The Present and Future of Four Top Operators

Planck 2022

Parallel session 3

TOBIAS THEIL

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

June 2, 2022

Top quark compositeness

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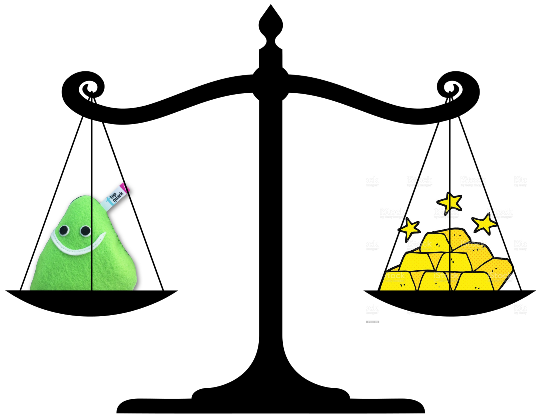

Top quark as the heaviest fermion in the SM , $m_t \approx 173\,\mathrm{GeV}$

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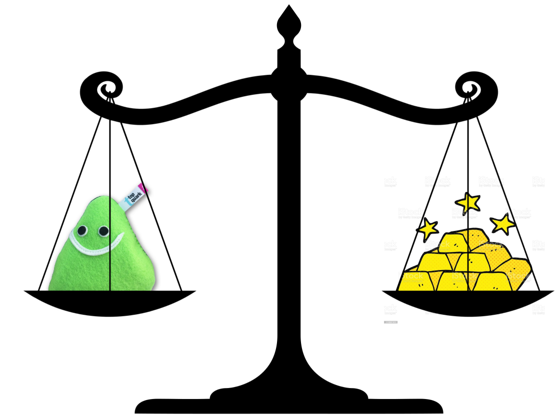

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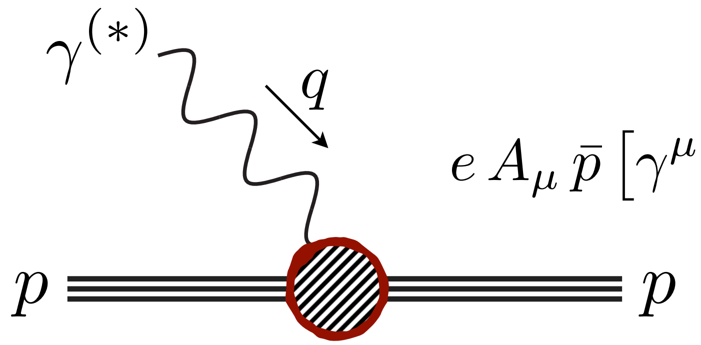

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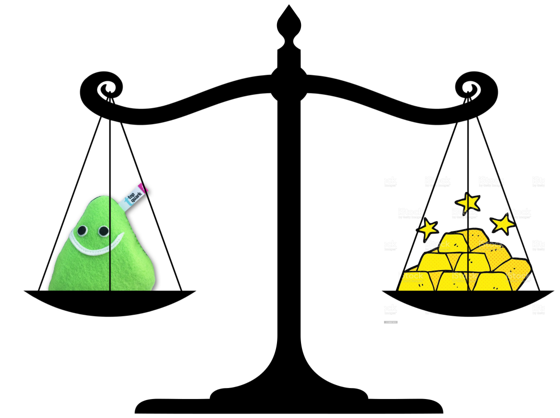

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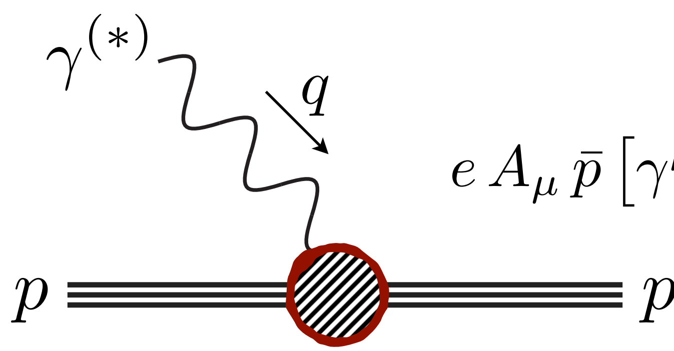

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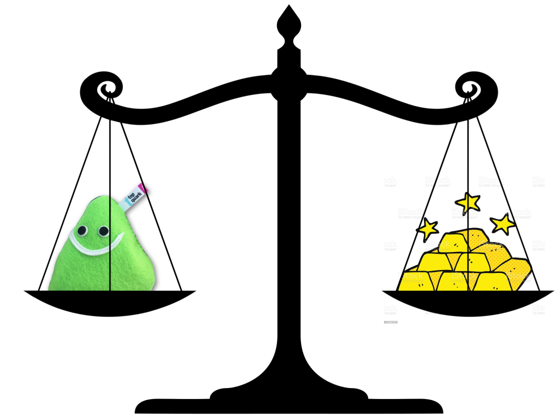

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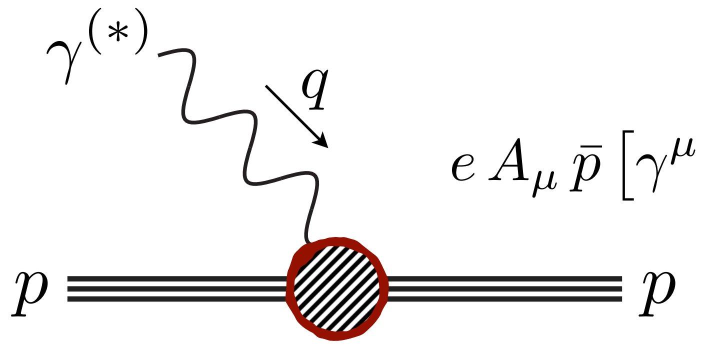

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We have not seen any new degrees of freedom around the top mass

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Serious idea or academic exercise?

- Possible connection to the electroweak scale and its hierarchy problem
- Composite Higgs models can naturally give rise to chiral compositeness

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

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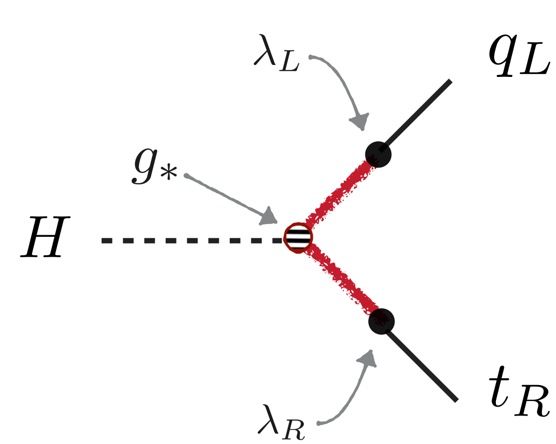

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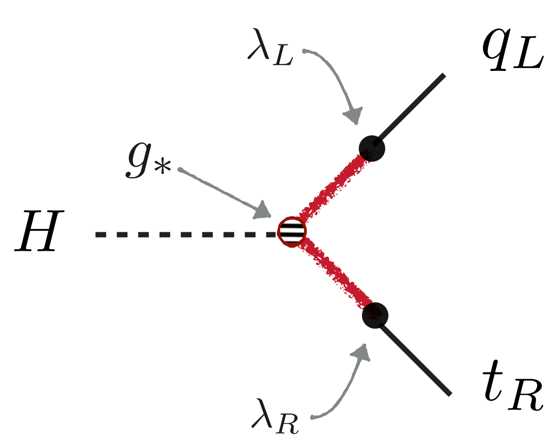

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Consider fully composite right-handed top: $\boxed{\lambda_R \to 1,\ \lambda_L \to y_t/g_*}$

Top compositeness as an EFT

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Parametrize top compositeness with effective operators

[Georgi et al. '94]

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

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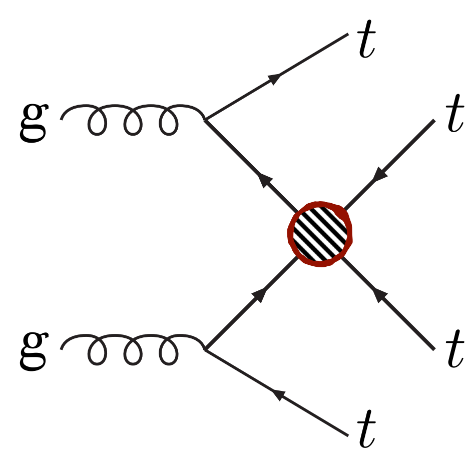
In the $\lambda_R = 1$ limit:

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



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

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

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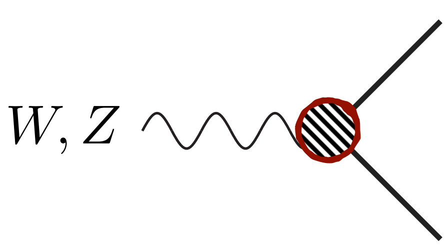

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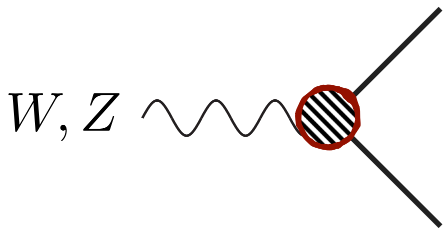

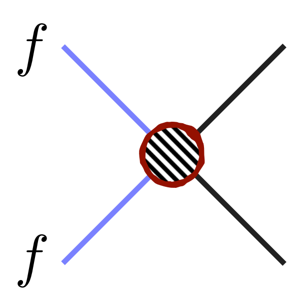

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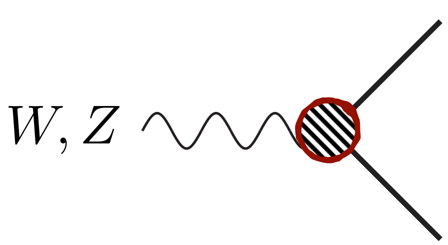

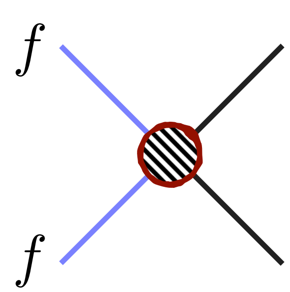

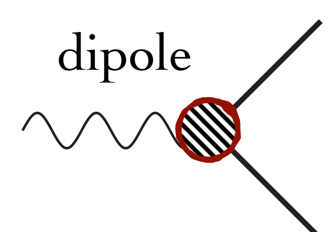

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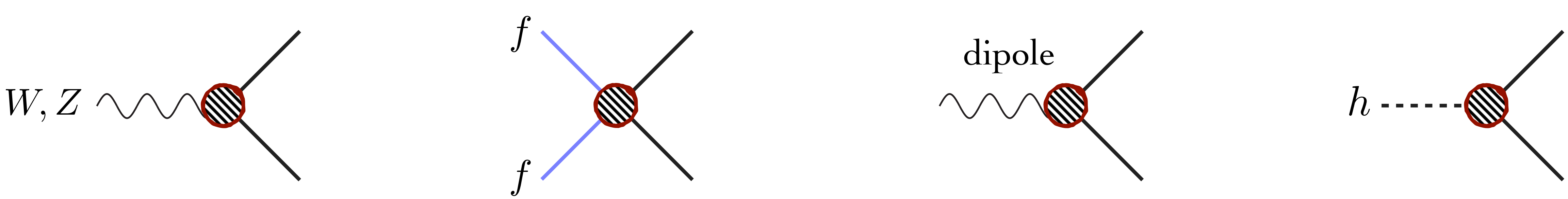

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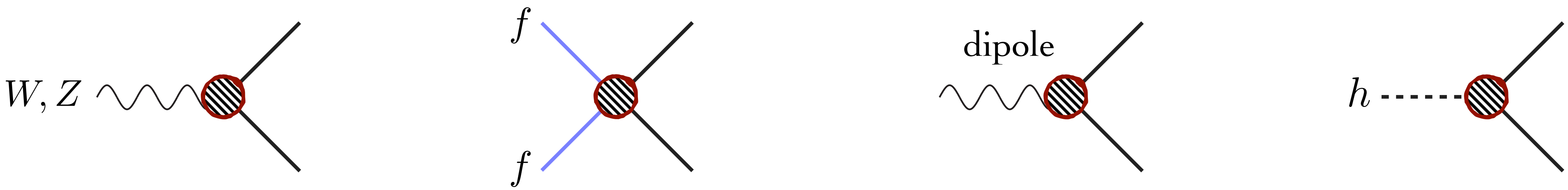

Operators involve other SM fields and mostly not enhanced by strong coupling

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low sensitivity on tth coupling

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

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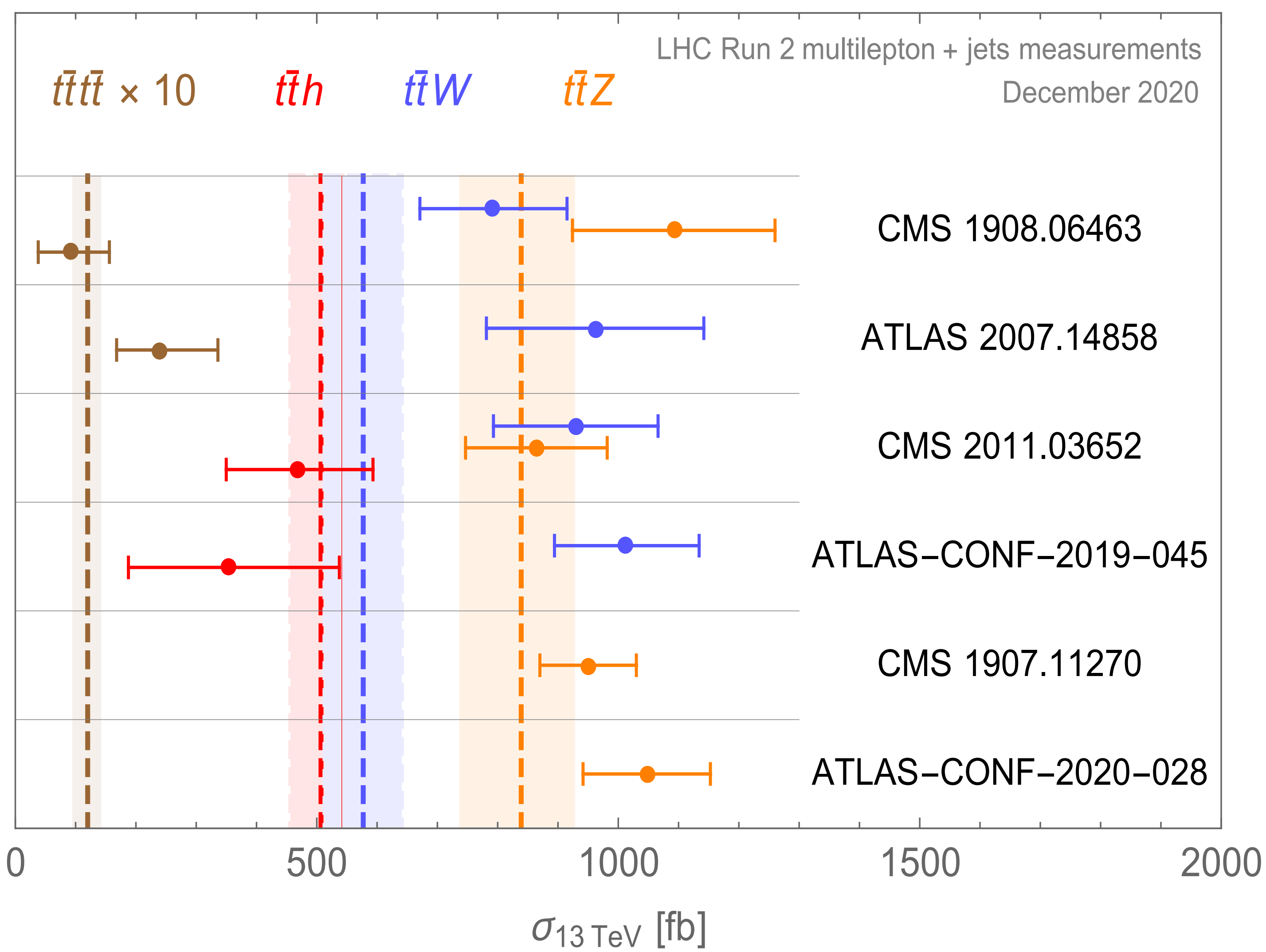

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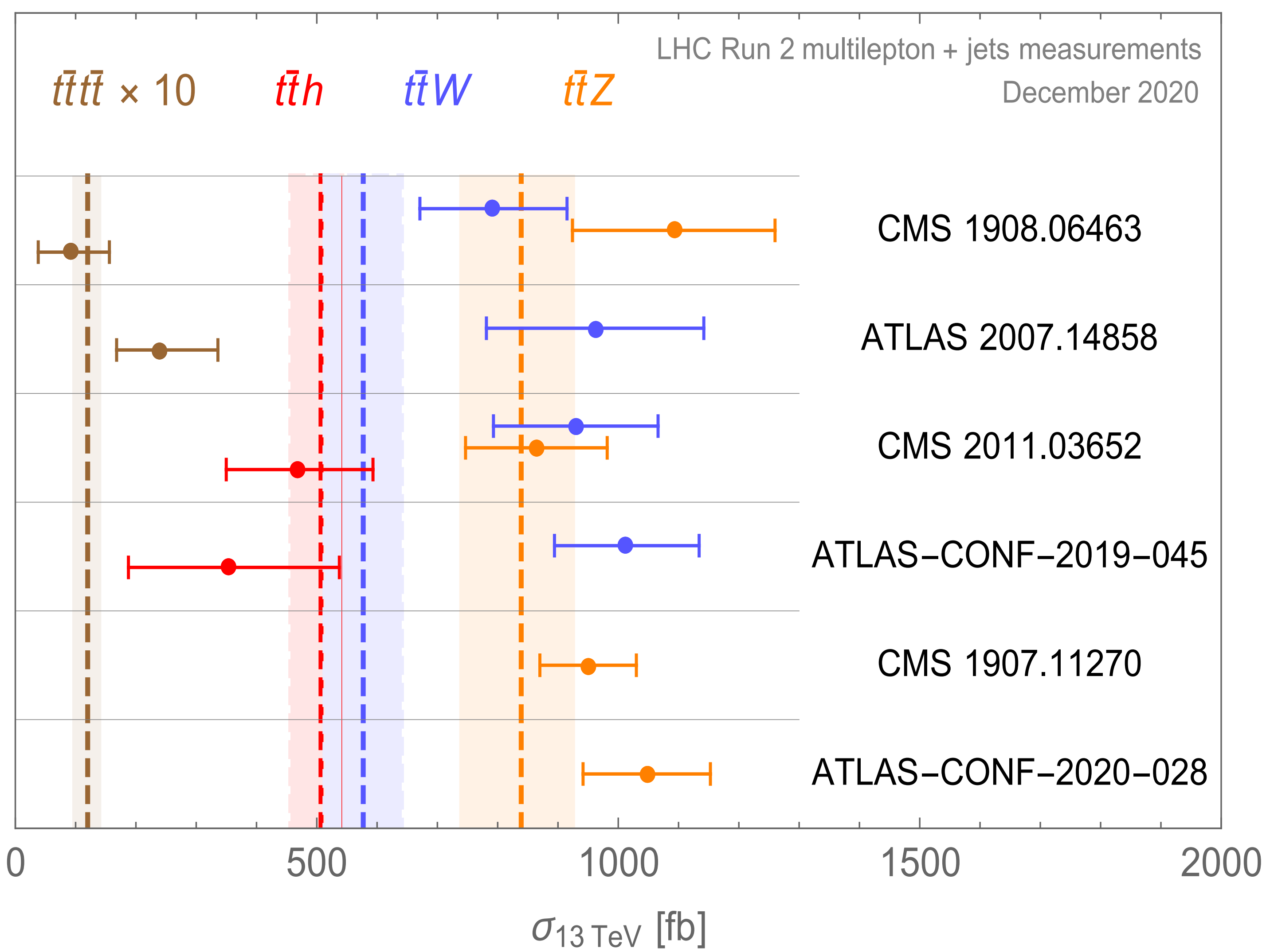

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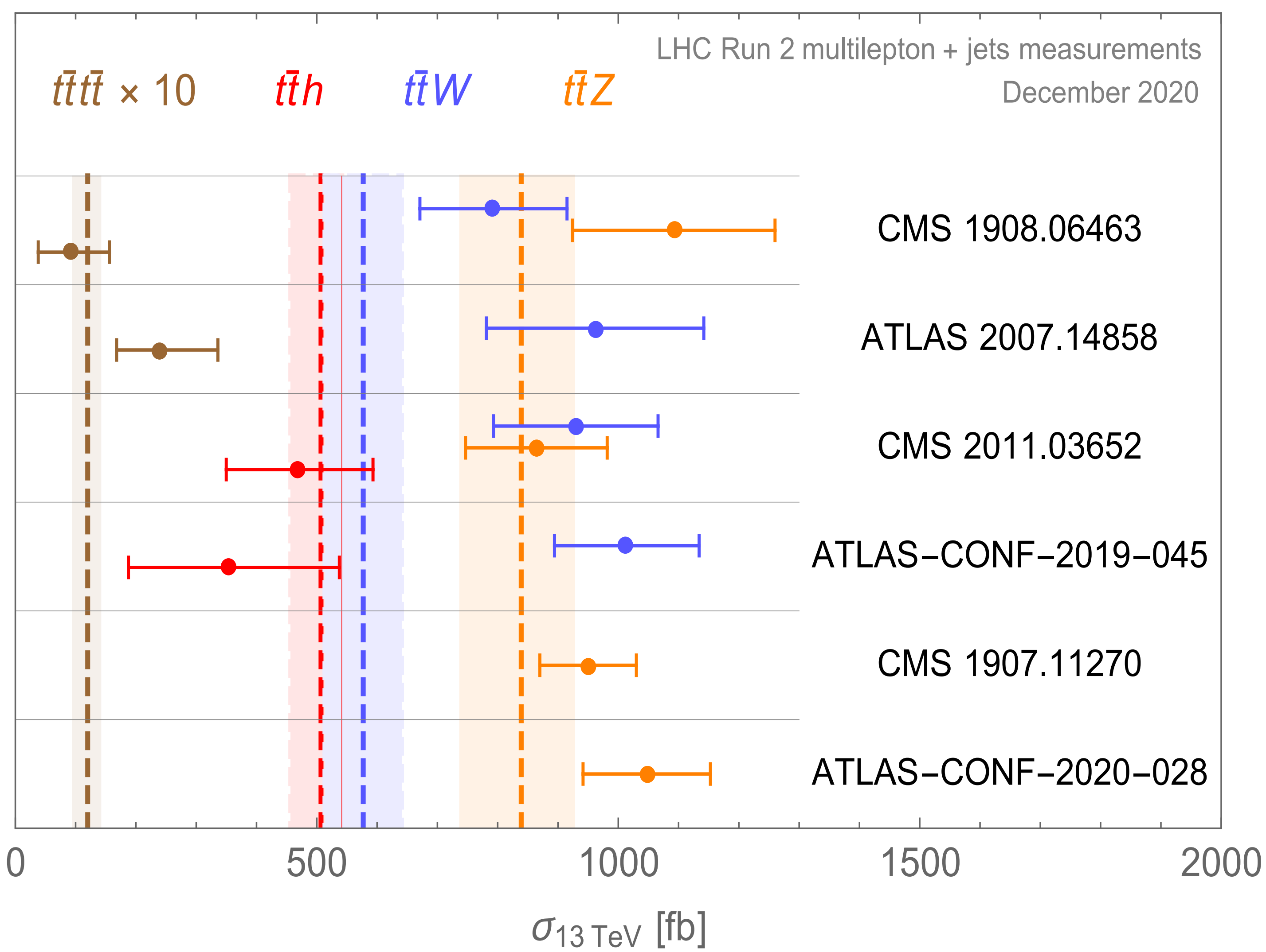

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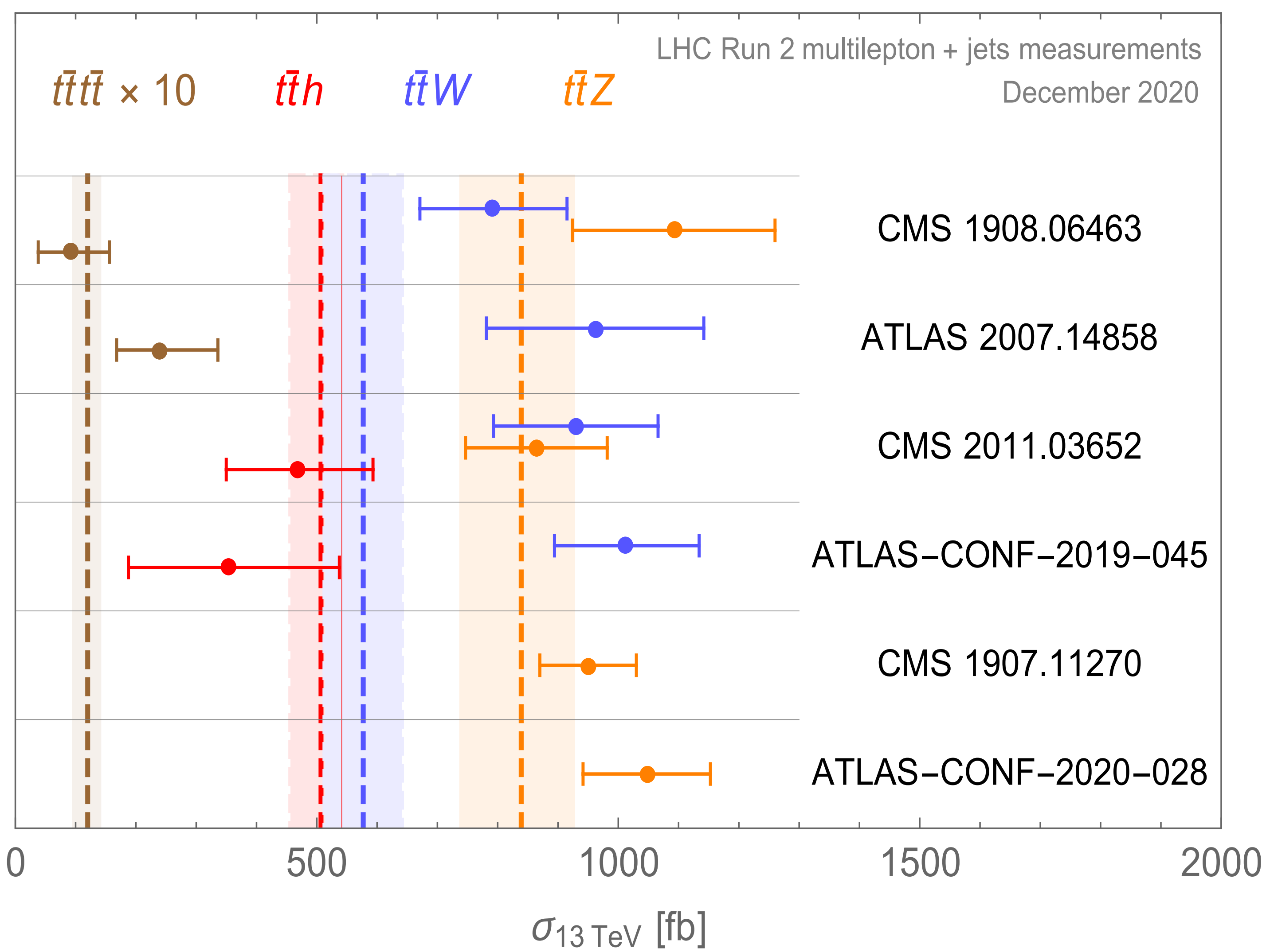

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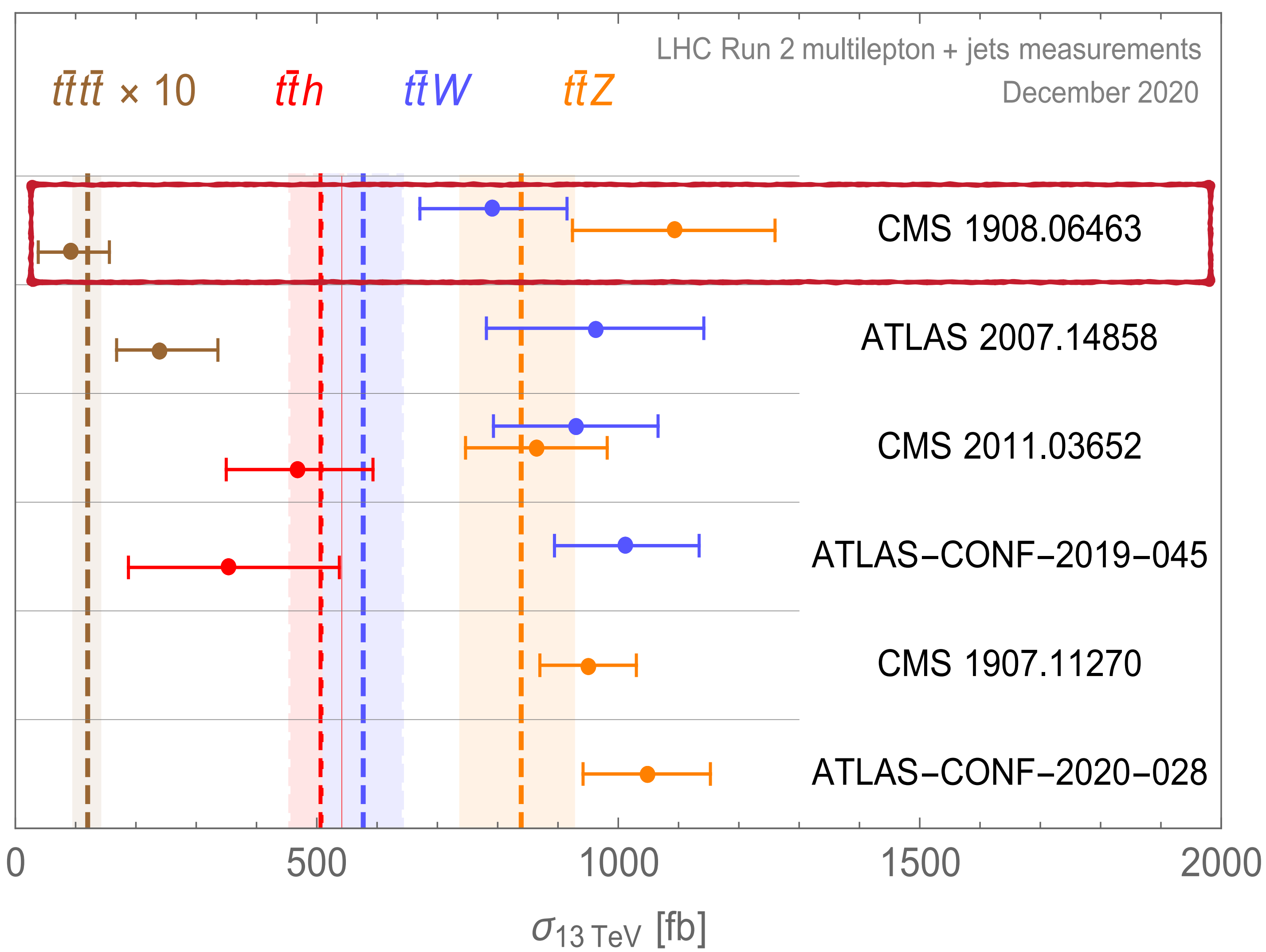

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Neglect:

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- Contribution of c_{Ht} to four-top production

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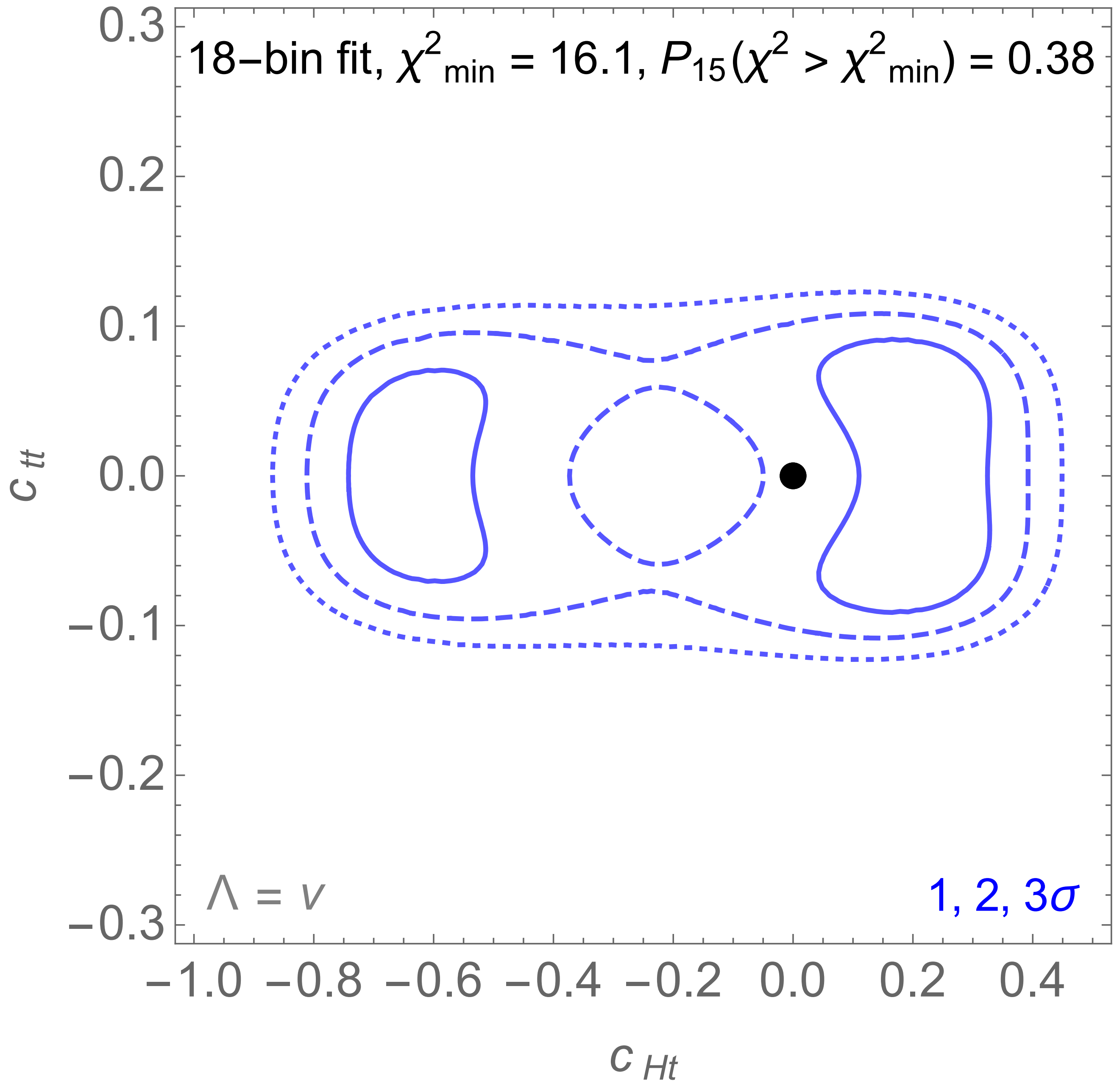

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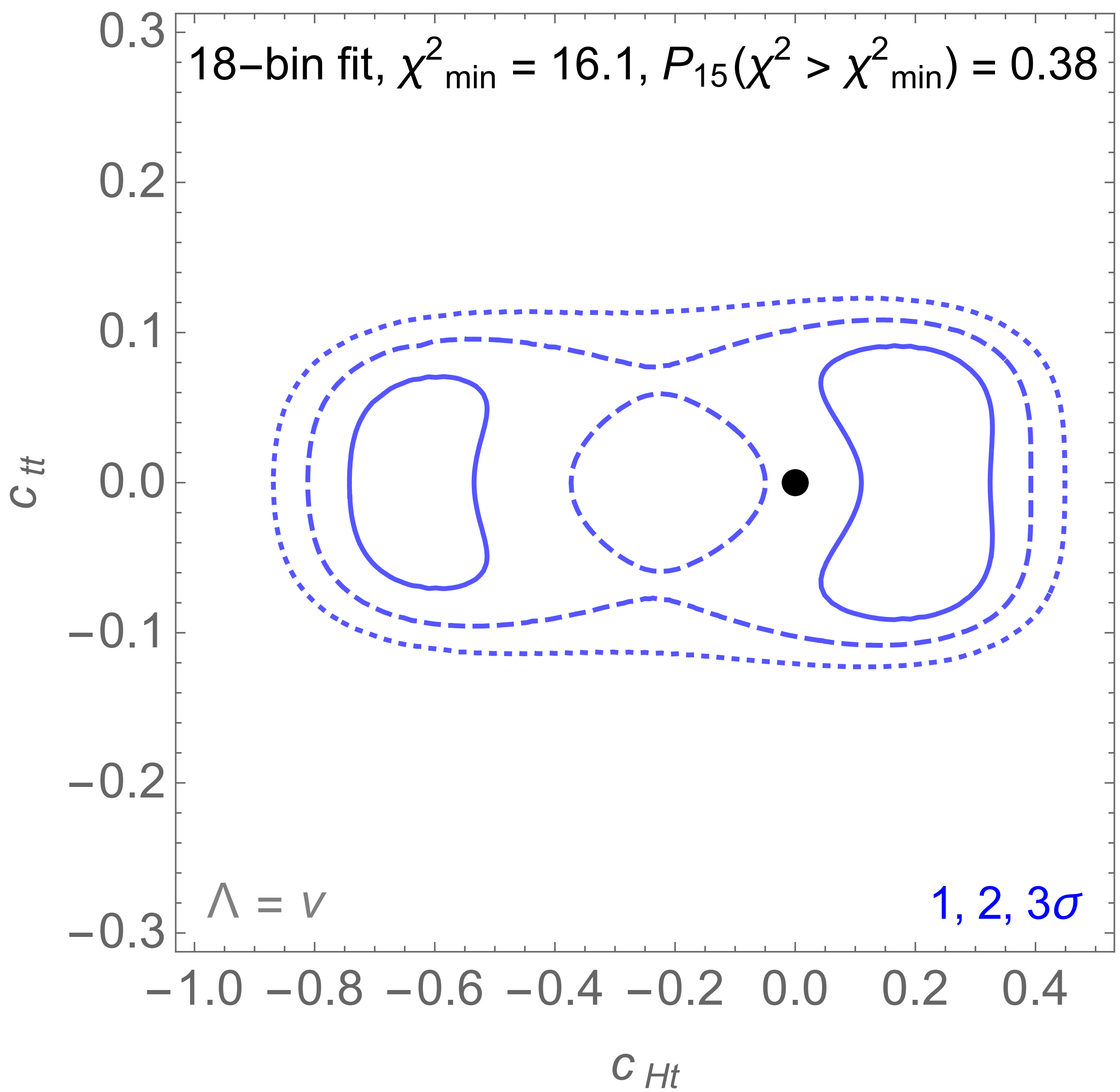

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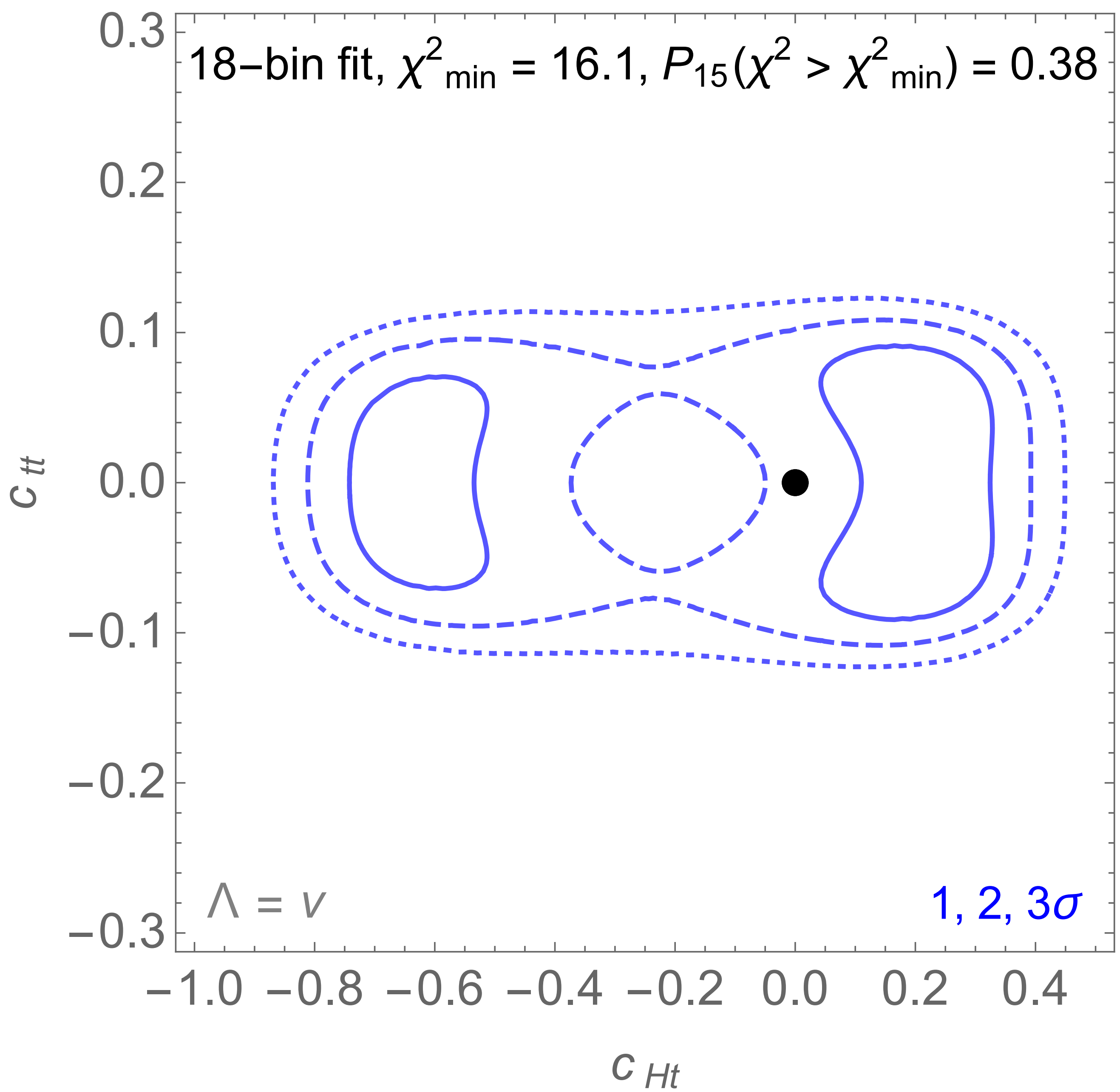

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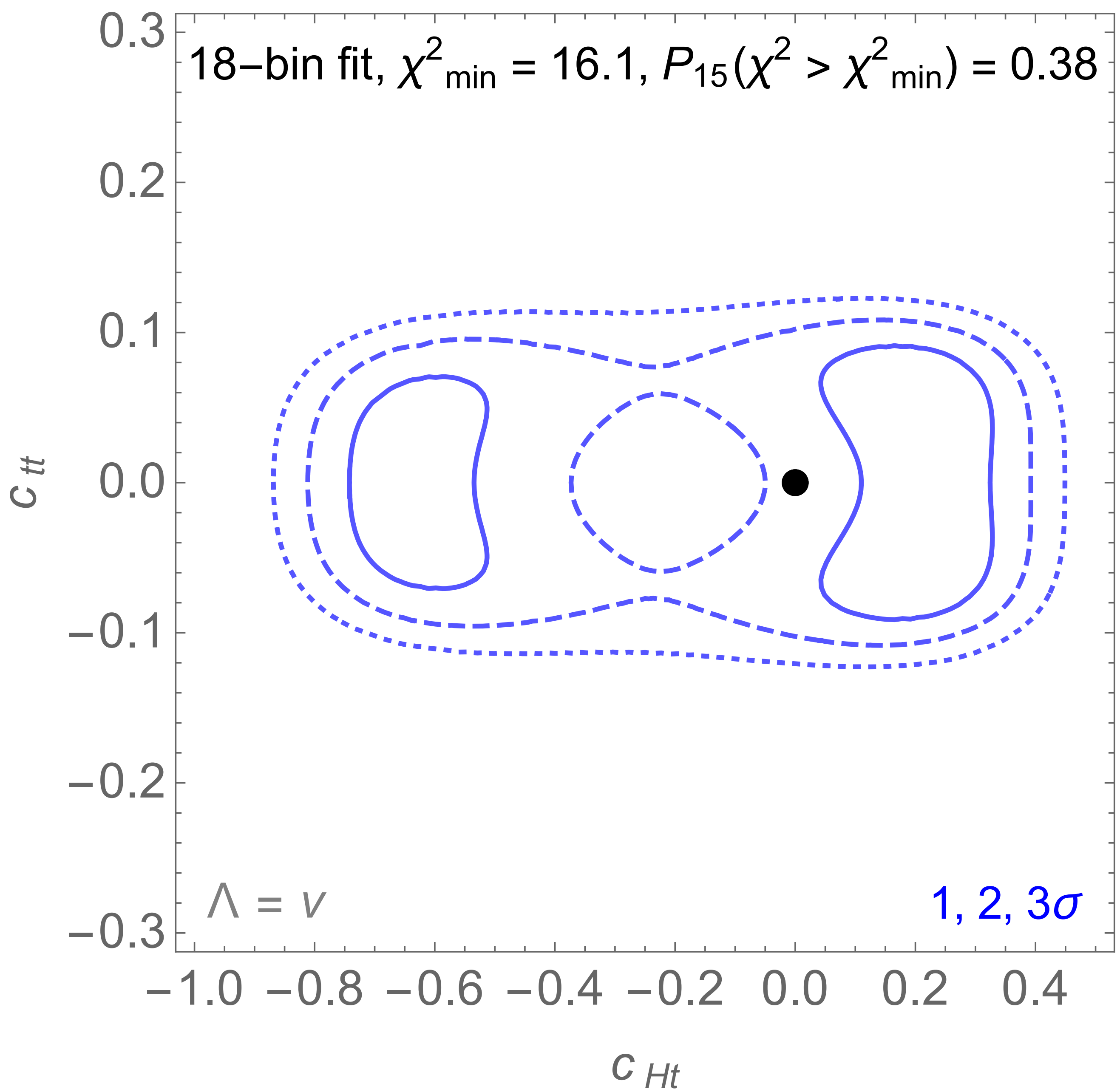

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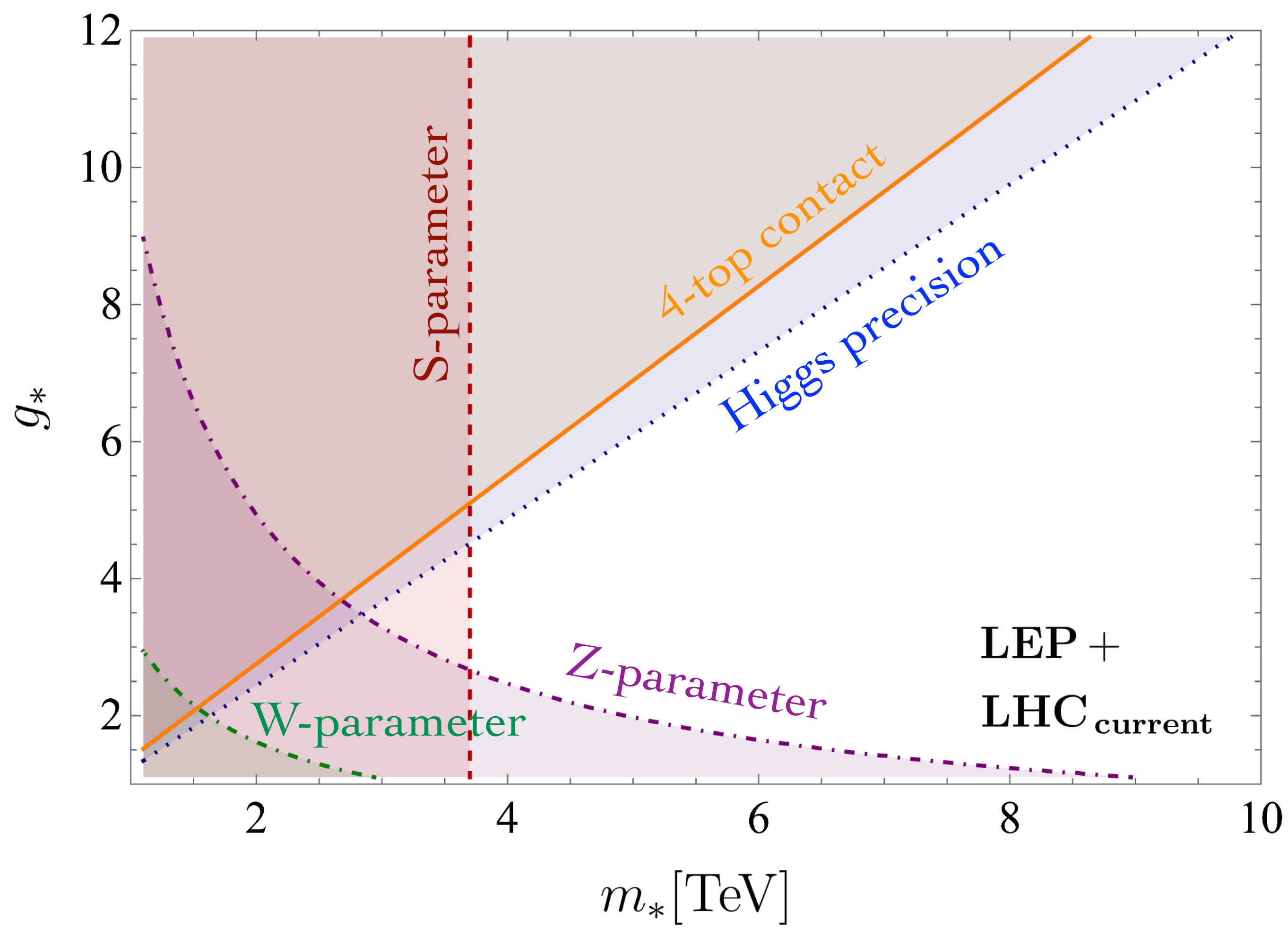
- Roughly consistent with experimental constraints
- Motivation for heavy, top-philic new physics

Now focus only on $\frac{c_{tt}}{\Lambda^2} \left(\bar{t}_R \gamma_\mu t_R\right)^2$

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 the FCC

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- Exploit the high energy compared to the LHC

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$$\frac{\sigma_{4t,FCC}}{\sigma_{4t,LHC}} \sim 350 \qquad \text{vs.} \qquad \frac{\sigma_{t\bar{t}W,FCC}}{\sigma_{t\bar{t}W,LHC}} \sim 40$$

[Frederix, Pagani, Zaro 1711.02116]

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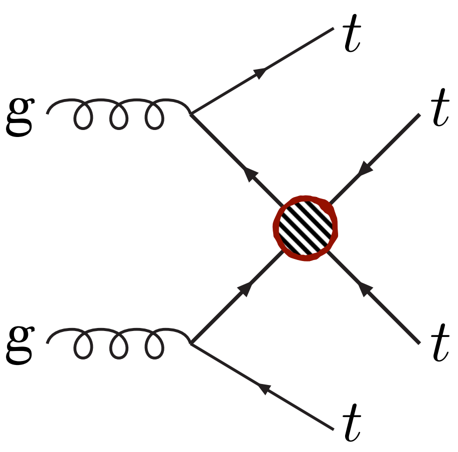

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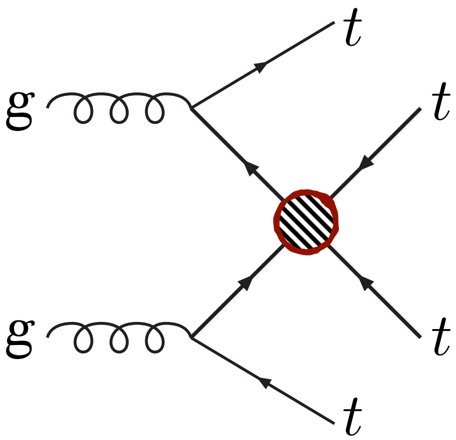

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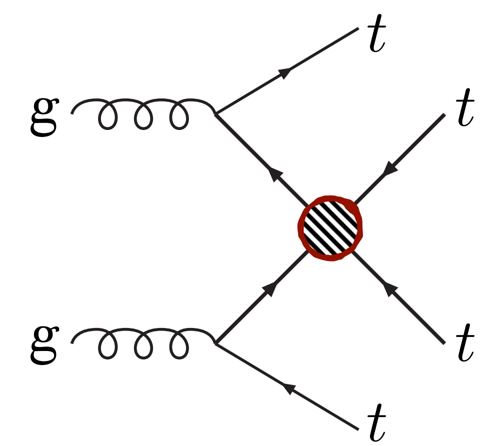

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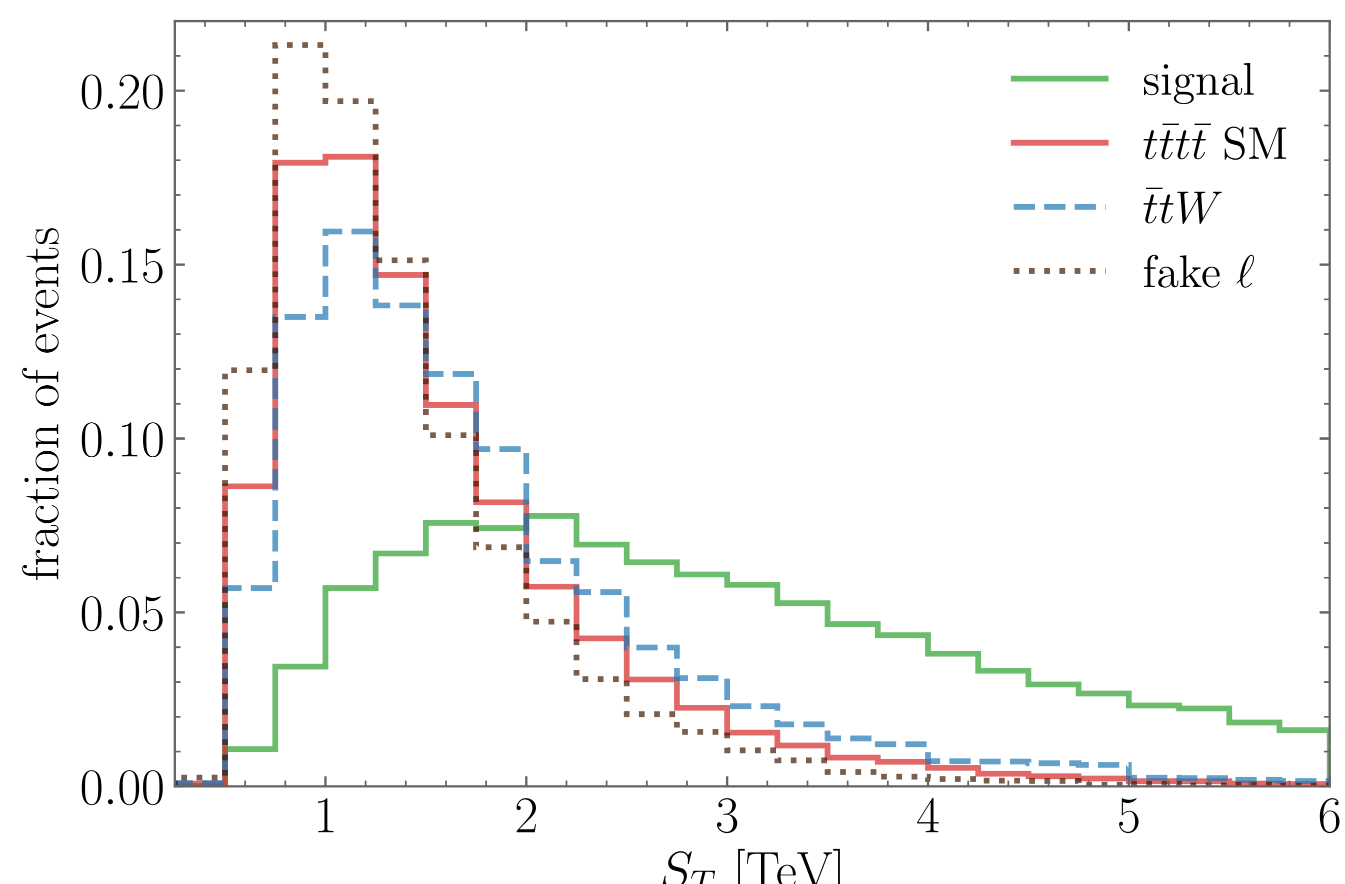
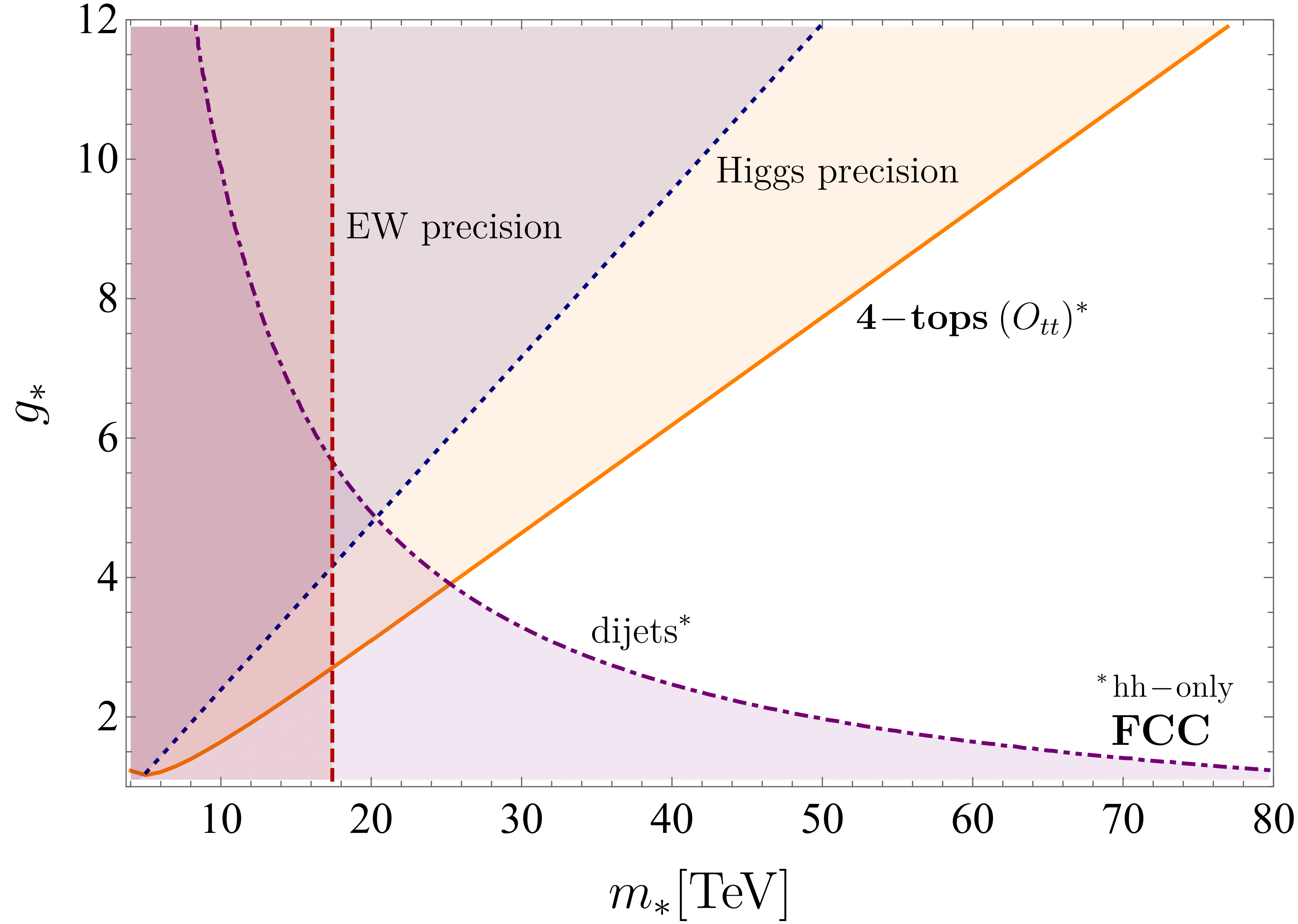


$$S_T = \sum_{\text{leptons}} p_T + \sum_{\text{jets}} p_T$$

Top compositeness at the FCC



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

[Banelli et al. 2010.05915]

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

[de Blas et al. 1905.03764]

FCC-hh : $\sqrt{s} = 100\text{TeV},\ \mathcal{L} = 30\,\text{ab}^{-1}$

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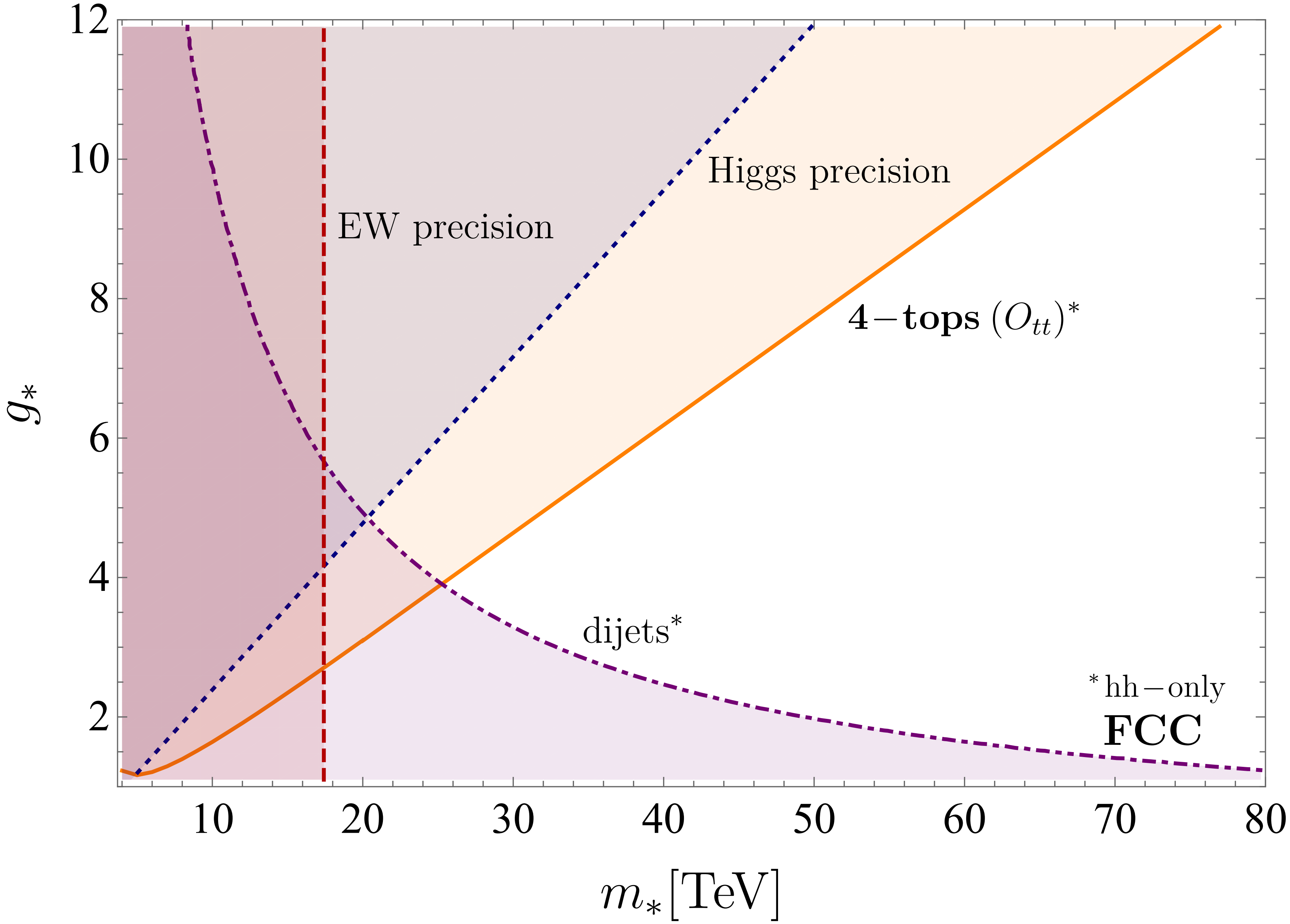

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Four-top production overtakes Higgs precision measurement, despite the FCC-ee precision

FCC-hh : $\sqrt{s} = 100\text{TeV},\ \mathcal{L} = 30\,\text{ab}^{-1}$

Top compositeness at future lepton colliders

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Four top production not achievable at most lepton colliders*

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

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

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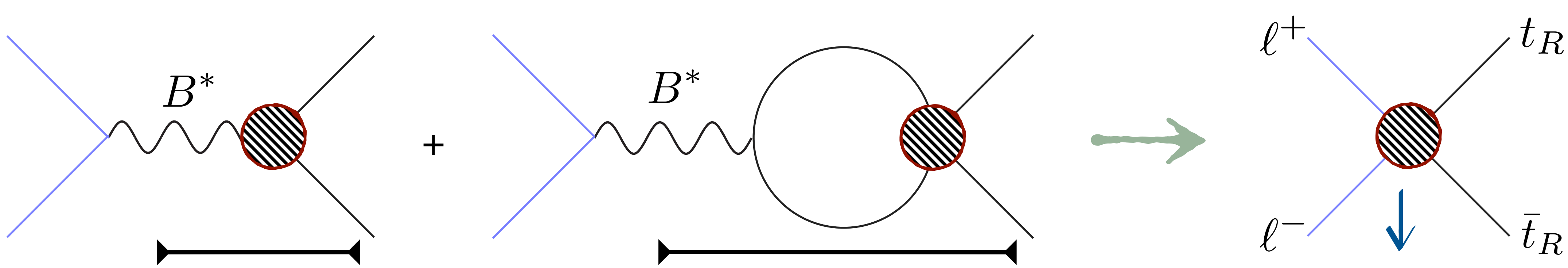

$$\frac{c_{tD}}{m_*^2}(\mu) = \frac{g'}{m_*^2}(m_*) + \frac{g_*^2}{m_*^2}(m_*)\frac{32}{9}\frac{g'}{16\pi^2}\log\left(\frac{m_*^2}{\mu^2}\right)$$

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

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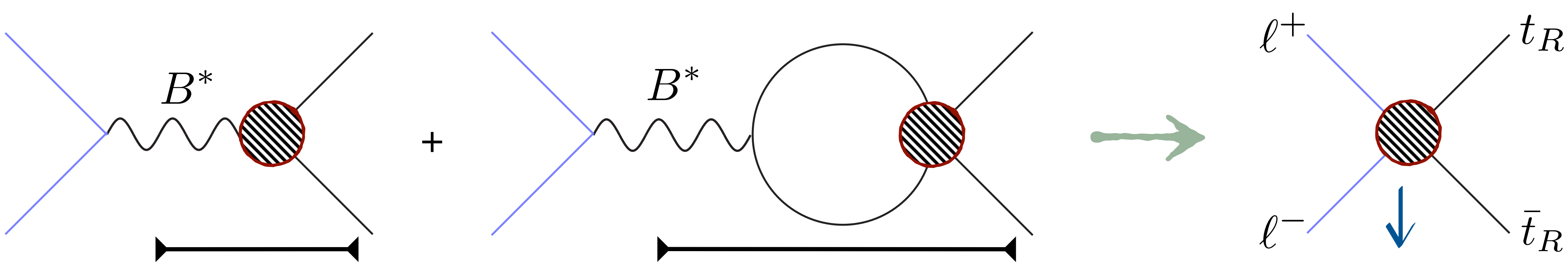

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→ For strongly coupled theories $g_* \gg 1$, RGE term leading contribution.

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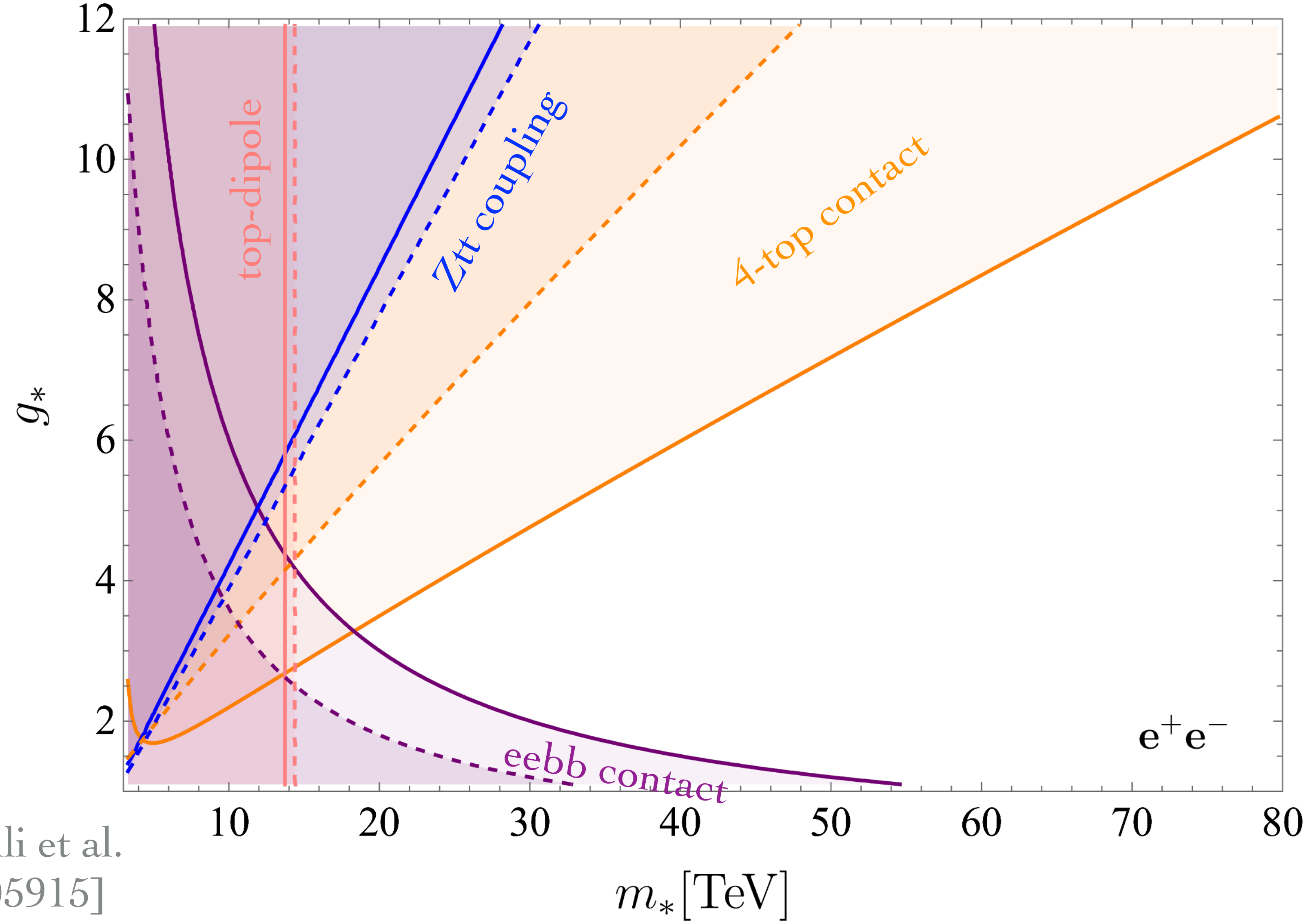
Top compositeness at ILC and CLIC

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



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[de Blas et al. 1902.00134]

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

—— CLIC : $\sqrt{s} = 0.38,\ 1.4,\ 3\,\mathrm{TeV},\ \mathcal{L} = 0.5,\ 1.5,\ 3\,\mathrm{ab}^{-1}$ - - - - - - ILC : $\sqrt{s} = 0.5,\ 1\,\mathrm{TeV},\ \mathcal{L} = 0.5,\ 1\,\mathrm{ab}^{-1}$

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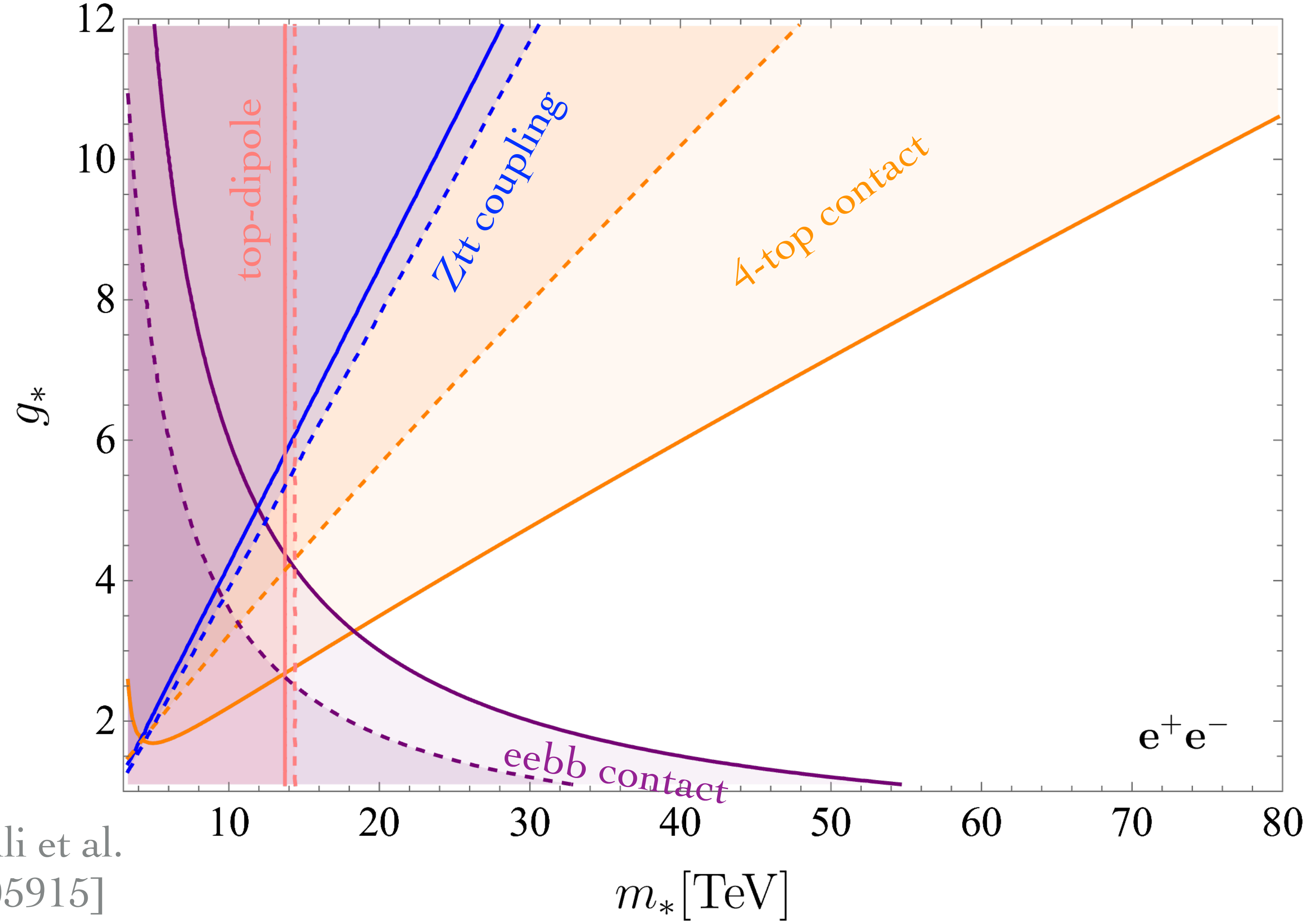

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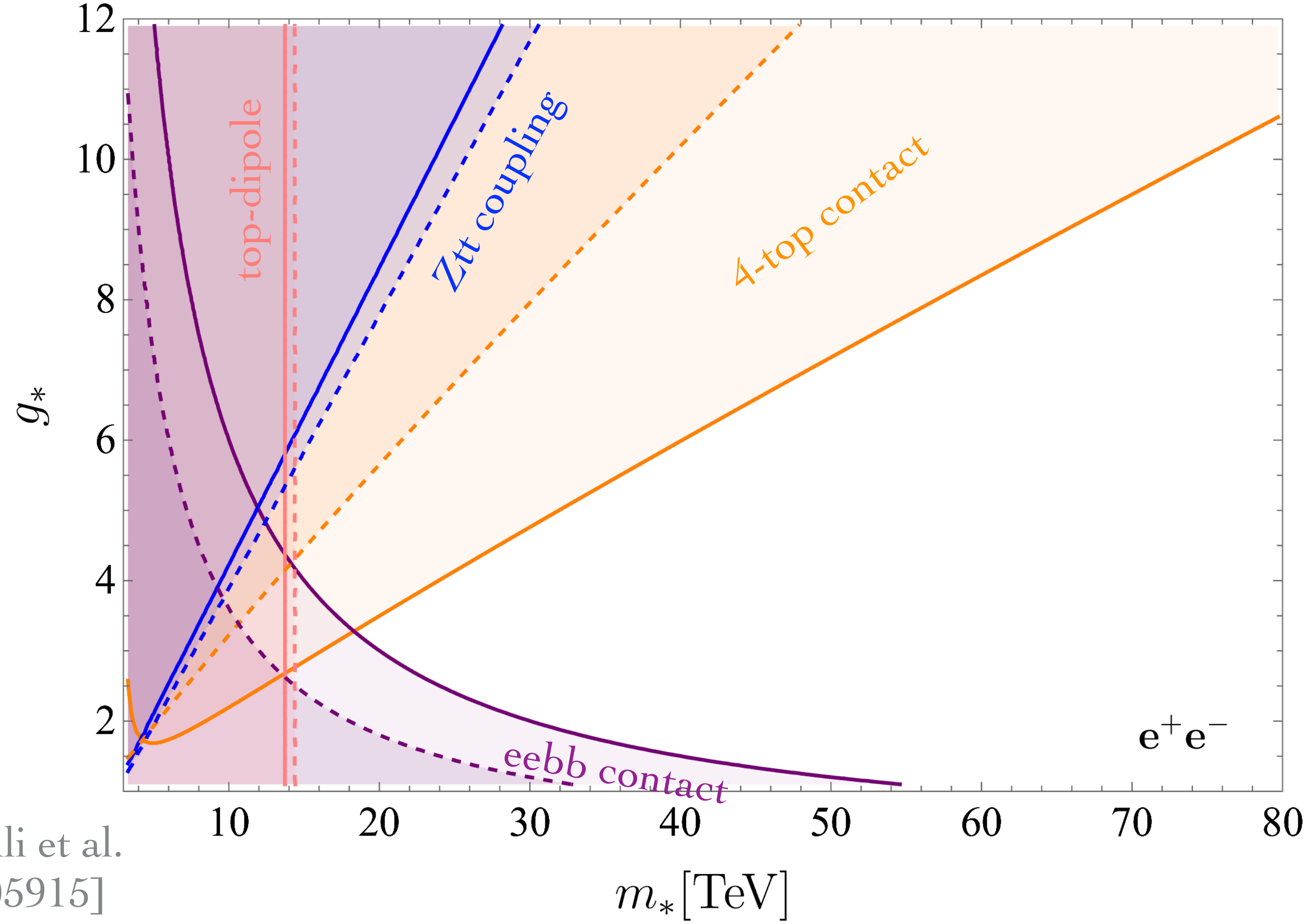

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Based on reinterpretation of results for sensitivity to the individual operators . [Durieux et al. 1807.02121] [Durieux et al. 1807.10273]

Contact interactions and highest-energy runs dominate the sensitivity.

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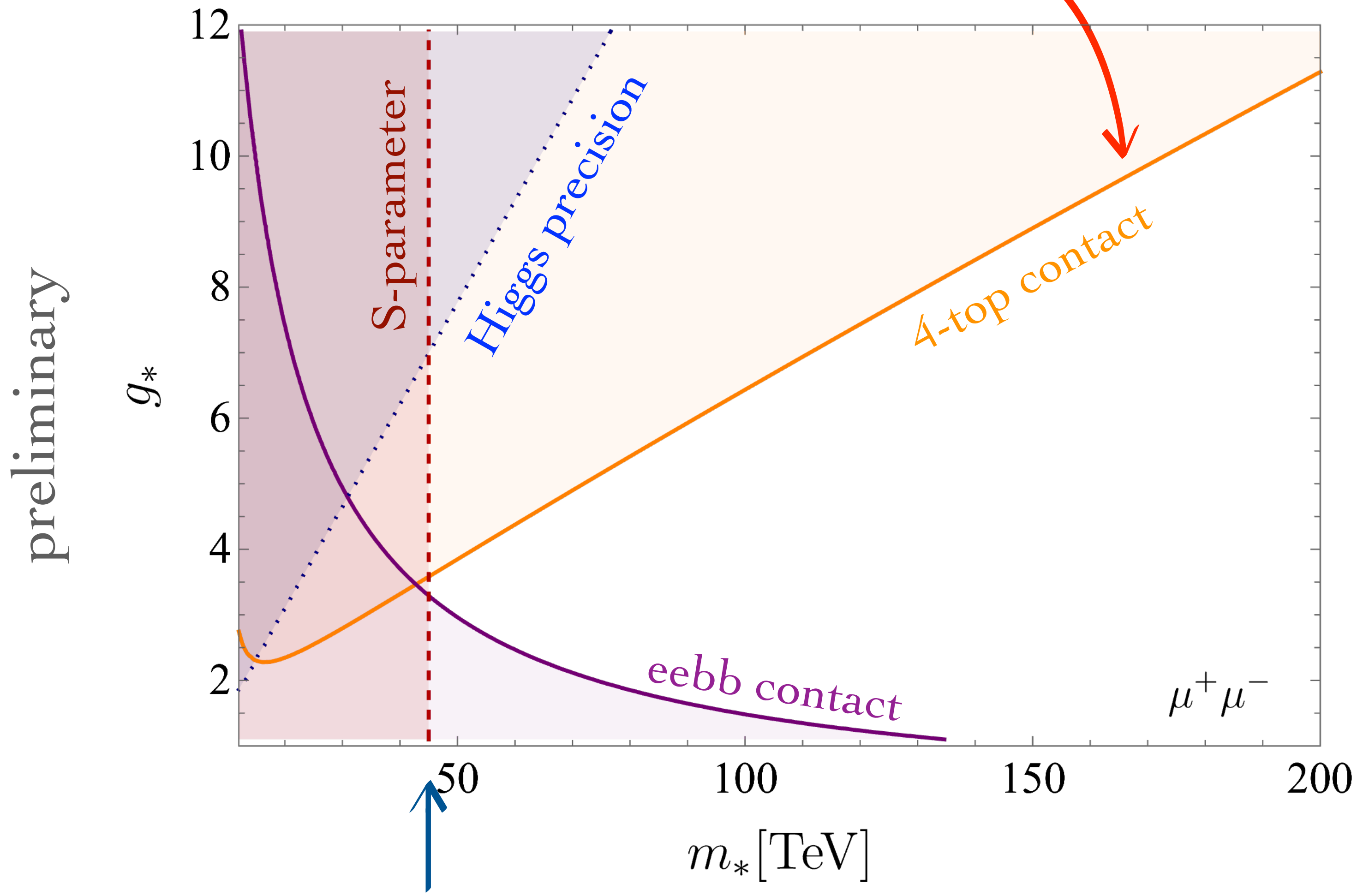

$\frac{m_*}{g_*} \gtrsim 18\,\text{TeV}$

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

[Han et al. 2008.12204]

[Buttazzo et al. 2012.02769]

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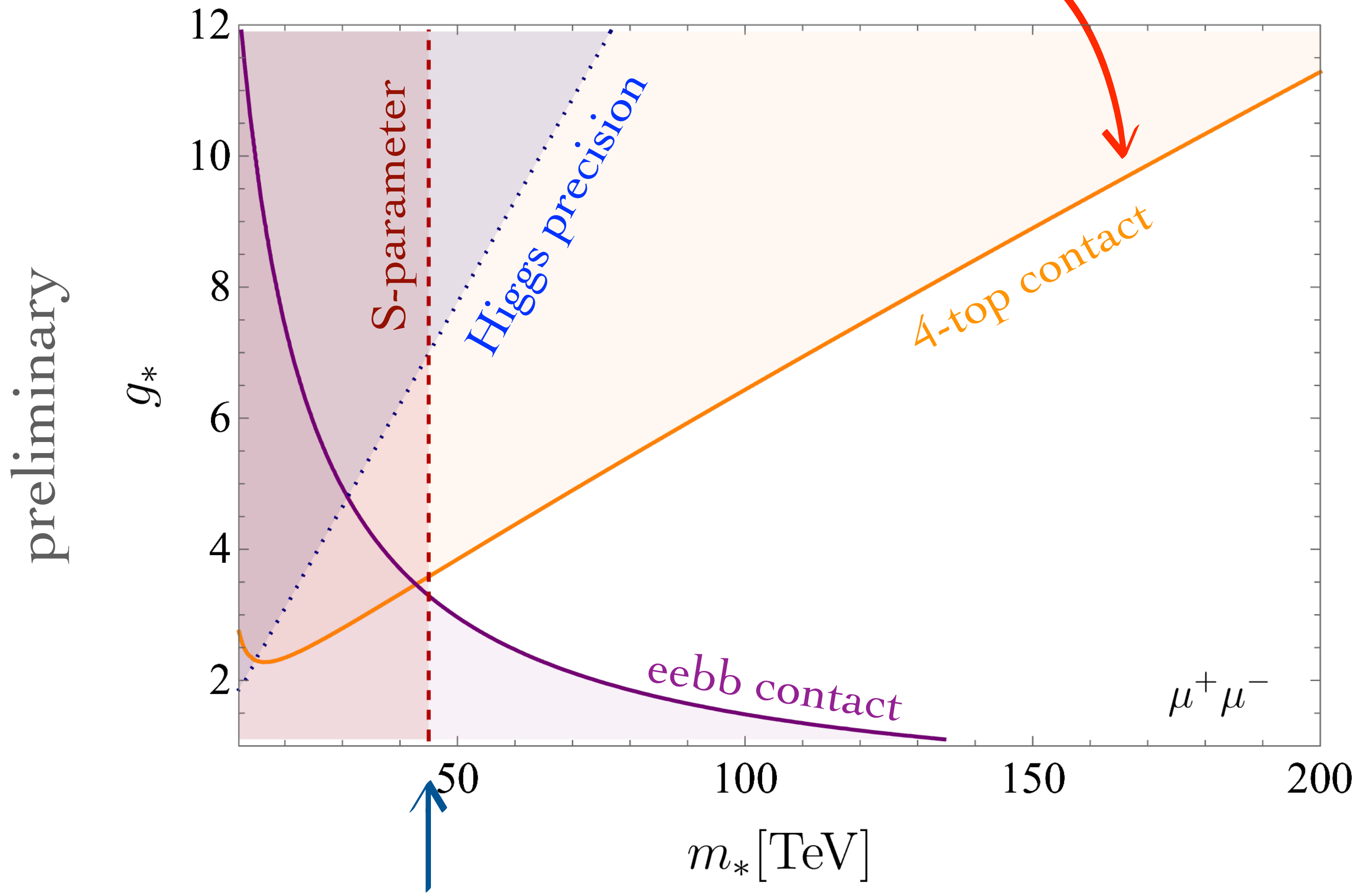

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Main assumption is that uncertainty remains statistically dominated.

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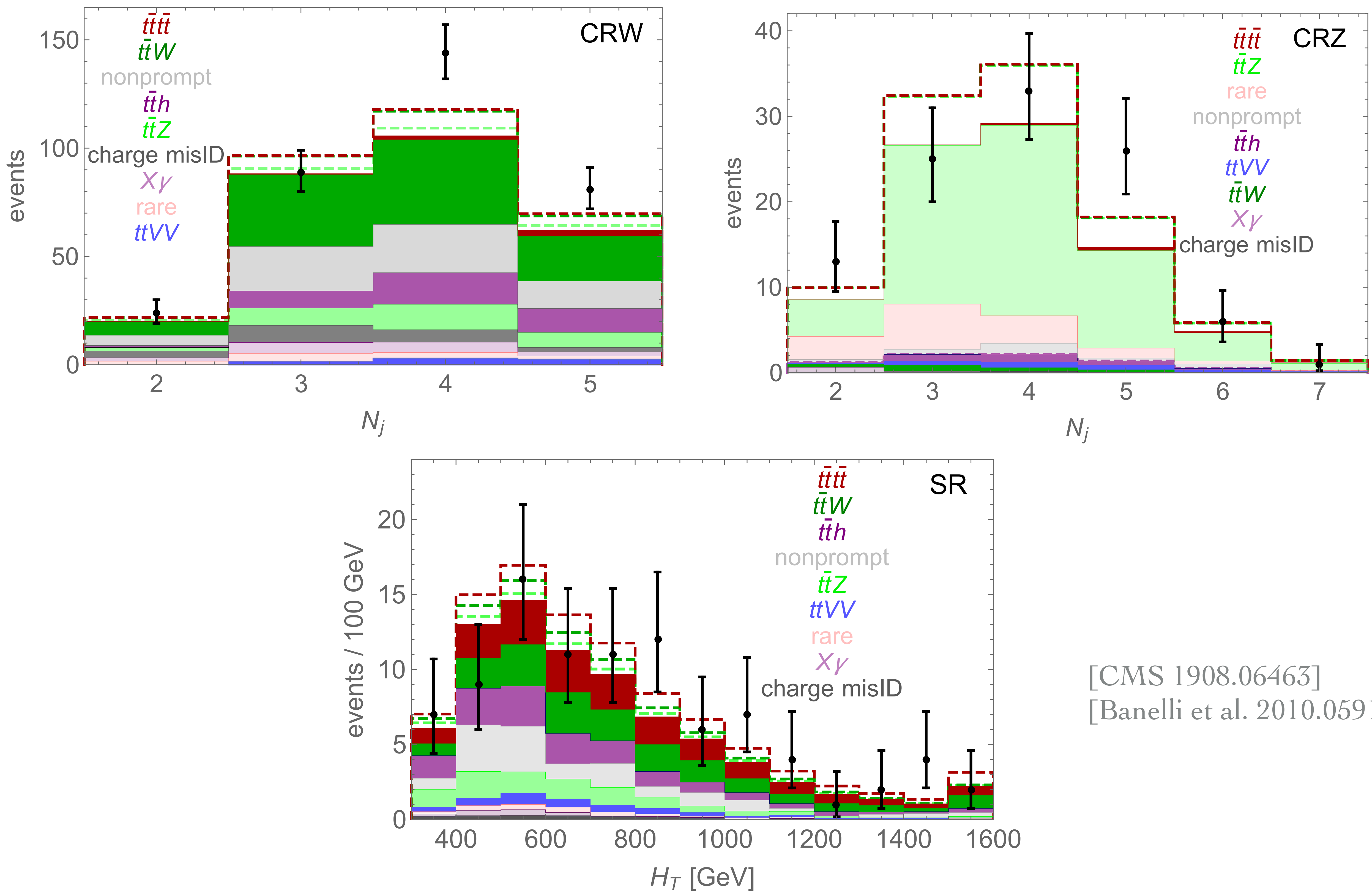
Backup

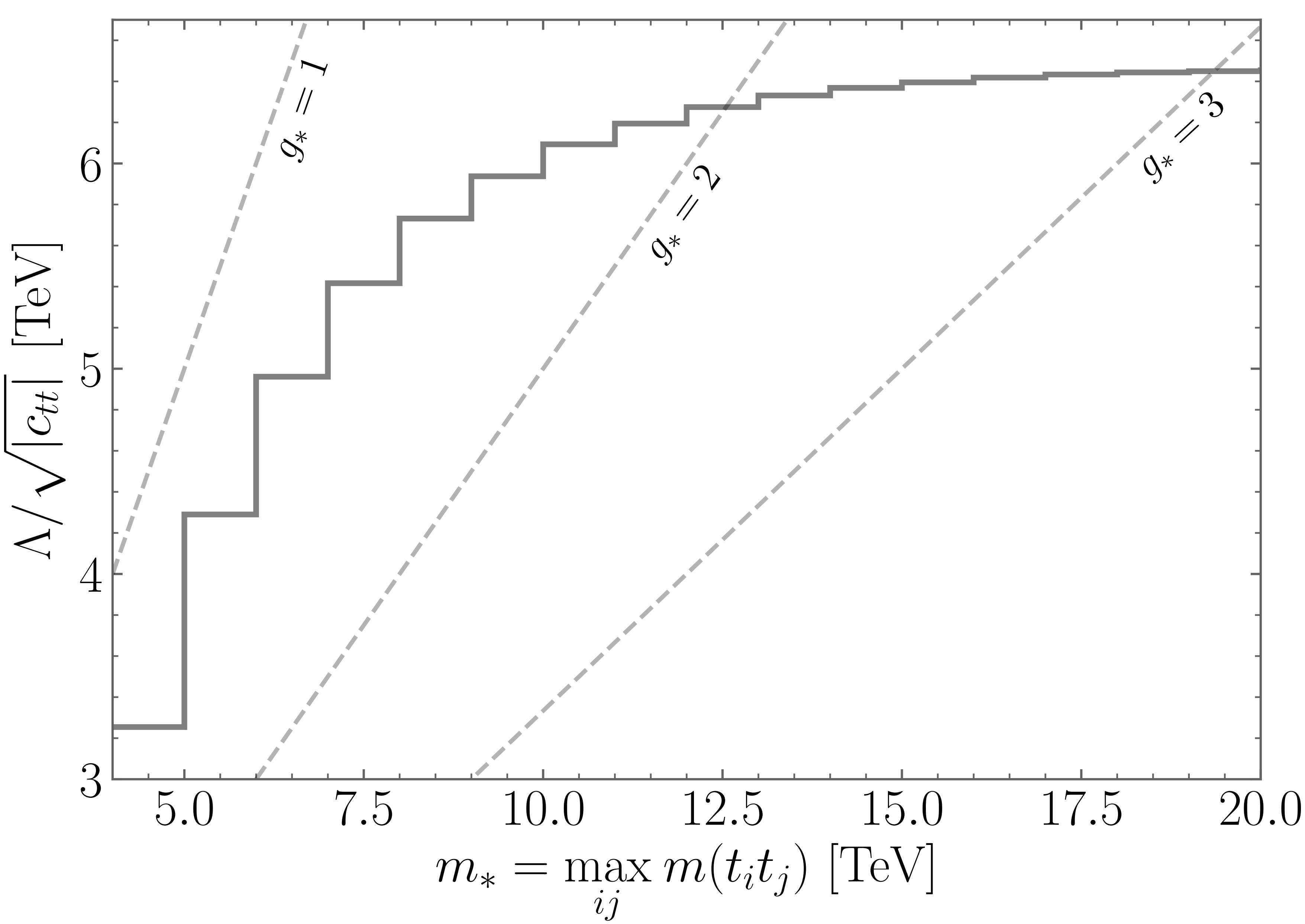
Further motivation: Multilepton + jet "excesses" at the LHC



[CMS 1908.06463]
[Banelli et al. 2010.05915]

EFT validity

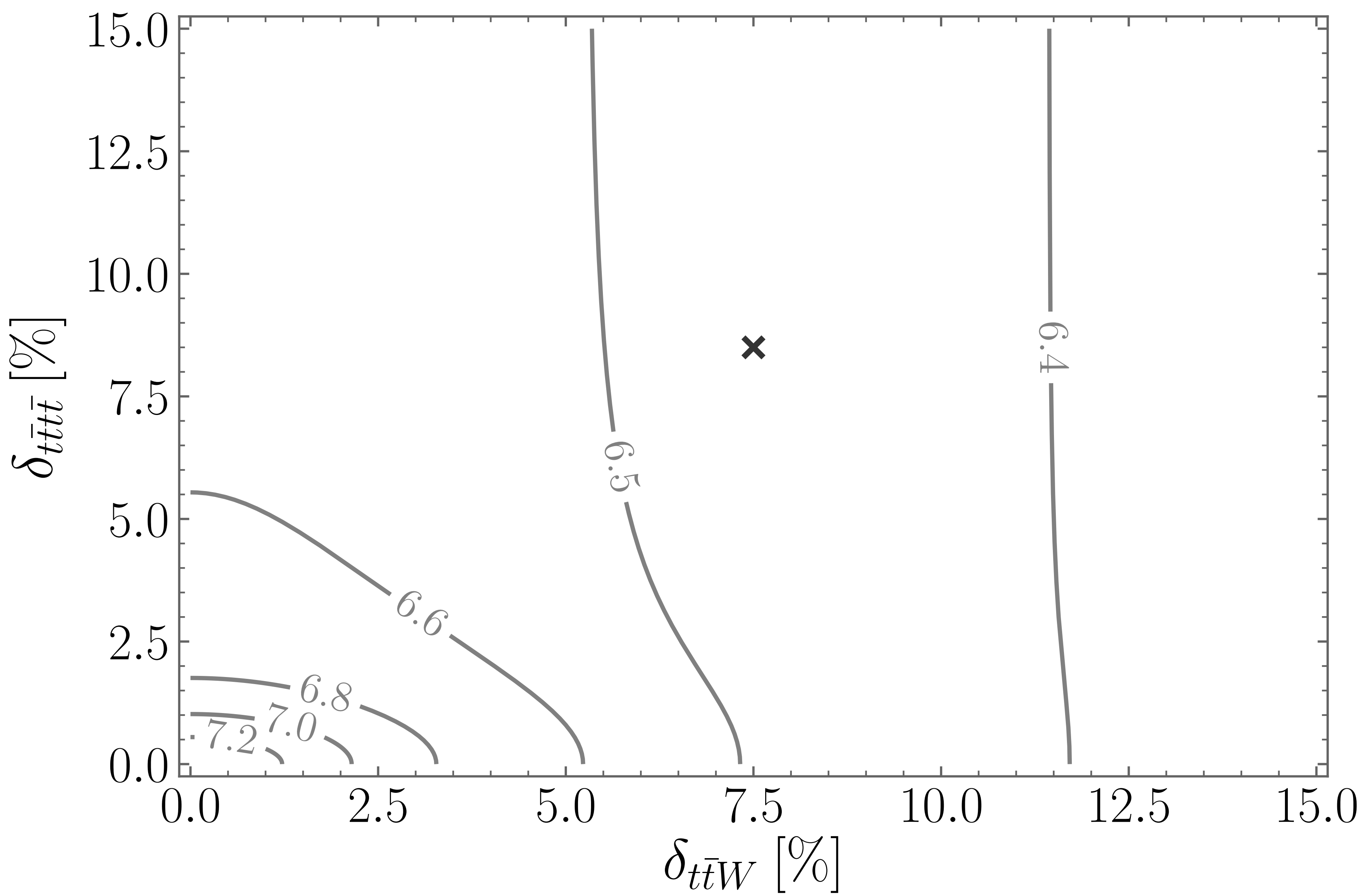
Estimate the region of EFT validity by discarding events with $\max_{ij} m(t_i t_j) > m_*$



Systematic uncertainties

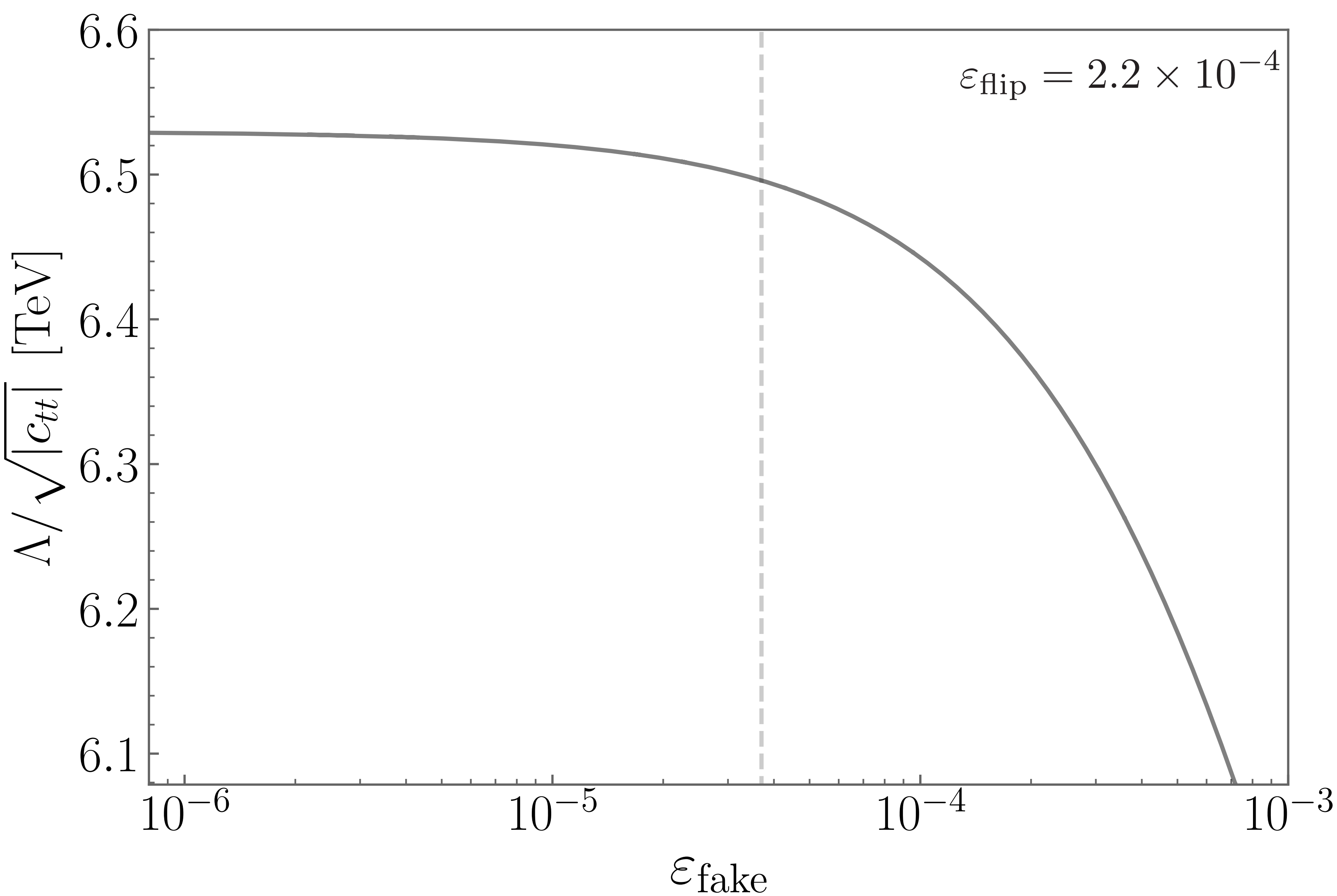
Systematics: $(\delta_{t\bar{t}t\bar{t}}, \delta_{t\bar{t}W}) = (8.5\%, 7.5\%)$, half of current theoretical uncertainites

[Frederix, Pagaini, Zaro 1711.02116]



Detector efficiencies

In the main analysis $(\epsilon_{\text{fake}}, \epsilon_{\text{flip}}) = (0.37, 2.2) \times 10^{-4}$ were used [arXiv:1611.05032]



Fully hadronic decay channel

At the FCC, highly boosted tops open up the possibility for top tagging algorithms

Requiring four tagged tops is limited by low statistics

↓

Require tag on hardest jets and reconstruct the resolved tops

$$\chi^2 = \left(\frac{m_{j1} - m_t}{\Gamma_t}\right)^2 + \left(\frac{m_{j2} - m_t}{\Gamma_t}\right)^2$$

Neural Network

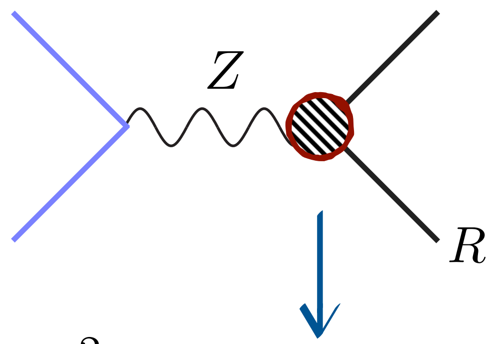
Neither yielded a bound comparable to the multilepton analysis

FCC-tailored/machine learning taggers could significantly enhance reach

Top compositeness at future lepton colliders

- Multiple operators enter top pair production

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



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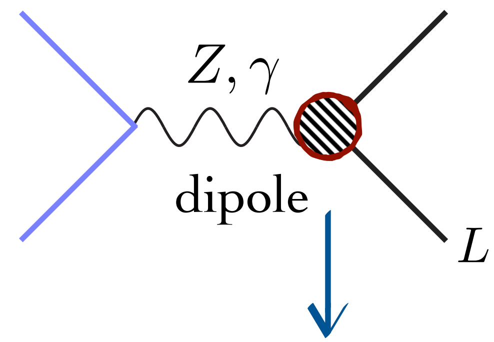

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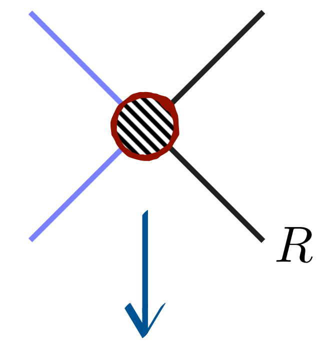


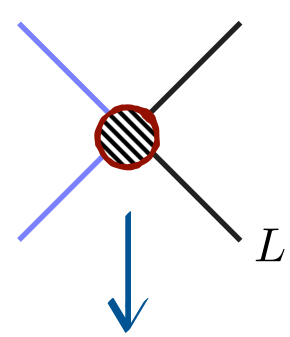
$$\frac{g_*^2}{m_*^2}(H^\dagger D_\mu H)(\bar{t}_R\gamma^\mu t_R) \qquad \frac{y_t g}{m_*^2}\bar{q}_L H\sigma_{\mu\nu}W^{\mu\nu}t_R \qquad \frac{c_{te}}{m_*^2}(\bar{e}_R\gamma_\mu e_R)(\bar{t}_R\gamma^\mu t_R)$$

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

At high energies, contact interactions dominate

- Bottom pair-production sensitive to weak couplings

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



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

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