Four Top Quark Production and New Physics

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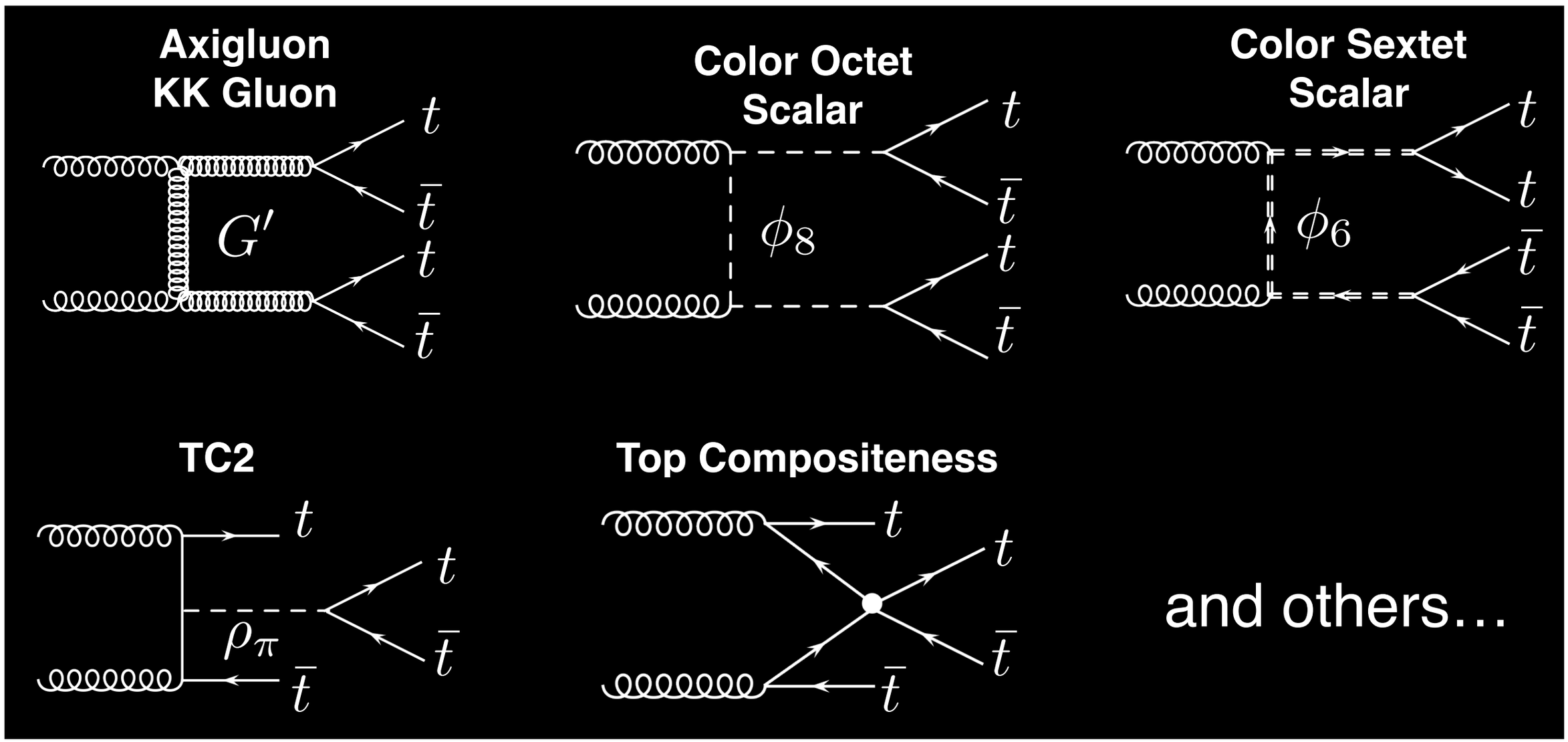
09-27-2019

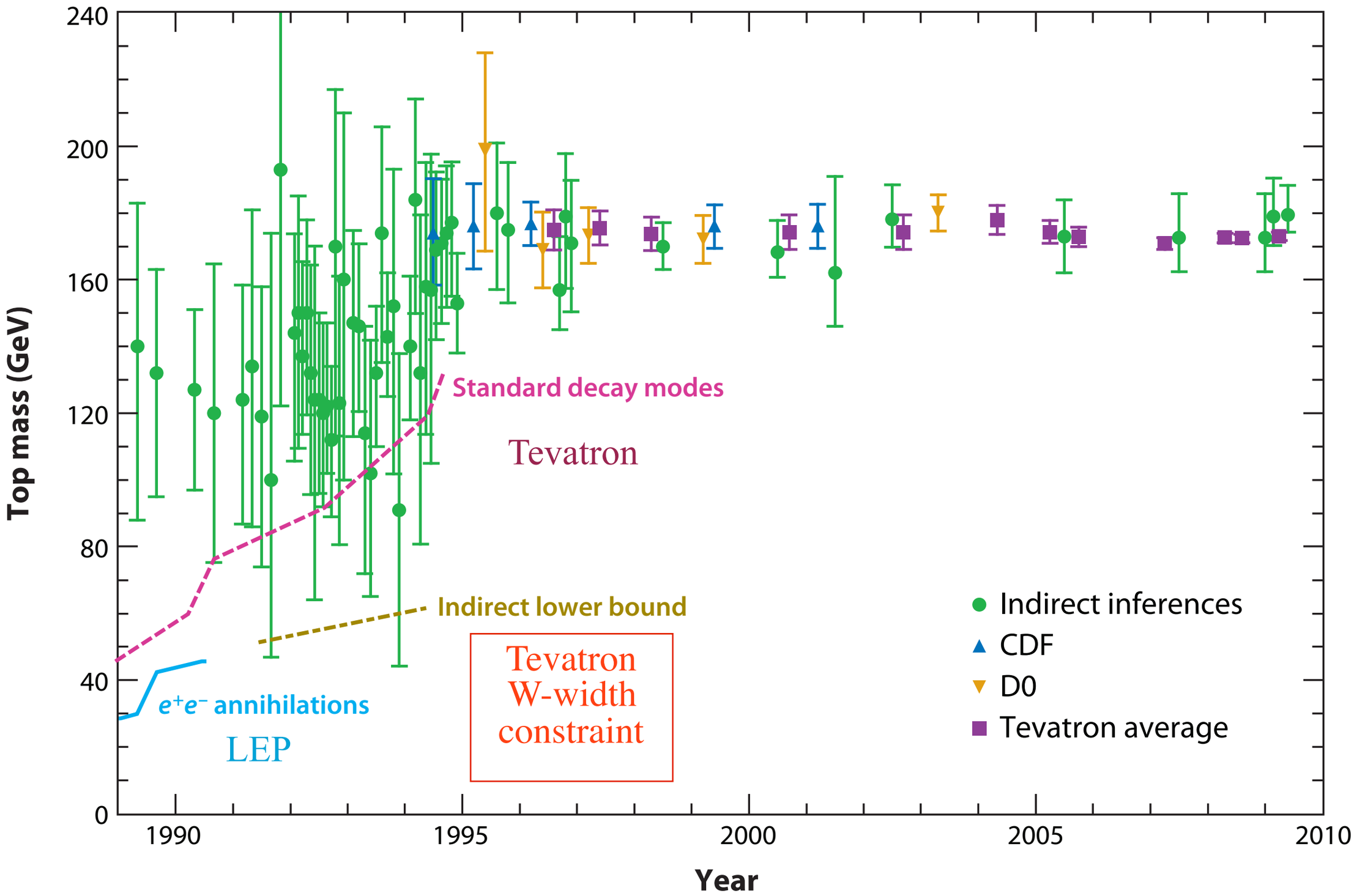
Top quark often plays a key role in EWSB in NP models.

Four top quarks are copiously produced in many NP models while top-quark pairs are not.



My apologies if I missed your works here

Top Quark Mass



Four-heavy-quark hadroproduction

Oct. 01, 1991

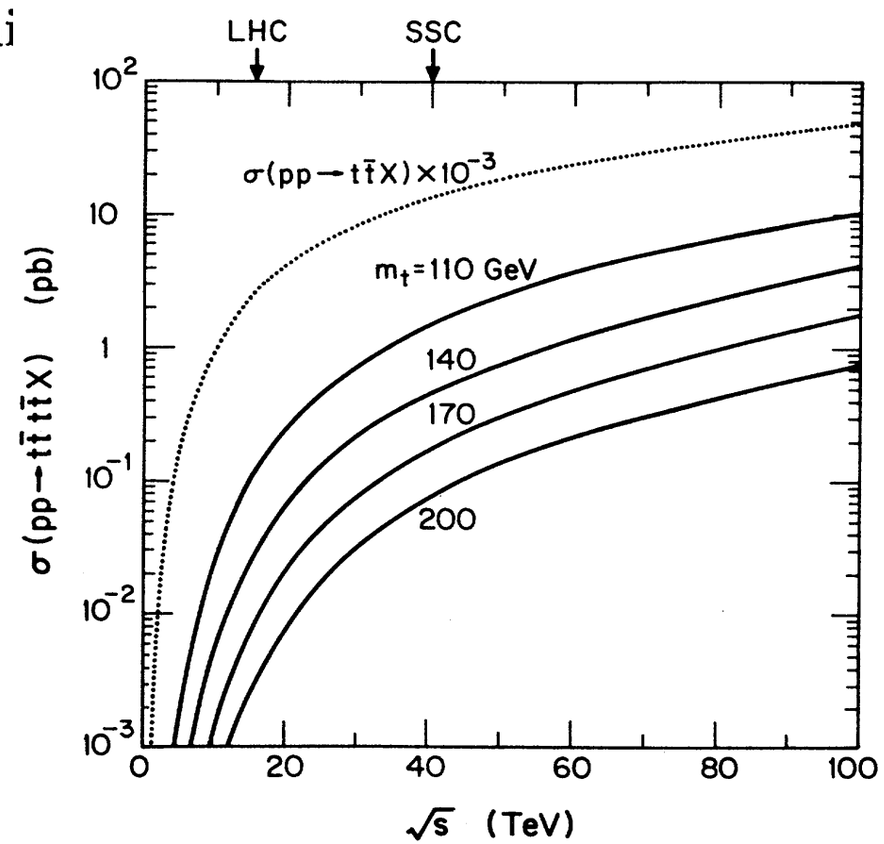
V. Barger and A. L. Stange
Physics Department, University of Wisconsin, Madison, Wisconsin 53706

R. J. N. Phillips
Rutherford Appleton Laboratory, Chilton, Didcot, Oxon, England
(Received 26 February 1991; revised manuscript received 25 June 1991)

We present new formulas for the numerical calculation of QCD production of two pairs of heavy quarks in hadron collisions, in leading order. We give results for $b\bar{b}b\bar{b}$, $b\bar{b}c\bar{c}$, and $c\bar{c}c\bar{c}$ production at the Fermilab Tevatron; the cross sections exceed 100 pb with all heavy quarks having $p_T > 10$ GeV. We also present results for $t\bar{t}t\bar{t}$ production in pp collisions for supercollider energies and briefly discuss the physics consequences for multi-W production via standard $t \to bW$ decays. For $m_t = 110$–140 GeV we predict of order 10–30 four-W events per year at the Superconducting Super Collider from this source, with all four weak bosons decaying to $e\nu_e$ or $\mu\nu_\mu$. Similar results are obtained for the CERN Large Hadron Collider, assuming ten times higher lumi

Very good accuracy

Today's discovery is tomorrow's background.



Four Top Quark Measurement

1908.06463

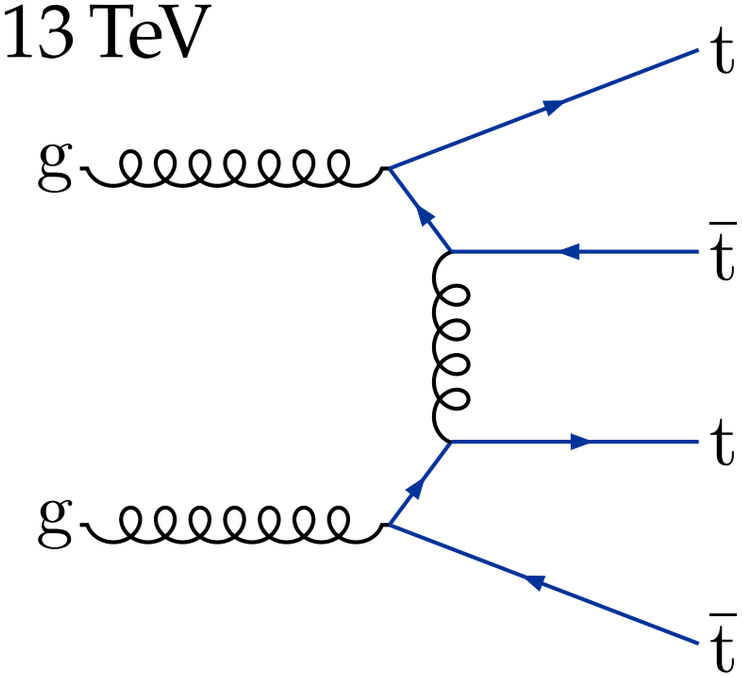
CERN-EP-2019-163
2019/08/20

CMS-TOP-18-003

Search for production of four top quarks in final states with same-sign or multiple leptons in proton-proton collisions at $\sqrt{s} = 13\,\text{TeV}$

13TeV+137fb^{-1}

$$\sigma(t\bar{t}t\bar{t}) = 12.6^{+5.8}_{-5.2}\ \text{fb}$$



Now four-top channel is a powerful tool to probe NP.

The cross section is expected to be constrained to 10%-28% total uncertainty at the HL-LHC. *CMS PAS FTR-18-031*

Top Quark and New Physics

SUSY, LH, Composite, RS, TC…

Weakly Interacting

Strongly Interacting

What should we see?

Natural NP models always have non-trial couplings between top quark and NP particles

Top

Effective Field Theory

Experimental Data

What could we see?

1) Top-philic Resonance (top-down)

Weak dynamics

2HDB Axigluon

Color octet/sextet

KK excitation

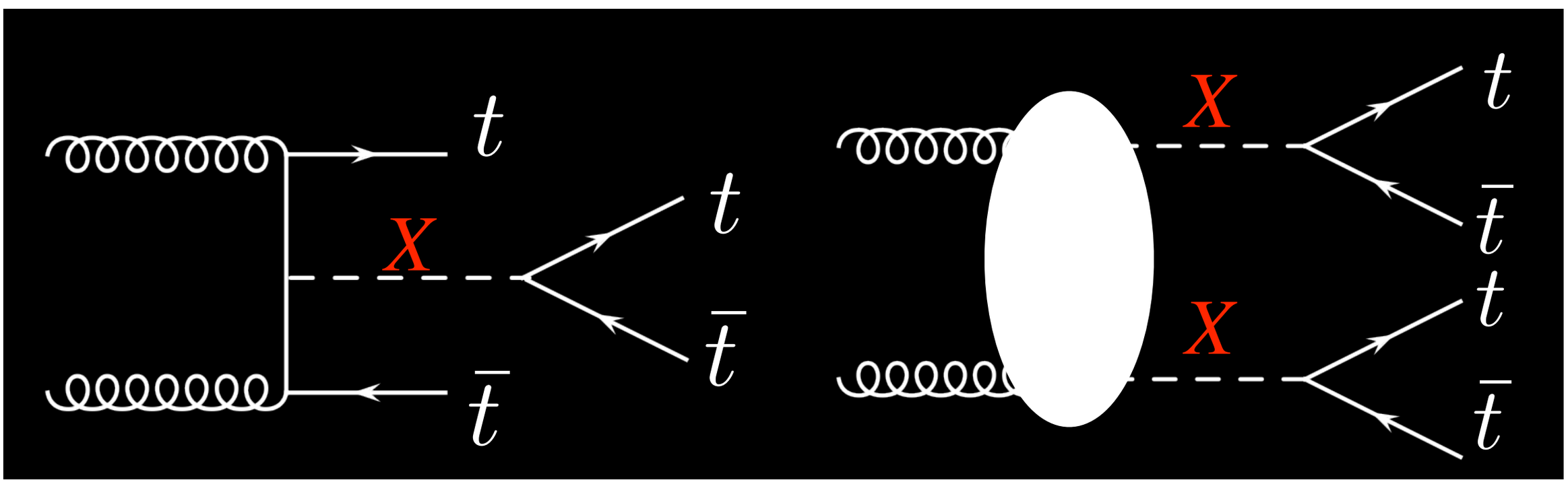
Strong dynamics

Top color

Composite Top

Composite Higgs

Characteristic diagrams



Two Higgs Doublet Models

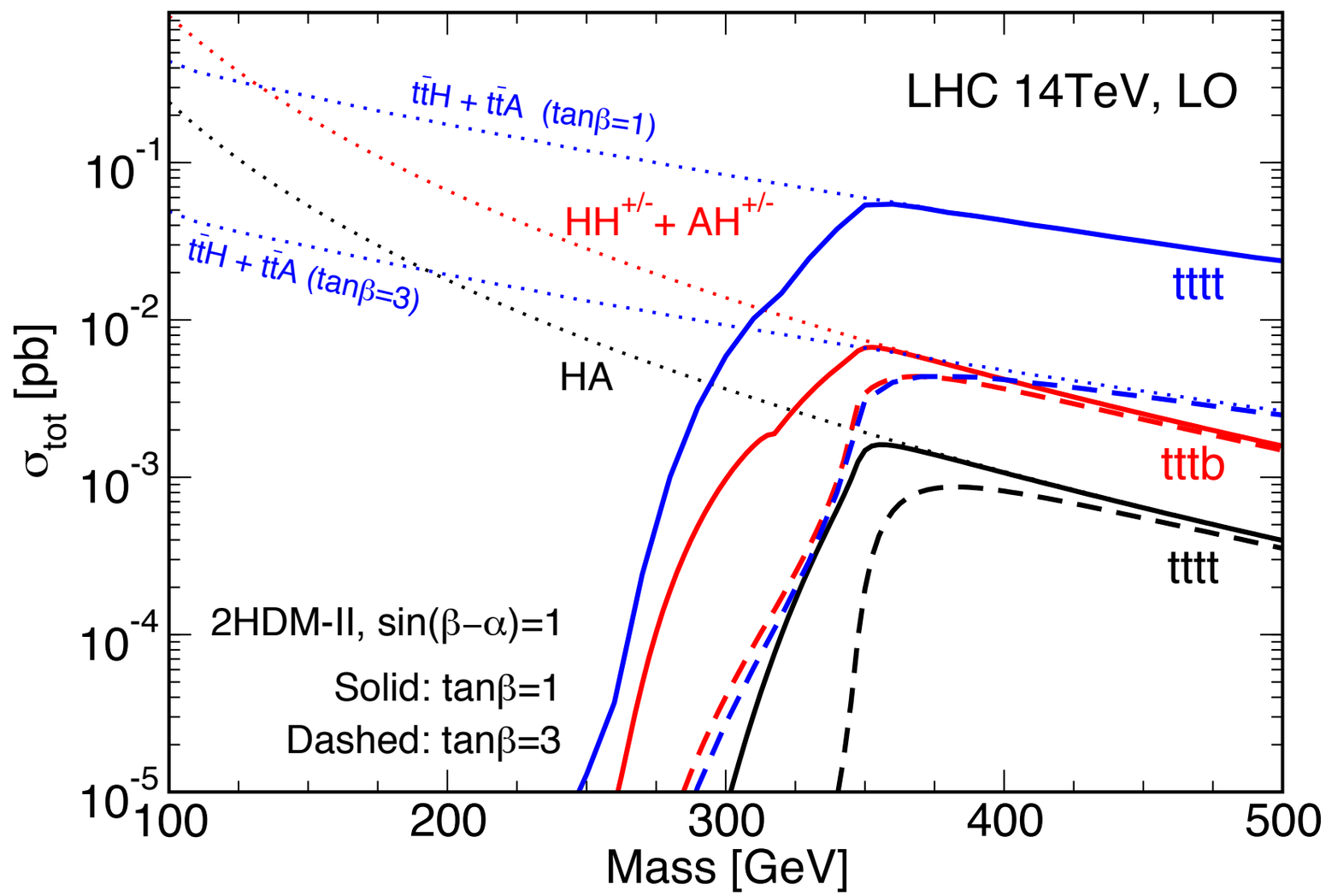
Kanemura, Yokoya and Zheng, 1505.01089

	ξ_h^u	ξ_h^d	ξ_h^ℓ	ξ_H^u	ξ_H^d	ξ_H^ℓ	ξ_A^u	ξ_A^d	ξ_A^ℓ
Type-I	c_α/s_β	c_α/s_β	c_α/s_β	s_α/s_β	s_α/s_β	s_α/s_β	$\cot\beta$	$-\cot\beta$	$-\cot\beta$
Type-II	c_α/s_β	$-s_\alpha/c_\beta$	$-s_\alpha/c_\beta$	s_α/s_β	c_α/c_β	c_α/c_β	$\cot\beta$	$\tan\beta$	$\tan\beta$
Type-X	c_α/s_β	c_α/s_β	$-s_\alpha/c_\beta$	s_α/s_β	s_α/s_β	c_α/c_β	$\cot\beta$	$-\cot\beta$	$\tan\beta$
Type-Y	c_α/s_β	$-s_\alpha/c_\beta$	c_α/s_β	s_α/s_β	c_α/c_β	s_α/s_β	$\cot\beta$	$\tan\beta$	$-\cot\beta$

$$pp \to t\bar{t}H \to t\bar{t}t\bar{t}$$
$$pp \to t\bar{t}A \to t\bar{t}t\bar{t}$$
$$pp \to HA \to t\bar{t}t\bar{t}$$

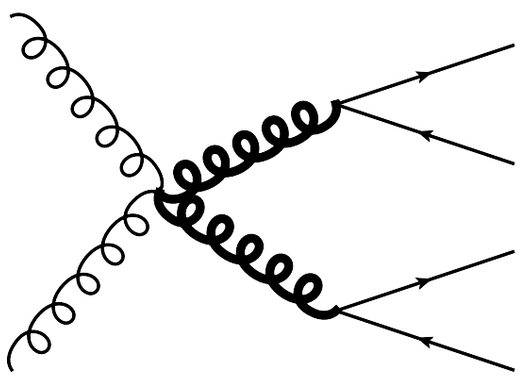
By-product

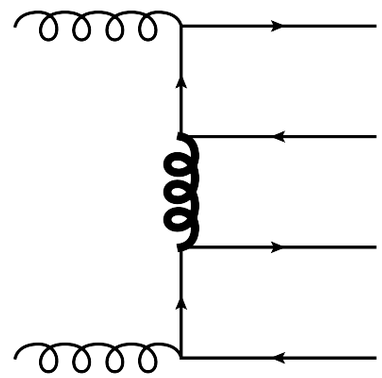
$$pp \to H^+H \to t\bar{b}t\bar{t}$$
$$pp \to H^+A \to t\bar{b}t\bar{t}$$

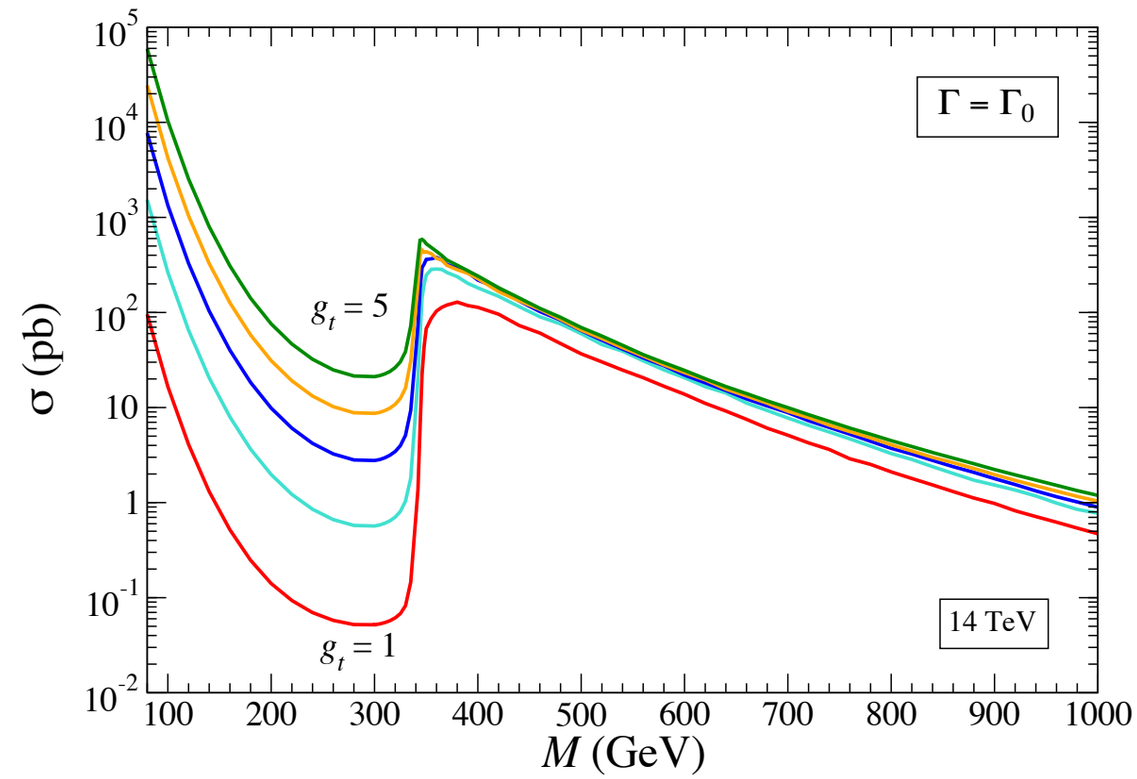


Axigluon or KK Gluon

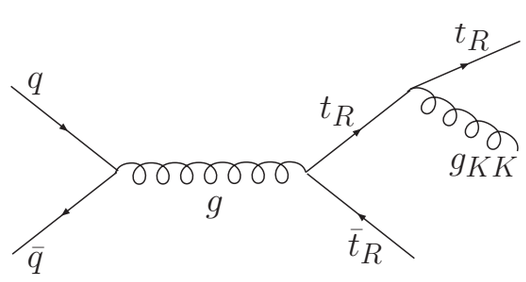
Antunan, Kuhn, Rodrigo, 0709.1652; Ferrario, Rodrigo, 0809.3353; Ferrario, Rodrigo , 0906.5541; Frampton, Shu, Wang, 0911.2955; Chivukula, Simmons, Yuan, 1007.0260; Aguilar-Saavedra, Santiago, 1112.3778

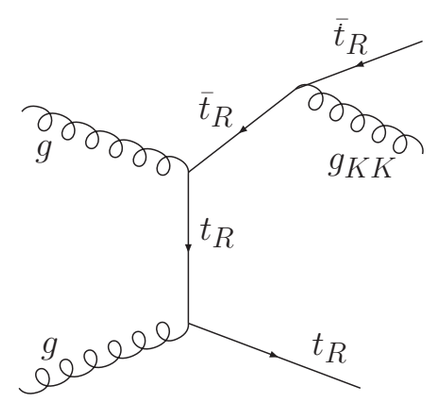






Guchait, F. Mahmoudi and K. Sridhar, 0710.2234;
Djouadi, Moreau, Richard, singh, 0906.0604





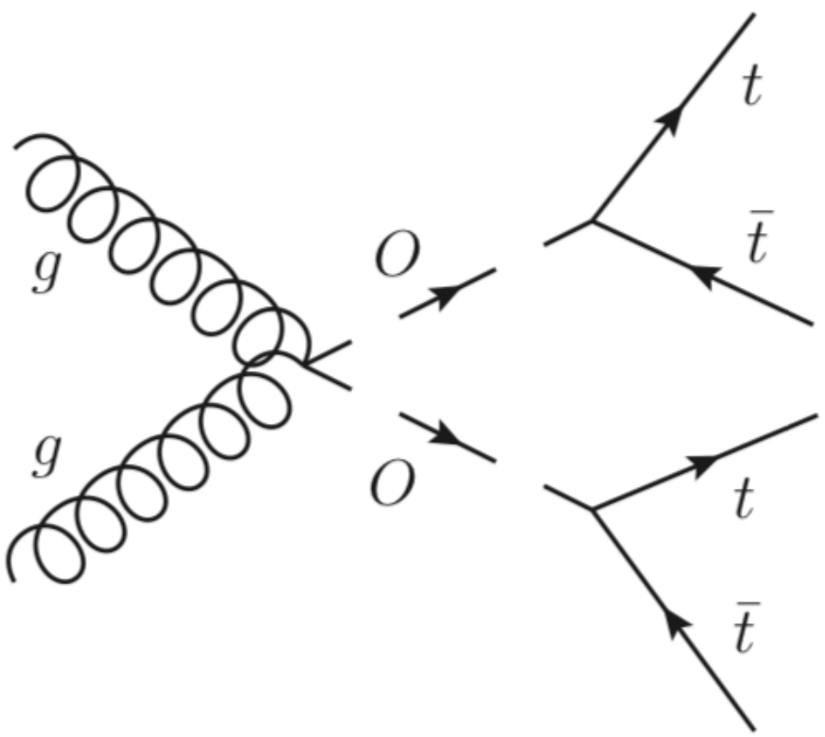
$$g_{KK} \to t\bar{t}$$

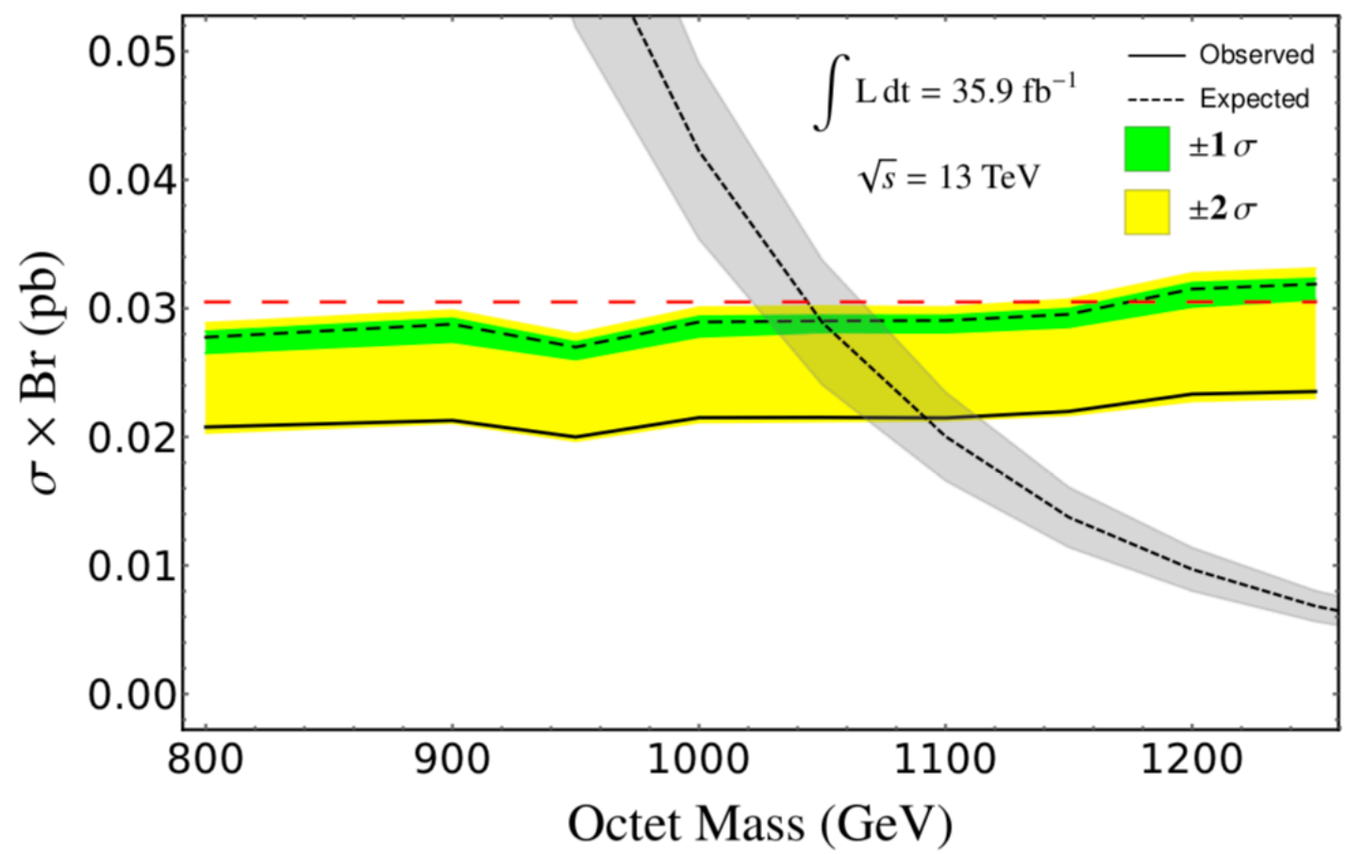
Associated production of a KK gluon with ttbar

Color Octet Scalar (sgluon)

Calvet, Fuks, Gris, Valery, 1212.3360
Darme, Fuks, Goodsell, 1805.10835

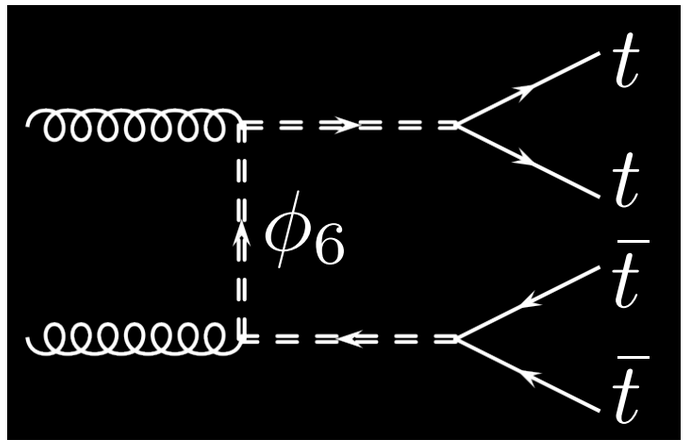
No coupling to light quarks and gluons



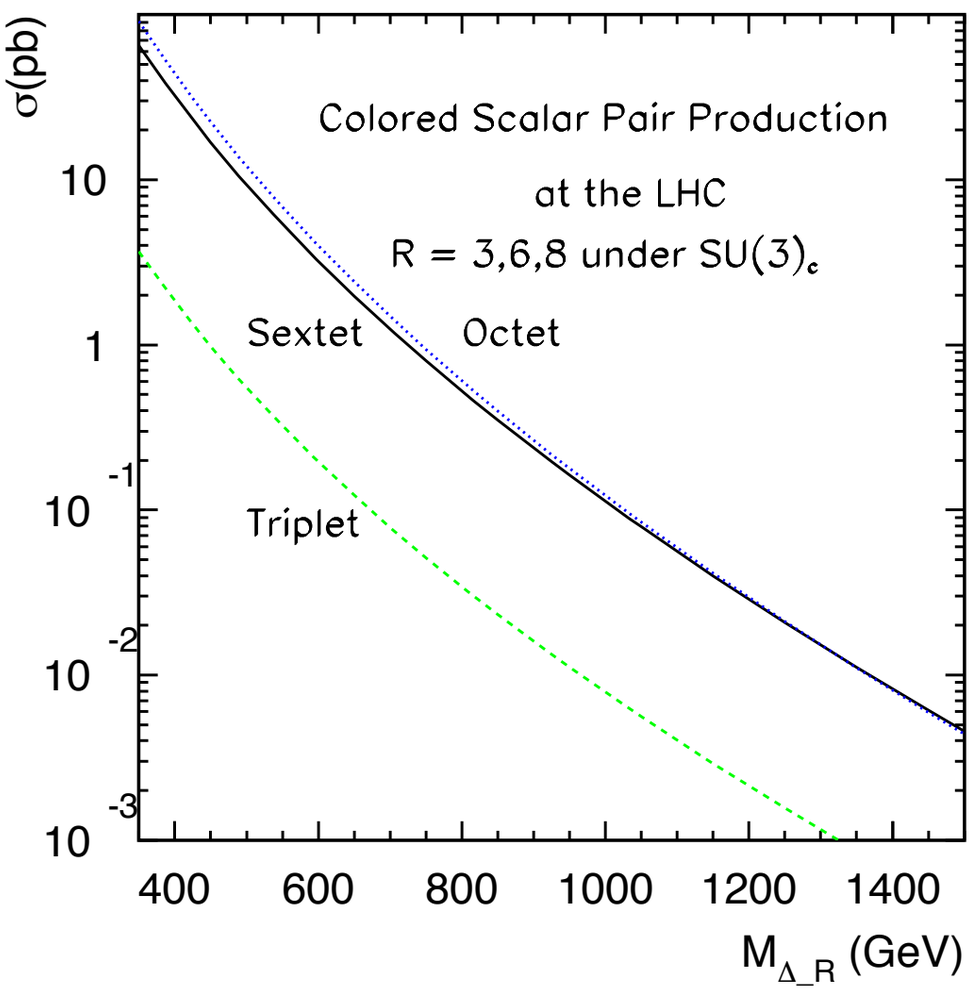


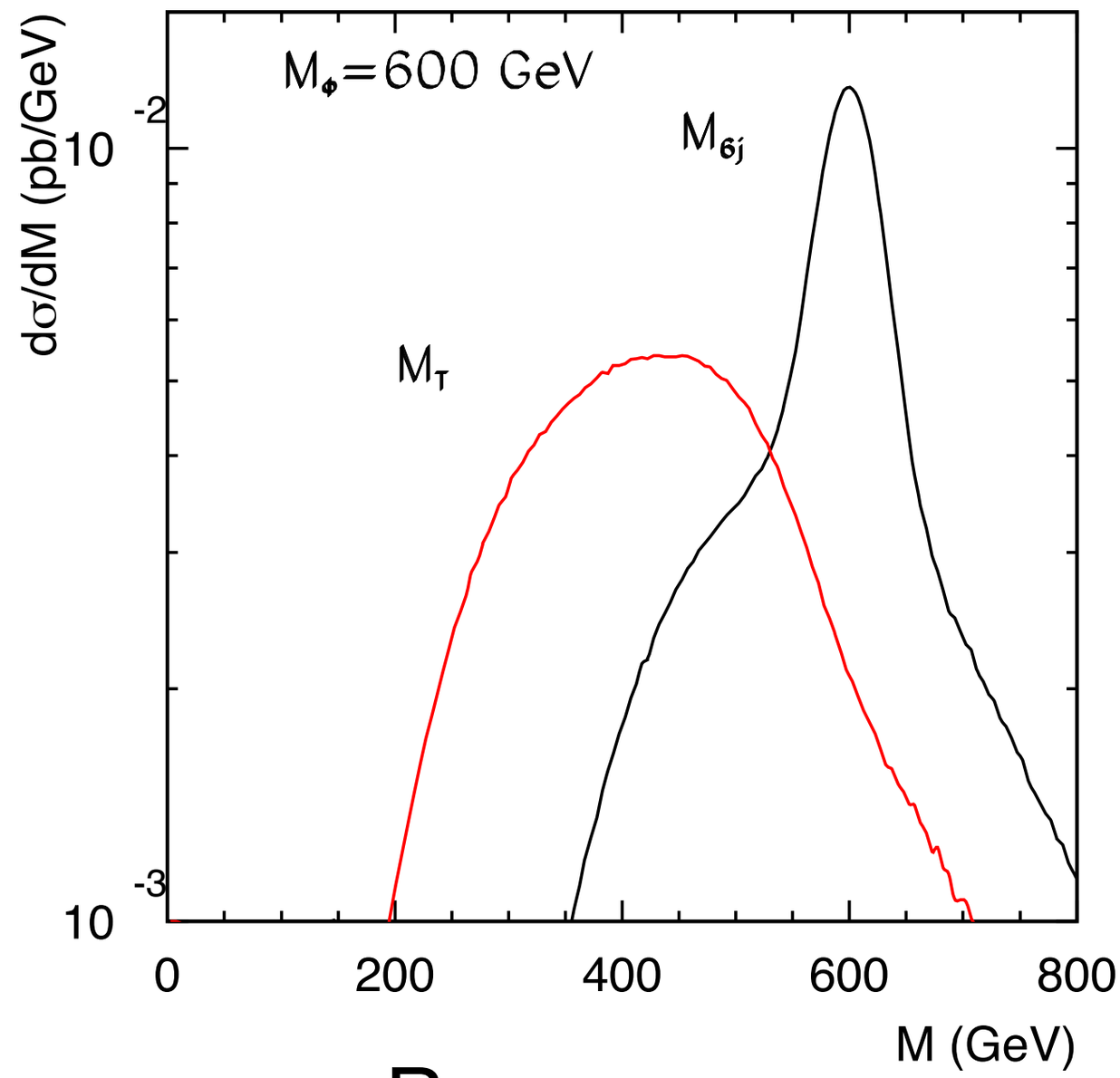
large production rate of four tops → stringent bound

Color Sextet Scalar



Chen, Klemm, Rentala, Wang, 0811.2105





Resonance

Broad Resonance in Composite Higgs

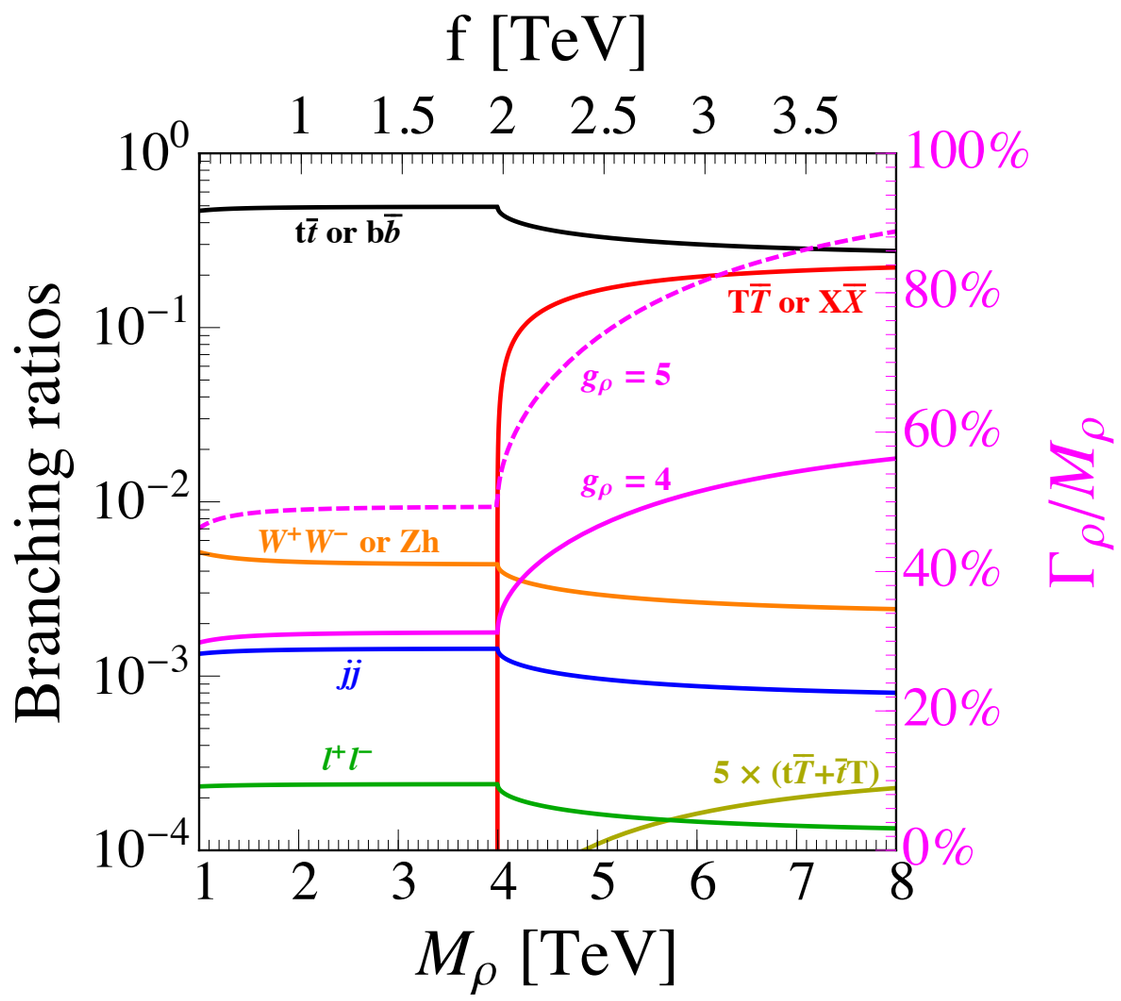
Gregoire, Katz, Sanz, 1101.1294

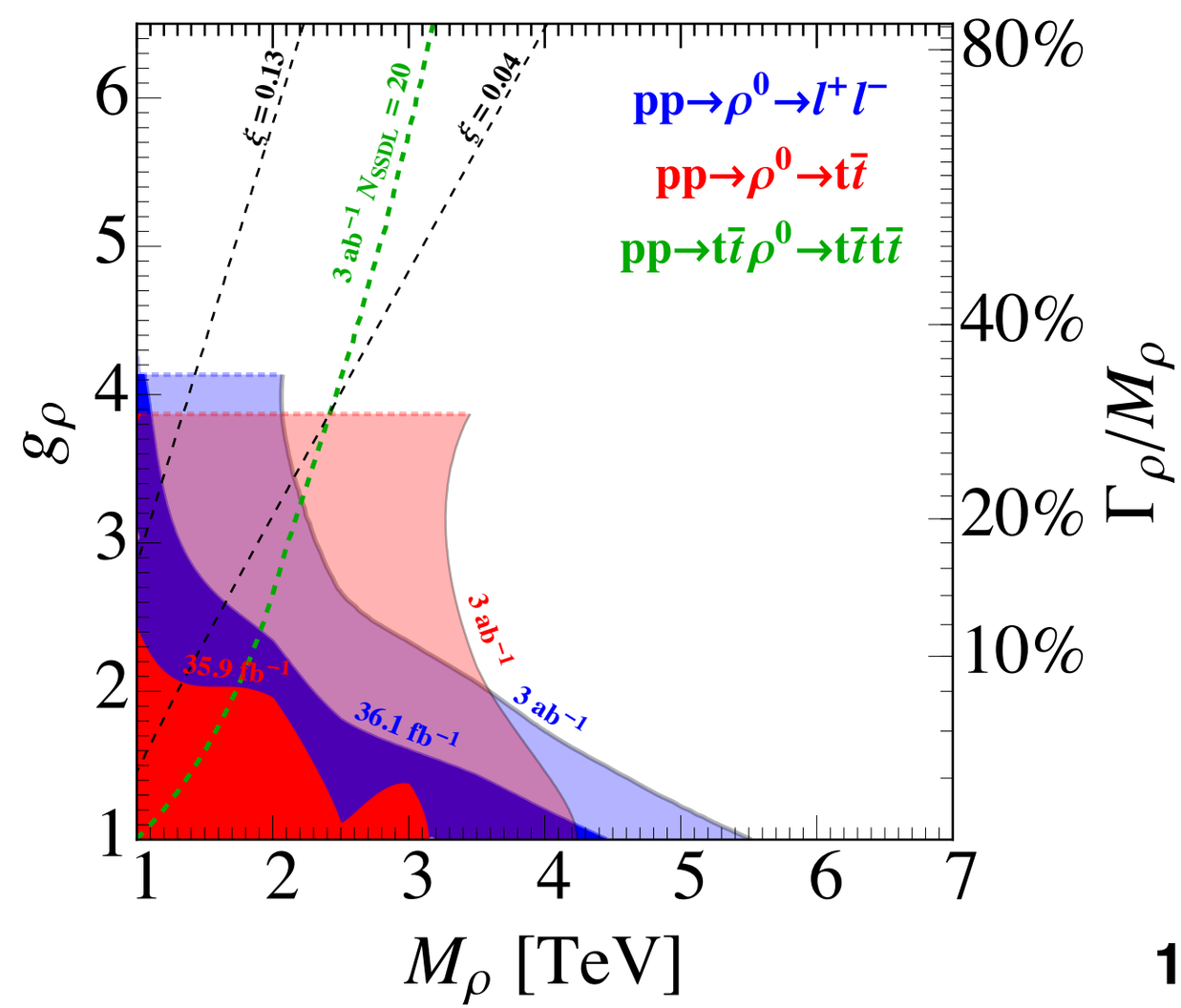
Cacciapaglia, Cai, Deandrea, Flacke, Lee, Parolini, 1507.02283

Liu, Wang, Xie, 1901.01674

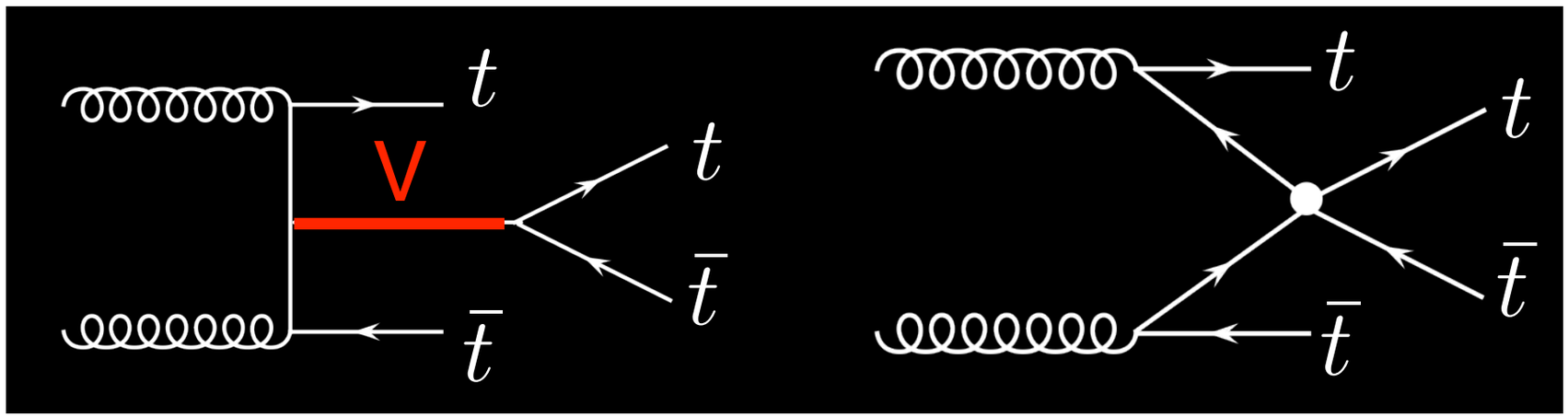
$SO(5)/SO(4)$ with left-handed 3rd generation fully composite

$$pp \to t\bar{t}\rho, \quad \rho \to t\bar{t}$$





Composite Top

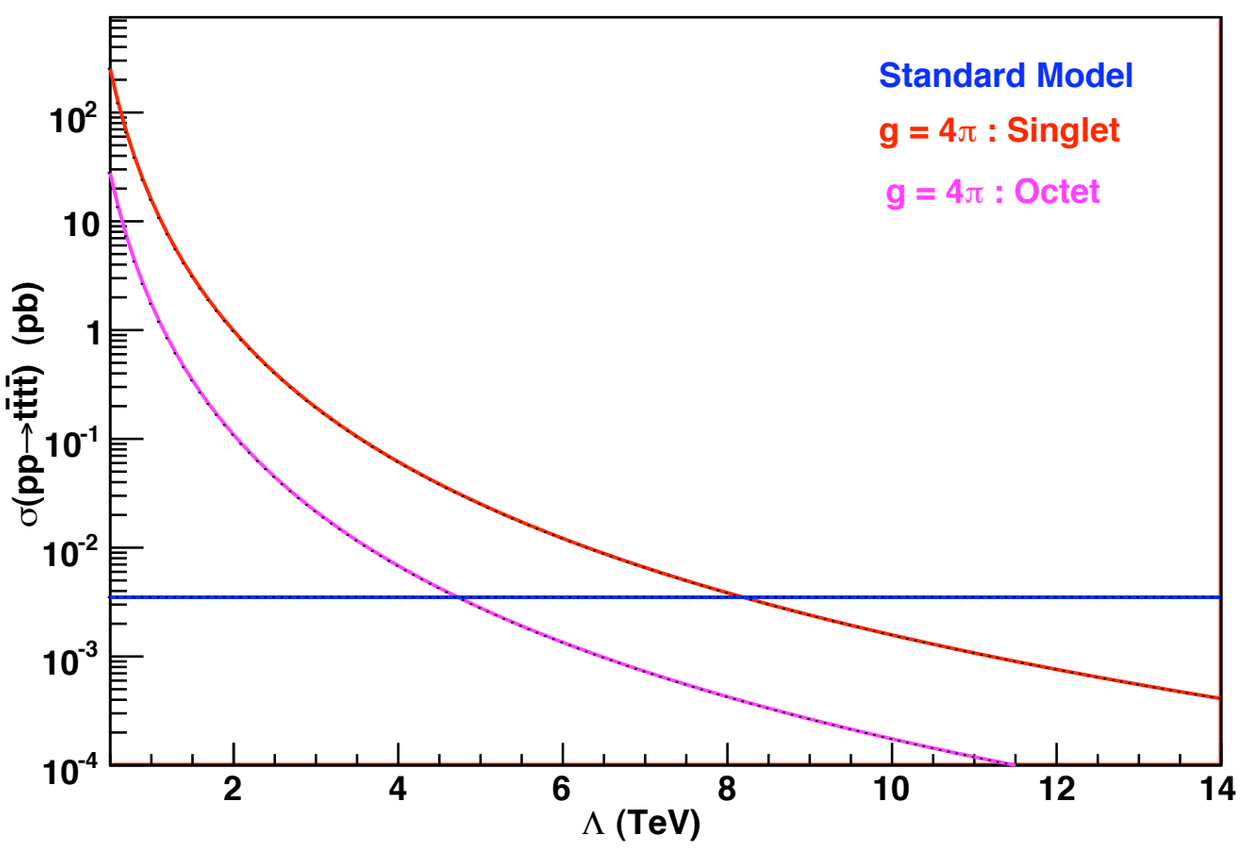


General feature:

four-top contact interaction

Or, presence of a color-octet vector boson with strong coupling to top quarks

$$\mathcal{O}_t = g^2 \left[\bar{t}^i \gamma^\mu P_R t_j\right] \left[\bar{t}^k \gamma_\mu P_R t_l\right]$$



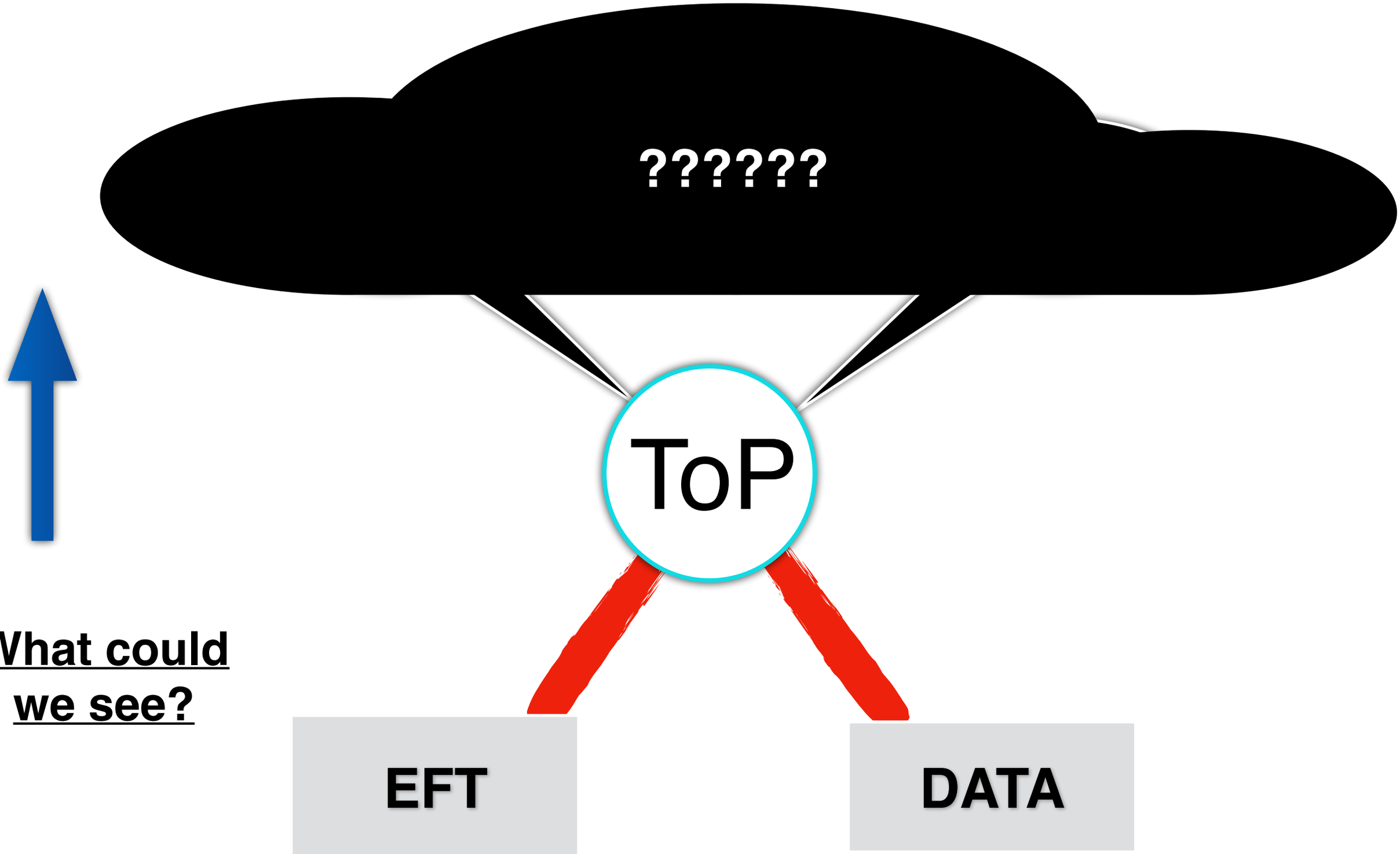
Ben Lillie, Jing Shu and Tait, 0712.3057

Alex Pomarol and Javi Serra, 0806.3247

Kumar, Tait and Vega-Morales, 0901.3808

Zhou, Whiteson, Tait, 1203.5862

2) EFT (bottom-up)

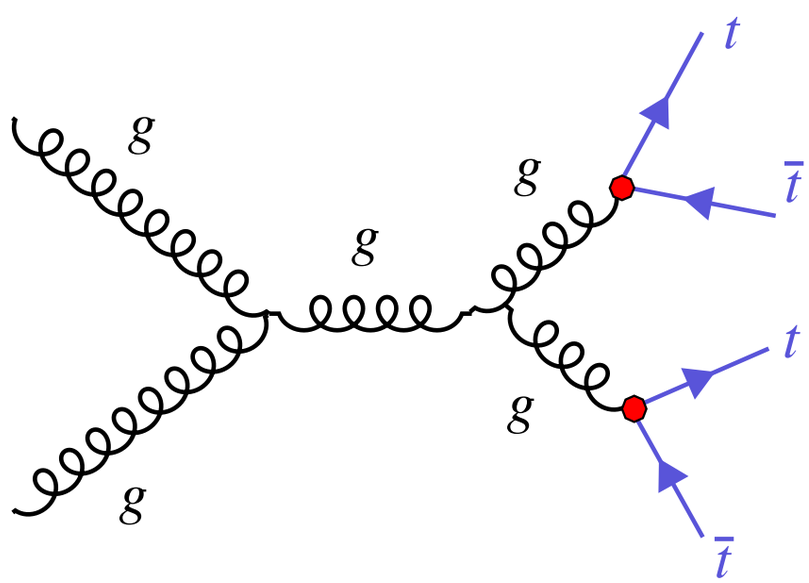


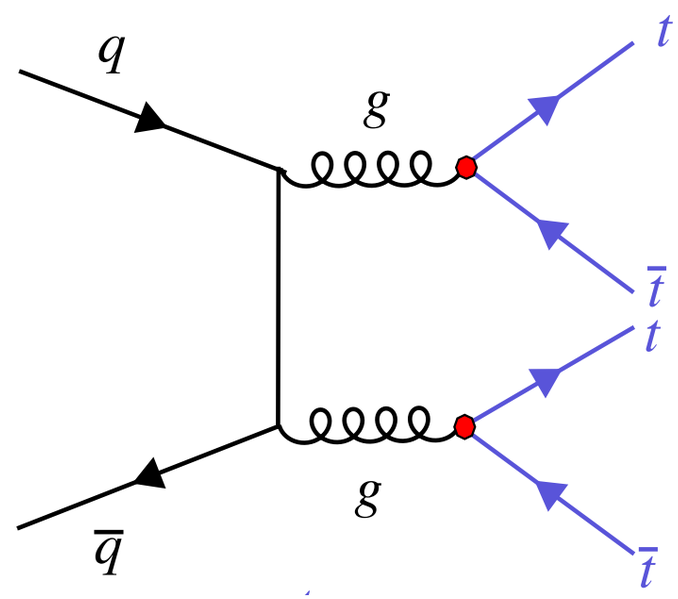
What could we see?

Color Electric and Magnetic Dipole

Malekhosseini, et al, 1804.05598

$$\mathscr{L}_{gt\bar{t}} = -g_s \bar{t} \frac{\lambda^a}{2} \gamma^\mu t G^a_\mu - g_s \bar{t} \lambda^a \frac{i\sigma^{\mu\nu} q_\nu}{m_t} \left(d^g_V + i d^g_A \gamma_5 \right) t G^a_\mu$$





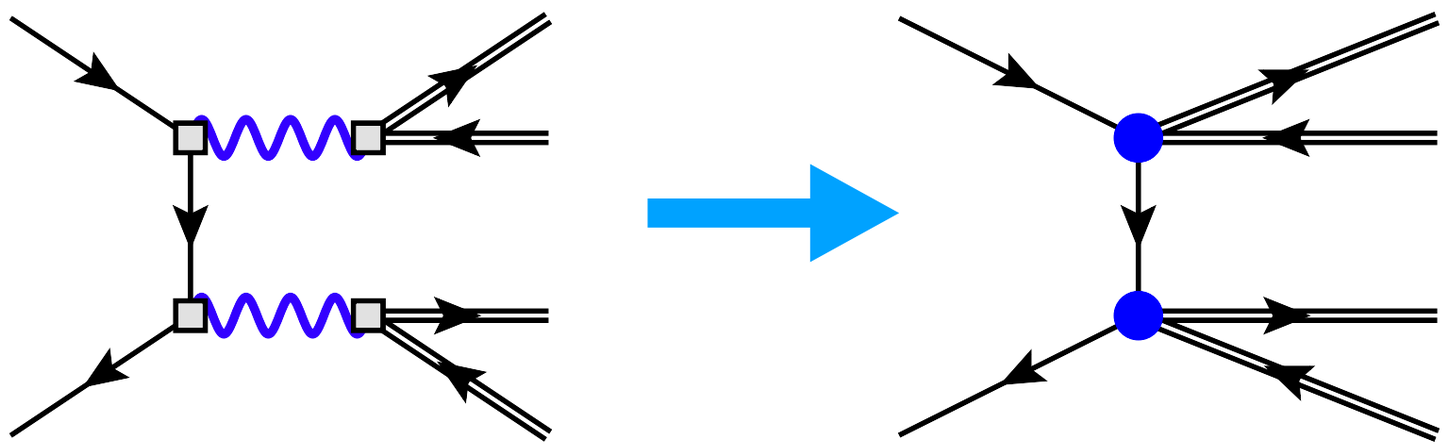
$$\sigma(pp \to t\bar{t}\bar{t}\bar{t})(fb) = \sigma_{\rm SM} + 154.827 \times d^g_V + 3404.44 \times \left(d^g_V \right)^2$$

$$\sigma(pp \to t\bar{t}t\bar{t})(fb) = \sigma_{\rm SM} + 2731.27 \times \left(d^g_A \right)^2$$

Four Fermion Operators

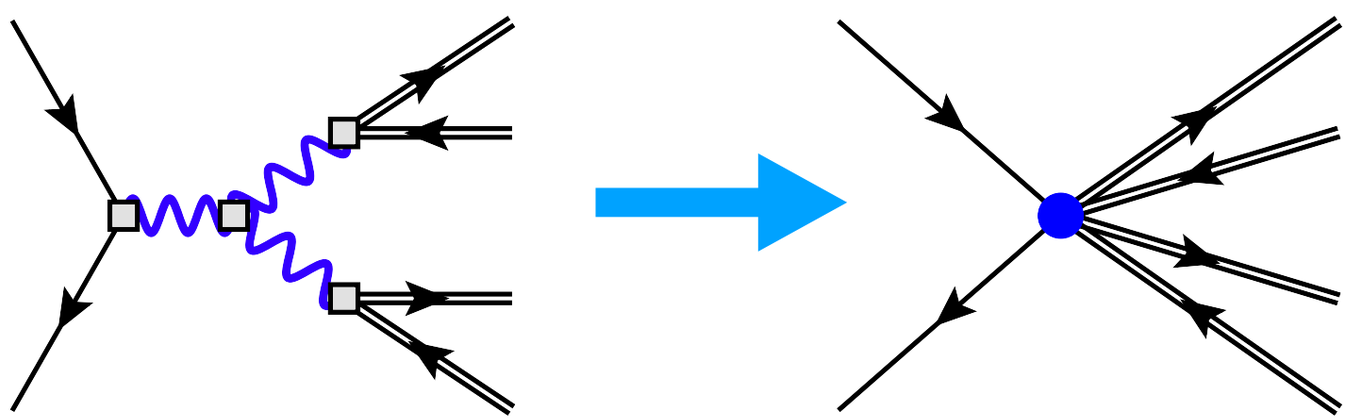
Cen Zhang, 1708.05928

Dim-6



$g_*^4 E^4 / \Lambda_{NP}^4$

Dim-10

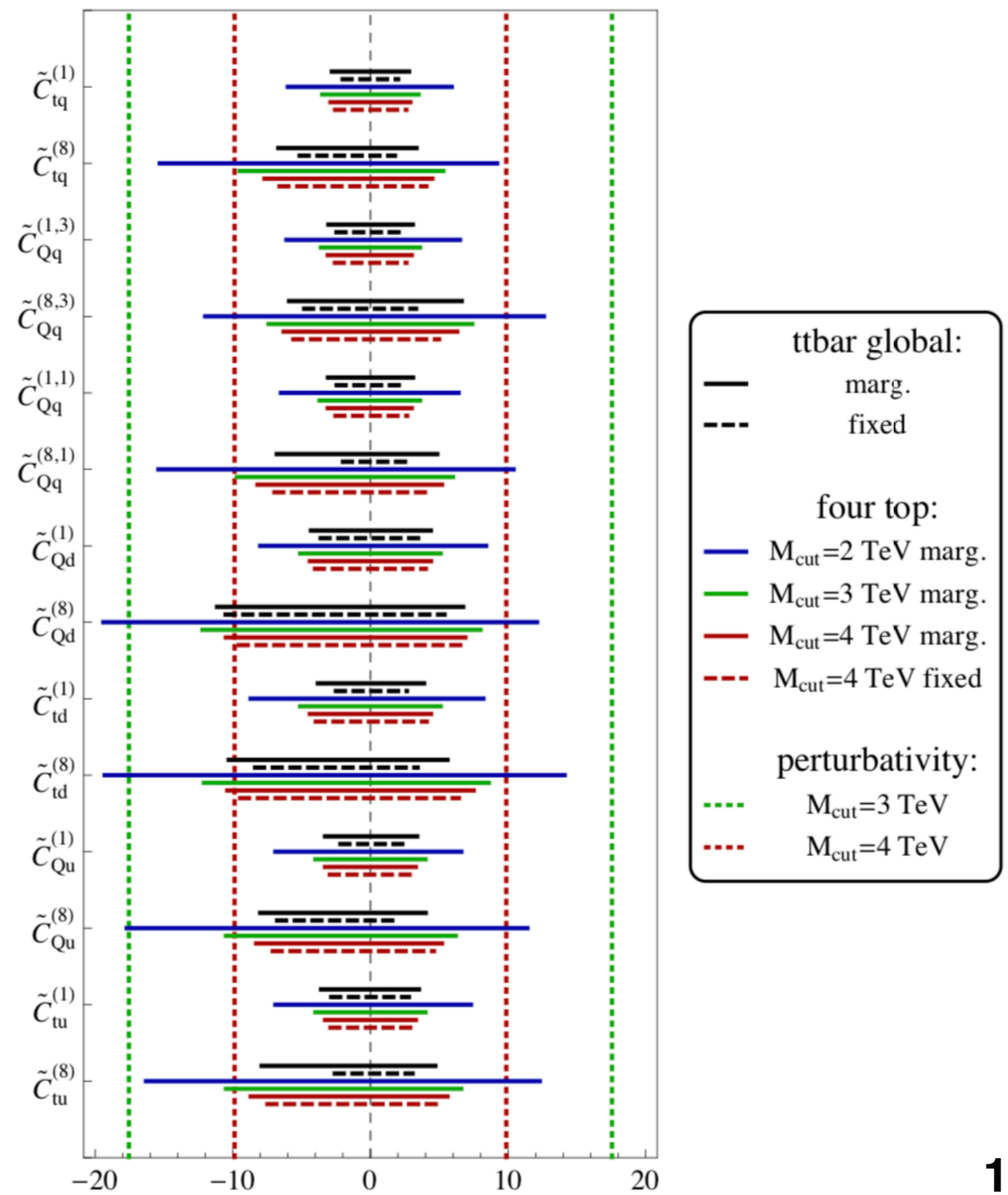


$g_*^4 E^6 / \Lambda_{NP}^6$

Four Fermion Operators

Cen Zhang, 1708.05928

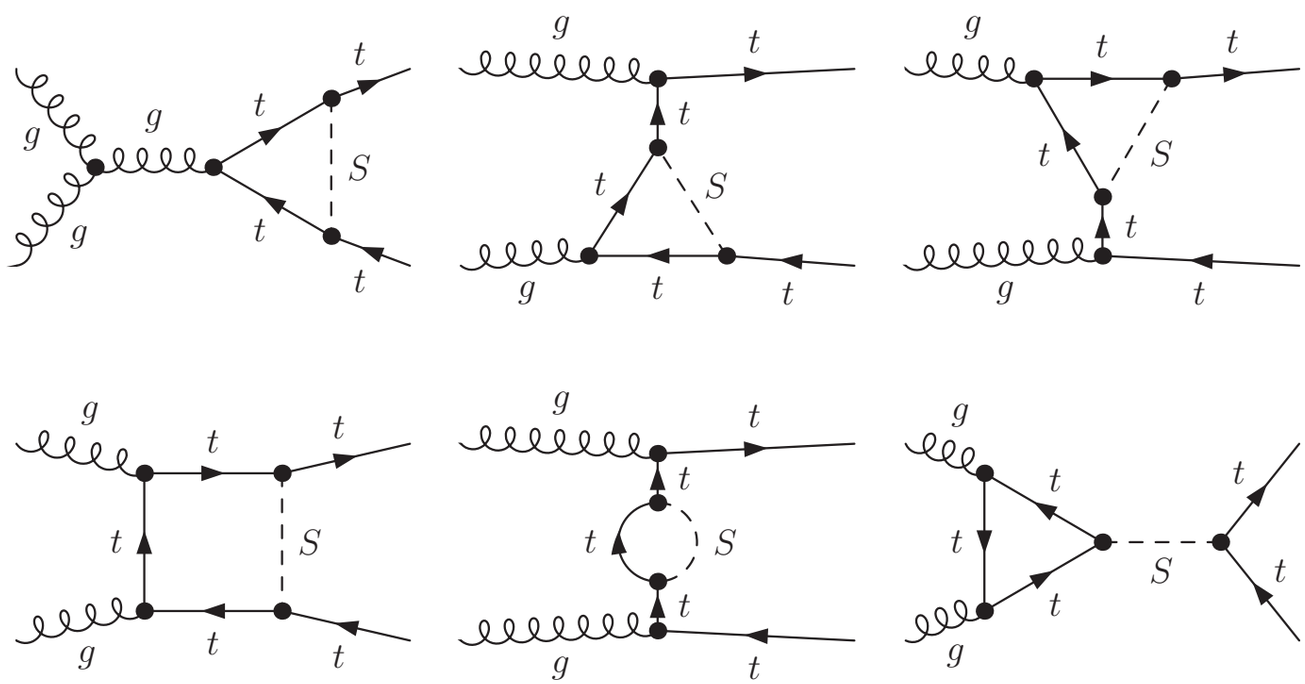
$$
\begin{aligned}
\mathcal{O}_{Qq}^{(8,3)} &= \left(\bar{Q}_L\gamma_\mu T^a\tau^i Q_L\right)\left(\bar{q}_L\gamma^\mu T^a\tau^i q_L\right)\\
\mathcal{O}_{Qq}^{(8,1)} &= \left(\bar{Q}_L\gamma_\mu T^a Q_L\right)\left(\bar{q}_L\gamma^\mu T^a q_L\right)\\
\mathcal{O}_{td}^{(8)} &= \left(\bar{t}_R\gamma_\mu T^a t_R\right)\left(\bar{d}_R\gamma^\mu T^a d_R\right)\\
\mathcal{O}_{tu}^{(8)} &= \left(\bar{t}_R\gamma_\mu T^a t_R\right)\left(\bar{u}_R\gamma^\mu T^a u_R\right)\\
\mathcal{O}_{tq}^{(8)} &= \left(\bar{t}_R\gamma_\mu T^a t_R\right)\left(\bar{q}_L\gamma^\mu T^a q_L\right)\\
\mathcal{O}_{Qd}^{(8)} &= \left(\bar{Q}_L\gamma_\mu T^a Q_L\right)\left(\bar{d}_R\gamma^\mu T^a d_R\right)\\
\mathcal{O}_{Qu}^{(8)} &= \left(\bar{Q}_L\gamma_\mu T^a Q_L\right)\left(\bar{u}_R\gamma^\mu T^a u_R\right)\\
\mathcal{O}_{Qq}^{(1,3)} &= \left(\bar{Q}_L\gamma_\mu \tau^i Q_L\right)\left(\bar{q}_L\gamma^\mu \tau^i q_L\right)\\
\mathcal{O}_{Qq}^{(1,1)} &= \left(\bar{Q}_L\gamma_\mu Q_L\right)\left(\bar{q}_L\gamma^\mu q_L\right)\\
\mathcal{O}_{td}^{(1)} &= \left(\bar{t}_R\gamma_\mu t_R\right)\left(\bar{d}_R\gamma^\mu d_R\right)\\
\mathcal{O}_{tu}^{(1)} &= \left(\bar{t}_R\gamma_\mu t_R\right)\left(\bar{u}_R\gamma^\mu u_R\right)\\
\mathcal{O}_{tq}^{(1)} &= \left(\bar{t}_R\gamma_\mu t_R\right)\left(\bar{q}_L\gamma^\mu q_L\right)\\
\mathcal{O}_{Qd}^{(1)} &= \left(\bar{Q}_L\gamma_\mu Q_L\right)\left(\bar{d}_R\gamma^\mu d_R\right)\\
\mathcal{O}_{Qu}^{(1)} &= \left(\bar{Q}_L\gamma_\mu Q_L\right)\left(\bar{u}_R\gamma^\mu u_R\right)
\end{aligned}
$$



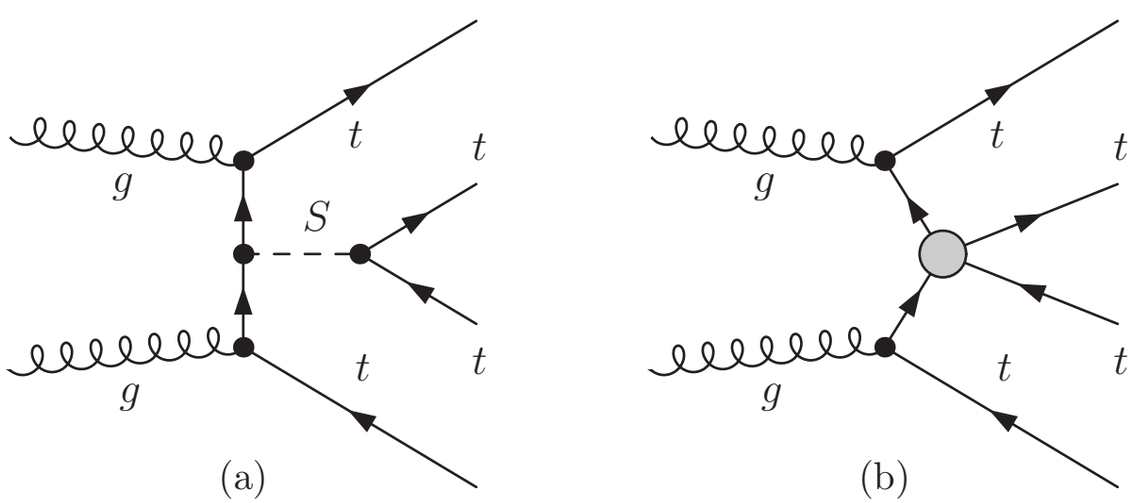
EFT and Scalar Extension of Top Sector

Englert, Galler, White, 1908.05588

Consider a simplified model (SM+S) and its EFT limit



$$\mathcal{O}_{tG} = \overline{Q}_L \Phi^c t^a \sigma^{\mu\nu} t_R G^a_{\mu\nu}$$

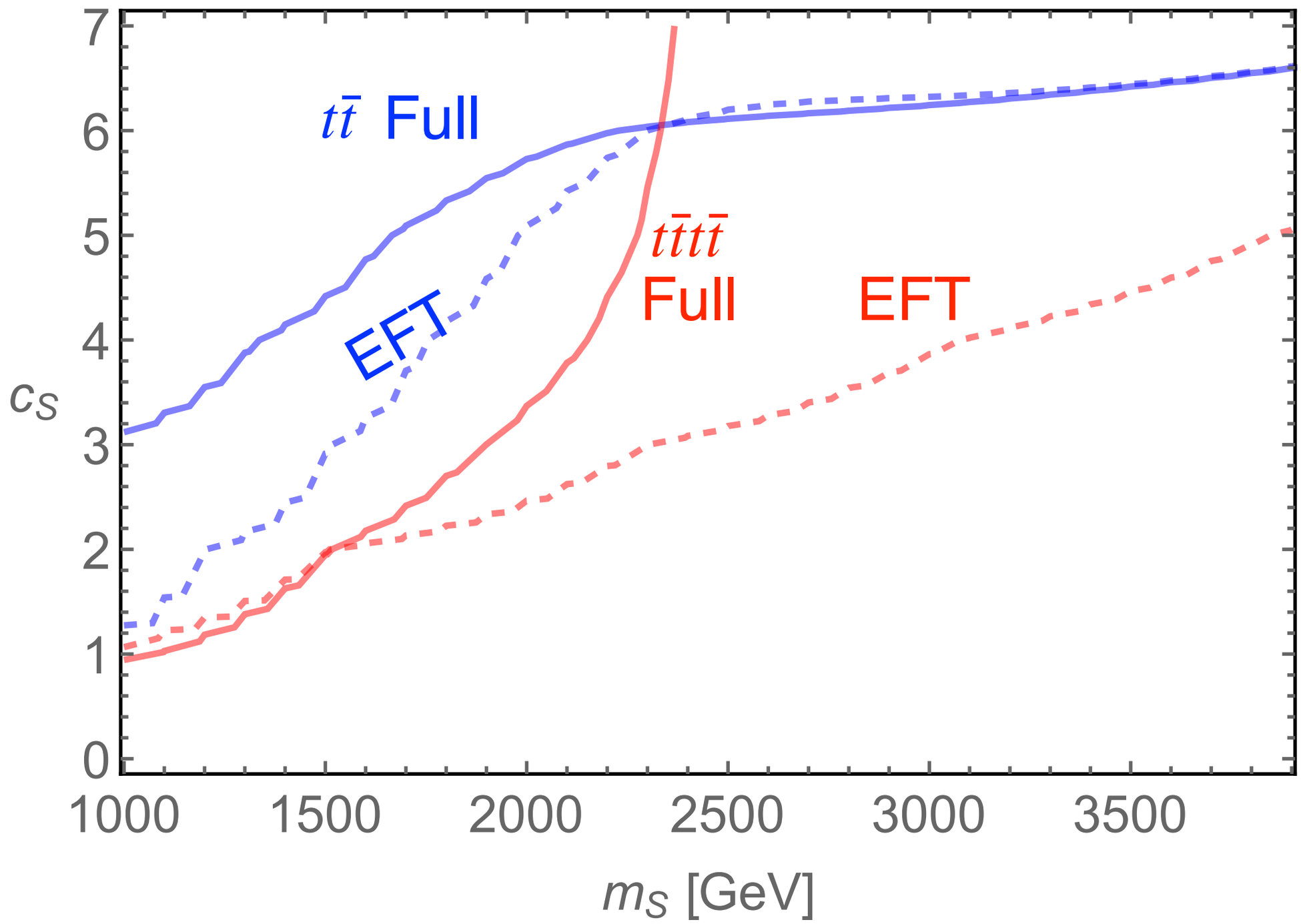


$$\mathcal{O}_{tttt}$$

EFT and Scalar Extension of Top Sector

Englert, Galler, White, 1908.05588

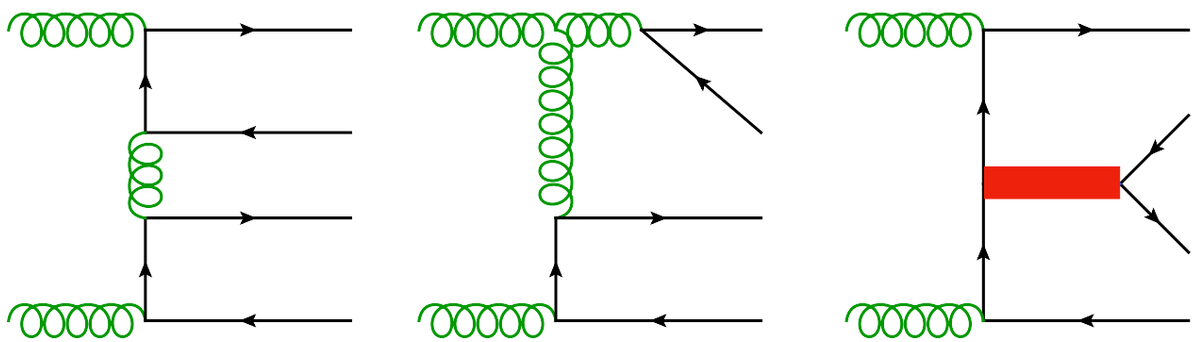
Consider a simplified model (SM+S) and its EFT limit



3) Indirect Effect of Top-philic Resonances

QHC, Chen, Liu, 1602.01934

Alvarez, Faroughy, Kamenik, Morles, Szynkman, 1611.05032



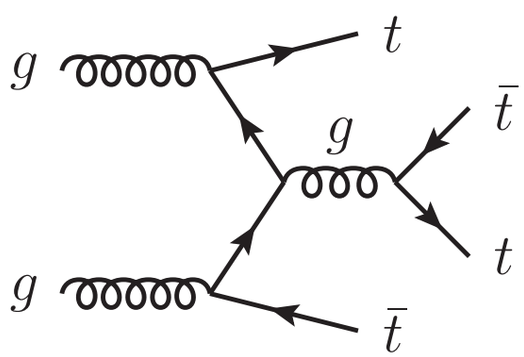
$m_X < 2m_t$

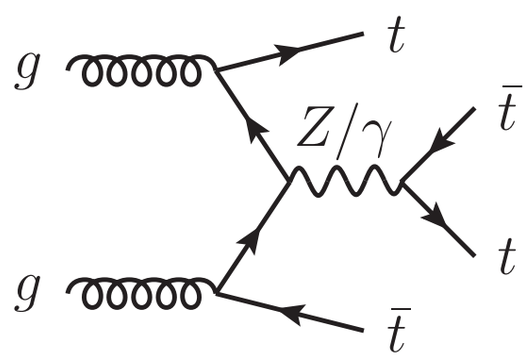
* Non-resonance effect
* Interference with the SM contribution

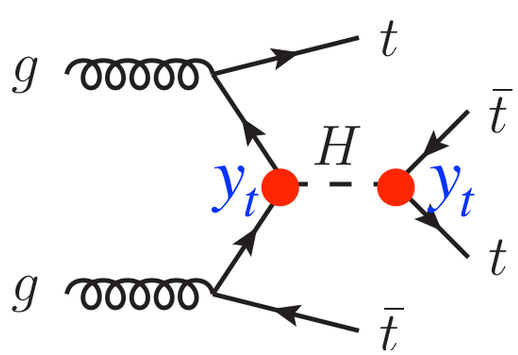
Limit on Top Yukawa Interactions

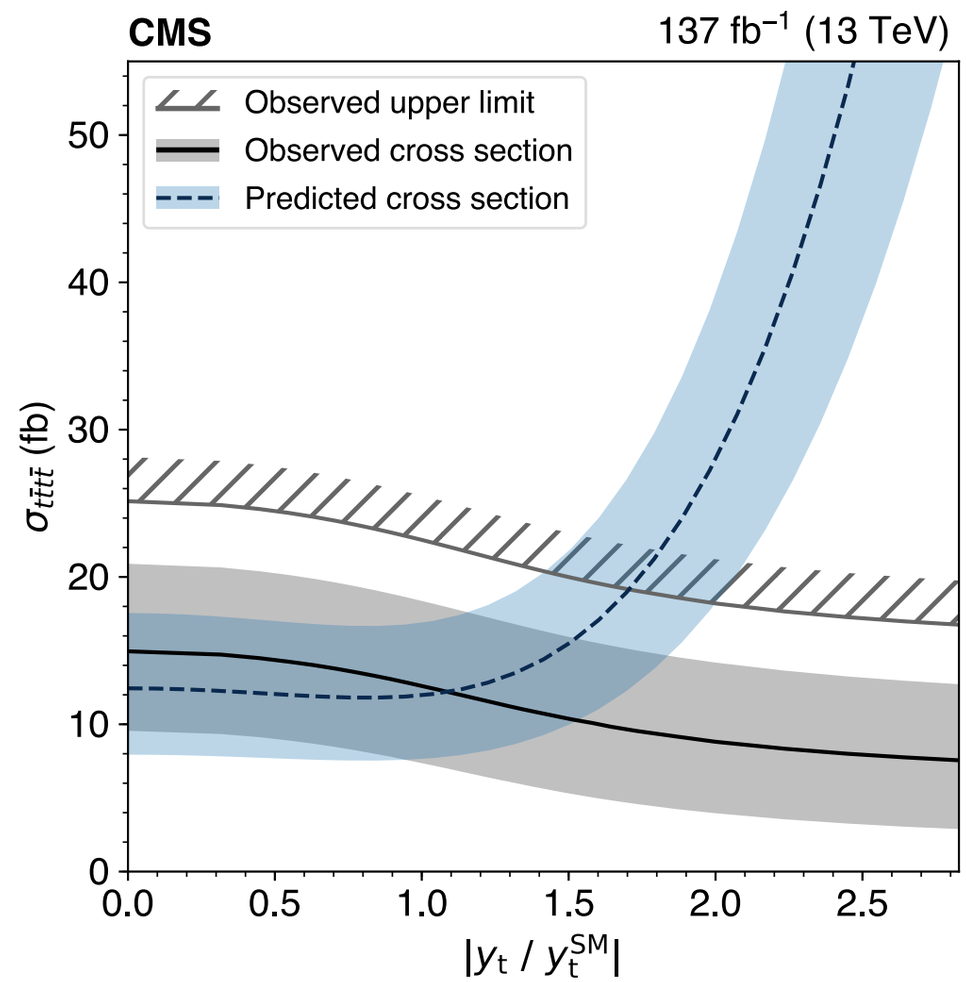
QHC, Chen, Liu, 1602.01934

QHC, Chen, Liu, Zhang, Zhang, 1901.04567







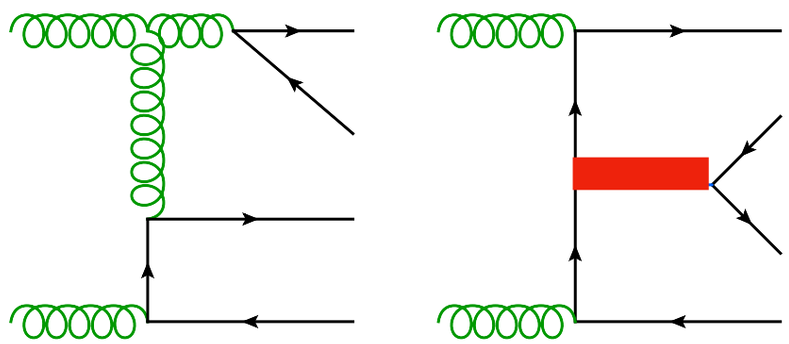


The x-section of four top is sensitive to top Yukawa coupling.

$$y_t < 1.7 \times y_t^{\rm SM} \quad @\ 95\%\ \text{CL}$$

Light Top-philic Scalar or Vector

Alvarez, Faroughy, Kamenik, Morles, Szynkman, 1611.05032

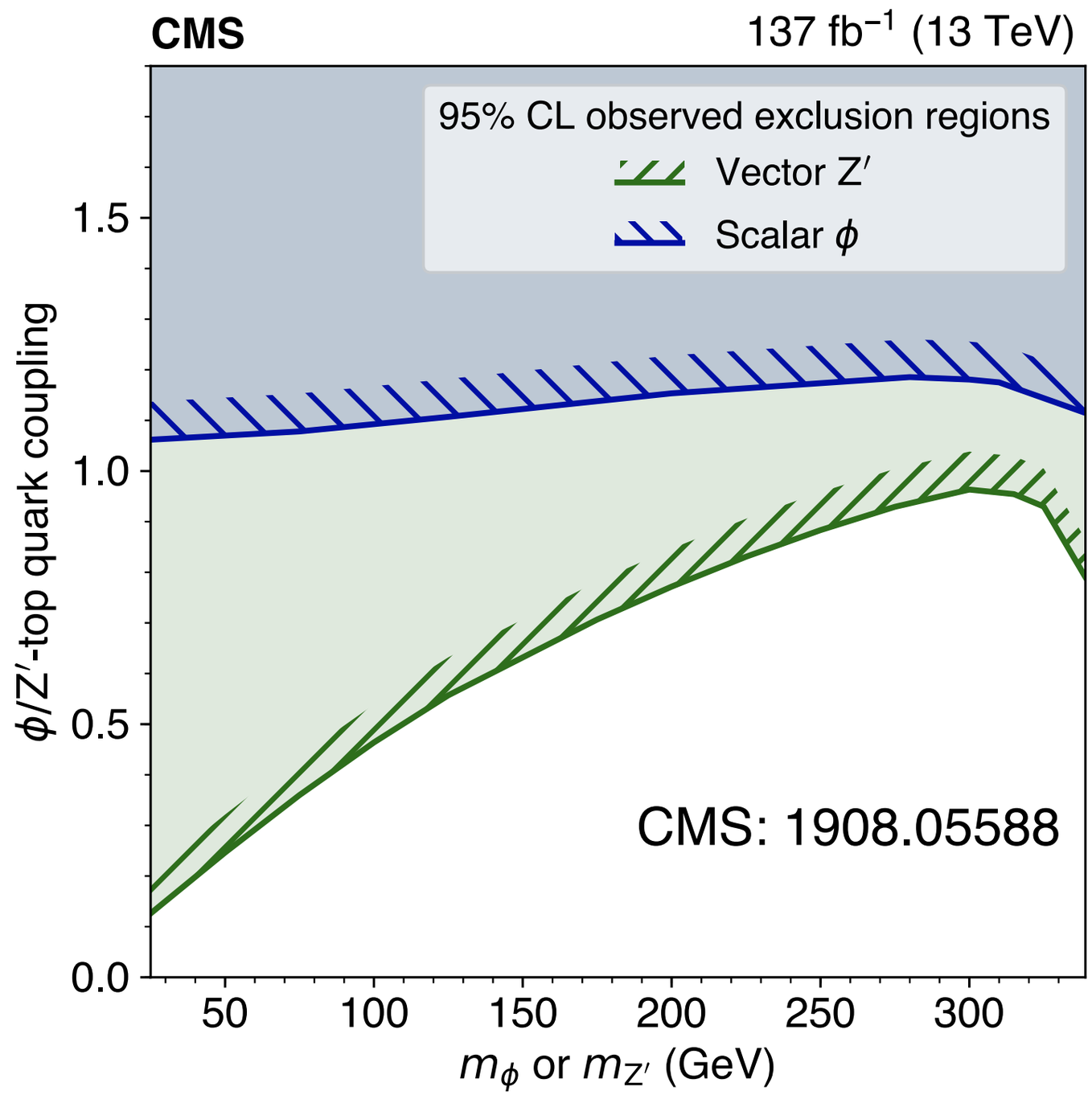


A light Z-prime

$$\mathscr{L}_{Z'} = -g_{tZ'}\bar{t}_R \not{A}' t_R$$

A light neutral scalar

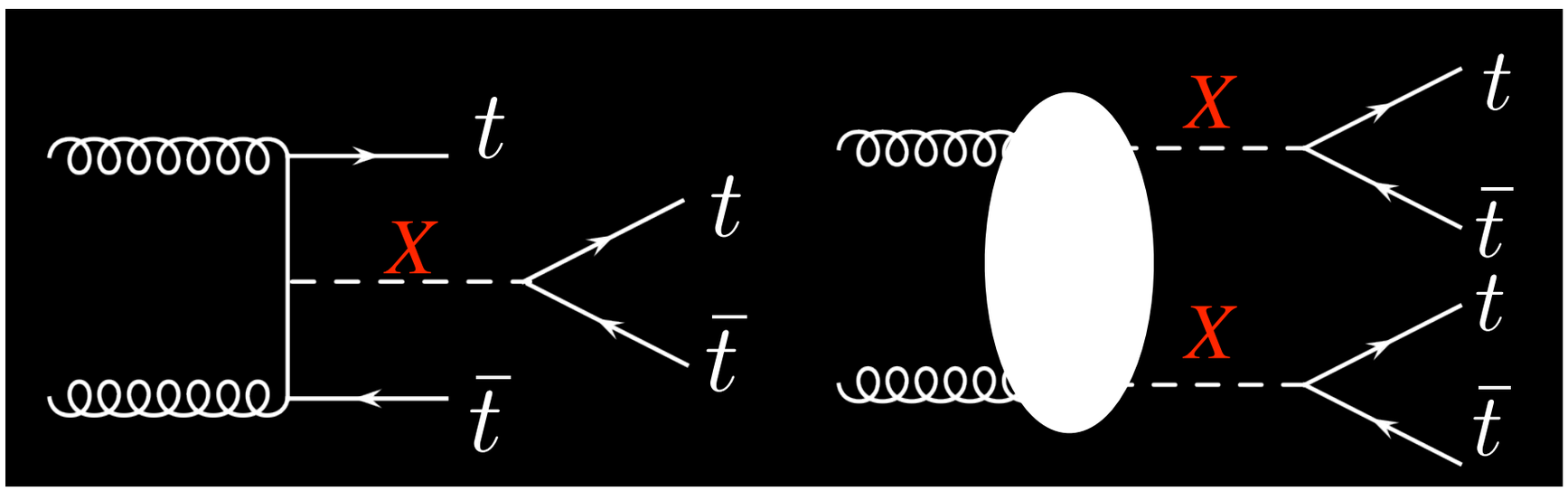
$$\mathscr{L}_{\phi} = -y_{t\phi}\bar{t}_L \phi t_R + \mathrm{h.c.}$$



Summary

Four-top production becomes a powerful tool to probe NP.

(e.g. 2HDB, Axigluon, KK gluon, Composite Higgs/top, SUSY…)



Four-top channel is complementary to the top-pair channel.

Thank You!