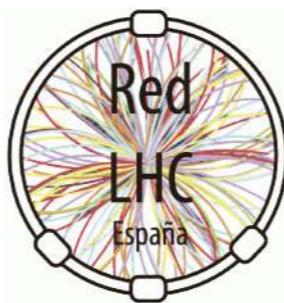


Effective 4-top production at the LHC and beyond

7th RED LHC workshop



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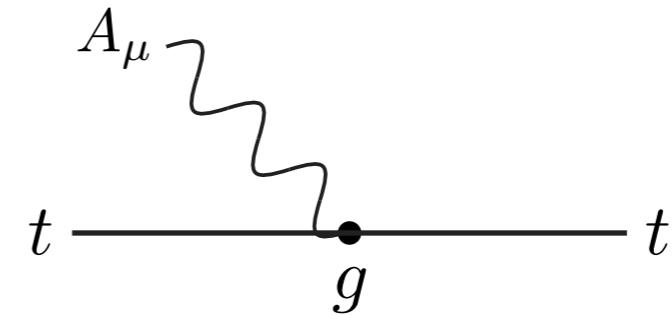
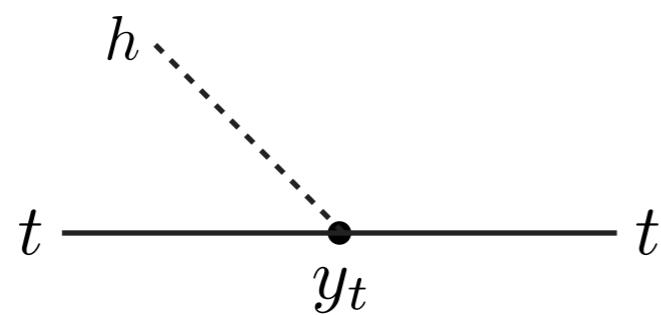


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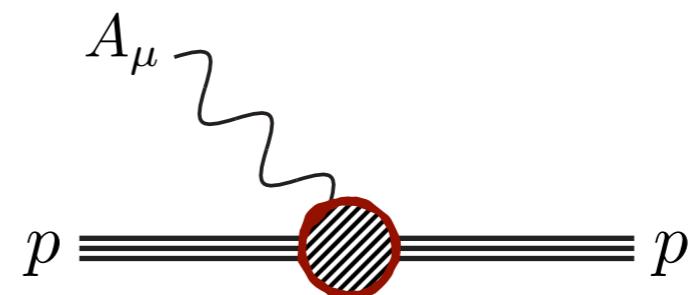
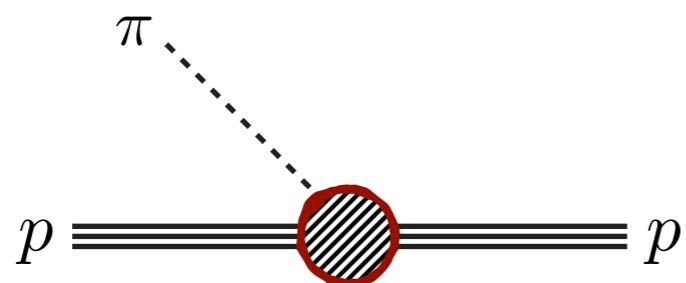
mostly based on arXiv:2010.05915 w/ G.Banelli, E.Salvioni, T.Theil and A.Weiler

Strongly-interacting top quark

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

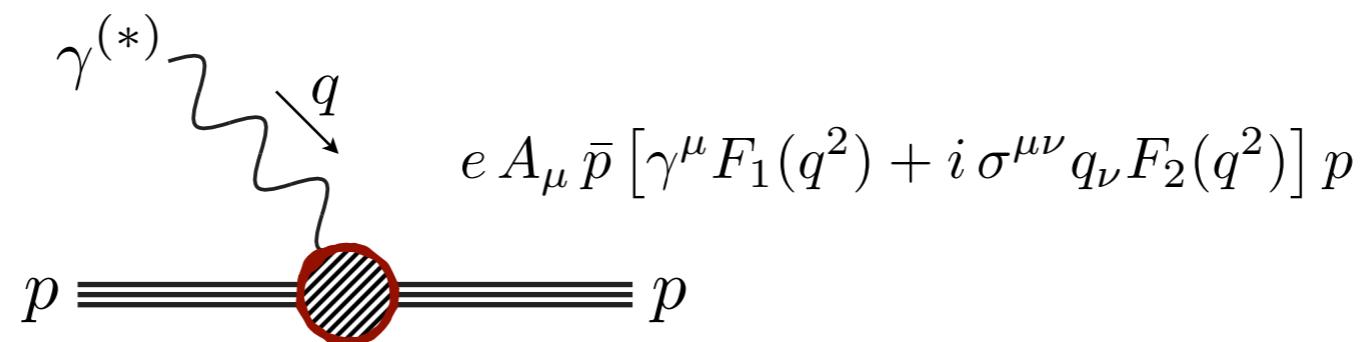


Compelling indication of a deeper structure behind the top quark.



Strongly-interacting → Composite top quark

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



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



Compositeness scale of order of the particle's mass.

$$m_* \sim m_p$$

Chiral top effective compositeness

$$t_R \rightarrow e^{i\alpha} t_R$$

$$q_L \rightarrow e^{-i\alpha} q_L$$

$$m_t \ll m_*$$



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

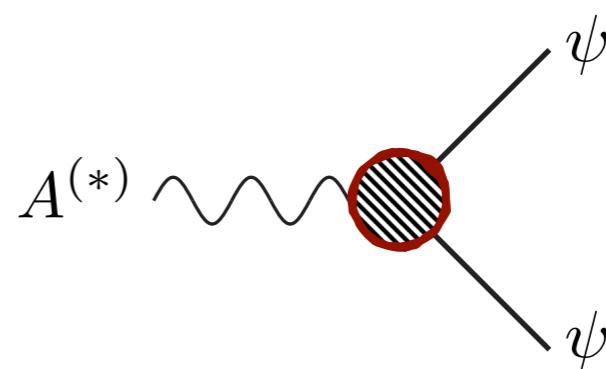
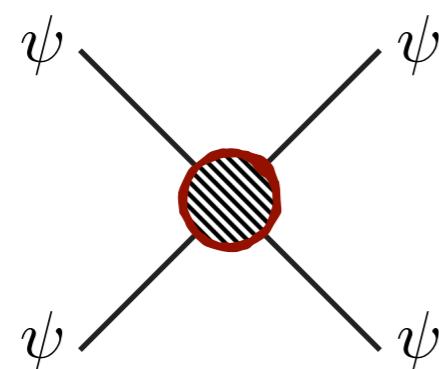
$$\psi = t_R, q_L$$

(Georgi et al. '94)

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

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

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



Two distinct types of non-standard effects.

Chiral top effective compositeness

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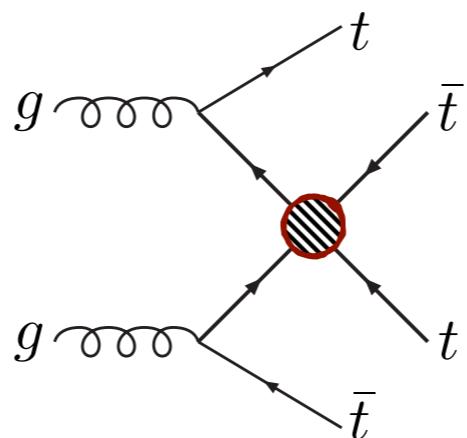
$$\frac{c_{\psi\psi}}{m_*^2} (\bar{\psi}\gamma_\mu\psi)^2$$

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

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

$$c_{\psi D} \sim 1$$

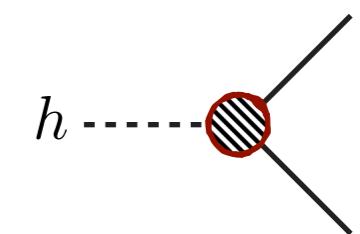
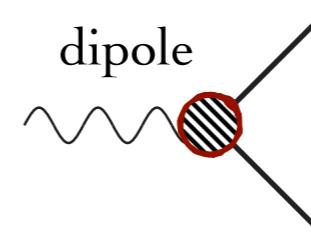
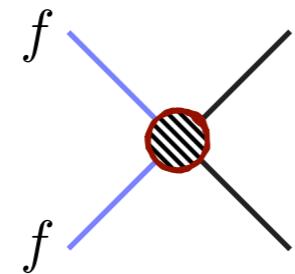
In physical processes, always involve other SM particles (equations of motion).

$$g^2 (H^\dagger D_\mu H)(\bar{\psi}\gamma^\mu\psi)$$

$$g^2 (\bar{f}\gamma_\mu f)(\bar{\psi}\gamma^\mu\psi)$$

$$gy_t \bar{q}_L H \sigma_{\mu\nu} F^{\mu\nu} t_R$$

$$y_t \lambda_H |H|^2 \bar{q}_L H t_R$$



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

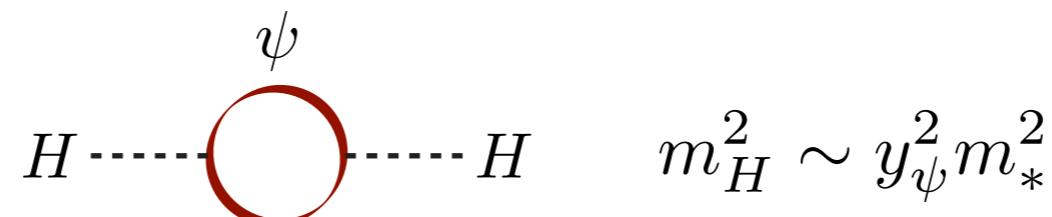
Why top compositeness

- 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.



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

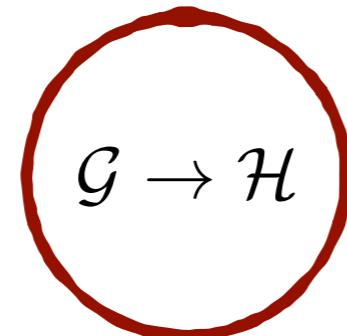
Composite pseudo-Goldstone Higgs

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

(Kaplan, Georgi '83)

$$H \rightarrow H + \Theta$$

strongly-coupled sector



$$V(H) = 0$$

Provides rationale why Higgs is lighter than compositeness scale.

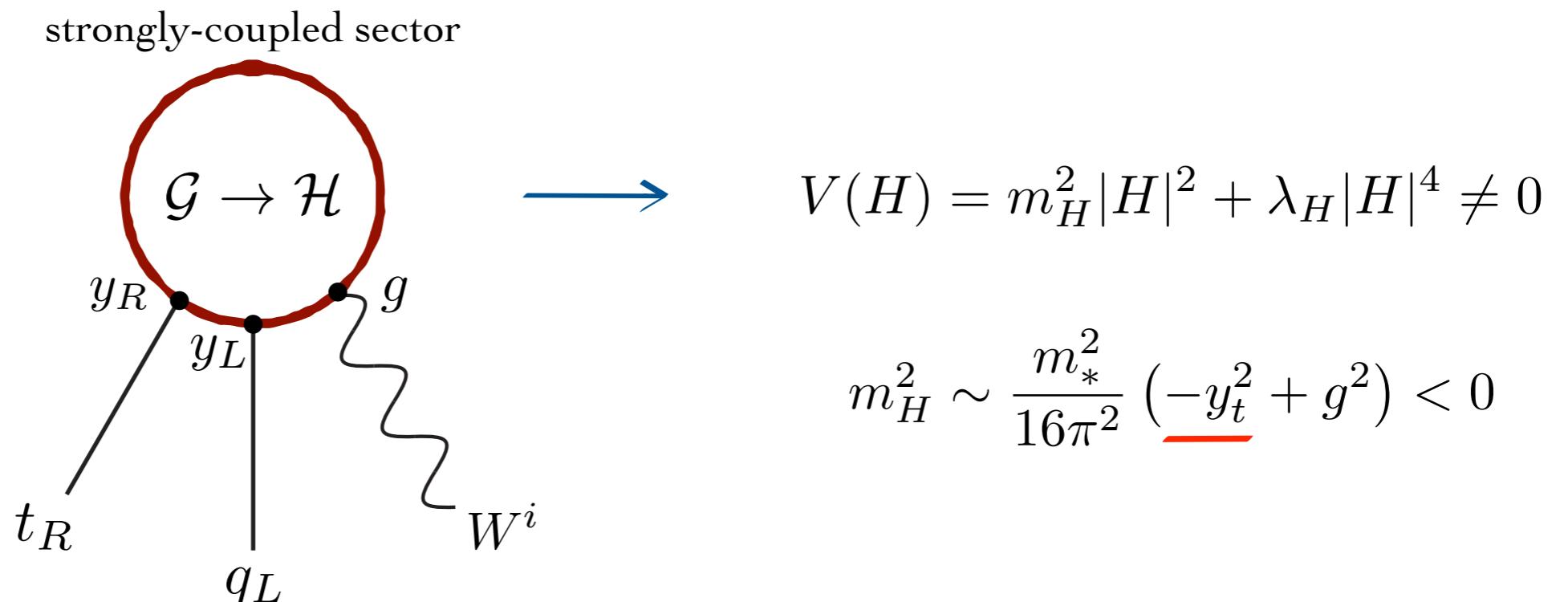
$$m_H \ll m_*$$

Composite pseudo-Goldstone Higgs

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The top quark is crucial to break the electroweak symmetry.

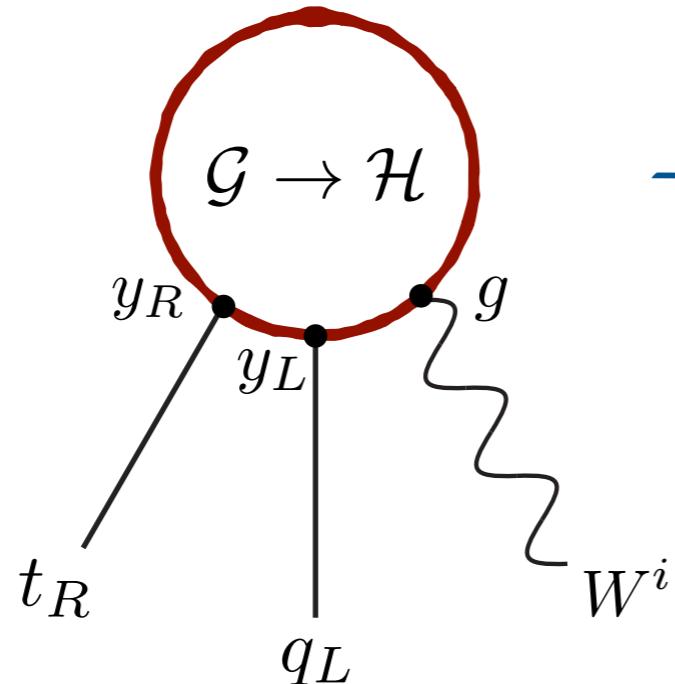
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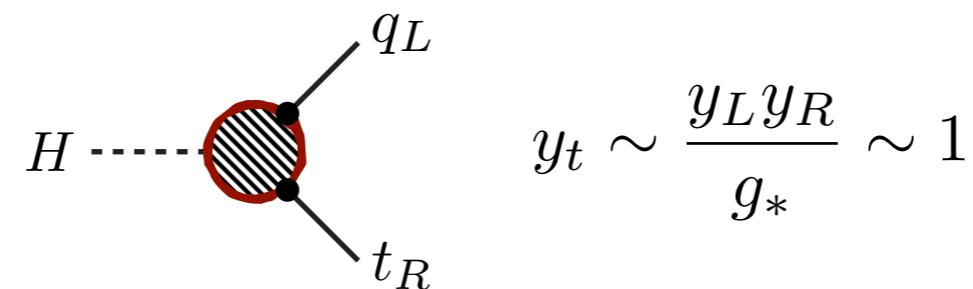
strongly-coupled sector



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

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

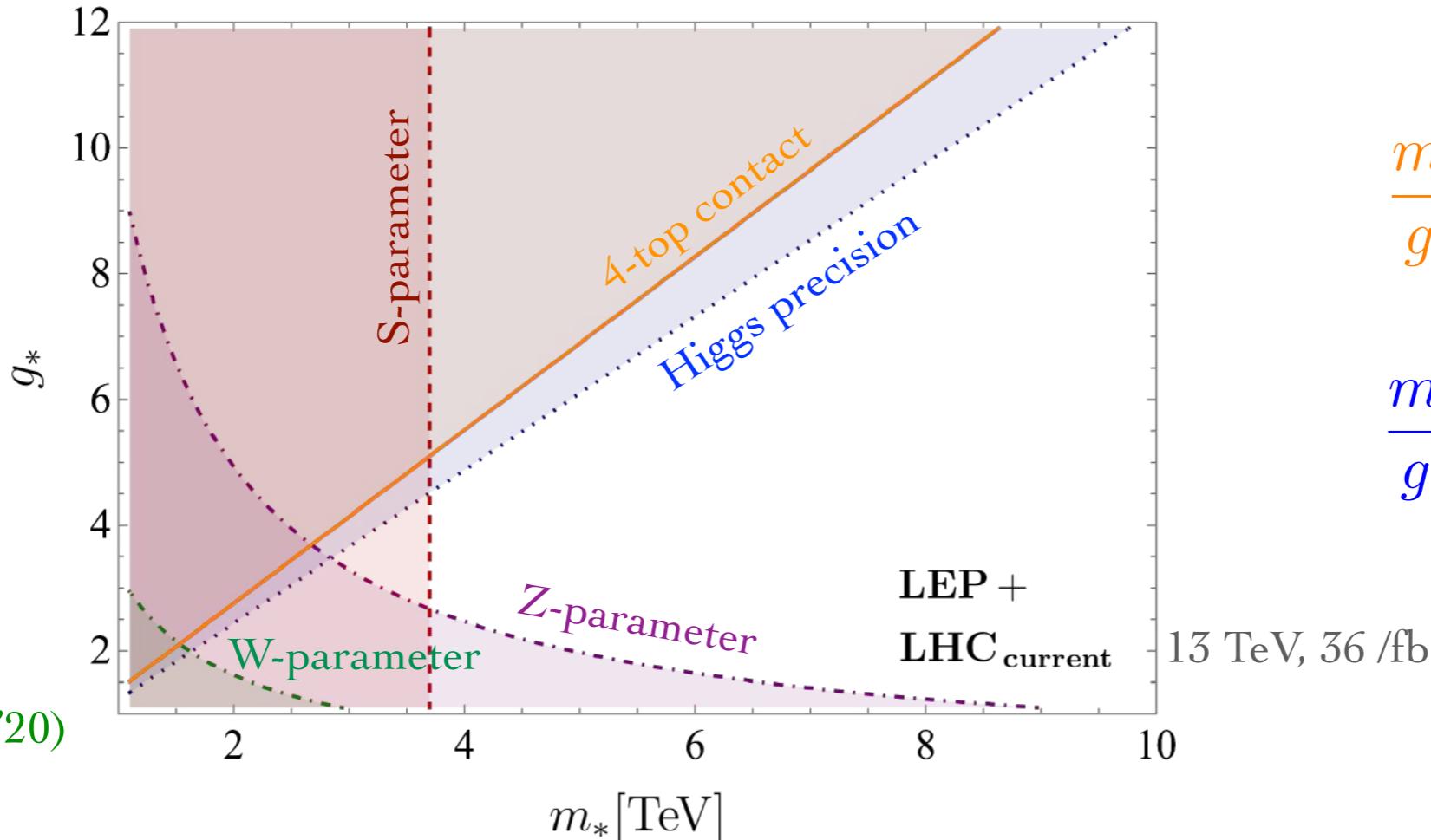
The large top Yukawa requires a large degree of top compositeness.



Top and Higgs compositeness

not quite Current status: LEP + LHC

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



(Banelli et al. '20)

- **4-top contact:** $\frac{g_*^2}{m_*^2} (\bar{t}_R \gamma_\mu t_R)^2$
- **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:** $\frac{g^2}{g_*^2 m_*^2} (D_\rho W_{\mu\nu})^2$

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

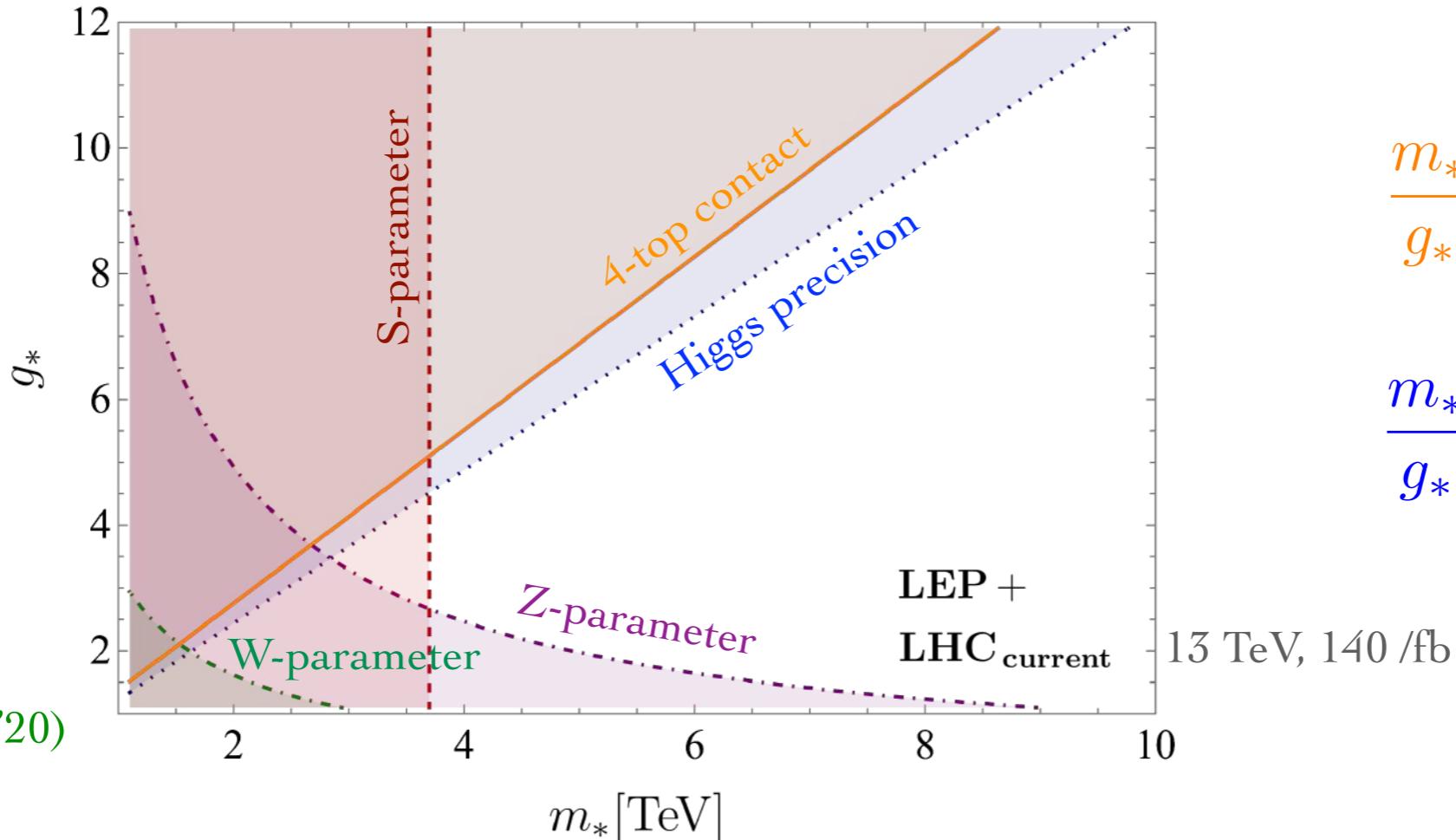
(ATLAS '18; 1811.02305)

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

(Cepeda et al. '19)

Current status: LEP + LHC

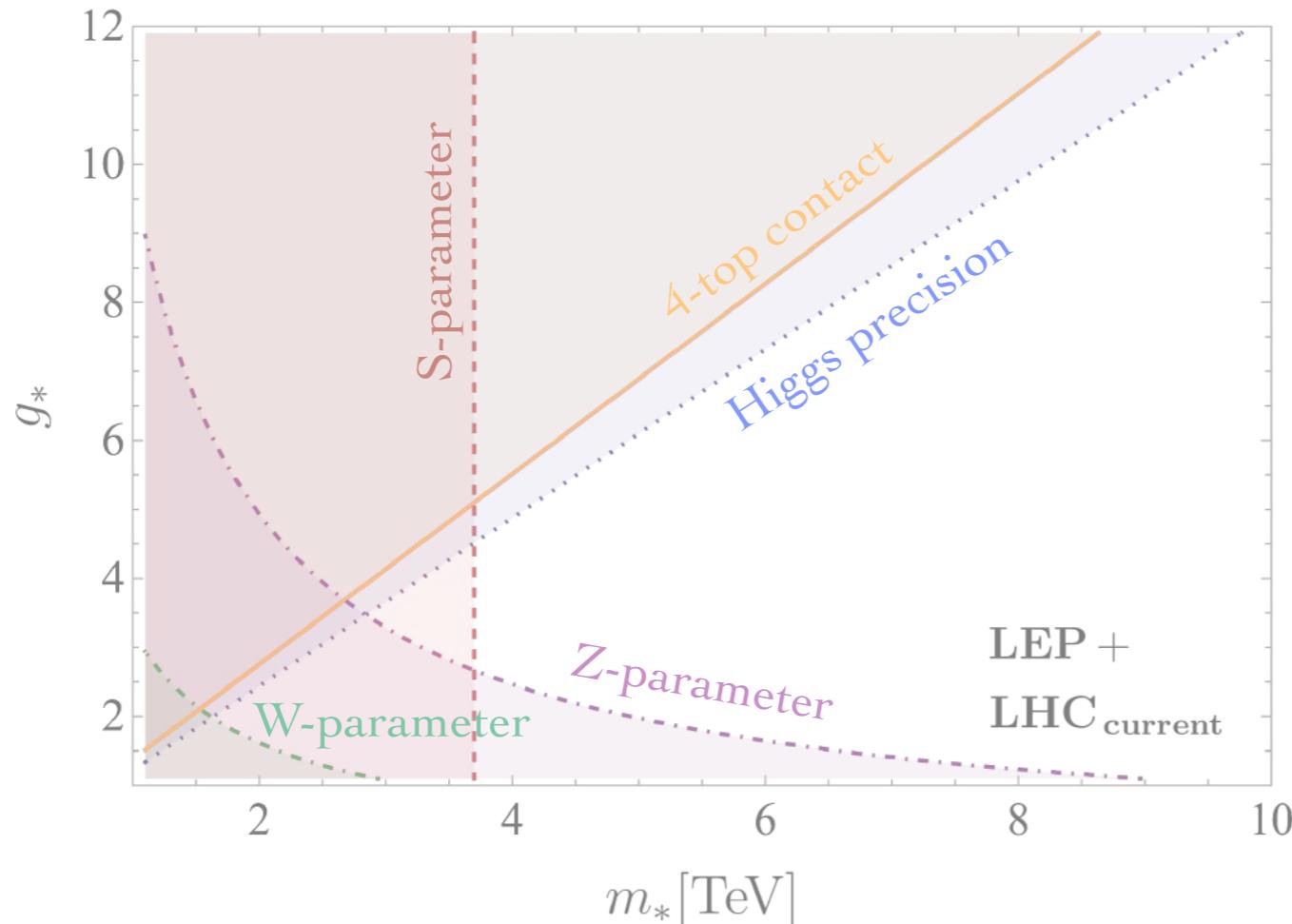
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- 4-top contact: $\frac{g_*^2}{m_*^2} (\bar{t}_R \gamma_\mu t_R)^2$
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- S-parameter: $\frac{gg'}{m_*^2} H^\dagger W_{\mu\nu} H B^{\mu\nu}$
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- W-parameter: $\frac{g^2}{g_*^2 m_*^2} (D_\rho W_{\mu\nu})^2$

near Future projection: LEP + HL-LHC

Constraints from 4-top production at the same level or stronger than from Higgs precision.



$$\frac{m_*}{g_*} \gtrsim (1.3 - 1.7) \text{ TeV}$$

(Banelli et al. '20)

$$\frac{m_*}{g_*} \gtrsim 1.4 \text{ TeV}$$

(Cepeda et al. '19)

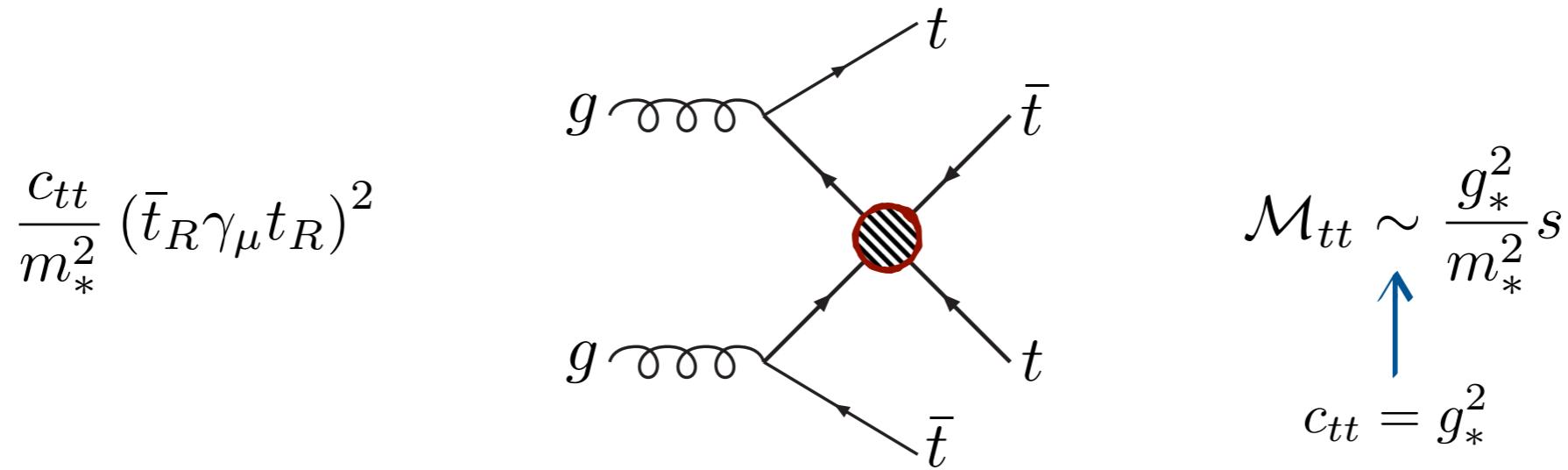
14 TeV, 3 /ab

- 4-top contact: $\frac{g_*^2}{m_*^2} (\bar{t}_R \gamma_\mu t_R)^2$
- Higgs precision: $\frac{g_*^2}{m_*^2} \partial_\mu |H|^2 \partial^\mu |H|^2$
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Future multi-TeV Colliders

Future hadron colliders: FCC-hh

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

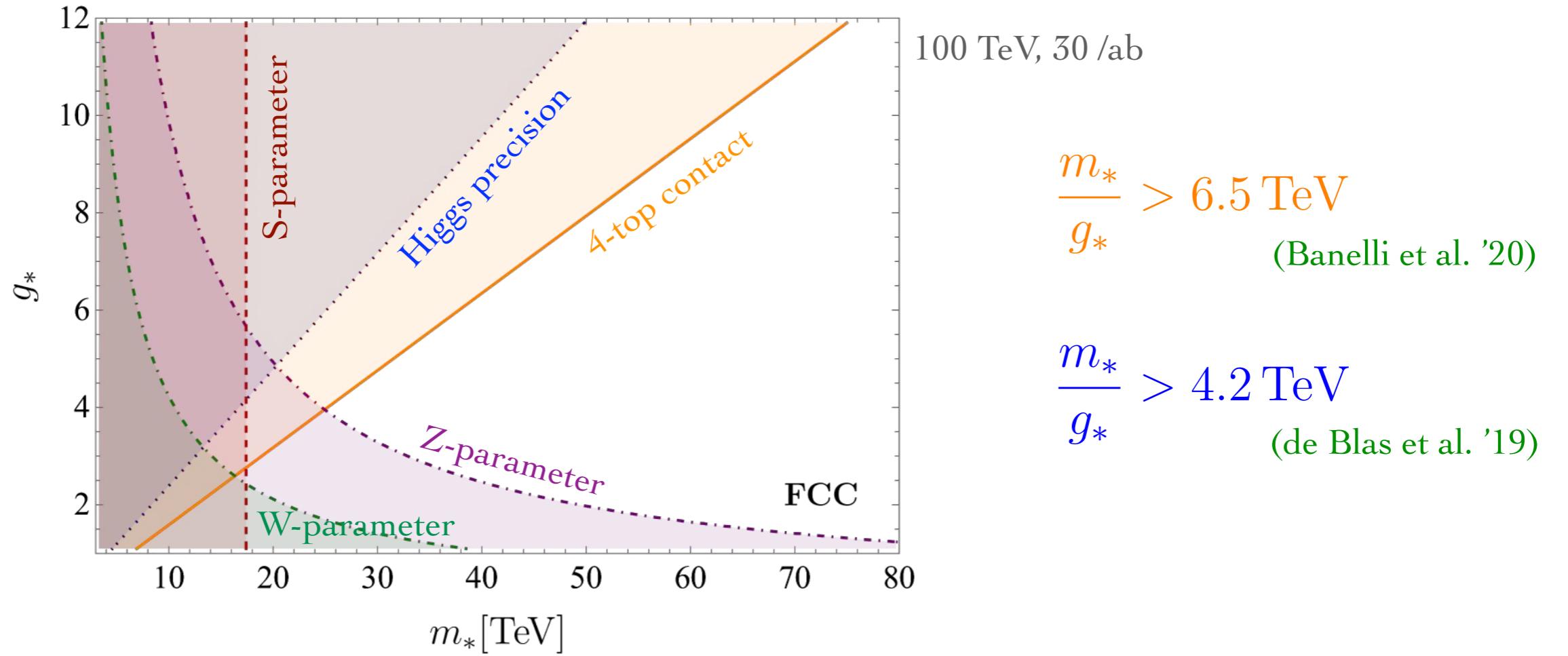


- Same-sign di-lepton and tri-lepton final states.
 - Larger relative SM 4-top rate than main backgrounds:
- | | | | |
|---|---------------|--|--------------|
| $\frac{\sigma_{100 \text{ TeV}}}{\sigma_{13 \text{ TeV}}} \Big _{t\bar{t}t\bar{t}}$ | ≈ 350 | $\frac{\sigma_{100 \text{ TeV}}}{\sigma_{13 \text{ TeV}}} \Big _{t\bar{t}W}$ | ≈ 40 |
|---|---------------|--|--------------|
- (Frederix, Pagani, Zaro '17)
- Builds on ATLAS (1811.02305), CMS (1908.06463) and SM-theory 4-top analyses (Alvarez et al '16).

Top and Higgs compositeness: FCC

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

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



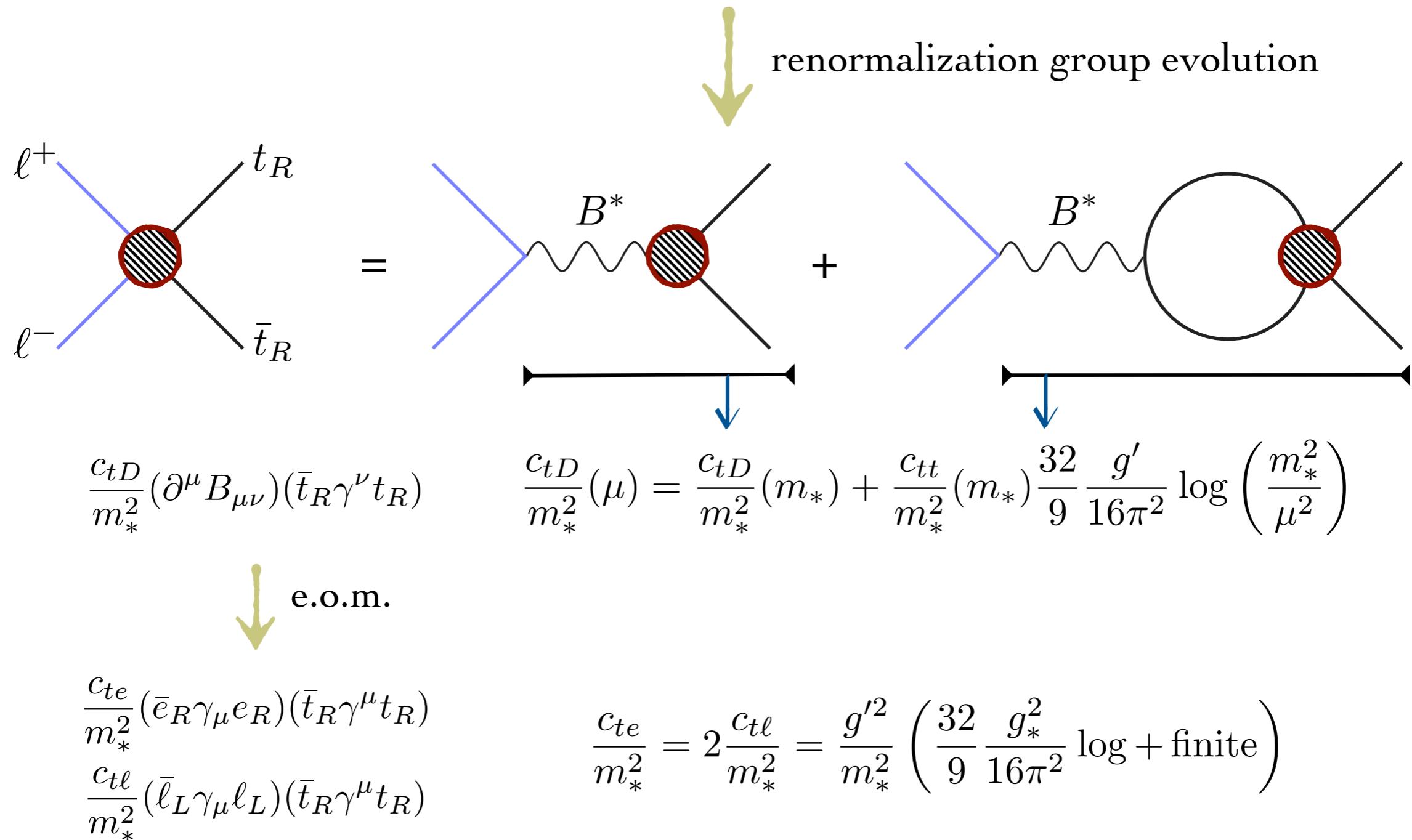
Higher than Higgs couplings even if these are from full FCC (-ee/-hh) program.

- 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

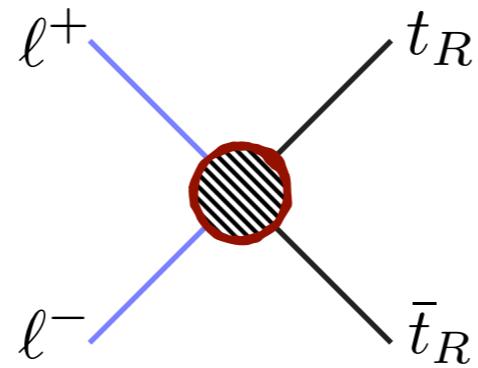
Not feasible to directly probe 4-top contact interactions at lepton colliders.



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

Future lepton colliders

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

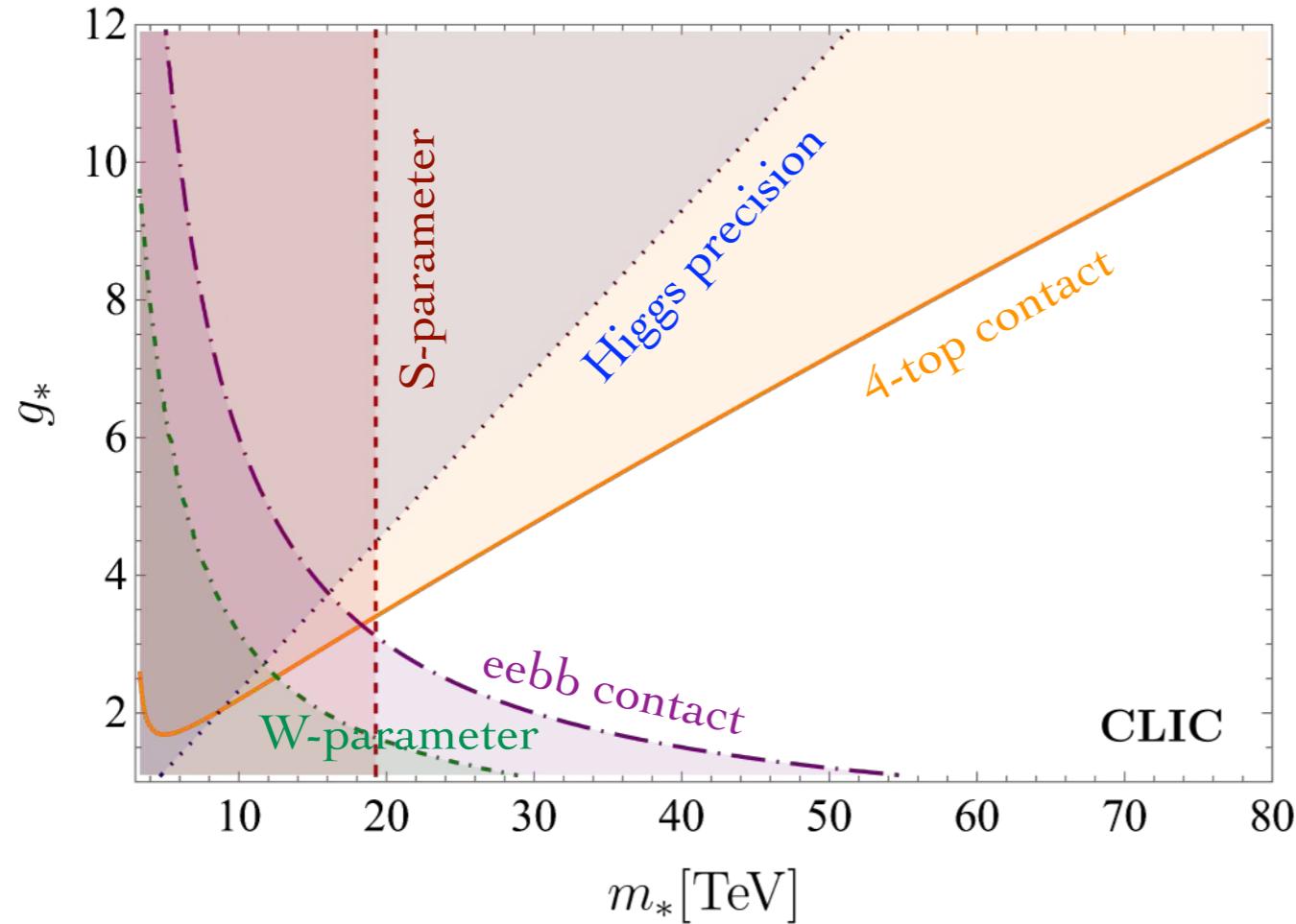
$$\frac{c_{te}}{m_*^2} (\bar{e}_R \gamma_\mu e_R)(\bar{t}_R \gamma^\mu t_R)$$

$$\mathcal{M}_{\ell^+ \ell^- \rightarrow t\bar{t}} \sim \frac{g_*^2}{m_*^2} s$$

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

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)

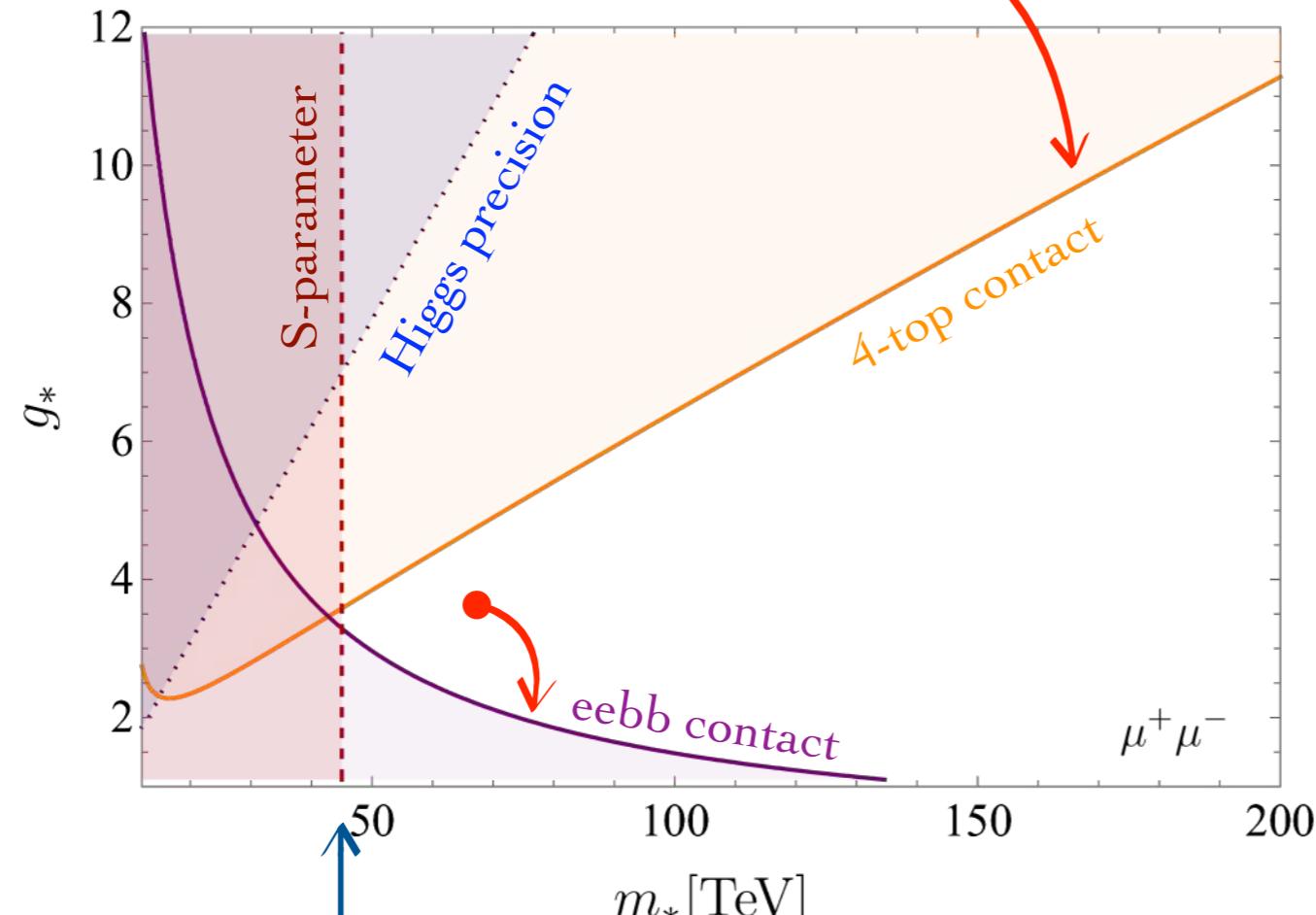
Based on reinterpretation of results for sensitivity to the individual operators: Durieux, Perelló, Vos, Zhang '18.
See also Durieux, Matsedonskyi '18.

Highest-energy colliders/runs dominate the sensitivity.

Top and Higgs compositeness: muon collider

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

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



(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.

See also Chen et al. '22.

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 $t\bar{t}$ -scattering in 4-top production.

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

$$\frac{m_*}{g_*} \left|_{\text{LHC, 140/fb}}^{4t} \right. \gtrsim 0.73 \text{ TeV} \quad \frac{m_*}{g_*} \left|_{\text{FCC-hh}}^{4t} \right. \gtrsim 6.5 \text{ TeV} \quad \frac{m_*}{g_*} \left|_{\text{CLIC 3}}^{t\bar{t}} \right. \gtrsim 7.7 \text{ TeV} \quad \frac{m_*}{g_*} \left|_{\text{muon 10}}^{t\bar{t}} \right. \gtrsim 18 \text{ TeV}$$

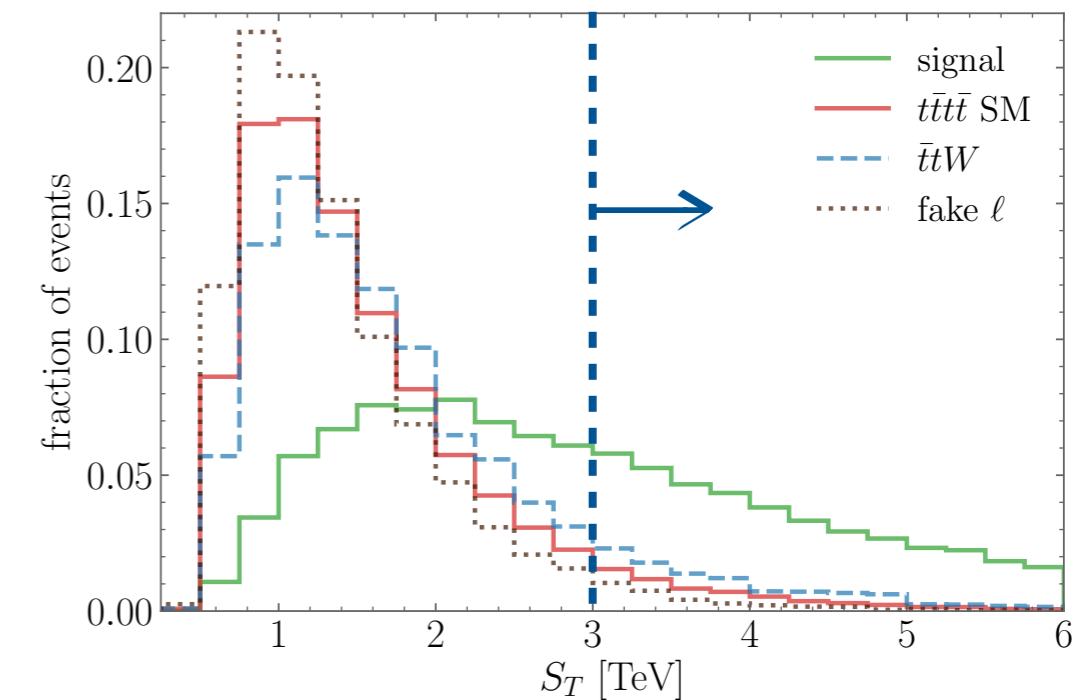
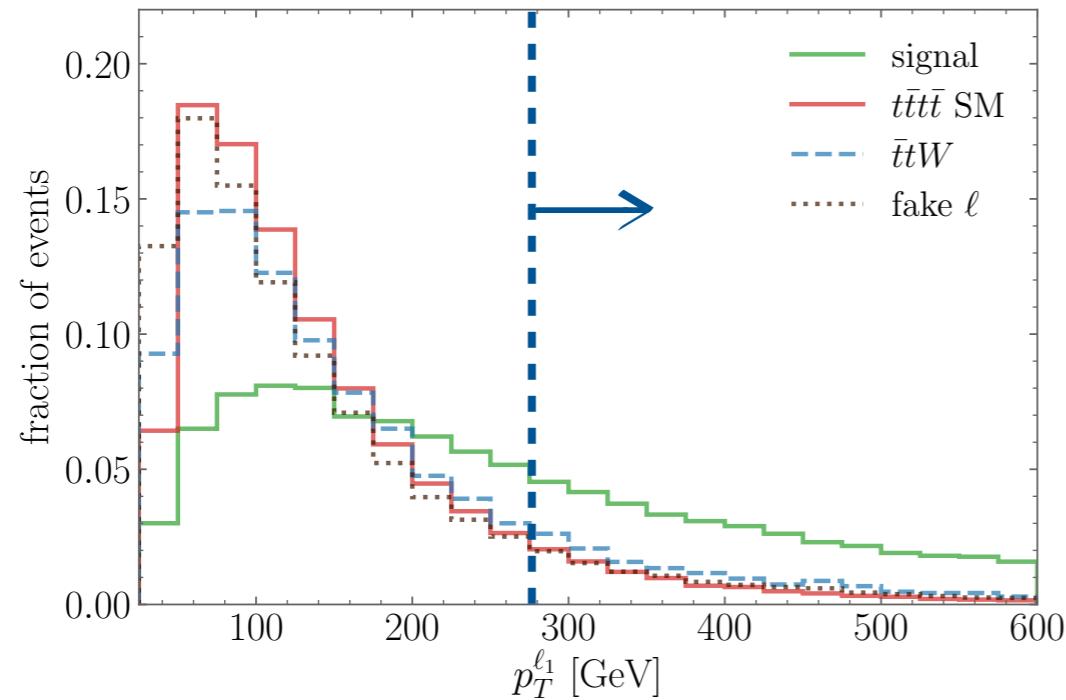
Exploring levels of electroweak-scale fine-tuning below the per-mille level.

Thank you.

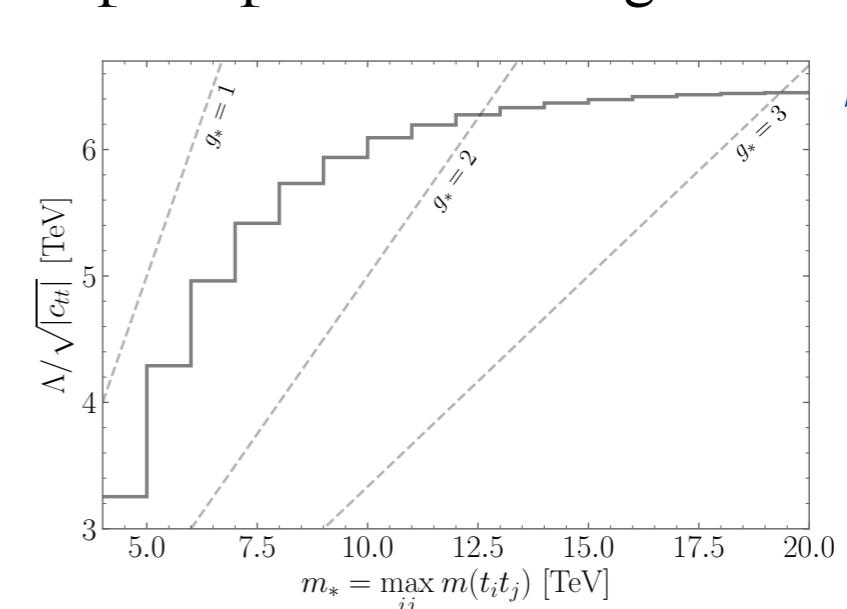
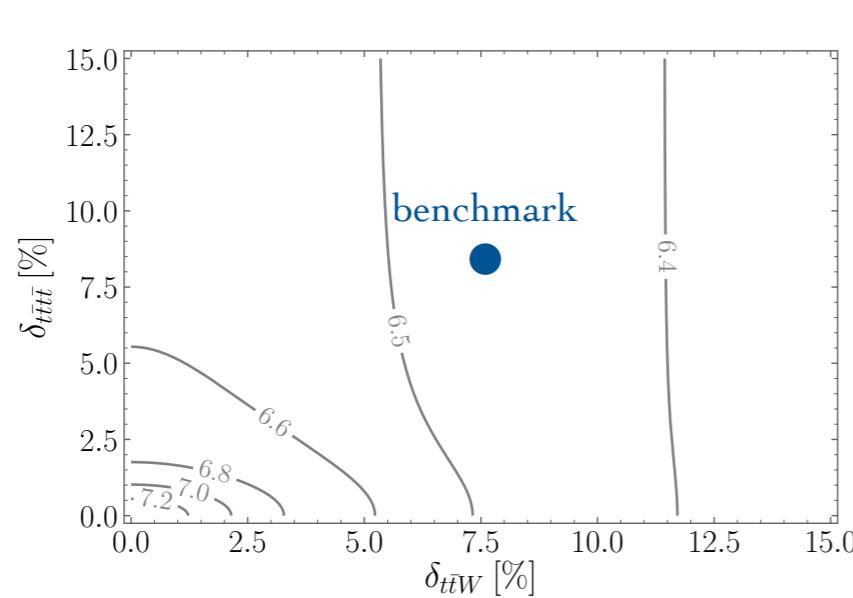
Future hadron colliders: FCC-hh

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

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

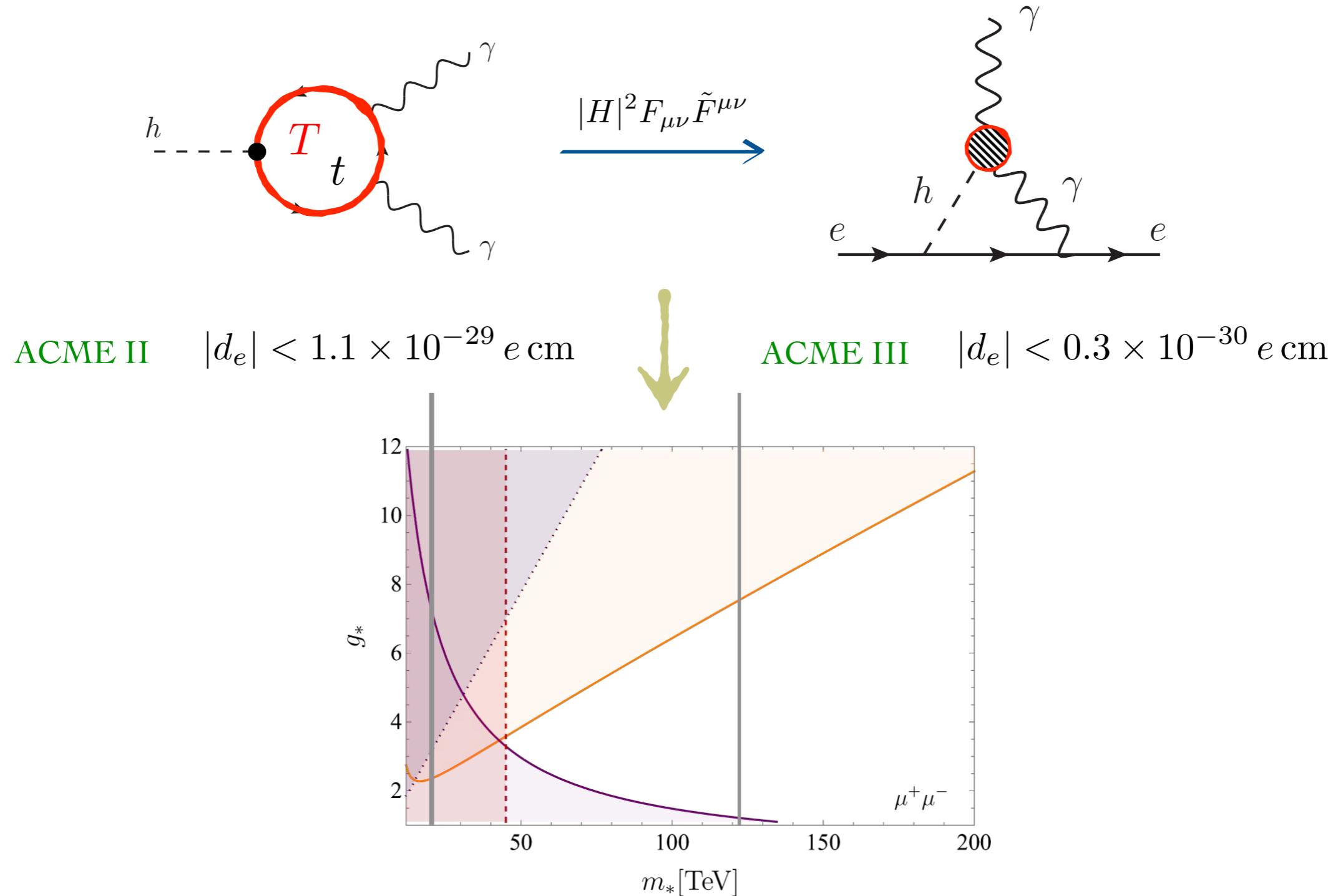


Checked dependence on background systematics, fake-lepton prob., EFT regime of validity.



Top and Higgs compositeness: e-EDM

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



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

Future lepton colliders

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

$$\mathcal{M}_{\ell^+ \ell^- \rightarrow t\bar{t}} \sim \begin{array}{c} \text{Diagram: } \text{Blue line (lepton)} \rightarrow \text{Wavy line (Z)} \rightarrow \text{Red circle (contact interaction)} \rightarrow \text{Two black lines (R)} \\ + \end{array}$$

$\frac{g_*^2}{m_*^2} (H^\dagger D_\mu H)(\bar{t}_R \gamma^\mu t_R)$

 $\sim \frac{g_*^2}{m_*^2} m_W^2$

$\frac{y_t g}{m_*^2} \bar{q}_L H \sigma_{\mu\nu} W^{\mu\nu} t_R$

 dipole

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

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

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

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

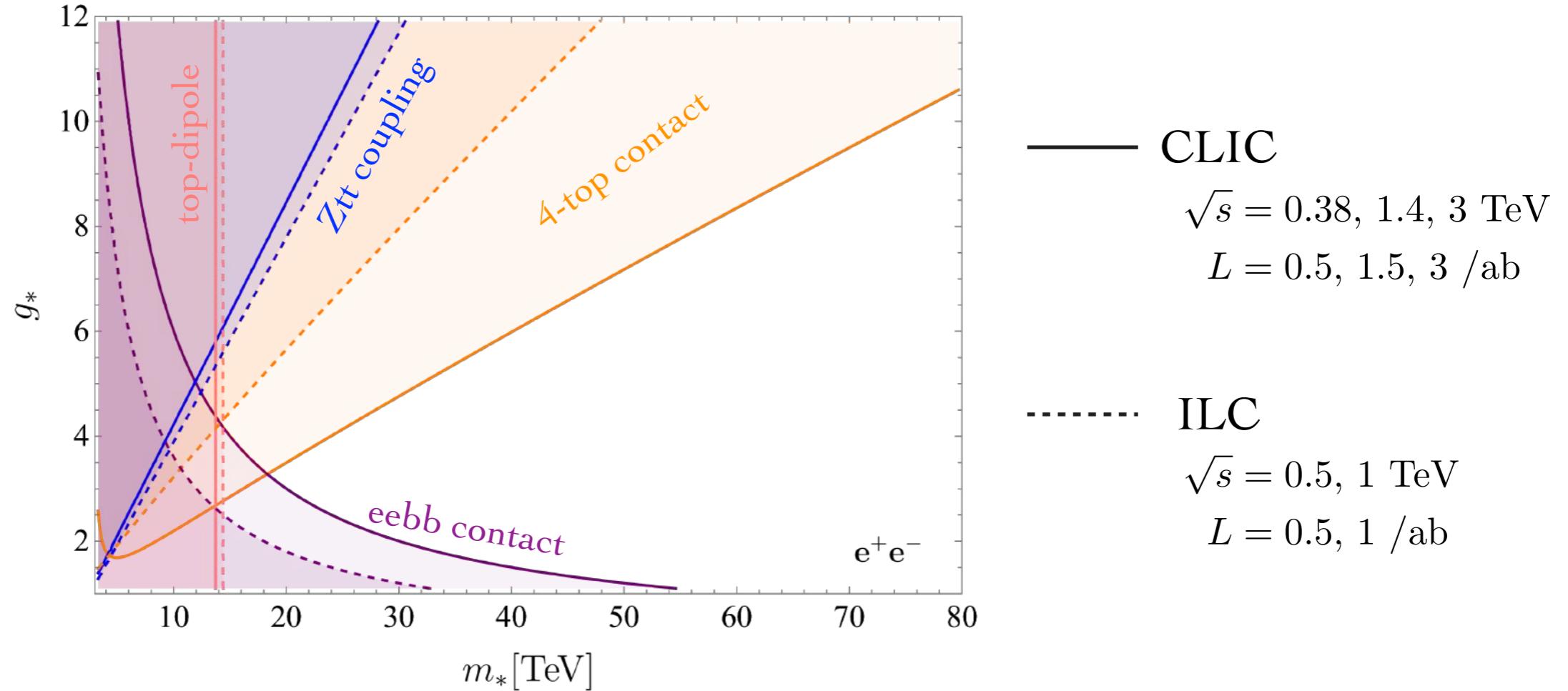
- Bottom pair-production provides sensitivity to the weakly coupled regime $g_* \sim 1$.

$$\mathcal{M}_{\ell^+ \ell^- \rightarrow b\bar{b}} \sim \begin{array}{c} \text{Diagram: } \text{Blue line (lepton)} \rightarrow \text{Red circle (contact interaction)} \rightarrow \text{Two black lines (L)} \\ \sim \frac{y_t^2 g^2}{g_*^2 m_*^2} s \end{array}$$

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

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.