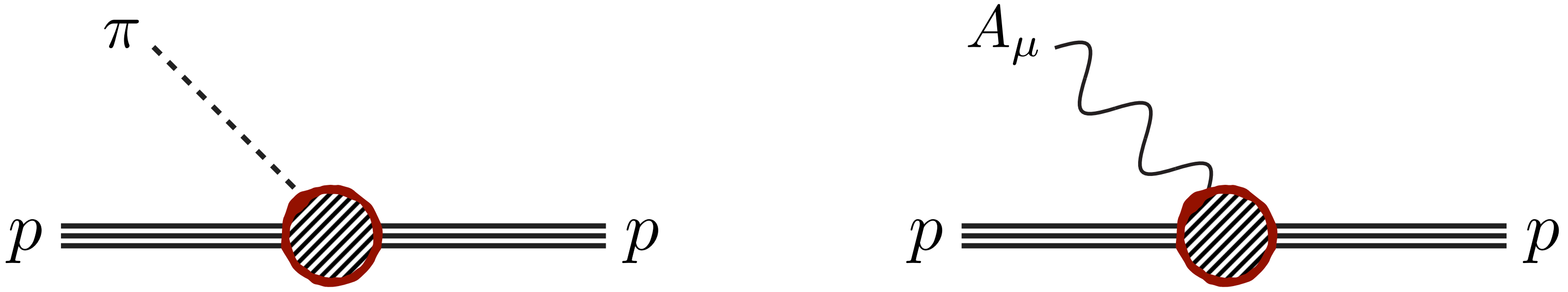
mostly based on arXiv:2010.05915 w/ G.Banelli, E.Salvioni, T.Theil and A.Weiler

Strongly-interacting top quark

The top quark is the heaviest, most strongly coupled (yet least known) fermion of the SM.

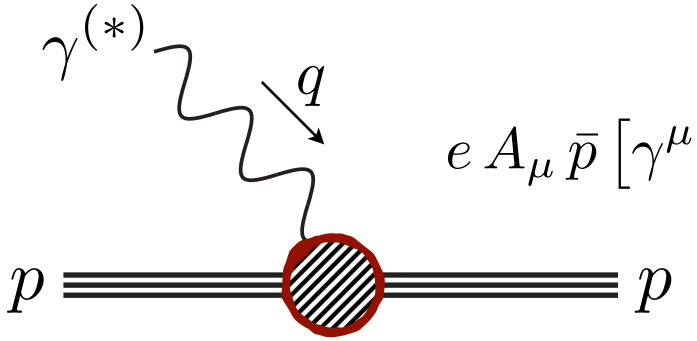


Compelling indication of a deeper structure behind the top quark.



Strongly-interacting → 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

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

$$m_t \ll m_*$$

$$\downarrow$$

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

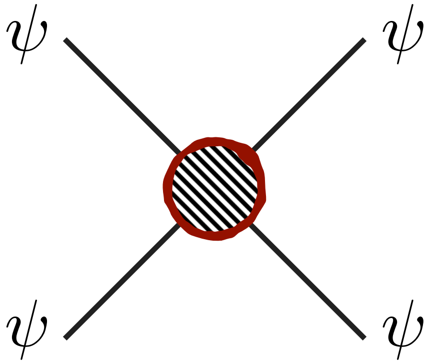
(Georgi et al. '94)

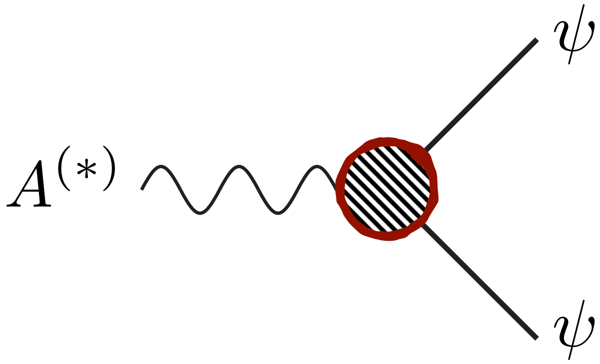
$$\psi = t_R,\, q_L$$

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

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

$$D^3_\mu \sim D^2 D_\mu,\; D_\nu D_\mu D^\nu,\; gF_{\mu\nu}D^\nu$$





Two distinct types of non-standard effects.

Chiral top effective compositeness

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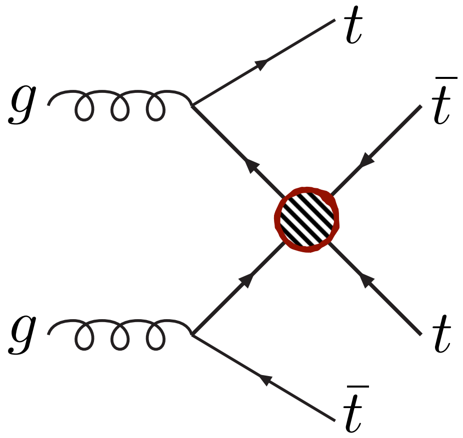
$$\boxed{\frac{c_{\psi\psi}}{m_*^2}\,(\bar\psi\gamma_\mu\psi)^2} \qquad \frac{c_{\psi D}}{m_*^2}\,\bar\psi D_\mu^3\gamma^\mu\psi$$

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.

Chiral top effective compositeness

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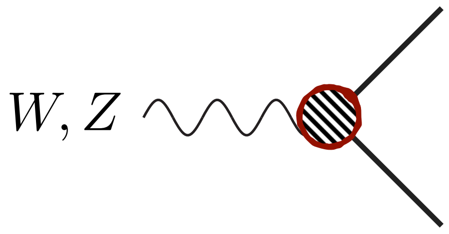
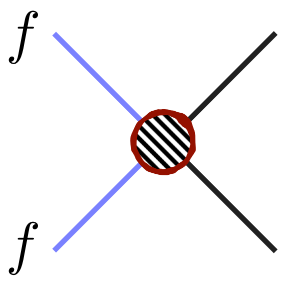
$$\psi = t_R,\, q_L$$

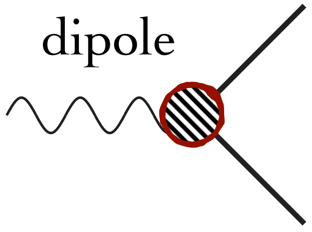
$$\frac{c_{\psi\psi}}{m_*^2}(\bar\psi\gamma_\mu\psi)^2 \qquad \boxed{\frac{c_{\psi D}}{m_*^2}\,\bar\psi D_\mu^3\gamma^\mu\psi} \qquad c_{\psi D} \sim 1$$

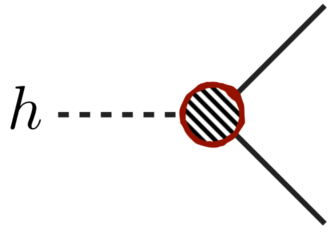
In physical processes, always involve other SM particles (equations of motion).

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









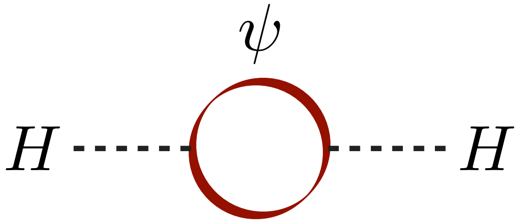
Not enhanced at strong coupling; other fields complicate top-compositeness interpretation.

Why top compositeness

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

None of these single out per se the top quark nor multi-TeV energies.

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



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

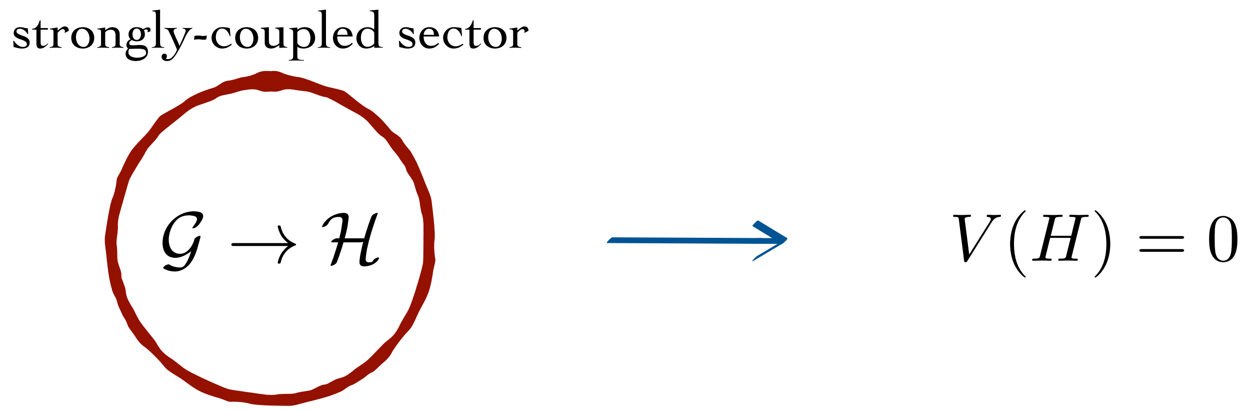
Large Yukawa indicates top quark plays key role in theories explaining EWSB.

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

$$\mathcal{G} \to \mathcal{H} \quad \longrightarrow \quad V(H) = 0$$

Provides rationale why Higgs is lighter than compositeness scale.

$$m_H \ll m_*$$

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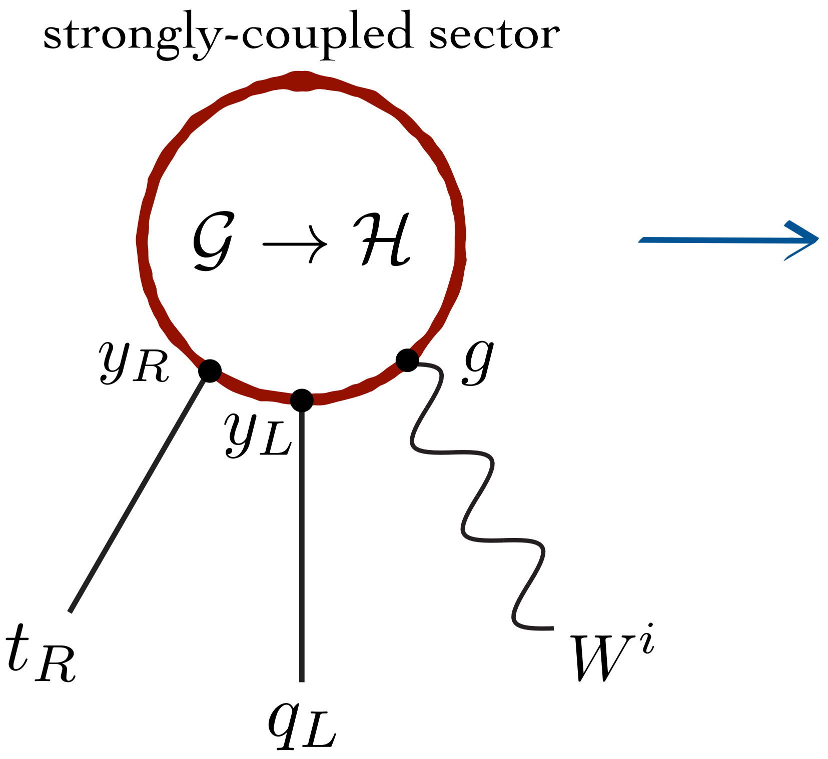

$$V(H) = m_H^2 |H|^2 + \lambda_H |H|^4 \neq 0$$

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

The top quark is crucial to break the electroweak symmetry.

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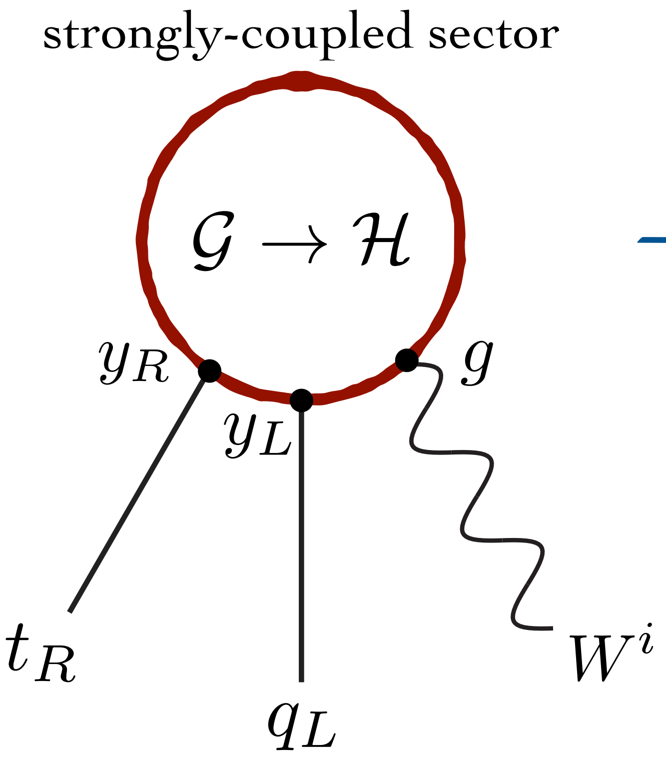
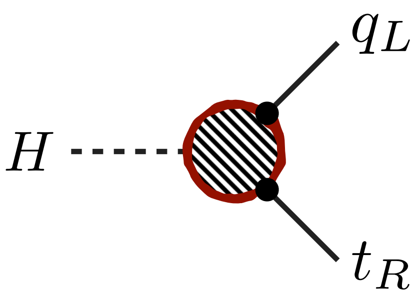


$$V(H) = m_H^2 |H|^2 + \lambda_H |H|^4 \neq 0$$

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

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

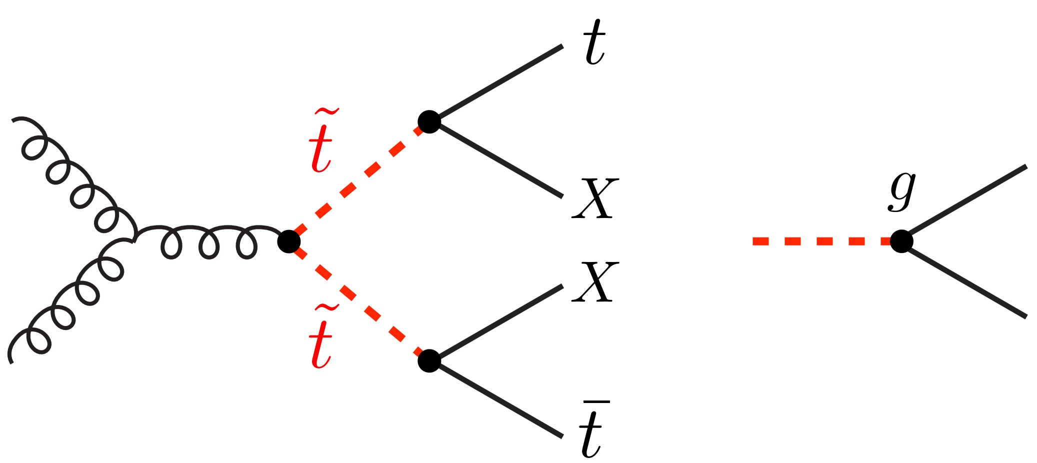


$$y_t \sim \frac{y_L y_R}{g_*} \sim 1$$

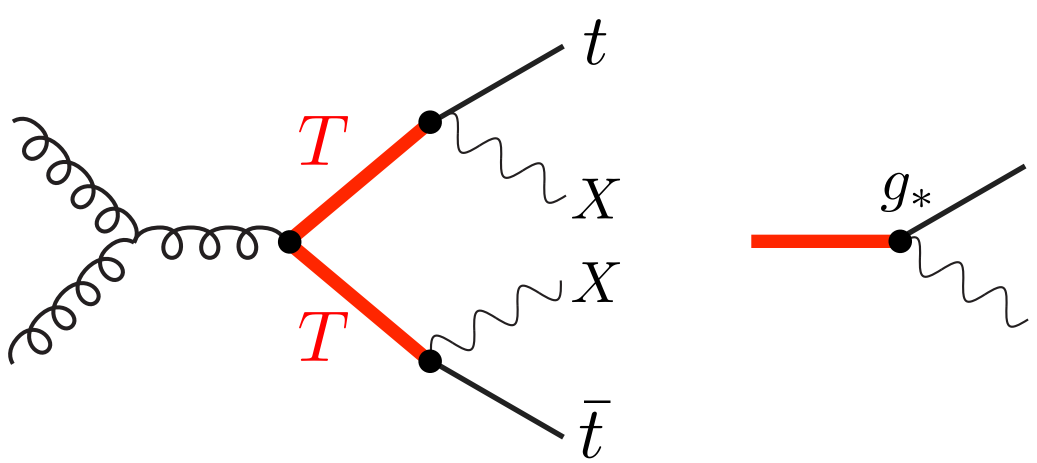
Weak vs Strong top-Higgs BSM

Both supersymmetry and compositeness typically predict resonances decaying to top + X.

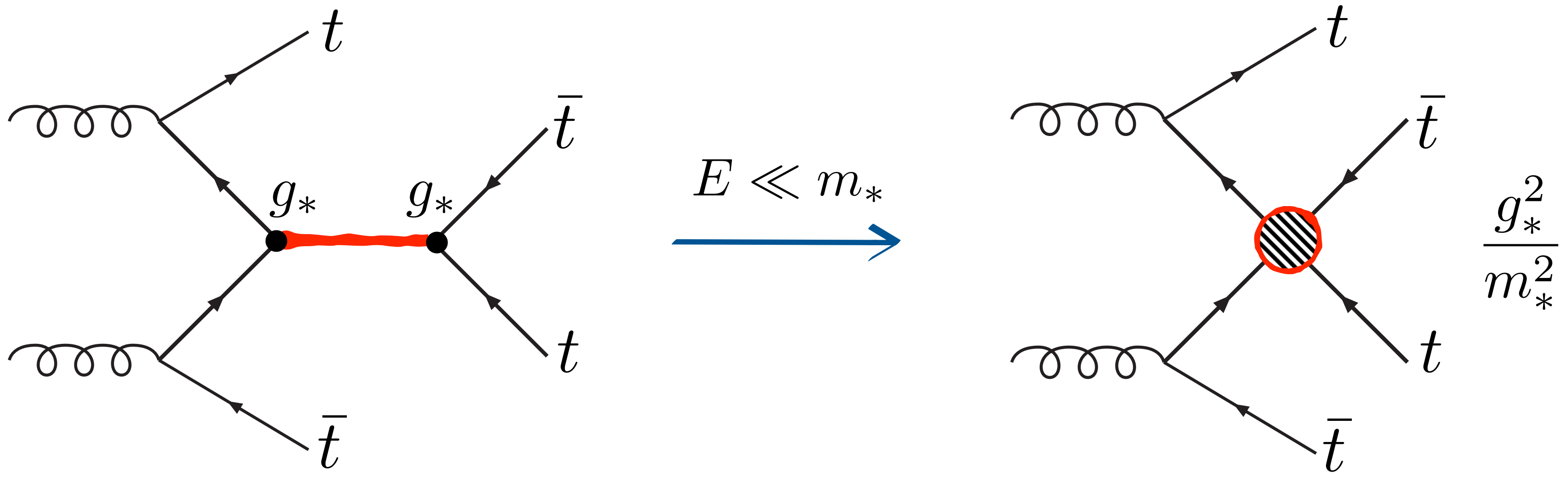
susy-tops



top-partners



Direct (on-shell) resonance searches directly limited by energy of collider.



Indirect (off-shell) effects remain large in strongly-coupled theories $g_* \gg 1$.

Top and Higgs compositeness

Limit* of **maximally strongly-coupled Higgs and right-handed top**:

$$y_R \to g_*$$
$$y_L \to y_t$$

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

⩔

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

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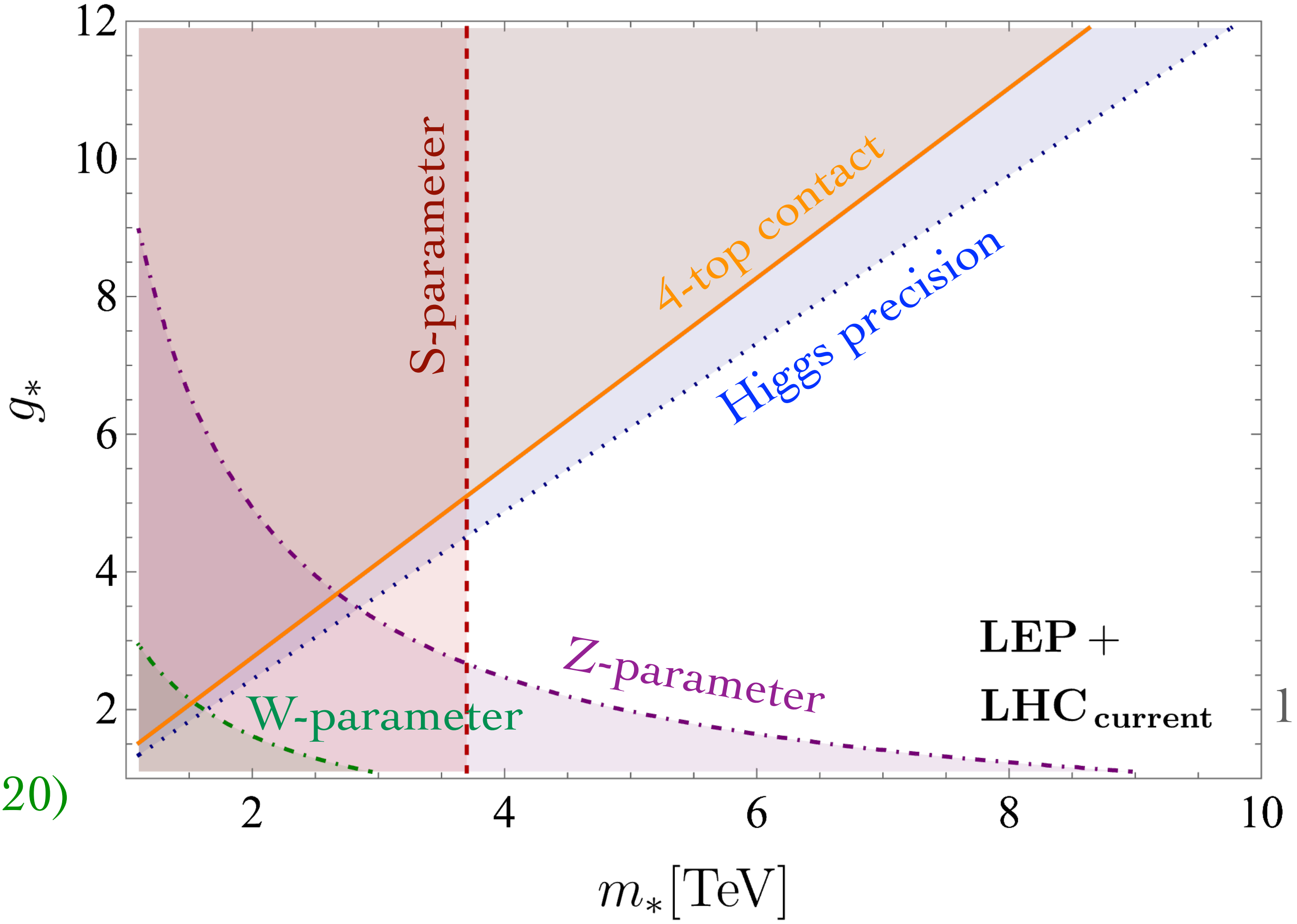
* Experimental consistency and fine-tuning.

Current status

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



13 TeV, 36 /fb

(Banelli et al. '20)

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

(ATLAS '18)

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

(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: $\frac{gg'}{m_*^2} H^\dagger W_{\mu\nu} H B^{\mu\nu}$
- Z-parameter: $\frac{g_s^2}{g_*^2 m_*^2}(D_\rho G_{\mu\nu})^2$
- W-parameter: $\frac{g^2}{g_*^2 m_*^2}(D_\rho W_{\mu\nu})^2$

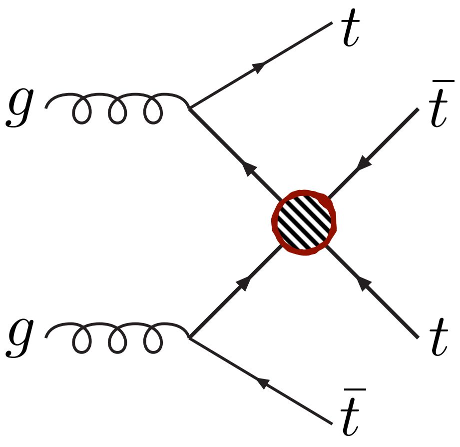
Future multi-TeV Colliders

(Banelli et al. 2010.05915)

Future hadron colliders: FCC-hh

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

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



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

$$\uparrow$$

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

- **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: $\left.\frac{\sigma_{100\,\mathrm{TeV}}}{\sigma_{13\,\mathrm{TeV}}}\right|_{t\bar{t}t\bar{t}} \approx 350 \qquad \left.\frac{\sigma_{100\,\mathrm{TeV}}}{\sigma_{13\,\mathrm{TeV}}}\right|_{t\bar{t}W} \approx 40$

(Frederix, Pagani, Zaro '17)

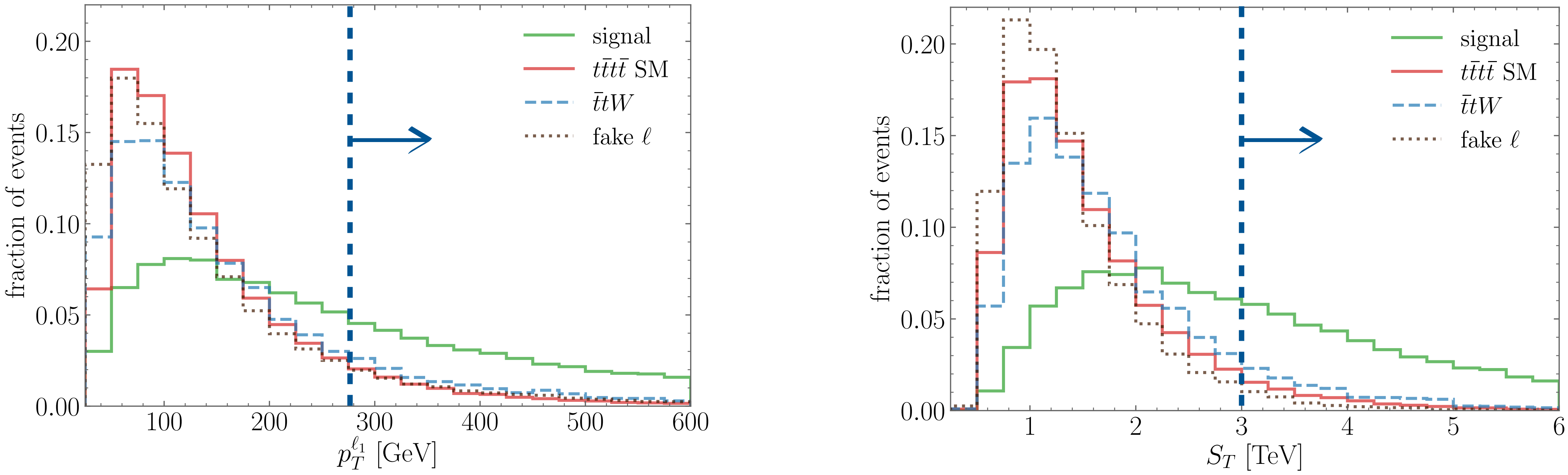
- Fake-lepton/charge-flip reducible backgrounds estimated/validated with top-pair + jets LHC data.
- Builds on ATLAS (1811.02305), CMS (1908.06463) and SM-theory 4-top analyses (Alvarez et al '16).

(Banelli et al. 2010.05915)

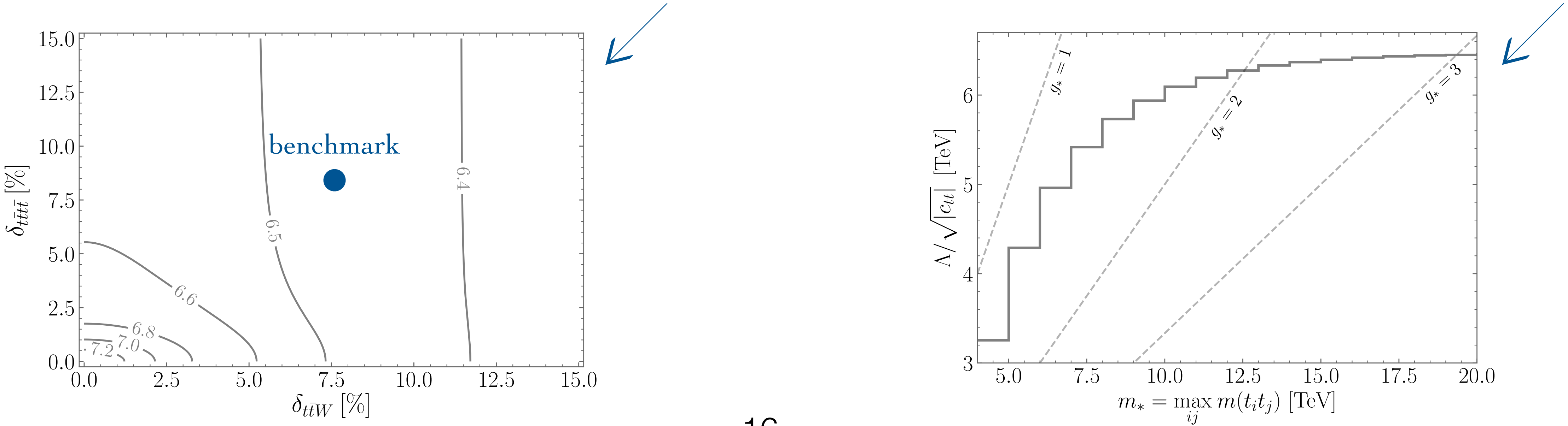
Future hadron colliders: FCC-hh

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

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



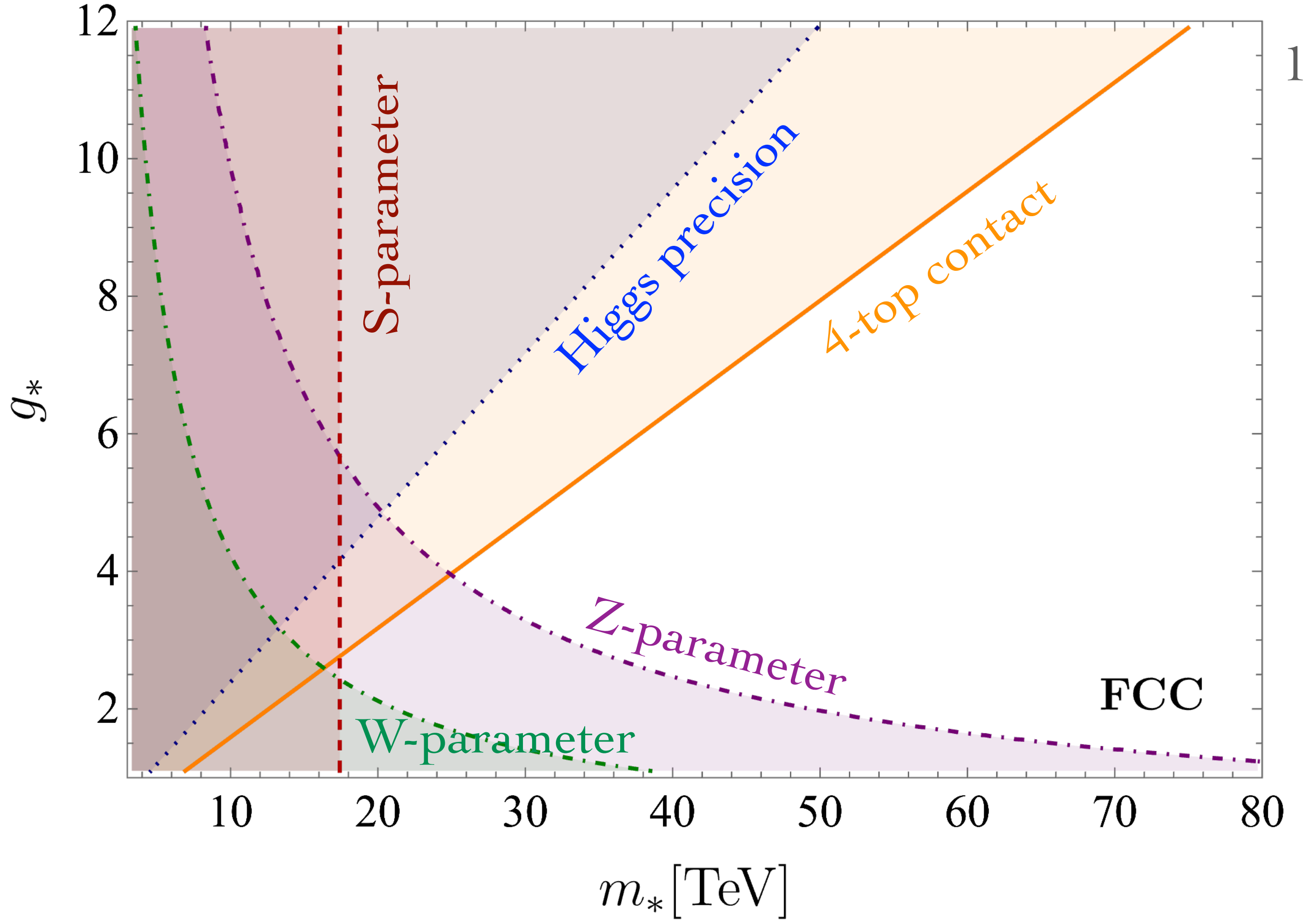
Checked dependence on <u>background systematics</u>, fake-lepton prob., <u>EFT regime of validity</u>.



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.

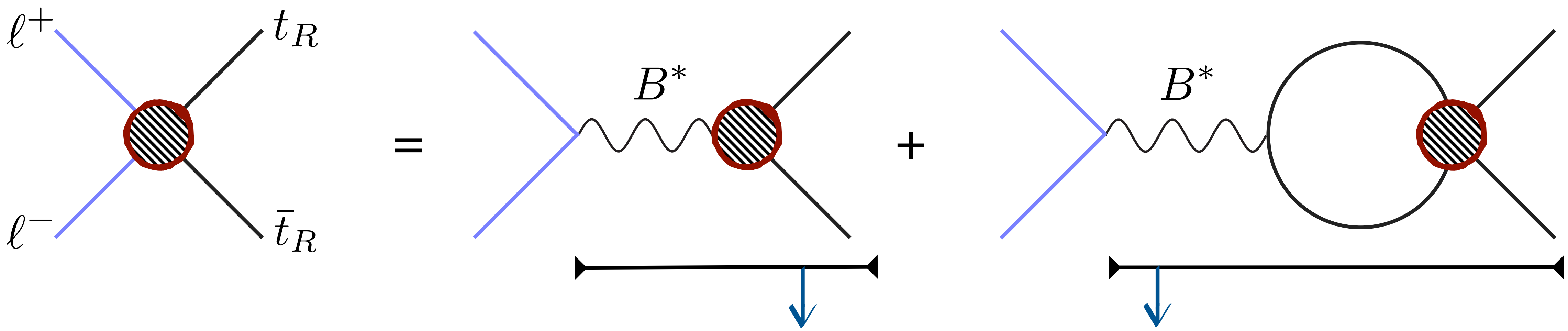
- Higgs precision: $\frac{g_*^2}{m_*^2}\partial_\mu |H|^2 \partial^\mu |H|^2$
- Z-parameter: $\frac{g_s^2}{g_*^2 m_*^2}(D_\rho G_{\mu\nu})^2$

(Banelli et al. 2010.05915)

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.

$$\frac{c_{te}}{m_*^2}(\bar e_R\gamma_\mu e_R)(\bar t_R\gamma^\mu t_R)$$

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

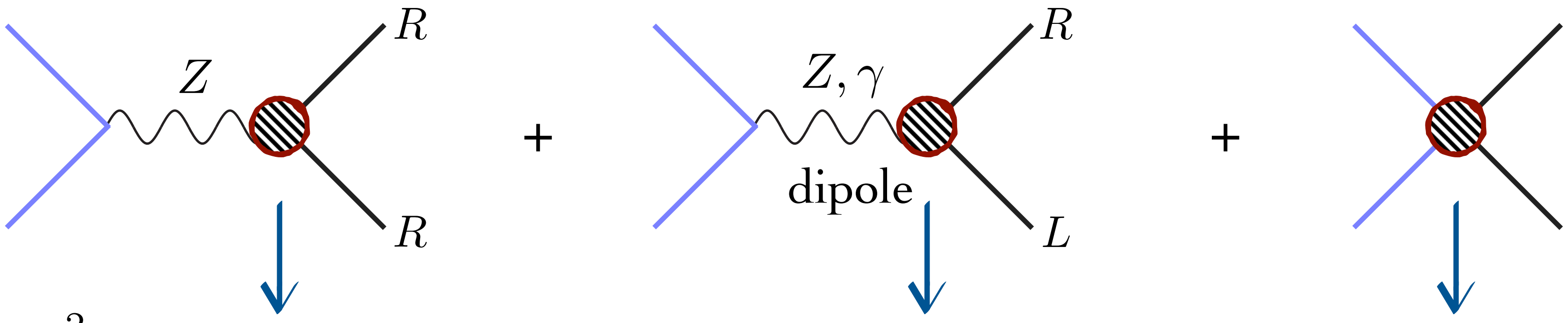
$$\frac{c_{te}}{m_*^2} = 2\frac{c_{t\ell}}{m_*^2} = \frac{g'^2}{m_*^2}\left(\frac{32}{9}\,\frac{g_*^2}{16\pi^2}\log + \text{finite}\right)$$

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

Future lepton colliders

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

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



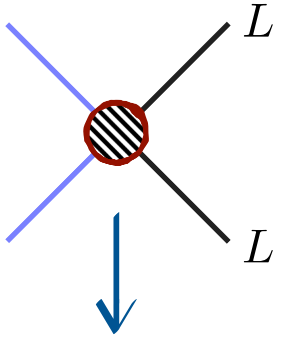
$$\frac{g_*^2}{m_*^2}(H^\dagger D_\mu H)(\bar{t}_R\gamma^\mu t_R) \qquad \frac{y_t g}{m_*^2}\bar{q}_L H\sigma_{\mu\nu}W^{\mu\nu}t_R \qquad \frac{c_{te}}{m_*^2}(\bar{e}_R\gamma_\mu e_R)(\bar{t}_R\gamma^\mu t_R)$$

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

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

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

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

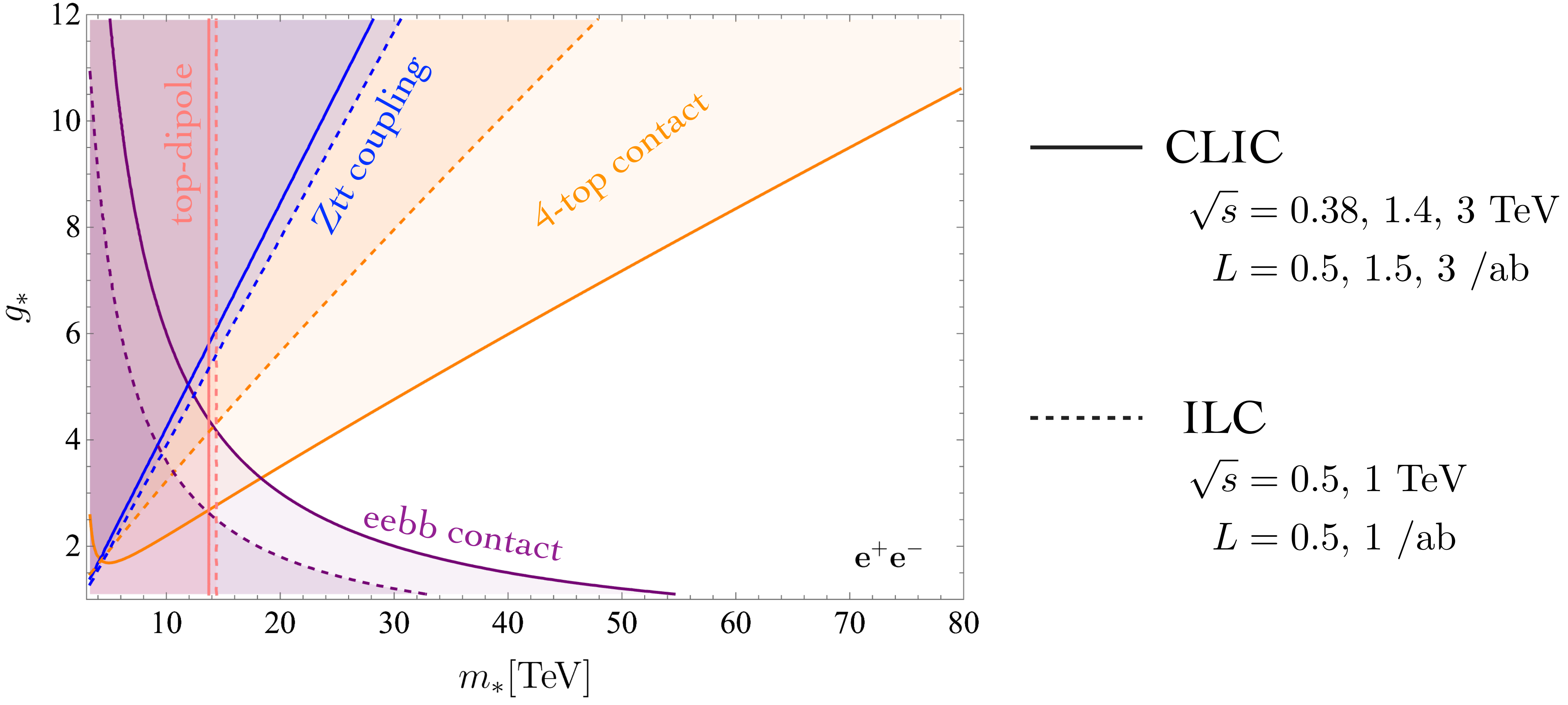


$$\sim \frac{y_t^2 g^2}{g_*^2 m_*^2}s$$

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

Future lepton colliders: ILC vs CLIC

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



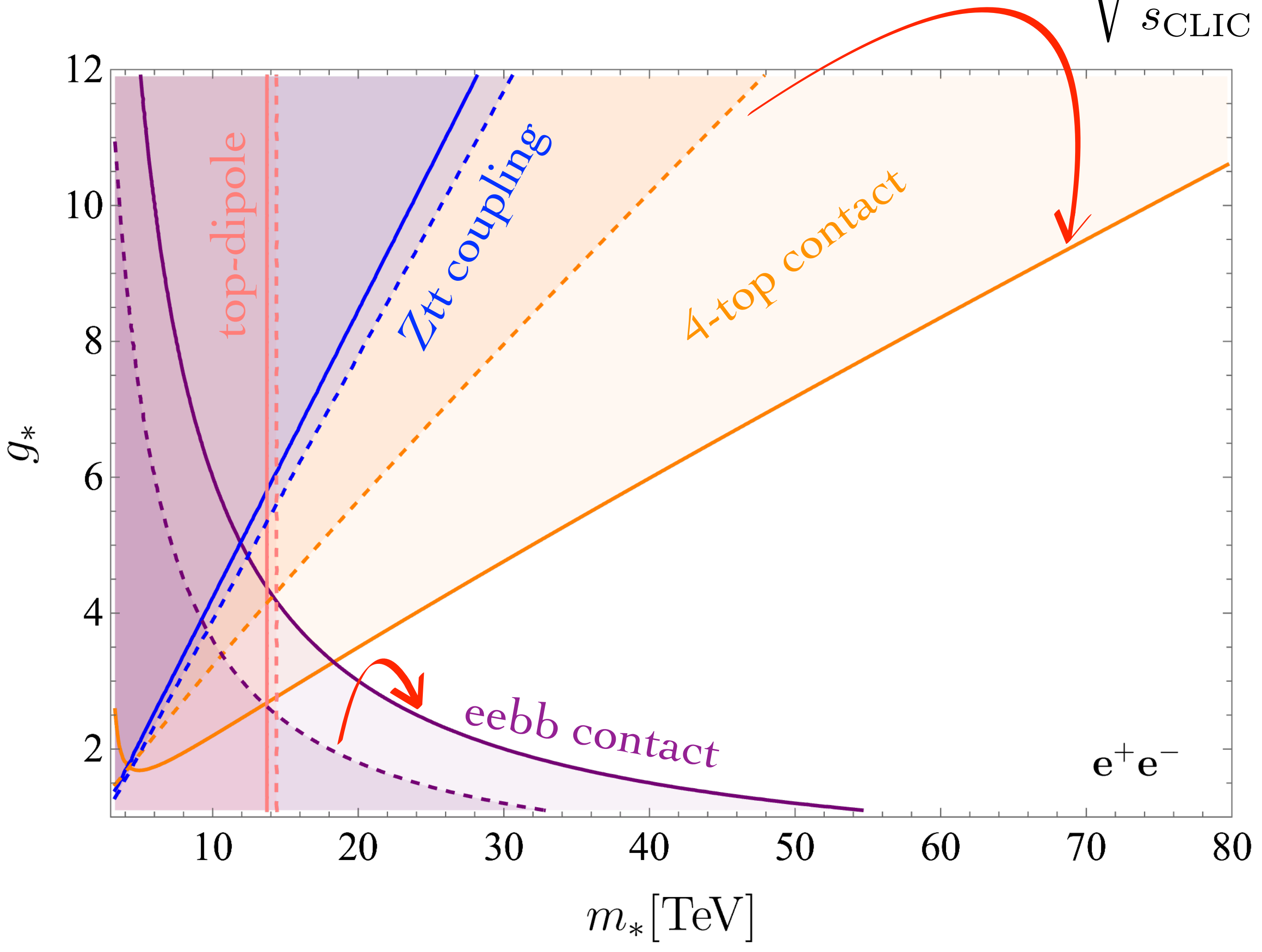
Based on reinterpretation of results for sensitivity to the individual operators: Durieux, Perelló, Vos, Zhang '18.
See also Durieux, Matsedonskyi '18.

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.

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



—— 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

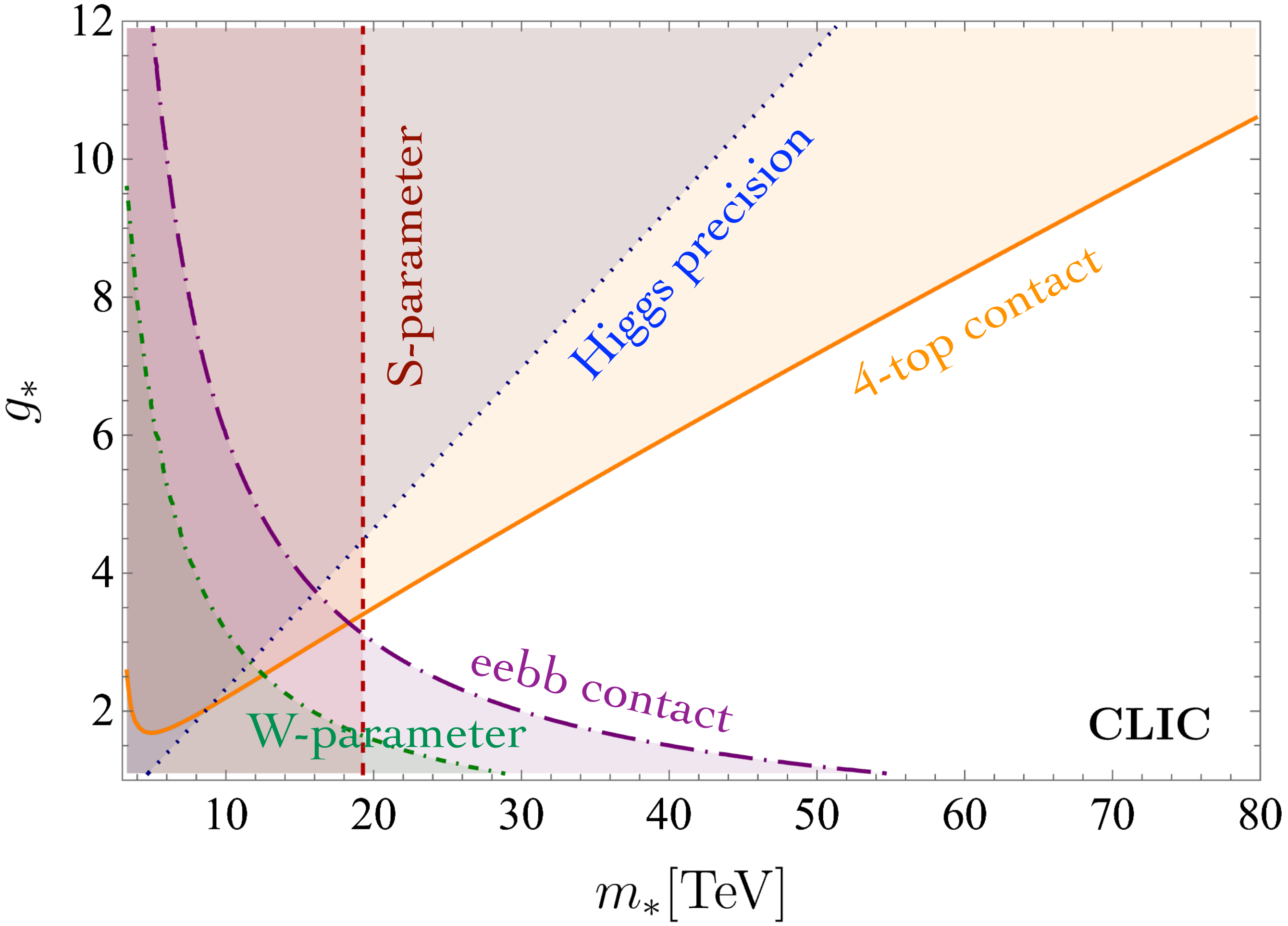
Based on reinterpretation of results for sensitivity to the individual operators: Durieux, Perelló, Vos, Zhang '18.
See also Durieux, Matsedonskyi '18.

Contact interactions and highest-energy runs dominate the sensitivity.

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)

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

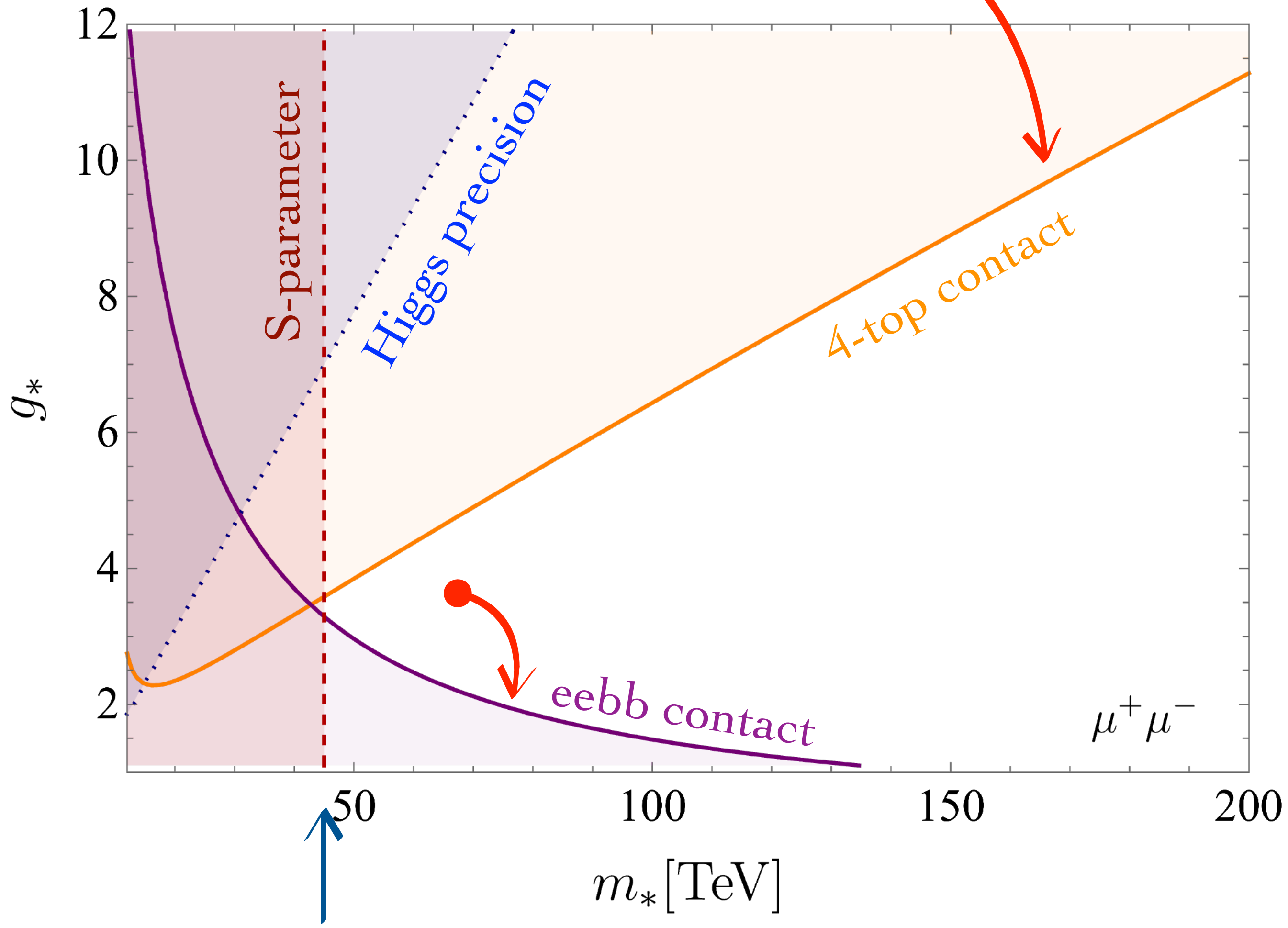
(de Blas et al. '19)

(JS preliminary)

Top and Higgs compositeness: muon collider

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

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



(Buttazzo et al. '20)

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

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

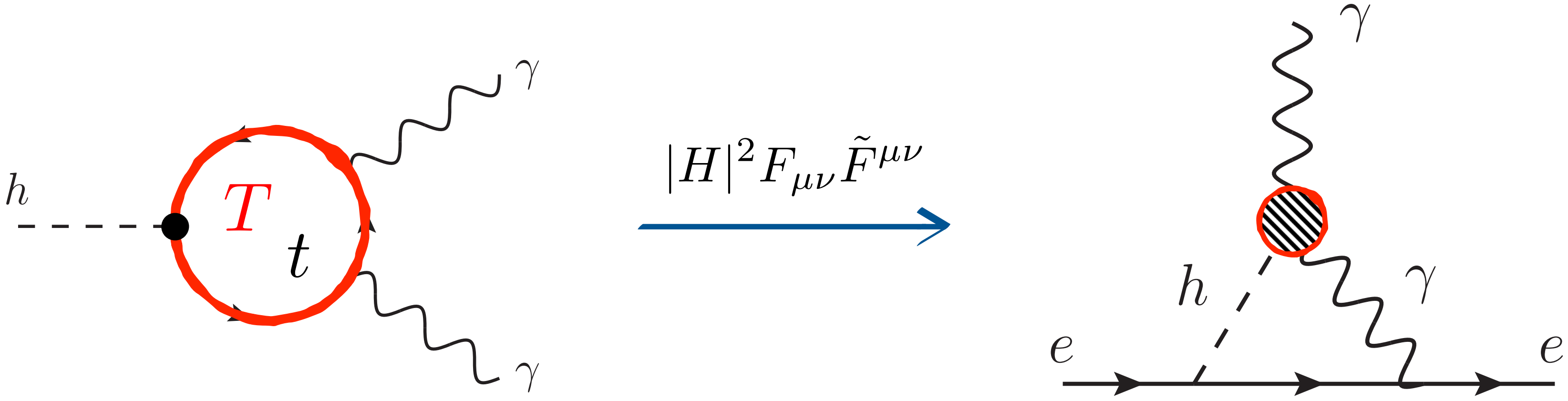
(Han et al. '20)

Main assumption is that uncertainty remains statistically dominated.

(Panico et al. '17, '18)

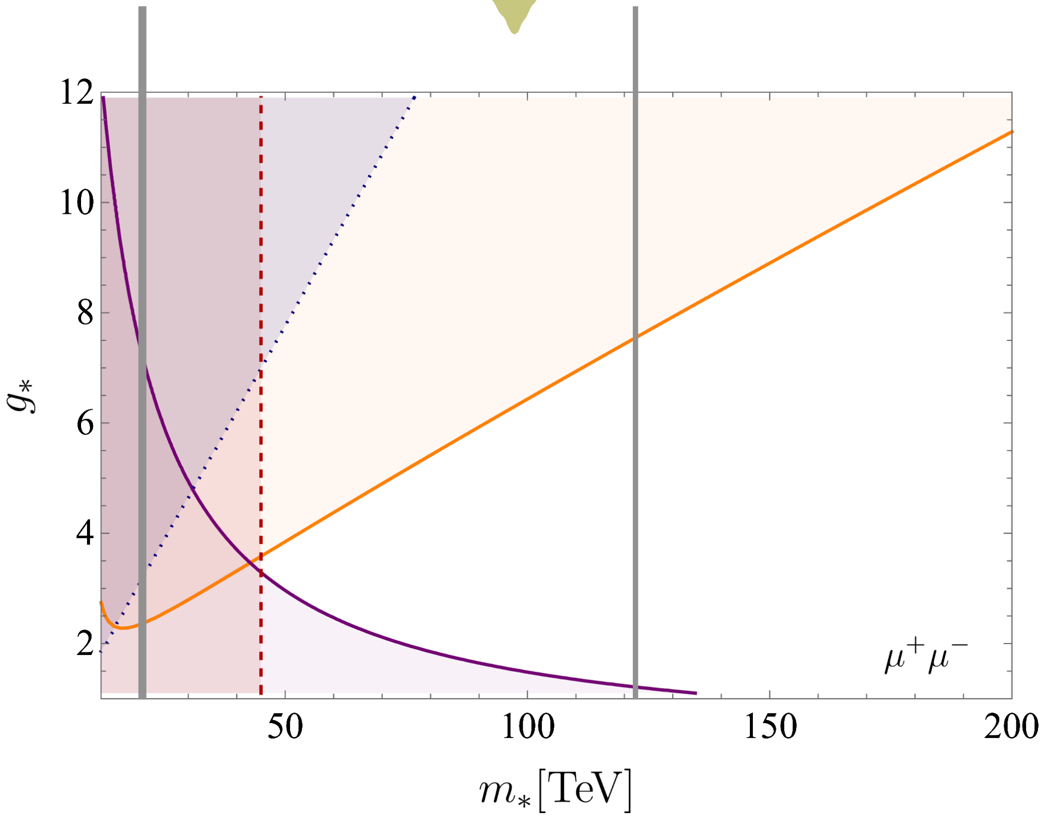
Top and Higgs compositeness: e-EDM

Another example of RGE running associated with the top: two-loop, CP-violating effect.



ACME II $|d_e| < 1.1 \times 10^{-29}\, e\,\mathrm{cm}$

ACME III $|d_e| < 0.3 \times 10^{-30}\, e\,\mathrm{cm}$



Impressive sensitivity to CP-violation by a strongly-interacting top and Higgs.

Outlook

Partial list of interesting future points/ideas/directions on multi-TeV colliders.

- Definite sign of BSM physics.

Outlook

Partial list of interesting future points/ideas/directions on multi-TeV colliders.

- Future hadron colliders (FCC-hh):
  - Sensitivity analysis of 4-top production in fully hadronic channel (machine learned).
  - Comparison of sensitivities with multiple top + Higgs production (e.g. strong tW-scattering).
- Future lepton colliders (FCC-ee, ILC, CLIC, muon-collider):
  - Other high-energy growing processes (Constantini et al. '20).
  - Assessment of boosted top production (systematic) uncertainties at muon-collider.
- Independent:
  - Global analysis of leading operators in top-Higgs sector (tree and loop; EW, Higgs, top data).
  - EFT matching to "UV-complete" models (few resonances).

Conclusions

- 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 becoming very interesting.

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

- 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.

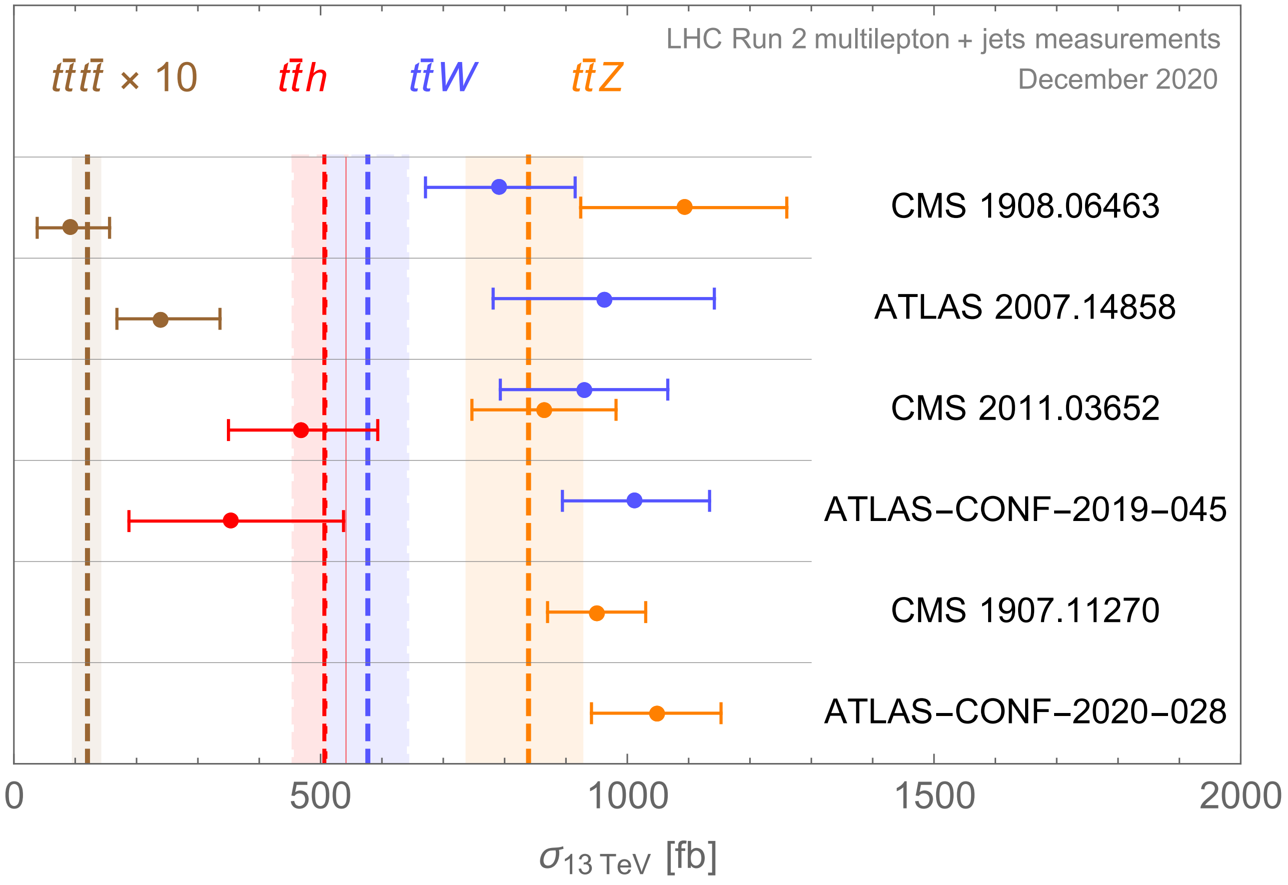
$$\frac{m_*}{g_*}\Big|^{4t}_{\mathrm{LHC,\,36/fb}} \gtrsim 0.73\,\mathrm{TeV} \qquad \frac{m_*}{g_*}\Big|^{4t}_{\mathrm{FCC-hh}} \gtrsim 6.5\,\mathrm{TeV} \qquad \frac{m_*}{g_*}\Big|^{t\bar{t}}_{\mathrm{CLIC\,3}} \gtrsim 7.7\,\mathrm{TeV} \qquad \frac{m_*}{g_*}\Big|^{t\bar{t}}_{\mathrm{muon\,10}} \gtrsim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

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

Thank you.

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.