Opportunities for top quark physics at a μ-collider

Snowmass Energy Frontier Workshop Restart:

Parallel session EF03

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based on 2010.05915 with G.Banelli, E.Salvioni, J. Serra and A. Weiler

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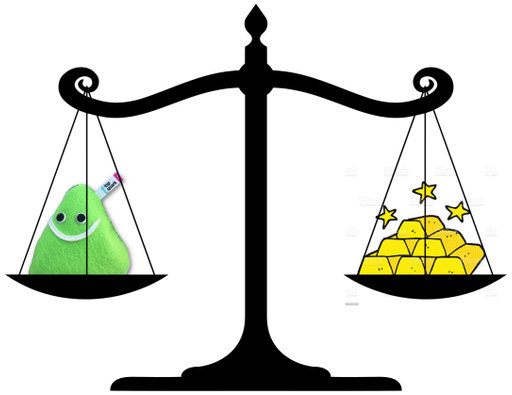
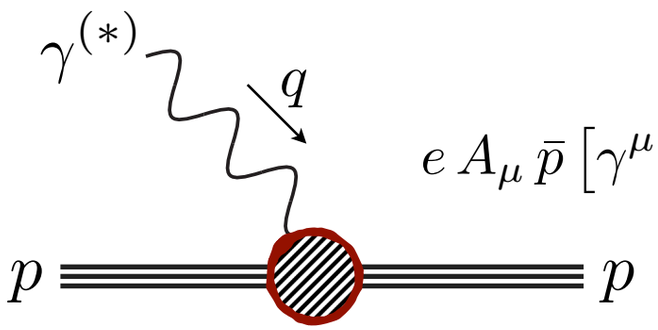
Top quark compositeness



Top quark as the heaviest fermion in the SM , $m_t \approx 173\,\mathrm{GeV}$

As far as we know, the top is elementary, compare e.g. to the proton



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

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

Substructure is resolved around the proton mass

$$m_* \sim m_p$$

We have not seen any new degrees of freedom around the top mass

Higgs compositeness and the top

The Higgs field arises from the breaking of a new global symmetry.

[Kaplan, Georgi '83]

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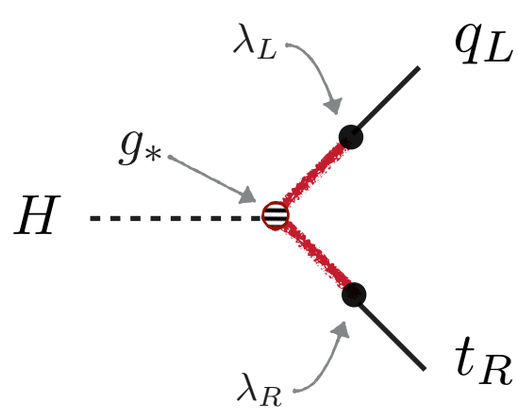
Explicit breaking by couplings to the elementary sector

Like for the pions in QCD, this generates a hierarchy of scales $m_H \ll m_*$

Couplings of fermions must reproduce known Yukawas



$$y_t \sim g_* \lambda_L \lambda_R$$

Consider fully composite right-handed top: $\lambda_R \to 1,\ \lambda_L \to y_t/g_*$

Top compositeness as an EFT

Parametrize top compositeness with effective operators

[Georgi et al. '94]

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

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

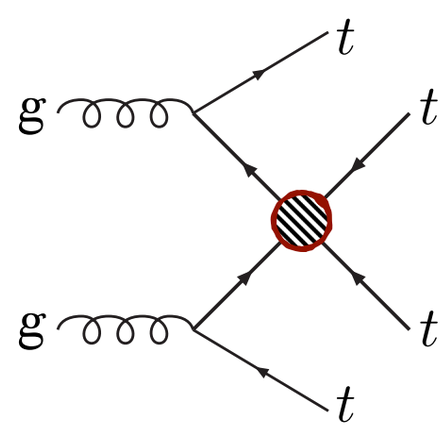
$$D_\mu^3 \sim D^2 D_\mu,\ D_\nu D_\mu D^\nu,\ gF_{\mu\nu}D^\nu$$

Power counting important to estimate size of different contributions

$$\frac{m_*^4}{g_*^2}O\left(\lambda_{L/R}\frac{g_*\psi_{L,R}}{m_*^{3/2}},\frac{g_*H}{m_*},\frac{\partial_\mu}{m_*},\frac{gV}{m_*}\right)$$

In our limit:

$$\frac{c_{tt}}{\Lambda^2}\,(\bar{t}_R\gamma_\mu t_R)^2$$



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

Leading effect for strongly coupled theories $g_* \gg 1$

Top compositeness as an EFT

Power counting important to estimate size of different contributions

$$\frac{m_*^4}{g_*^2} O\left(\lambda_{L/R}\frac{g_*\psi_{L,R}}{m_*^{3/2}}, \frac{g_* H}{m_*}, \frac{\partial_\mu}{m_*}, \frac{gV}{m_*}\right)$$

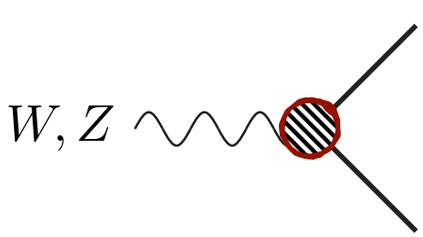
$$\frac{c_{\psi D}}{m_*^2}\,\bar{\psi} D_\mu^3 \gamma^\mu \psi$$

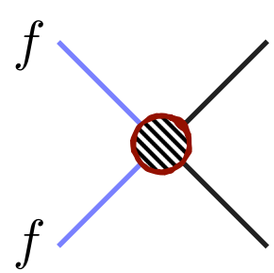
$$\{g_*^2, y_t^2\}(H^\dagger \overleftrightarrow{D}_\mu H)\,(\bar{\psi}\gamma_\mu\psi)$$

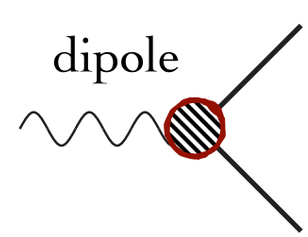
$$g^2(\bar{f}\gamma_\mu f)(\bar{\psi}\gamma^\mu\psi)$$

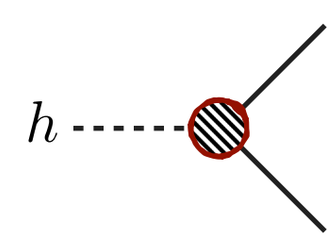
$$g y_t\,\bar{q}_L H \sigma_{\mu\nu} F^{\mu\nu} t_R$$

$$y_t g_*^2 |H|^2\,\bar{q}_L H t_R$$









Operators involve other SM fields and mostly not enhanced by strong coupling

Top compositeness as an EFT

Power counting important to estimate size of different contributions

$$\frac{m_*^4}{g_*^2} O\left(\lambda_{L/R}\frac{g_*\psi_{L,R}}{m_*^{3/2}}, \frac{g_* H}{m_*}, \frac{\partial_\mu}{m_*}, \frac{gV}{m_*}\right)$$

There are a few exceptions:

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

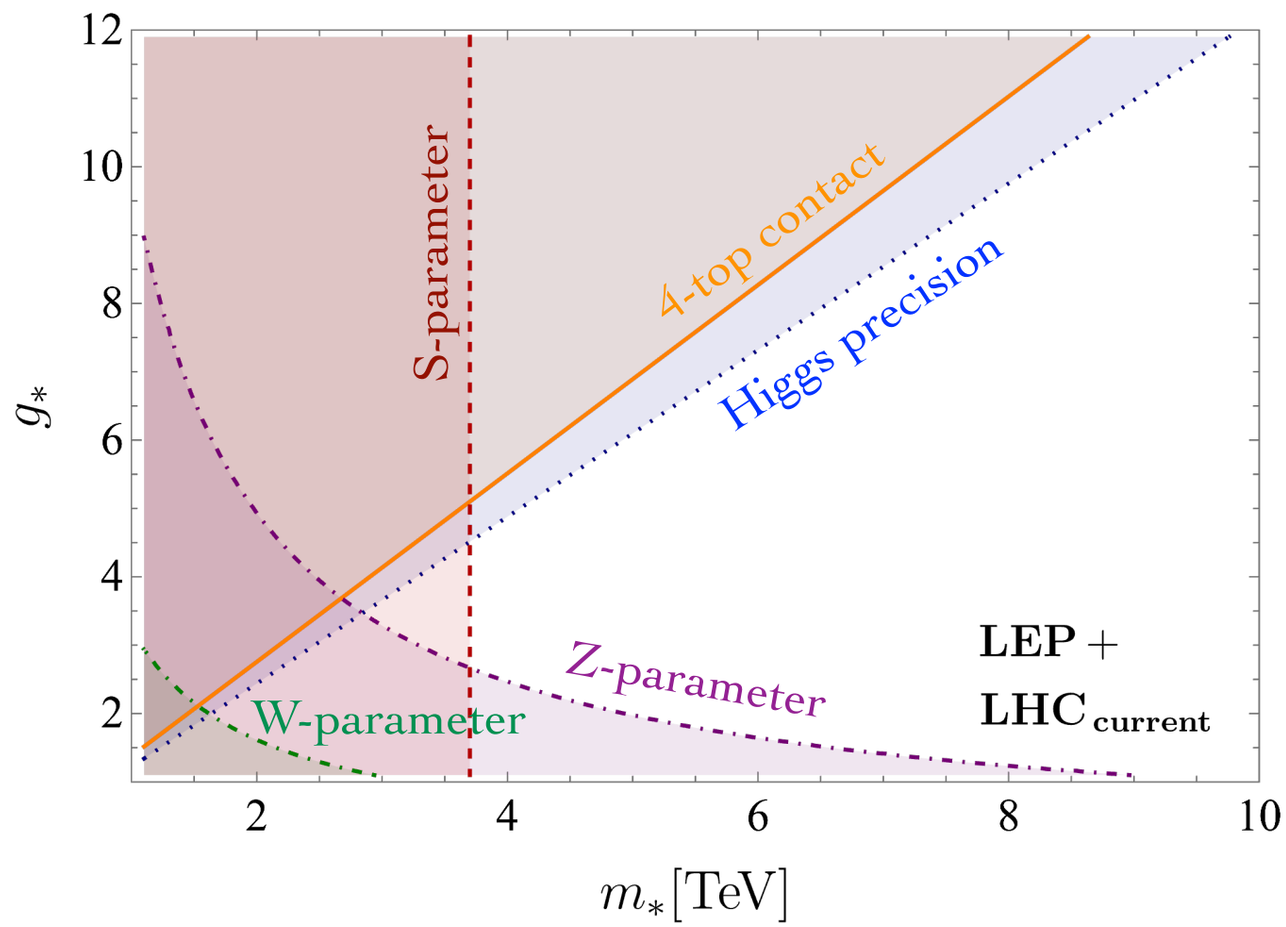
$$\frac{g_*^2}{m_*^2}\left(H^\dagger \overleftrightarrow{D}_\mu H\right)\left(\bar{t}_R \gamma_\mu t_R\right)$$ loop suppressed

$$\frac{y_t g_*^2}{m_*^2}|H|^2\,\bar{q}_L H t_R$$ low sensitivity on tth coupling

Enhanced operator without top quarks: $\frac{g_*^2}{m_*^2}\left(\partial|H|^2\right)$

Top compositeness at the LHC

- LHC bounds are relatively weak
- Top contact interaction comparable to Higgs precision



[Banelli et al. 2010.05915]

$$\frac{m_*}{g_*} > 730\,\text{GeV}$$

[CMS 1811.02305]

$$\frac{m_*}{g_*} > 820\,\text{GeV}$$

[de Blas et al. 1902.00134]

Not a global fit

Operators with different power counting estimates provide different exclusion regions

LHC : $\sqrt{s} = 7,\ 8,\ 13\,\text{TeV},\ \mathcal{L} = 5,\ 20,\ 35.9\,\text{fb}^{-1}$

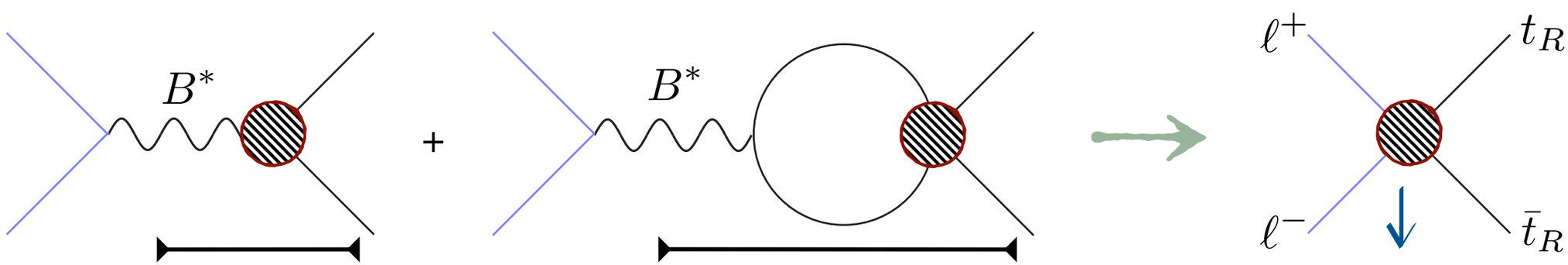
Top compositeness at future lepton colliders

Four top production not achievable at most lepton colliders*

↓

Exploit renormalization group effects in pair production

$$\frac{c_{tD}}{m_*^2}(\partial^\mu B_{\mu\nu})(\bar{t}_R\gamma^\nu t_R) \xrightarrow{\text{EOM}} \frac{c_{te}}{m_*^2}(\bar{e}_R\gamma_\mu e_R)(\bar{t}_R\gamma^\mu t_R)$$



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

$$\frac{c_{te}}{m_*^2} = 2\frac{c_{t\ell}}{m_*^2} = g'\frac{c_{tD}}{m_*^2}$$

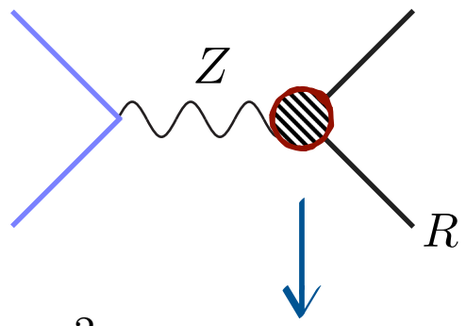
→ For strongly coupled theories $g_* \gg 1$, RGE term leading contribution.

* High energy colliders can open up this channel, but $\sigma(4t)_{\mu\mu}^{10\ \mathrm{TeV}} \sim O(\mathrm{ab})$

Top compositeness at future lepton colliders

- Multiple operators enter top pair production

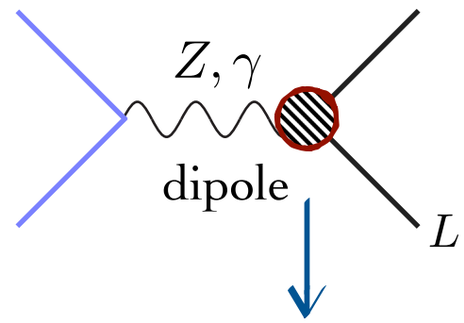
$\mathcal{M}_{\ell^+\ell^-\to t\bar{t}} \sim$



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

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

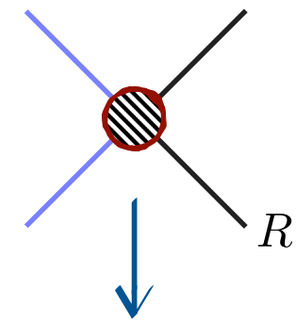
+



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

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

+



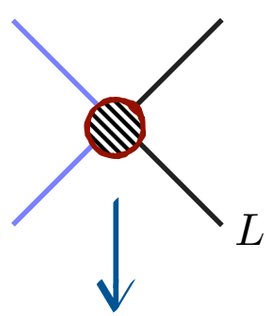
$$\frac{c_{te}}{m_*^2}(\bar{e}_R\gamma_\mu e_R)(\bar{t}_R\gamma^\mu t_R)$$

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

At high energies, contact interactions dominate

- Bottom pair-production sensitive to weak couplings

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

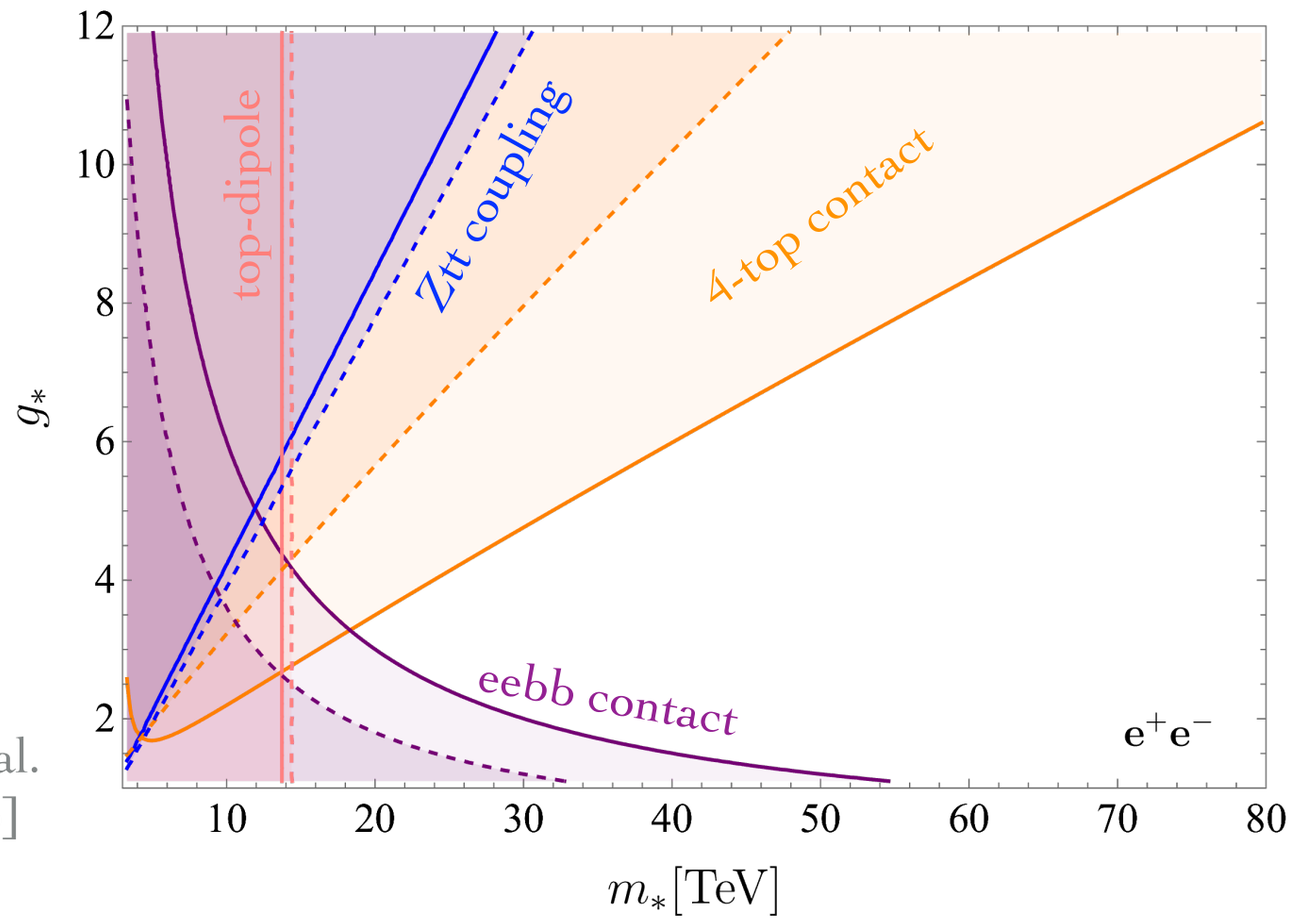


$$\sim \frac{y_t^2 g^2}{g_*^2 m_*^2}s$$

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

Top compositeness at ILC and CLIC

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



[Banelli et al. 2010.05915]

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

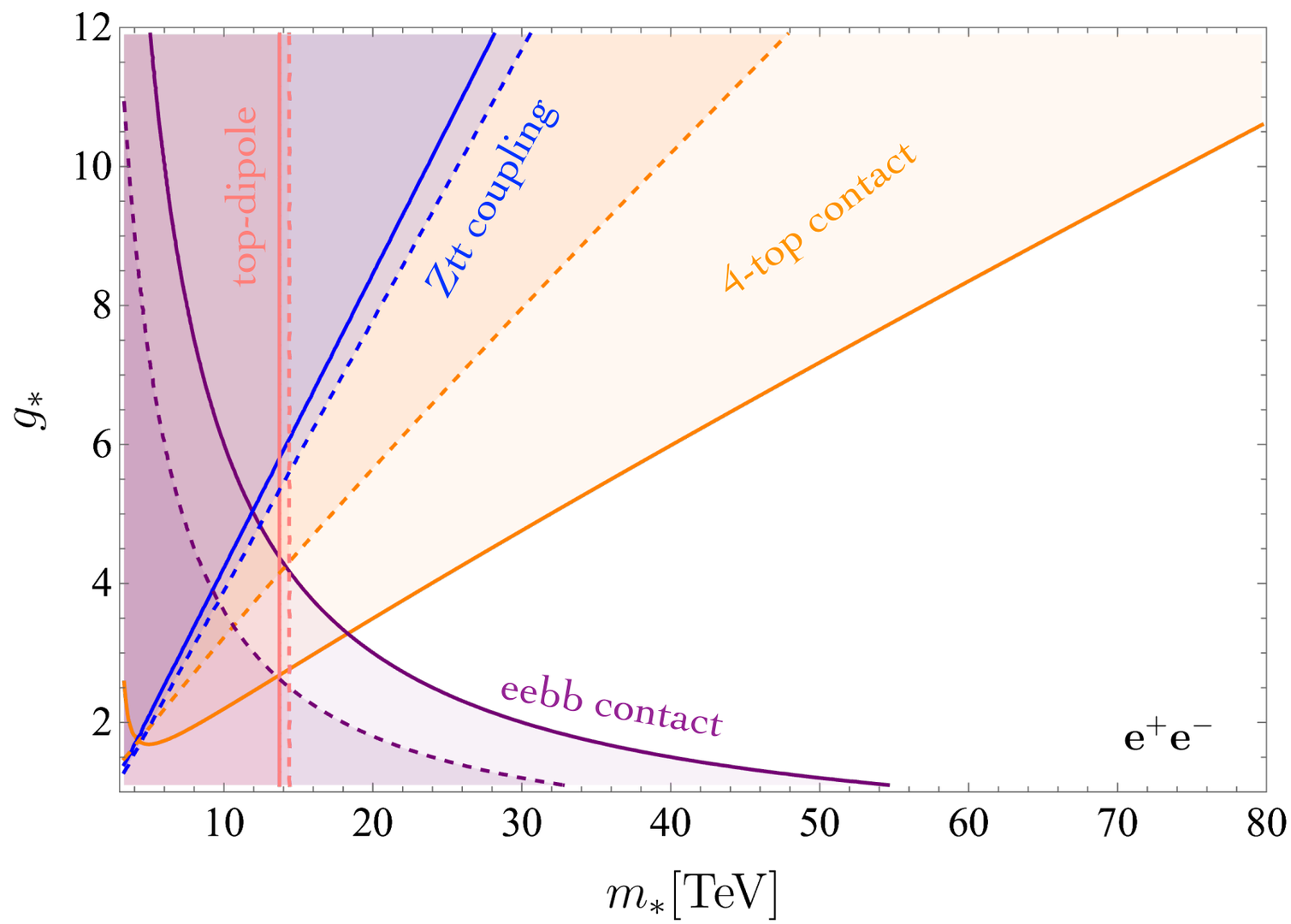
Based on reinterpretation of results for sensitivity to the individual operators .

[Durieux et al. 1807.02121]
[Durieux et al. 1807.10273]

Contact interactions and highest-energy runs dominate the sensitivity.

Top compositeness at ILC and CLIC

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



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

[Banelli et al. 2010.05915]

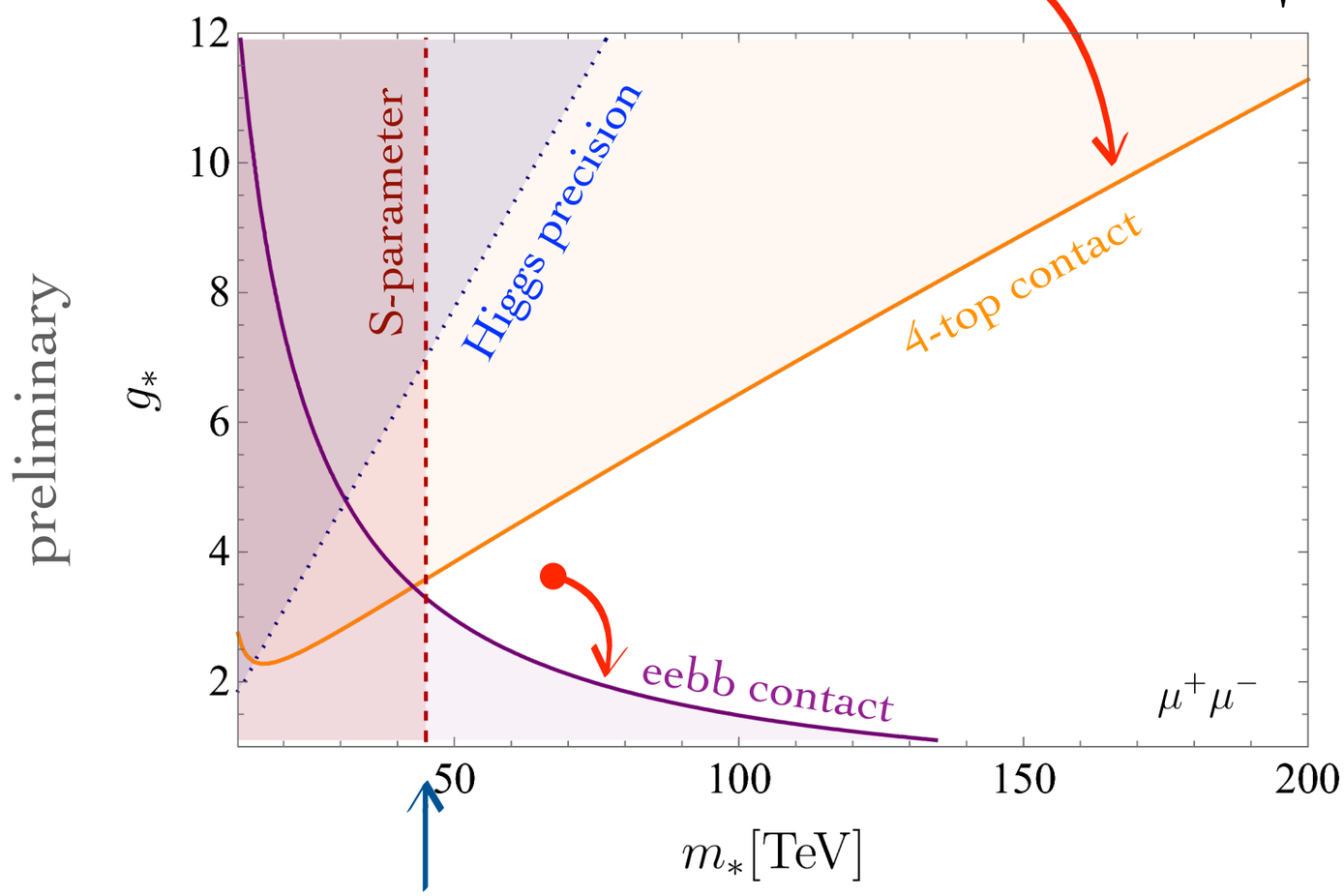
$$\frac{m_*}{g_*} > 4.3\,\text{TeV}$$

[de Blas et al. 1902.00134]

Top compositeness at μ-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)



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

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

[Han et al. 2008.12204]

[Buttazzo et al. 2012.02769]

Main assumption is that uncertainty remains statistically dominated.

Summary and outlook

- Top compositeness provide an exciting probe of composite Higgs models

- Leading effects from 4-top contact interaction

direct, 4t production (LHC, FCC)

indirect, pair-production (CLIC, ILC, μ-Collider)

- At lepton colliders:

Sensitivity from RGE contributions to lepton-top contact interactions

Highest gain from highest energy runs

$$\left(\frac{m_*}{g_*}\right)_{\text{LHC}} > 730 \text{ GeV}, \qquad \left(\frac{m_*}{g_*}\right)_{\text{CLIC}} > 7.7 \text{ TeV} \qquad \left(\frac{m_*}{g_*}\right)_{\mu\mu,10\text{TeV}} > 18 \text{ TeV}$$