Constraints on BSM from top-quark physics

Fabio Maltoni
Center for Cosmology, Particle Physics and Phenomenology (CP3), UCLouvain Belgium

[Degrassi et al., 2012]

refs are linked

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News from the LHC

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- No sign of…

News from the LHC

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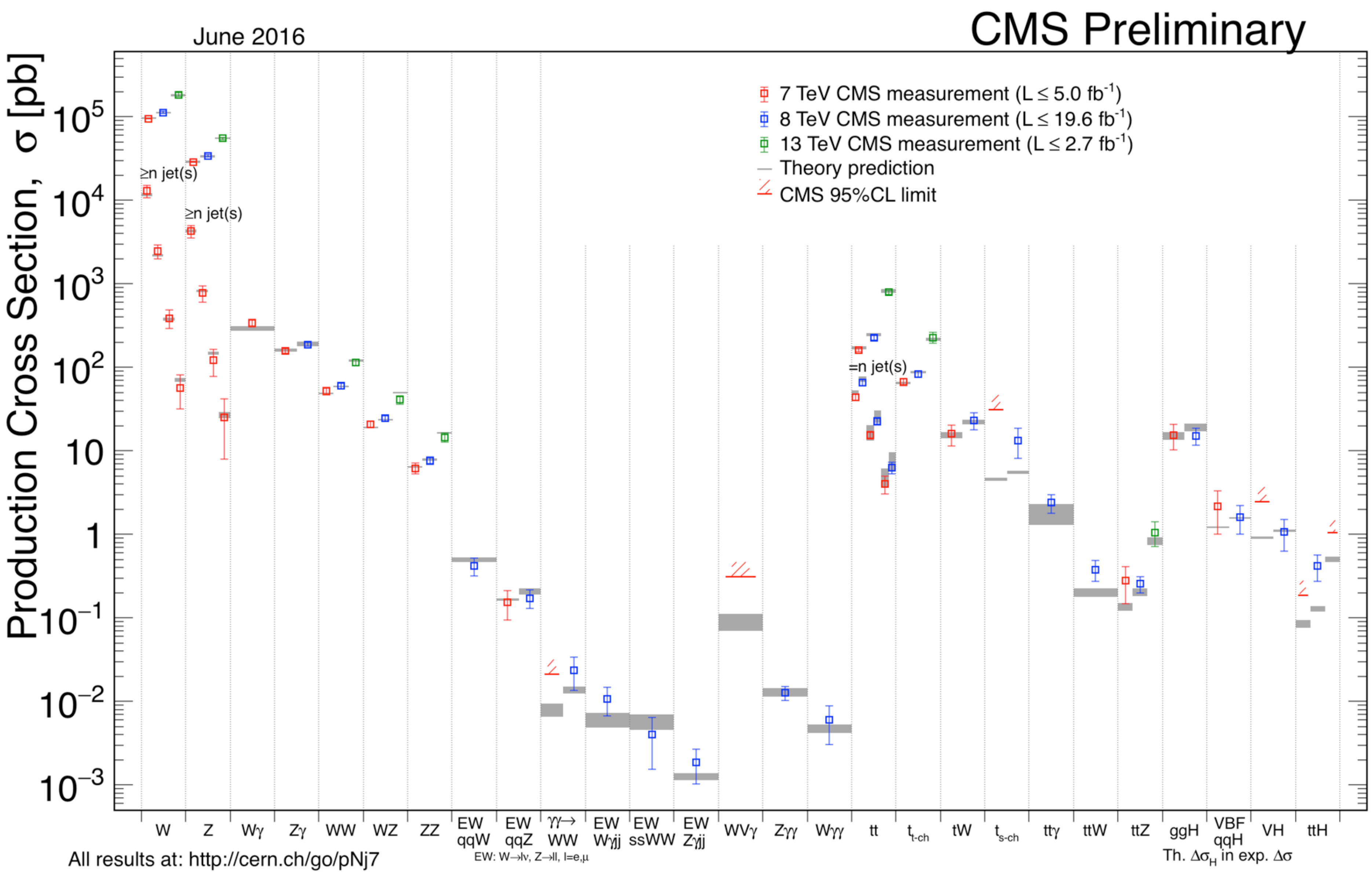

[CMS coll., 2016]

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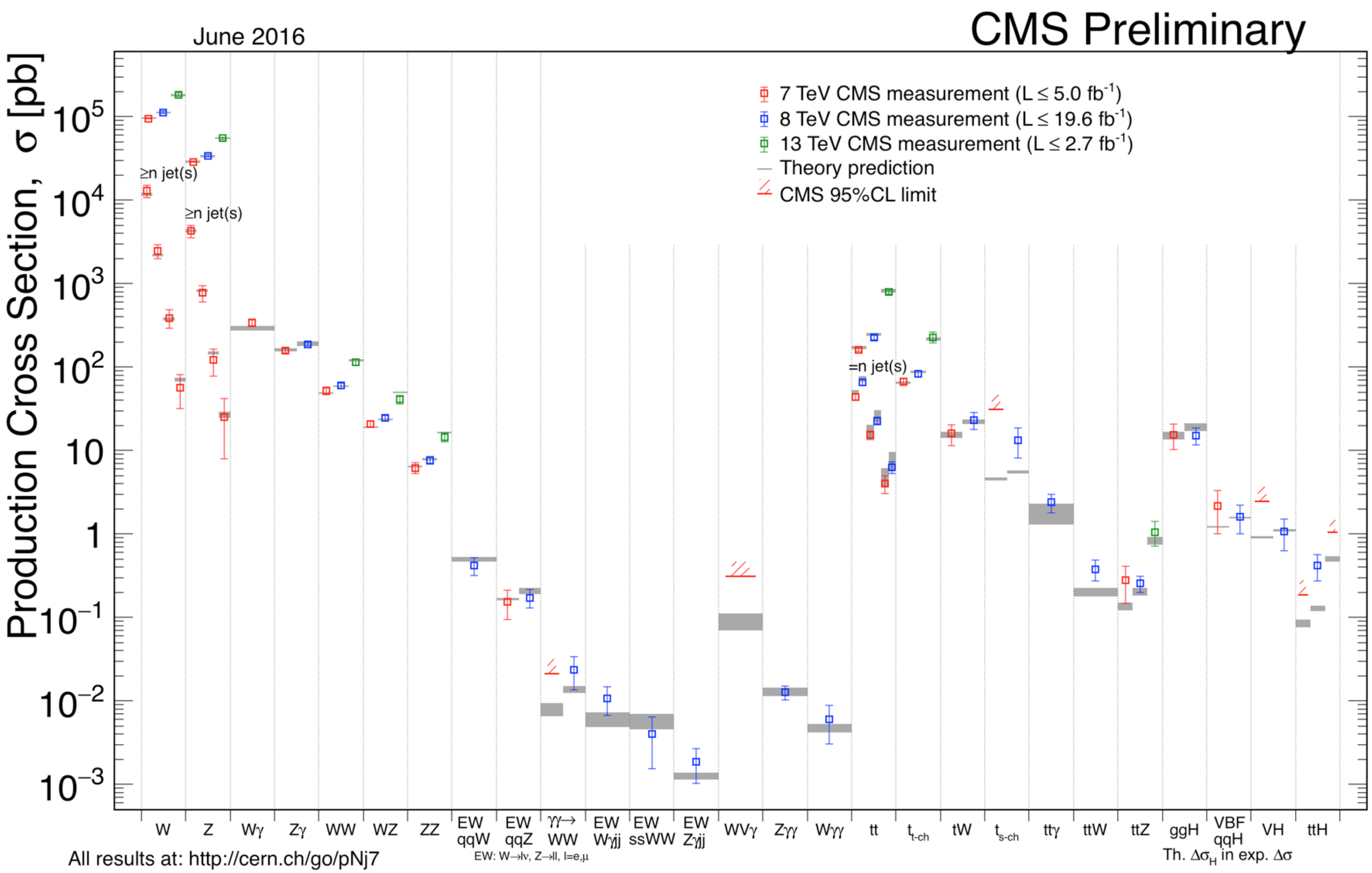

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…New Physics (from the LHC)!

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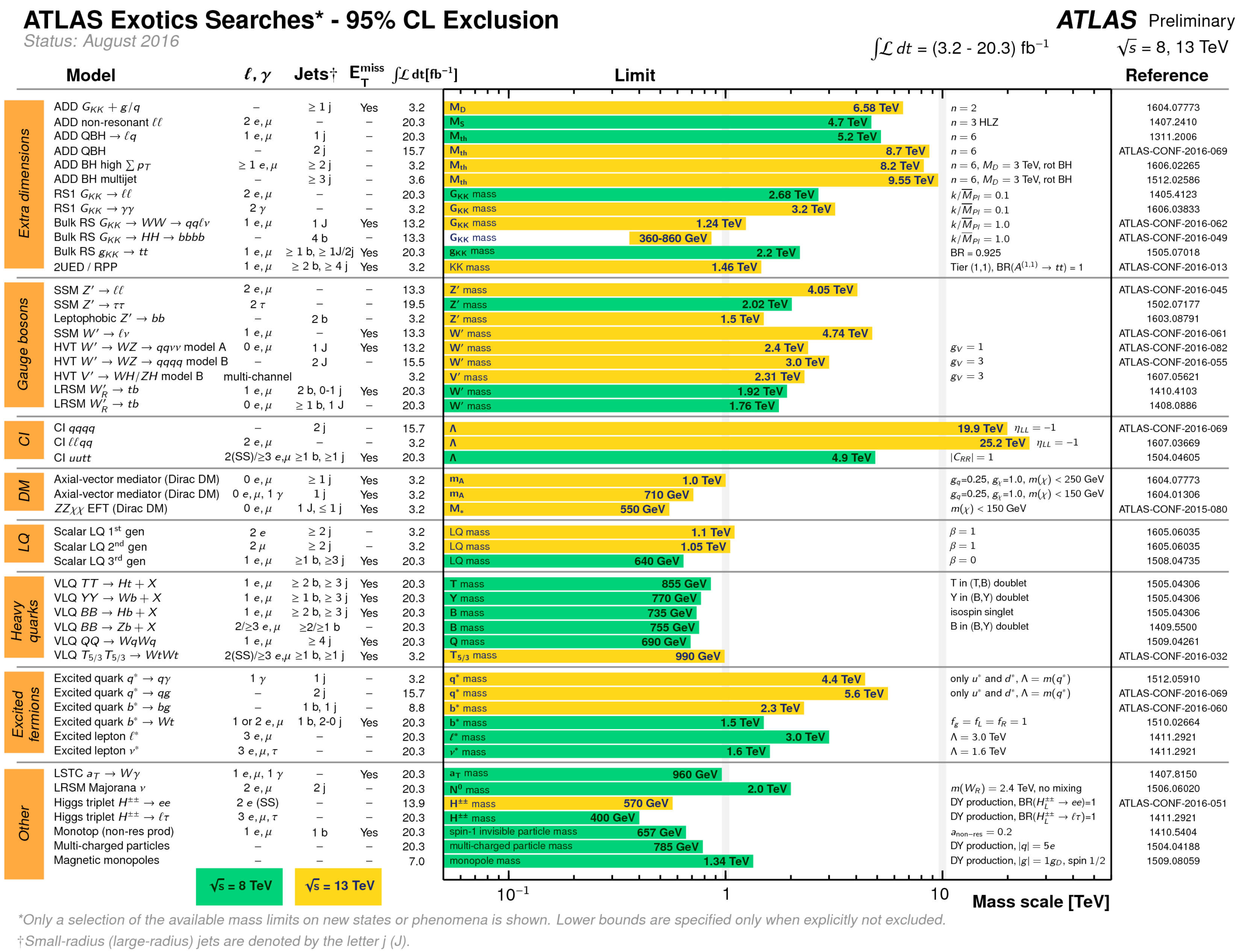

[ATLAS coll., 2016]

…New Physics (from the LHC)!

What (if any) is the best strategy?

STATEMENT #2

The Higgs provides a privileged searching ground

STATEMENT #3

Vis-à-vis the Higgs, the top is a special quark
(or equivalently it is the only normal one)

What (if any) is the best strategy?

STATEMENT #1

The only viable approach to look for NP at the LHC is to cover the widest range of TH- and/or EXP-motivated searches.

STATEMENT #2

The Higgs provides a privileged searching ground

STATEMENT #3

Vis-à-vis the Higgs, the top is a special quark (or equivalently it is the only normal one)

The top quark is special

In the SM, it is the ONLY quark

1. With a "natural mass"

$$m_{\rm top} = y_t v/\sqrt{2} \simeq 174\,{\rm GeV} \;\Rightarrow y_t \simeq 1$$

It "strongly" interacts with the Higgs sector.

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2. That decays semi-weakly, and before hadronizing and way before spin-flipping

$\tau_{had} \approx h/\Lambda_{QCD} \approx 2 \bullet 10^{-24}$ s

$\tau_{flip} \approx h\ m_t / \Lambda_{QCD}^2 >> \tau_{had}$

$\tau_{top} \approx h/\Gamma_{top} = 1/(G_F\ m_t^3\ |V_{tb}|^2/8\pi\sqrt{2}) \approx 5 \bullet 10^{-25}$ s

Compare with $\tau_b \approx (G_F^2\ m_b^5\ |V_{bc}|^2\ k)^{-1} \approx 10^{-12}$ s)

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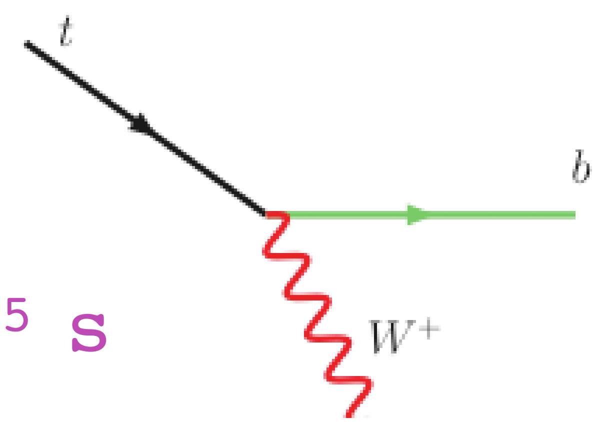
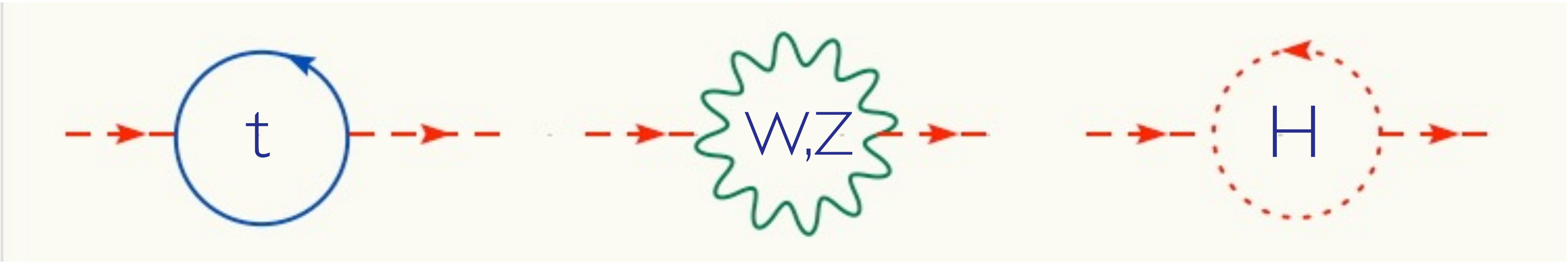


The top quark is special

3. That dramatically affects the stability of the Higgs mass. Consider the SM as an effective field theory valid up to scale Λ:



$$m_H^2 = m_{H0}^2 \qquad - \frac{3}{8\pi^2} y_t \Lambda^2 \qquad + \frac{1}{16\pi^2} g^2 \Lambda^2 \qquad + \frac{1}{16\pi^2} \lambda^2 \Lambda^2$$

Putting numbers, one gets:

$$(125\,\mathrm{GeV})^2 = m_{H0}^2 + \left[-(2\,\mathrm{TeV})^2 + (700\,\mathrm{GeV})^2 + (500\,\mathrm{GeV})^2\right] \left(\frac{\Lambda}{10\mathrm{TeV}}\right)^2$$

The top quark is special

$mh^2 \sim (125\ \text{GeV})^2$

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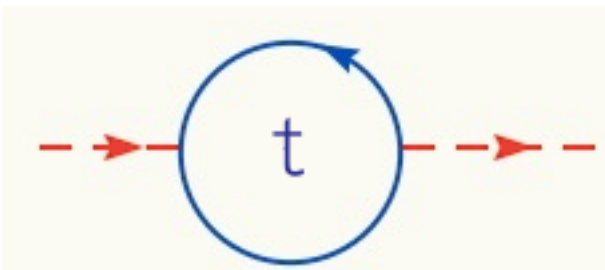
Definition of naturalness: less than 90% cancellation:

$\Lambda_t < 3\,\text{TeV}$ $\Rightarrow$ top partners must be “light”

Model building inspired by naturalness



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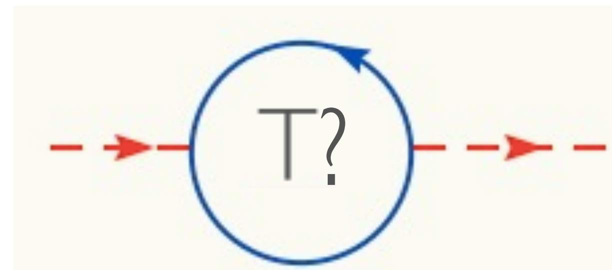

$$= \frac{8}{3\pi^2} m_T^2 \log \Lambda$$

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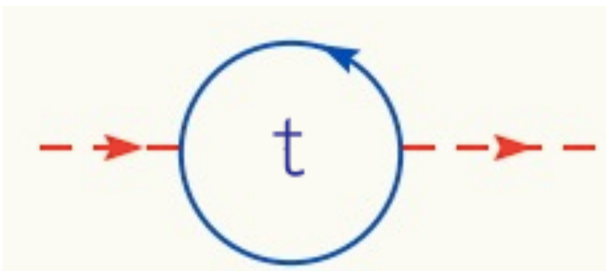

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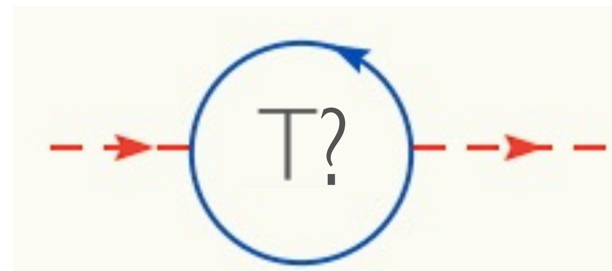

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- stops as the lightest squarks

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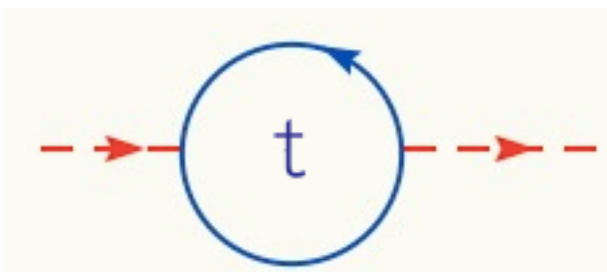

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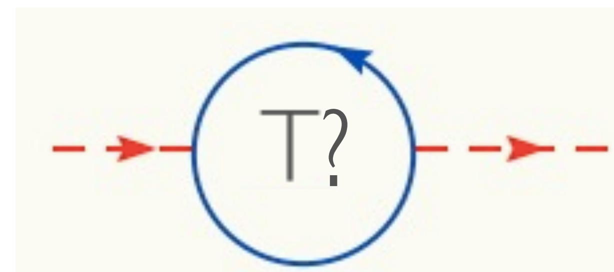

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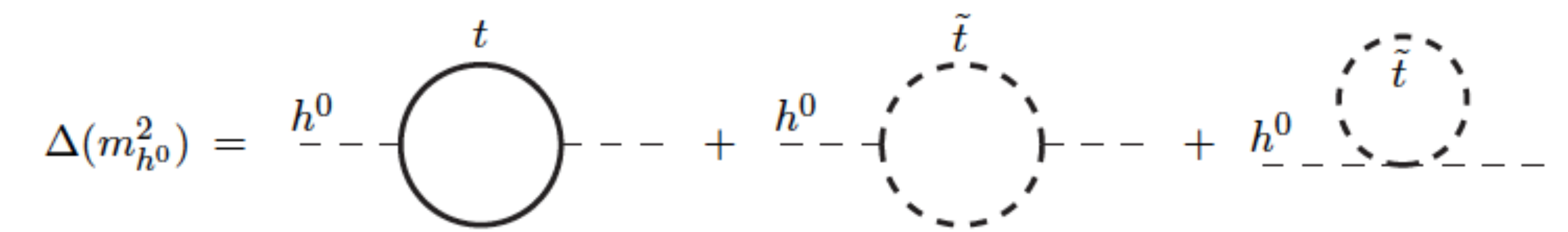
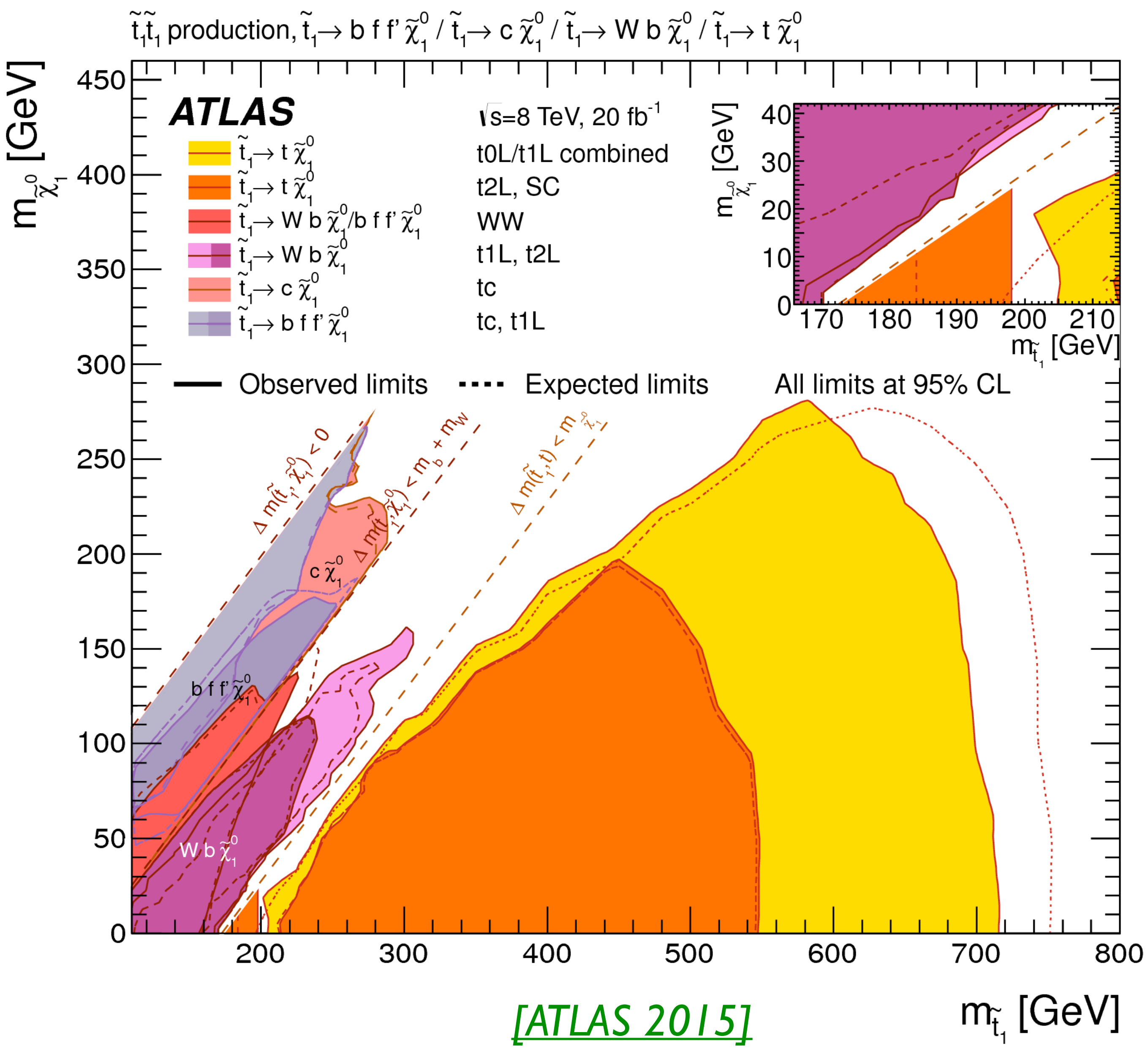
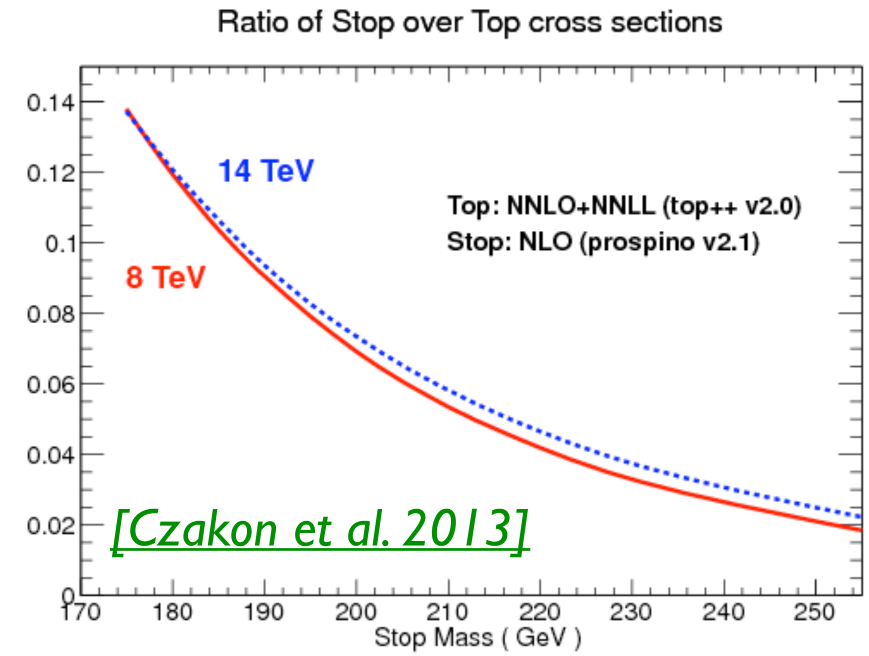


Direct stop searches



[ATLAS 2015]

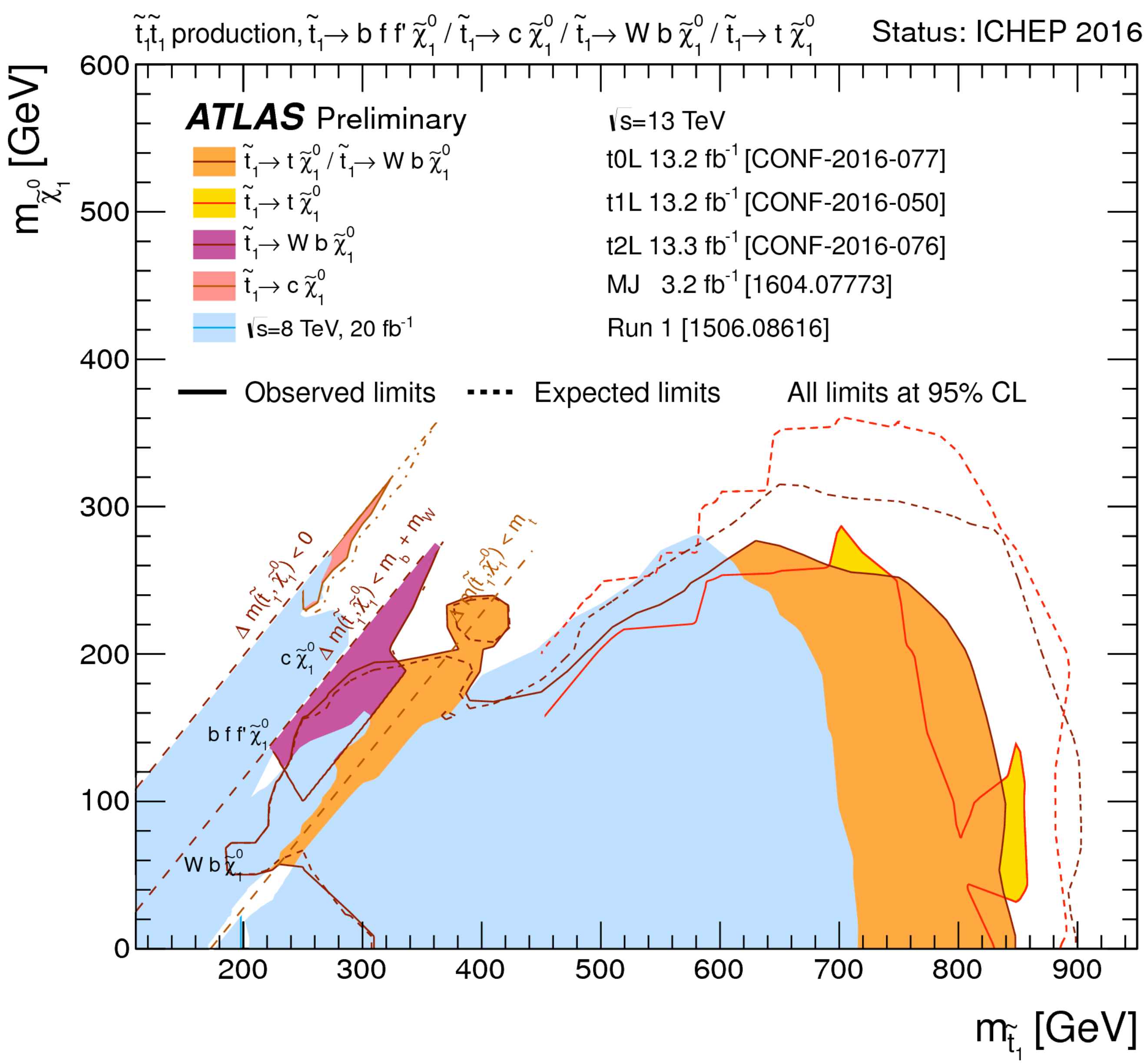


[Czakon et al. 2013]

- Stop direct searches based on four different final states:

1. stop → t+n1 (w/ stop1 mostly right),
2. stop → W+b+n1 (3-body decay for m(stop) < m(top) + m(ne1)),
3. stop → c + n1
4. stop → f+f'+b+n1 (4-body decay).

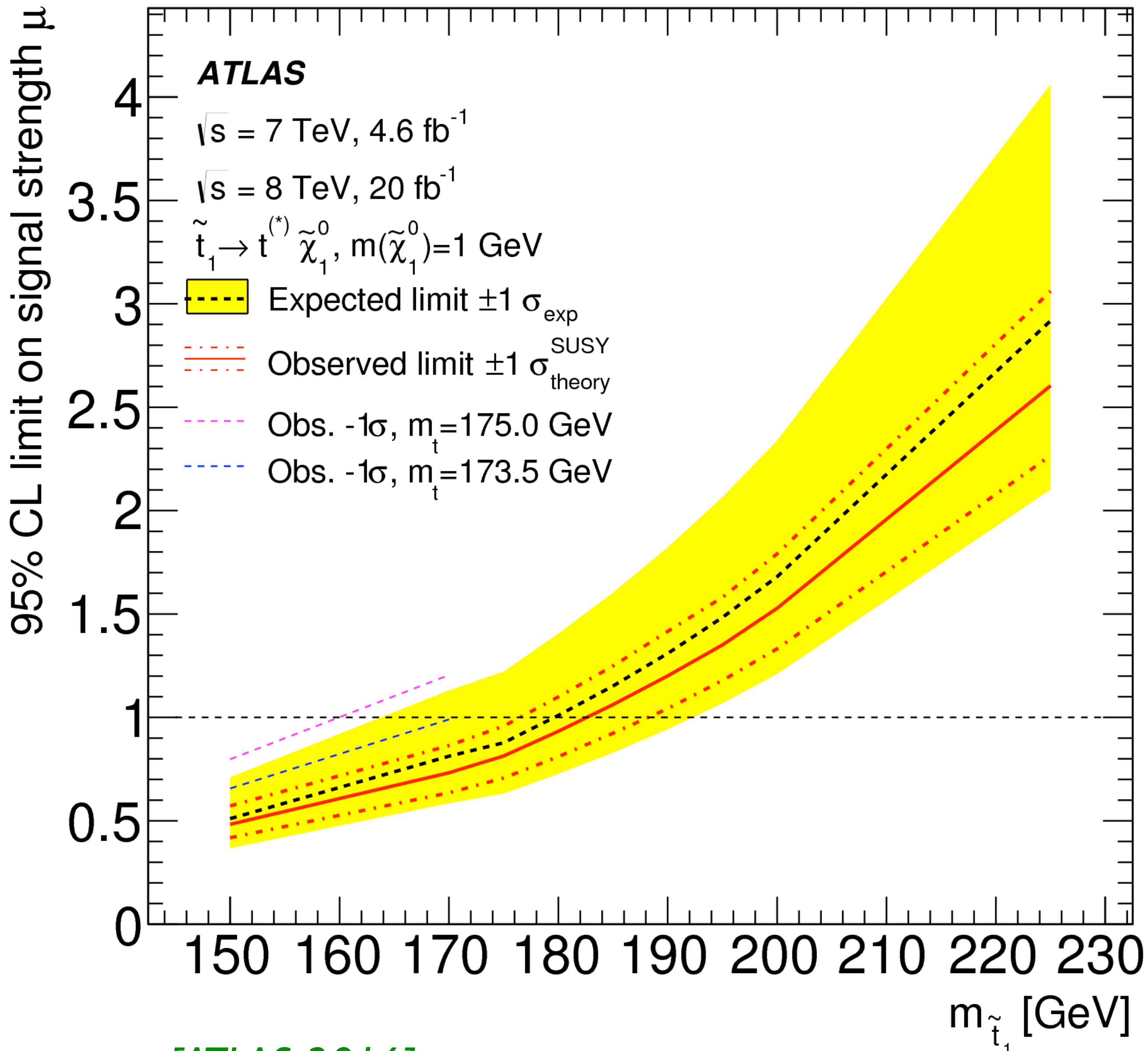
Direct stop searches



[ATLAS 2016]

- Funnels being closed…but
  - still present at small masses
  - compressed spectrum issues including the width treatment and evaluation
  - different decay channels are needed
  - If widths are small, displaced vertices might arise.

Precision stop searches



[ATLAS 2016]

From an idea proposed in [Czakon et al., 2014]

Expected and observed 95% CL limits on the signal strength μ (defined as the ratio of the obtained stop cross section to the theoretical prediction) for the production of $\tilde{t}$ pairs as a function of $m\tilde{t}$.

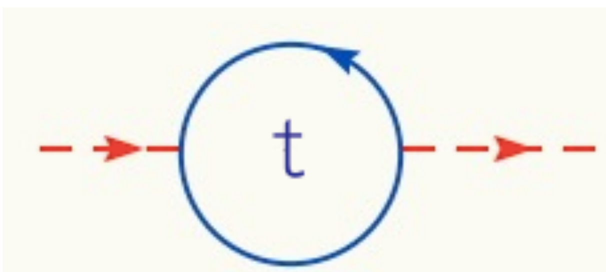
The stop is assumed to decay as $\tilde{t}\to t\tilde{\chi}$ or through its three-body decay depending on its mass. The neutralino is assumed to have a mass of 1 GeV.

The black dotted line shows the expected limit with ±1σ uncertainty band shaded in yellow, taking into account all uncertainties except the theoretical cross-section uncertainties on the signal.

The red solid line shows the observed limit, with dotted lines indicating the changes as the nominal signal cross section is scaled up and down by its theoretical uncertainty.

The short blue and purple dashed lines indicate how the observed limits with the signal cross section reduced by one standard deviation of its theoretical uncertainty for $m\tilde{t}$ 1<mtop when the top quark mass is assumed instead to be 173.5±1.0 and 175.0±1.0 GeV.

Model building inspired by naturalness



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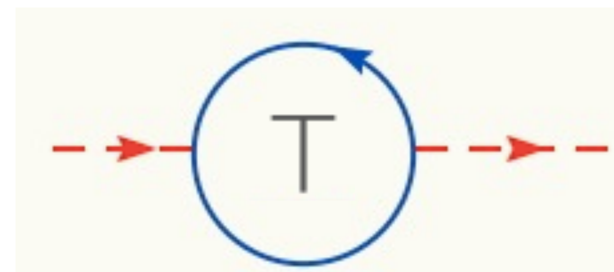

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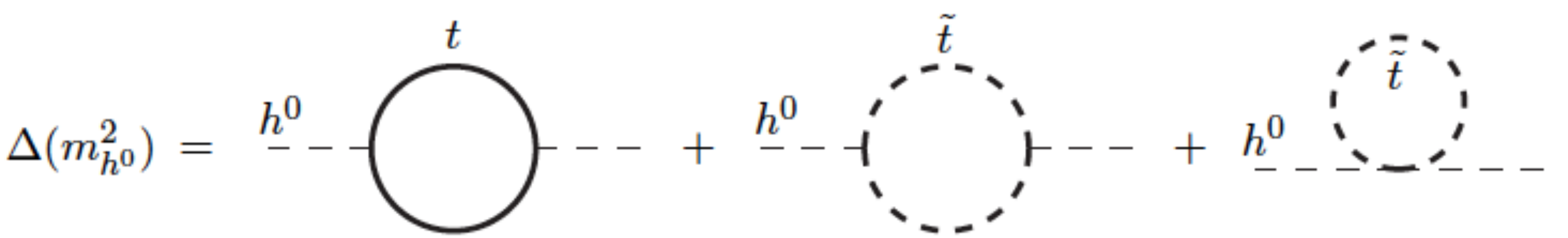
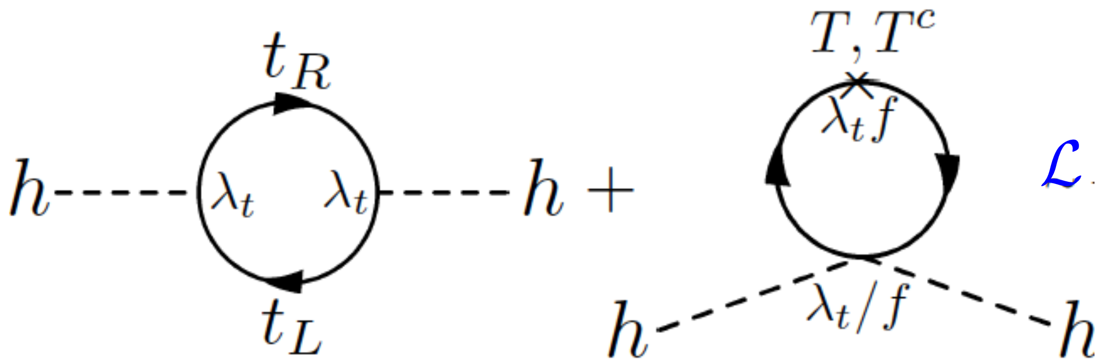


- composite Higgs ⇒ vectorial top quark partners

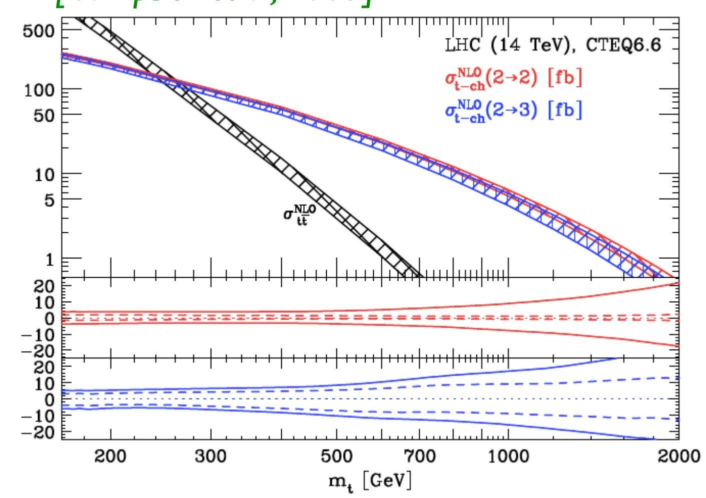


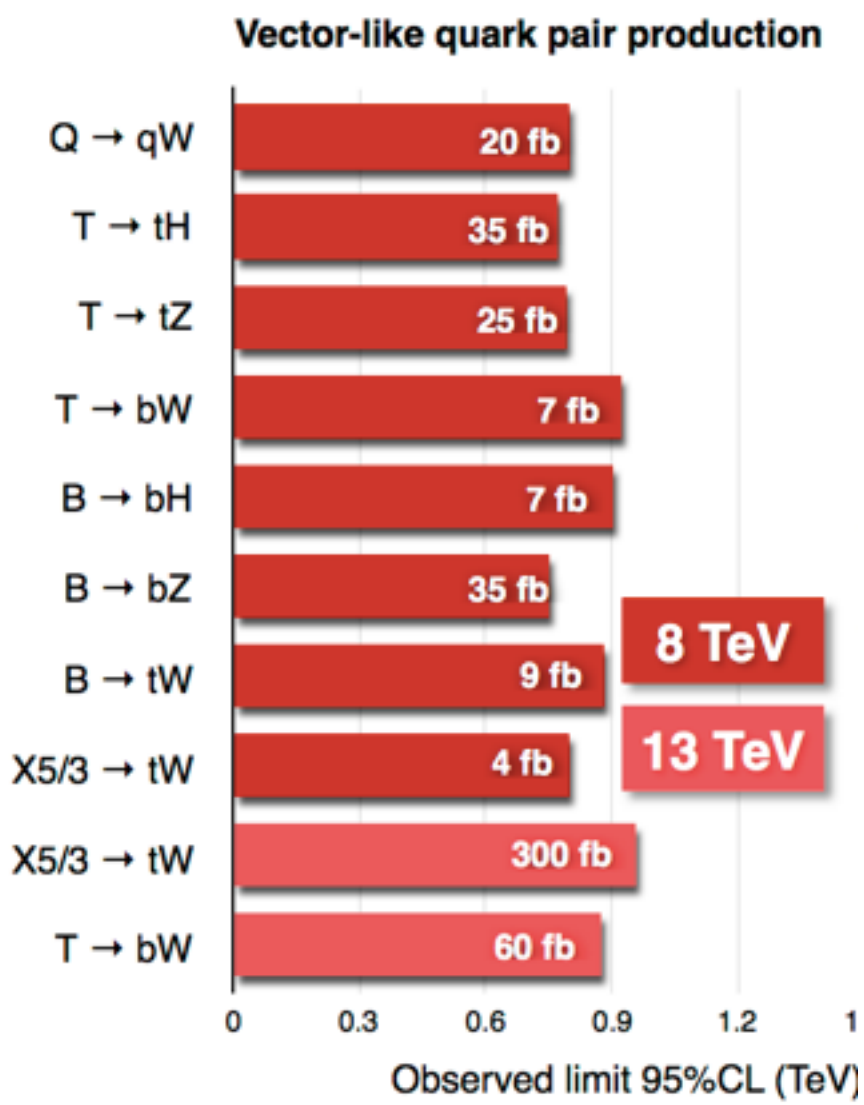
$$\mathcal{L} = y_t \left[iqht^c + f \left((1 - \frac{h^\dagger h}{2f^2} \right) TT^c + \ldots \right] + h.c.$$

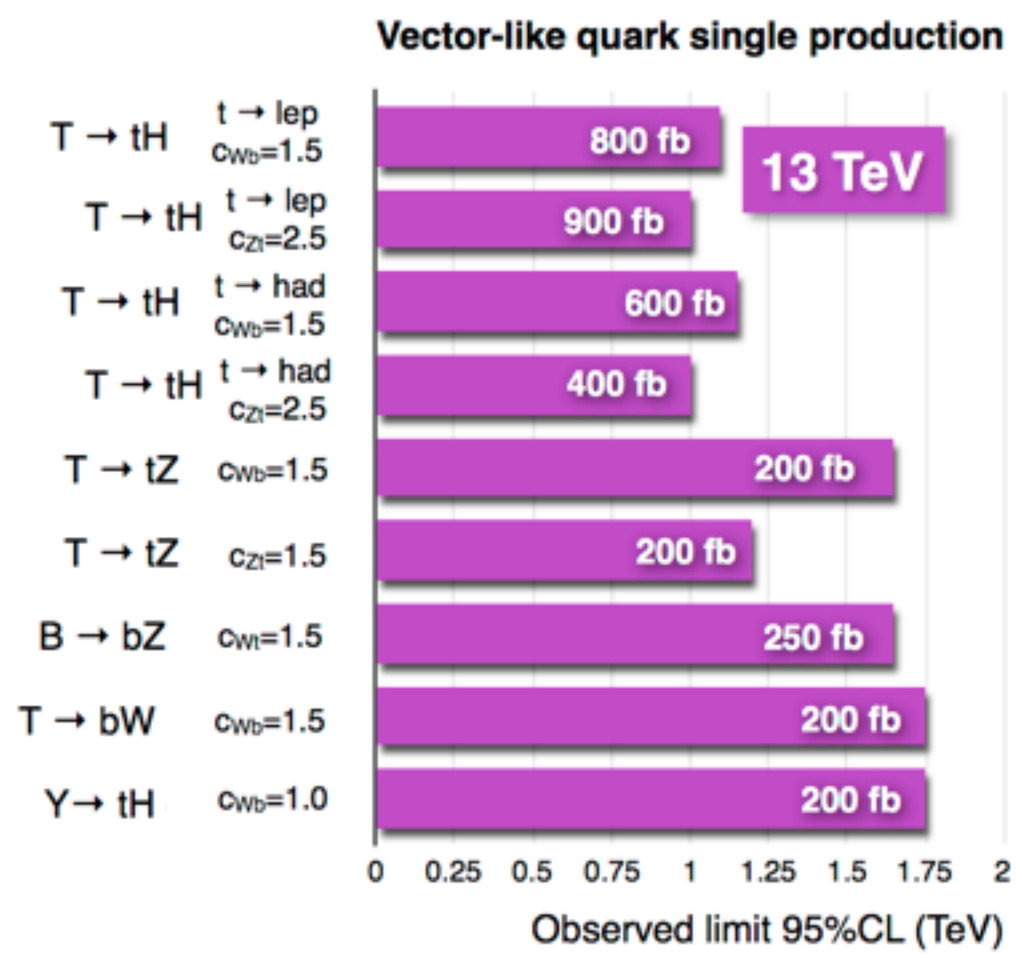
Direct vector-like quarks searches

Vector-like quarks can be produced in pairs or singly.

[Campbell et al, 2009]







[CMS - B2G 2016]

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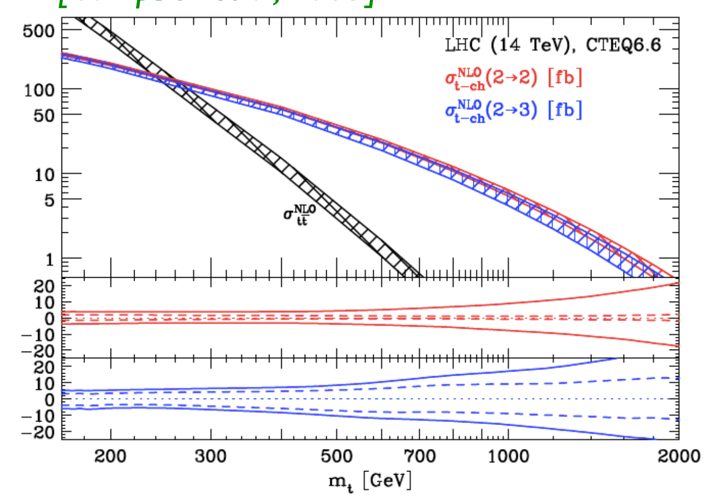
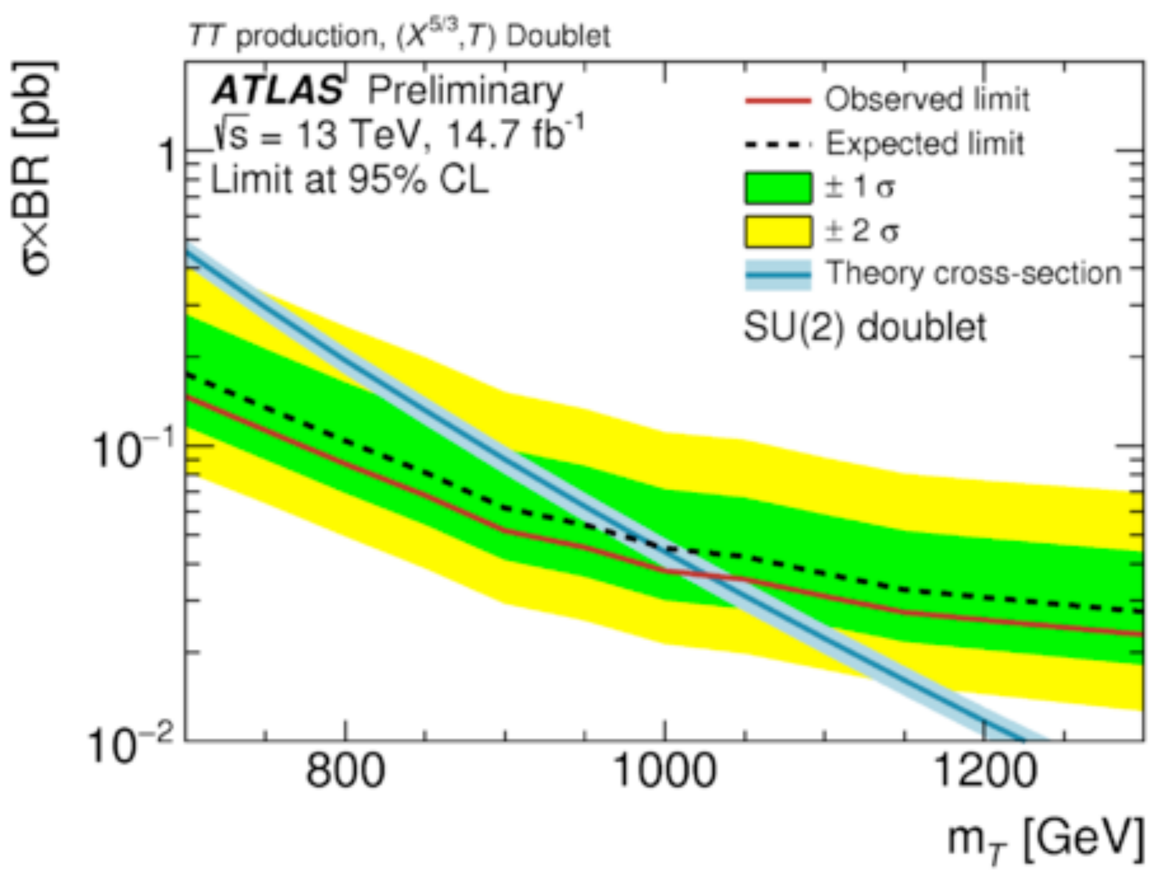
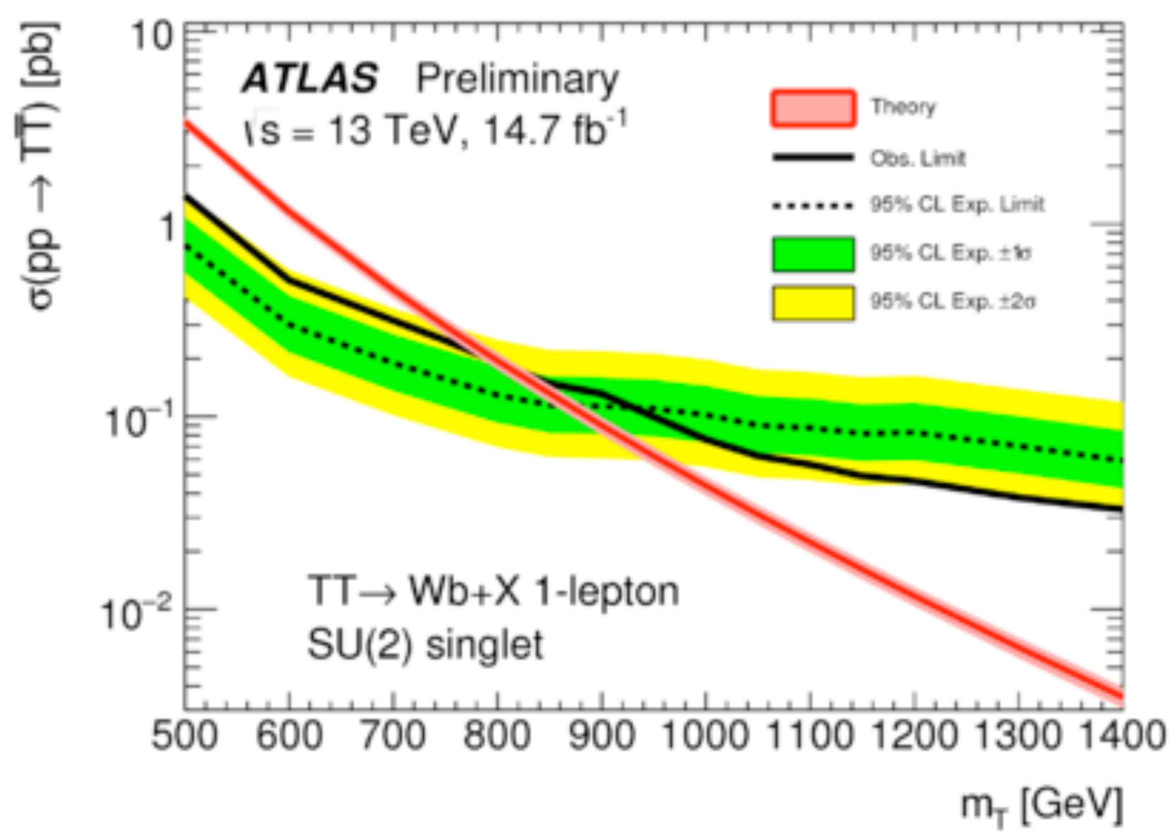




[ATLAS 2016]



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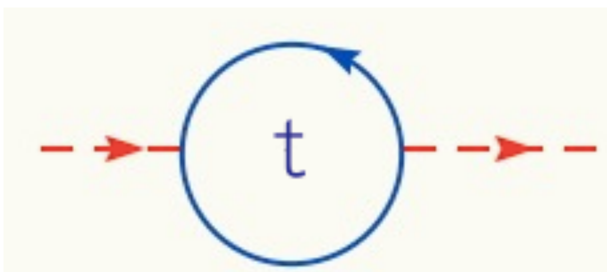
Model building inspired by naturalness



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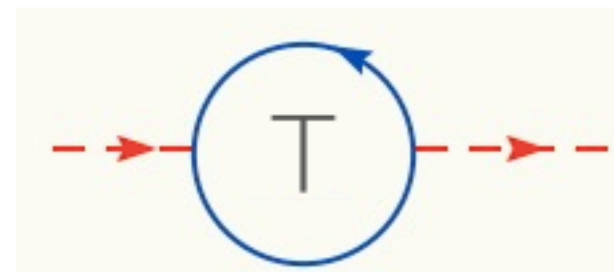
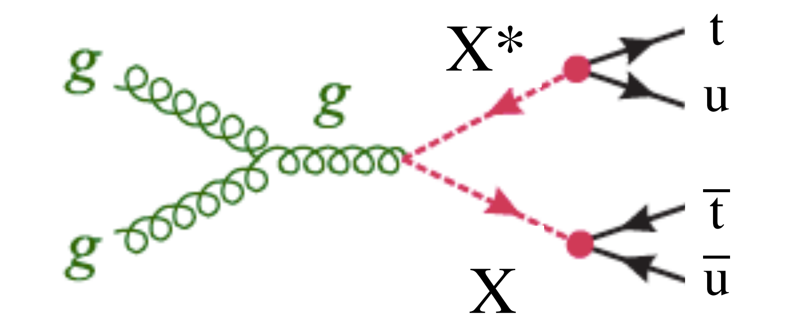
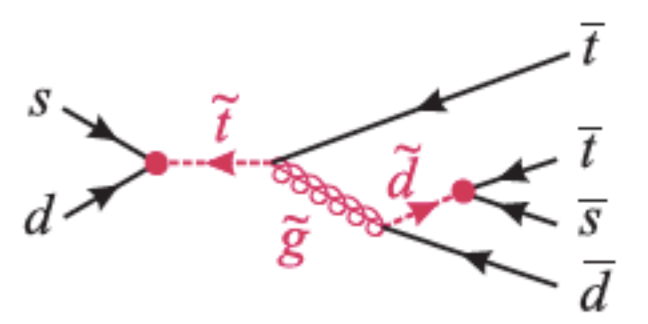


$$= \frac{8}{3\pi^2} m_T^2 \log \Lambda$$

Note that:



- Many variations exist of this mechanisms, such as for example partners that are not colored, or Hyperfolded SUSY. [Katz et al, in progress]
- Such models typically entail other particles in the spectrum that couple to the top (such as extra scalars or DM candidates) and might lead to new top interactions at low energy (such as RPV).



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Model-dependent ⟷ Model-independent

SUSY, 2HDM, ED,…

simplified models, EFT, …

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SUSY, 2HDM, ED,…		simplified models, EFT, …
Search for new states	⟷	Search for new interactions
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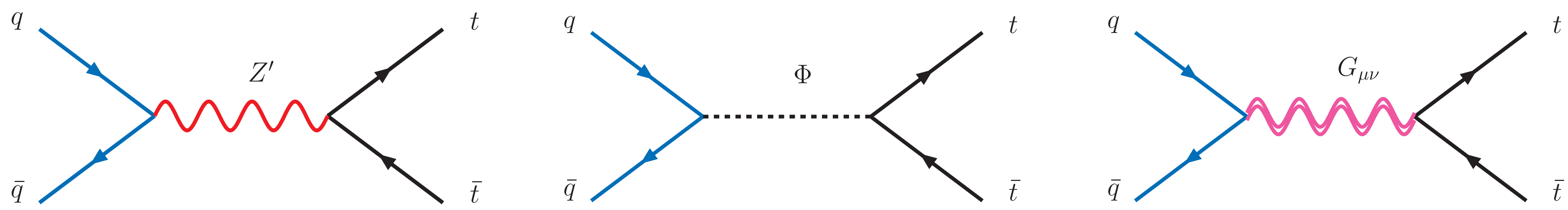
Exotic signatures	⟷	Standard signatures
precision measurements		rare processes

Resonances in ttbar

Very interesting and rich history of searches for resonances in ttbar and many proposals and results since the first days of the LHC, see e.g., [Frederix, FM, 2007]. Higher masses can be reached by boosted top tagging techniques. I will make only two points here:

1. Limits on models that feature a clear BW peak (Z', coloron) with a fixed width are continuously improved by the increase in energy and luminosity:



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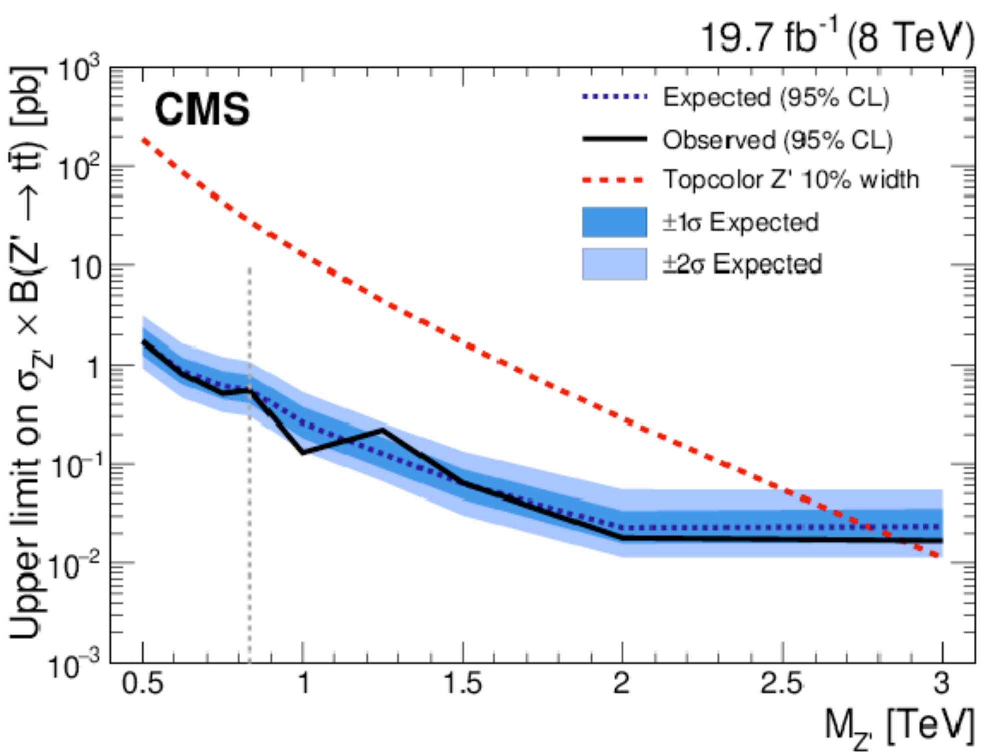
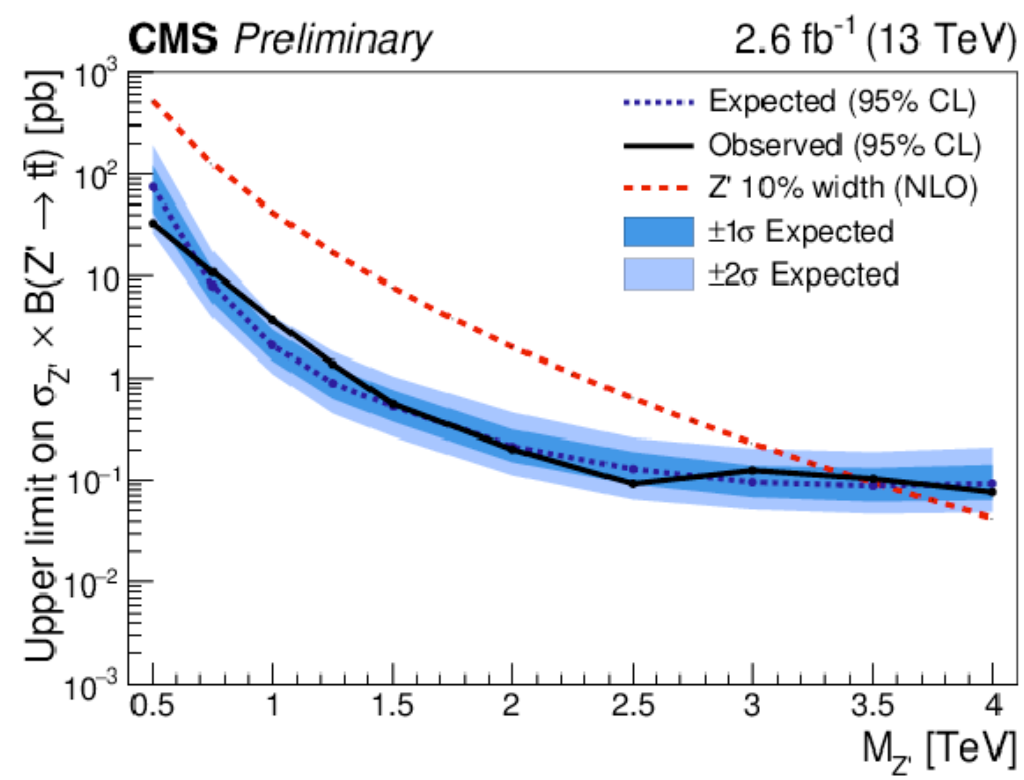
[CMS 2013]



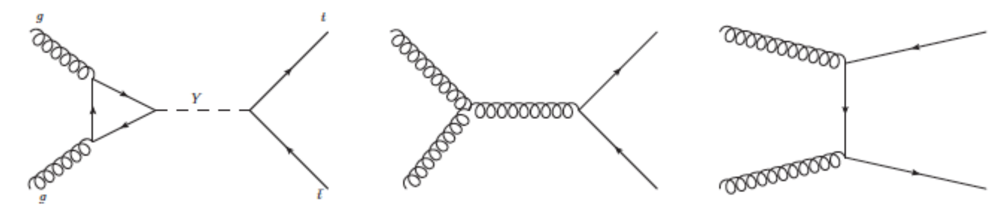
[CMS 2015]



Resonances in ttbar

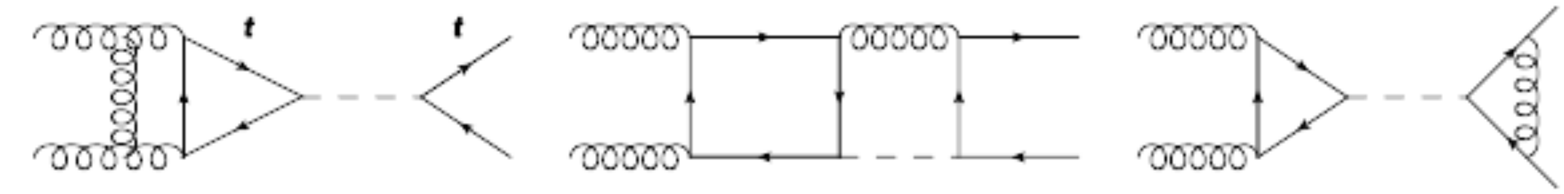
2. Analysis technology to look for BW peaks in place. Now it is time to consider more complicated situations, like peak-dip or even dips. In this case accurate predictions at NLO are challenging to obtain.

known



LO+reals

known — not-available — easy



two-loop virtuals

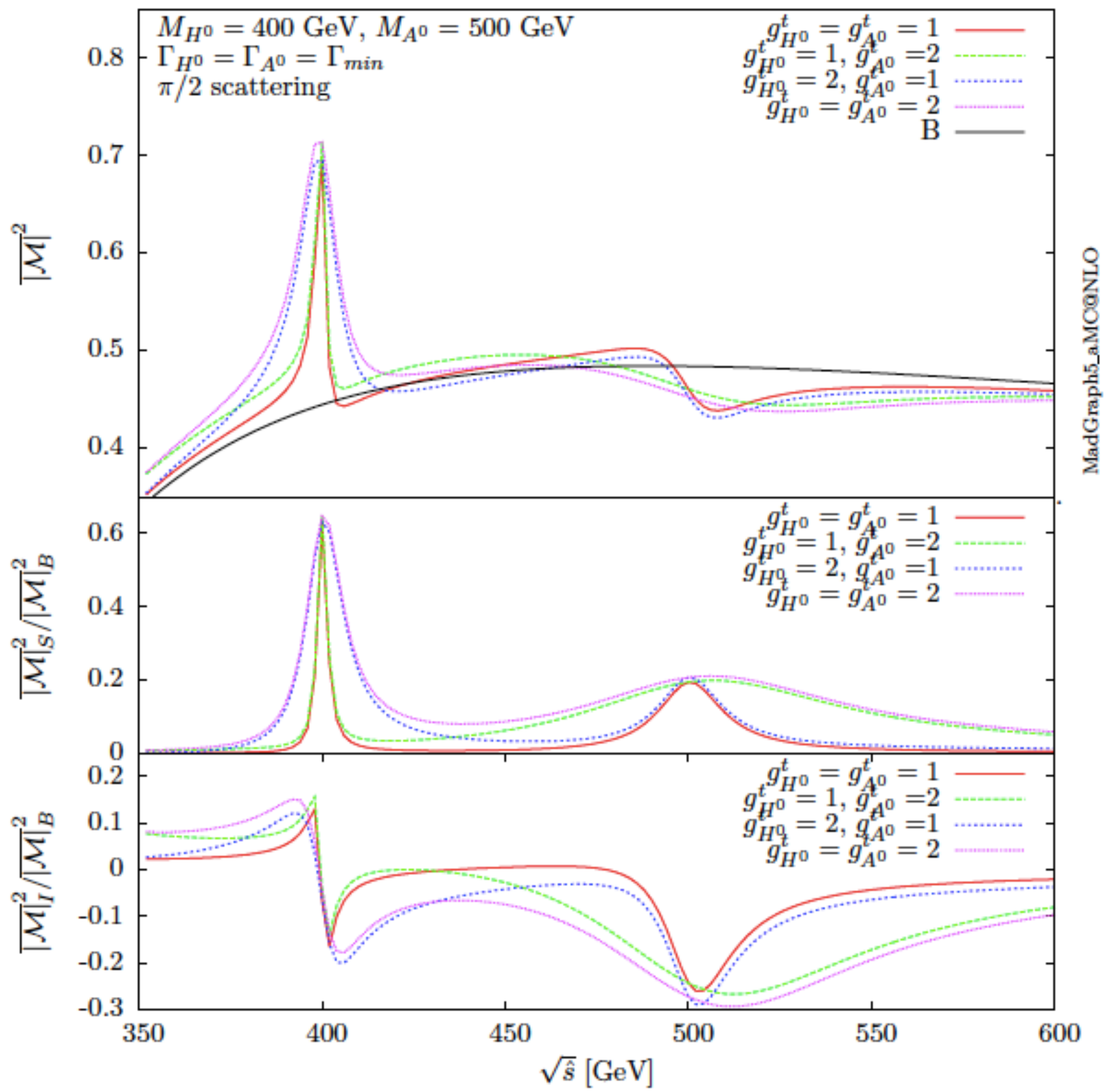
A possibility [Bernreuther et al., 2016] : compute the NLO corrections in the EFT and the soft limit for the interference.

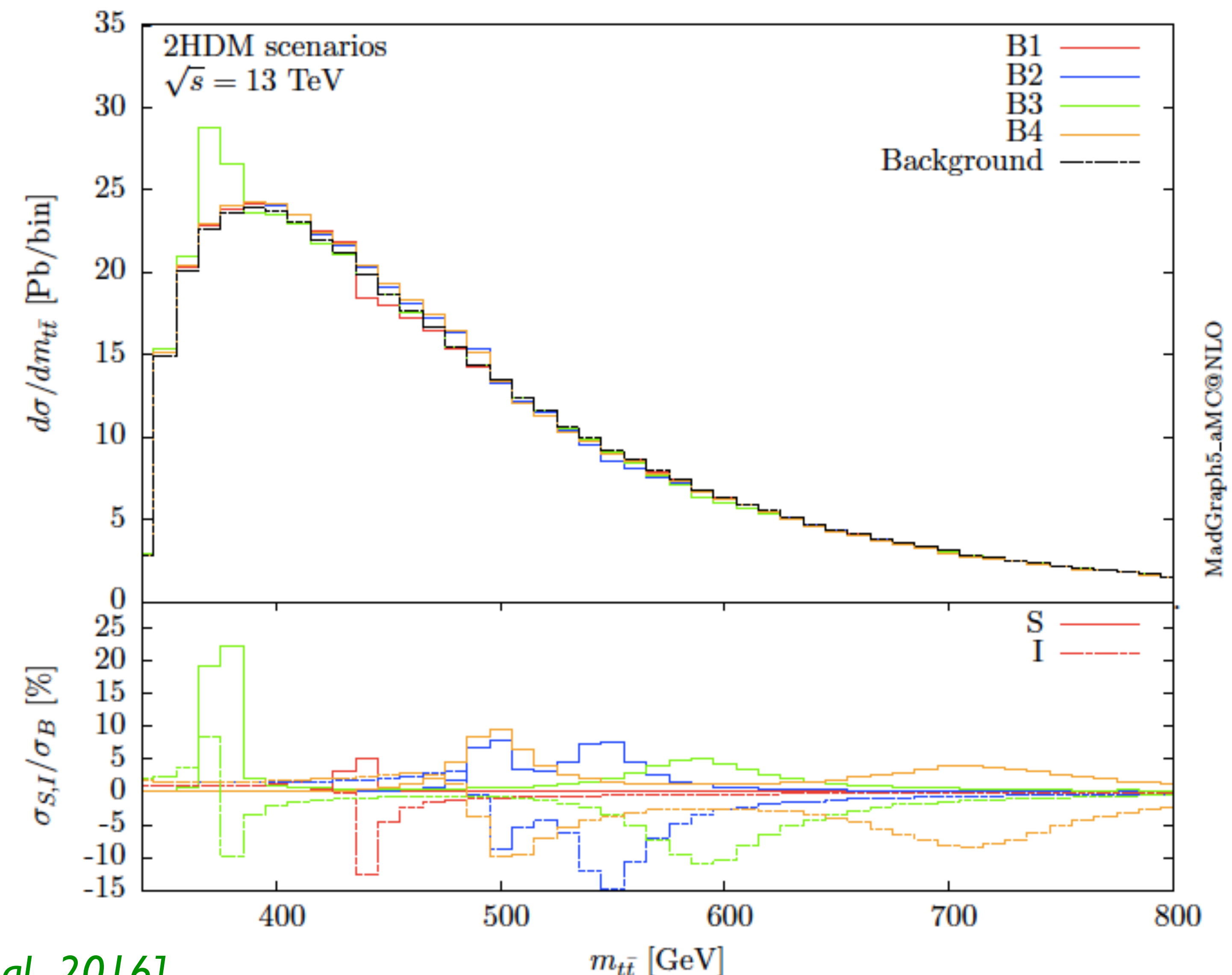
Another possibility [Hespel et al., 2016] : use the ansatz $\sigma_{NLO} = \sigma^{back}_{NLO} + \sigma^{signal}_{NLO} + \sigma^{inter}_{LO}\sqrt{K_S K_B}$

+ and tested/complemented by a calculation including all known elements (including all the real interference terms).

Resonances in ttbar

2. Analysis technology to look for BW peaks in place. It is time to consider more complicated situations, like peak-dip or even dips. While NLO accurate results are challenging to obtain, structures are stable under radiative correcs.

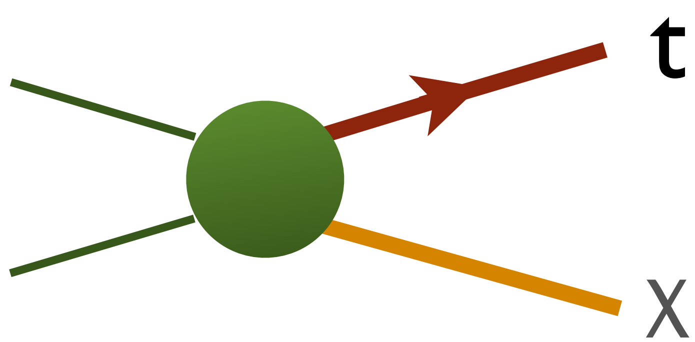




[Hespel et al., 2016]

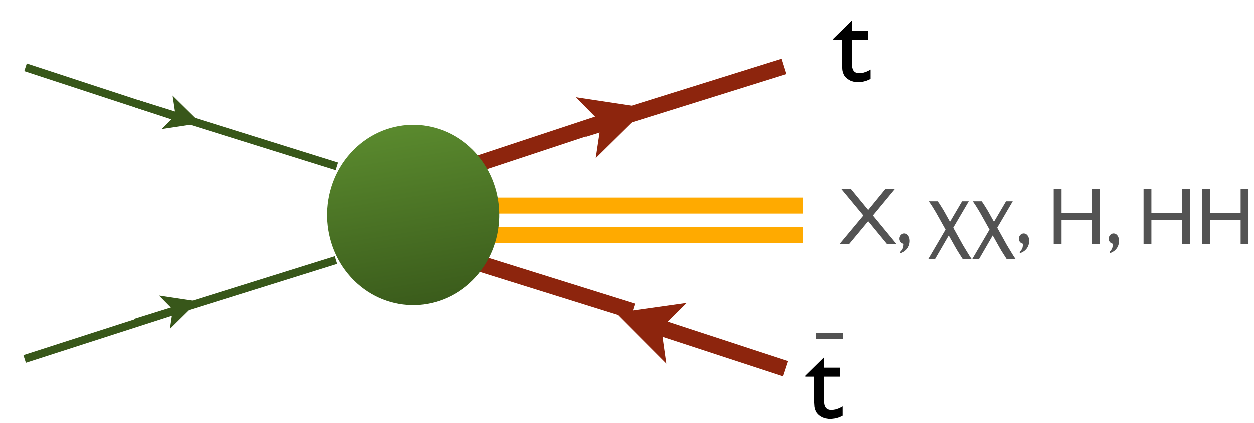
Exotic top-quark signatures

Searches for NP can be done in exotic or rare top signatures



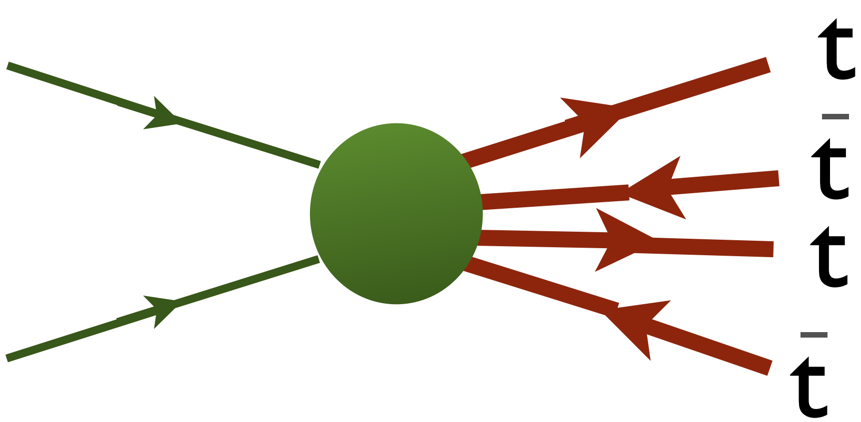
MONOTOPS

[Andrea et al. 2011]



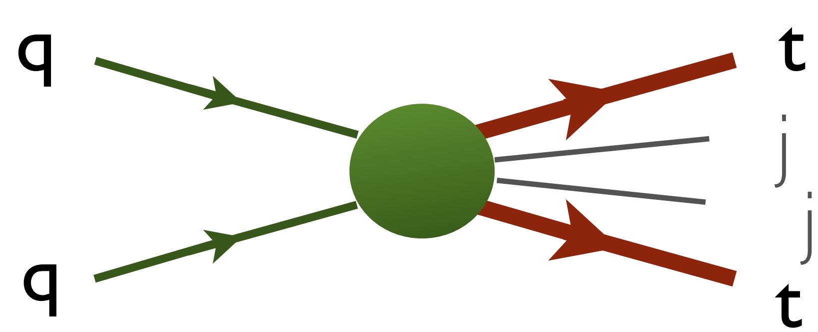
$t\bar{t} + \not{E}_T$, H,...

[Too long list here]



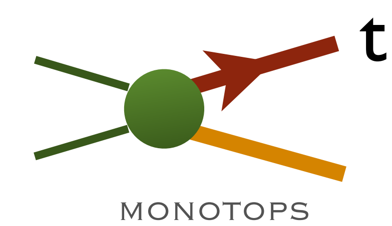
4 TOPS

[Tait et al, 2008, Gregoire et al,, 2011, Servant et al. , 2010, Cacciapaglia et al. 2011, Degrande 2010 , ...]



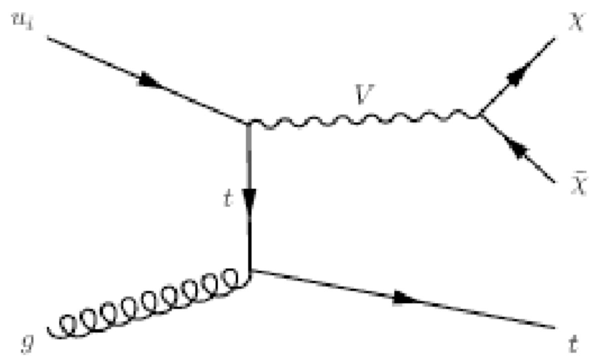
tt ($\bar{t}\bar{t}$) (+ JETS)

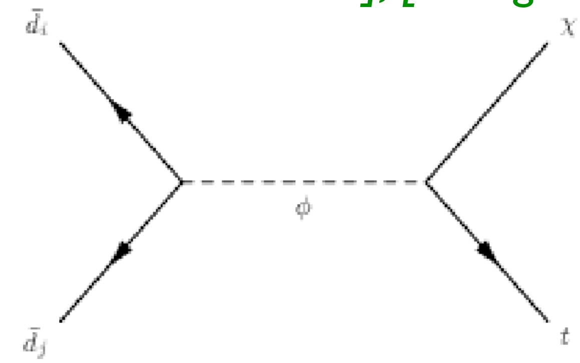
[Aguilar-Saavedra, 2011, Degrande et al. 2011, Kraml et al. 2006, Durieux et al. 2012,2013]



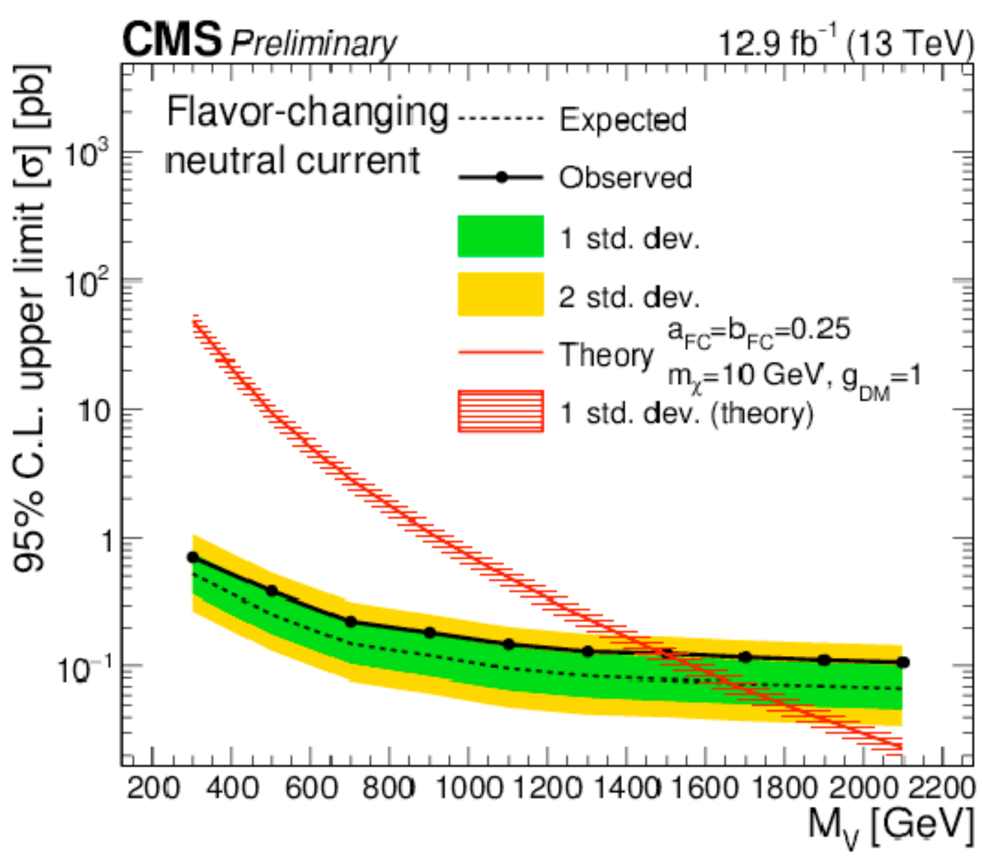
Exotic top-quark signatures

Several theoretical studies *[Andrea et al. 2011], [Wang et al. 2011], [Alvarez, 2013] [Agram, 2013]…*

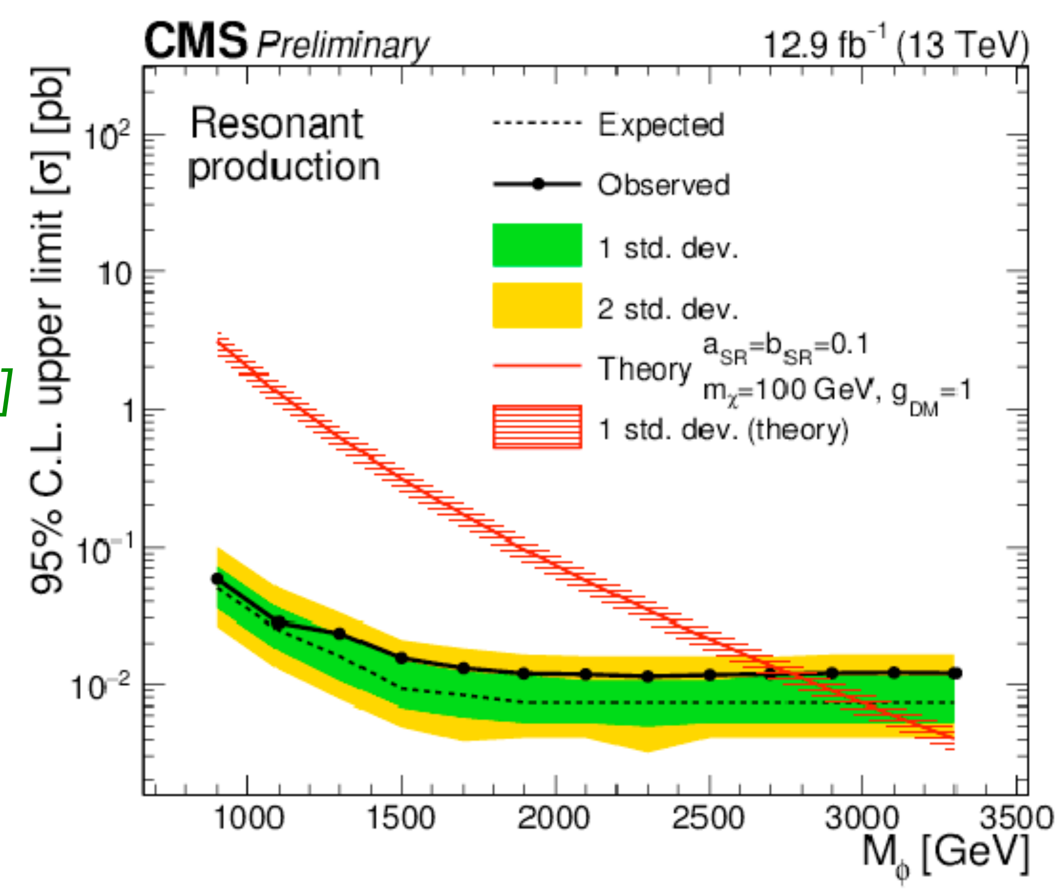




Several experimental analyses *[CMS, 2015], [ATLAS, 2014]*



[CMS 2016]



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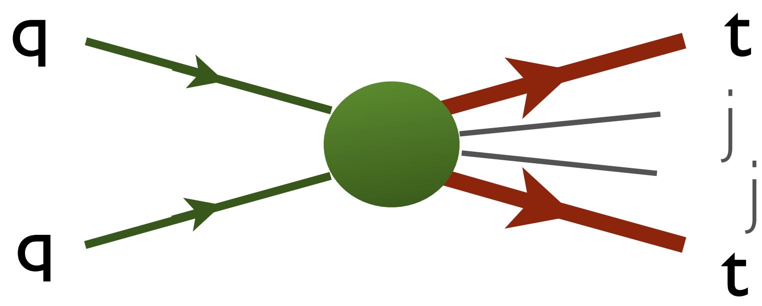
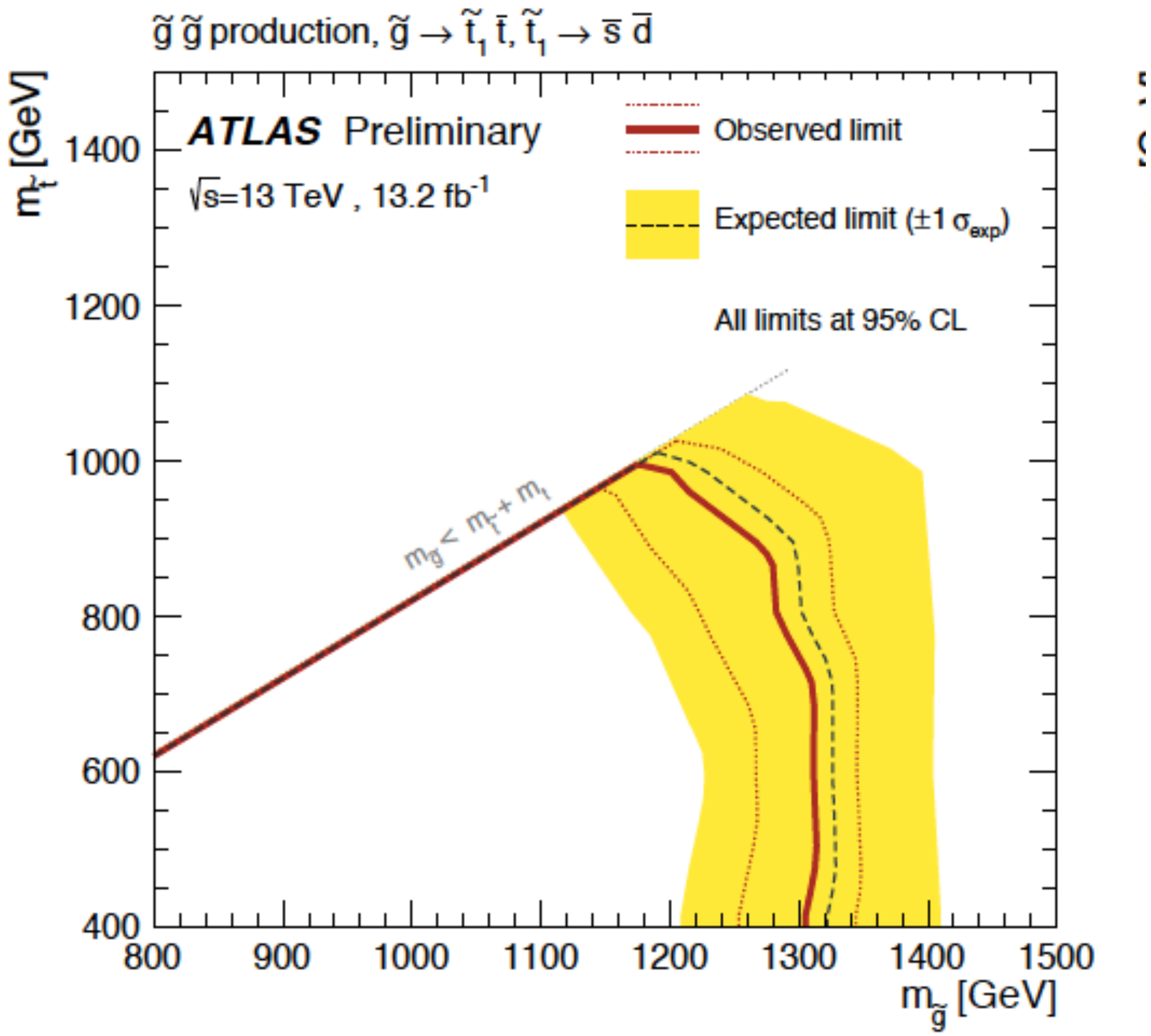
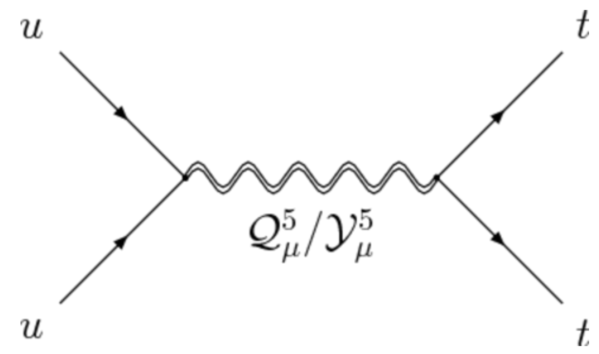
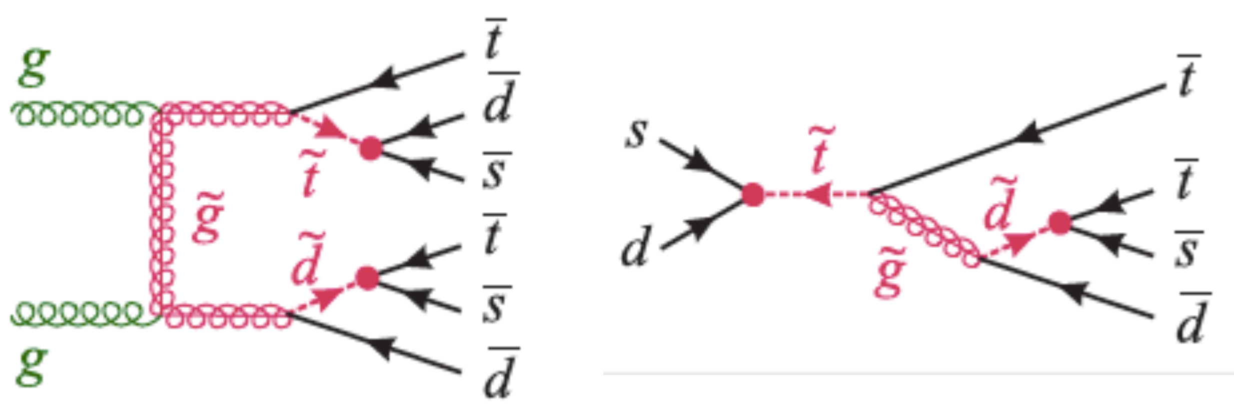


[ATLAS, 2016]



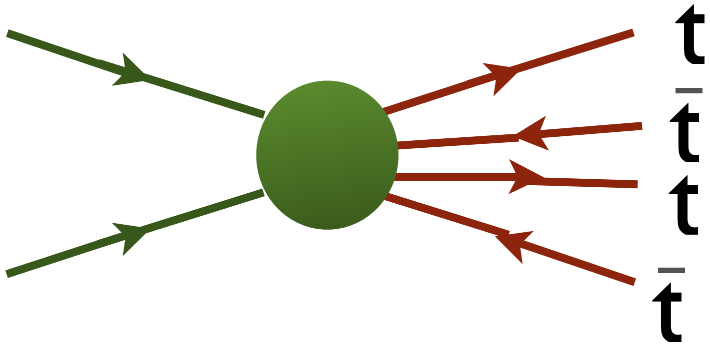


Signature that has attracted interest in the search of very exotic resonances, and more recently in interesting RPV scenarios. [Durieux and Smith, 2013]



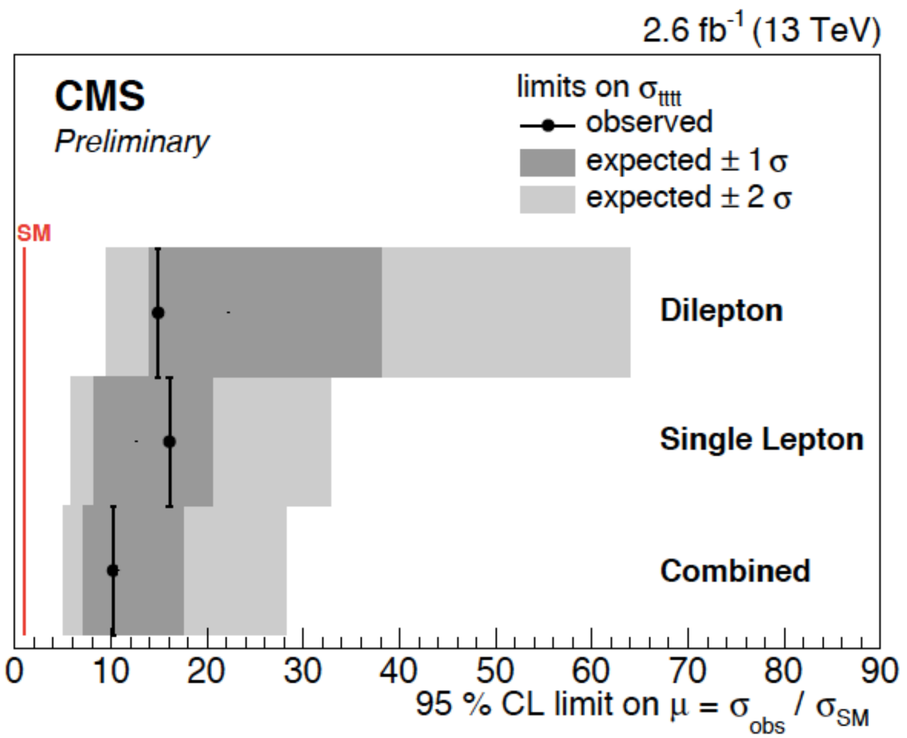
See also: [ATLAS, 2012], [CMS, 2013]

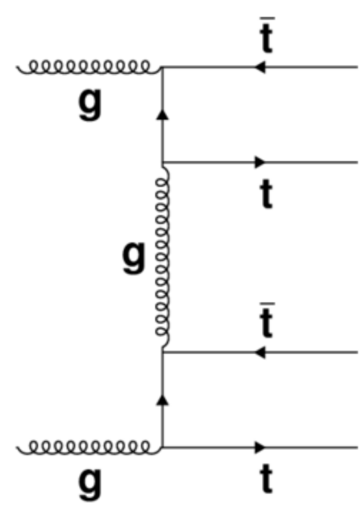
Exotic top-quark signatures

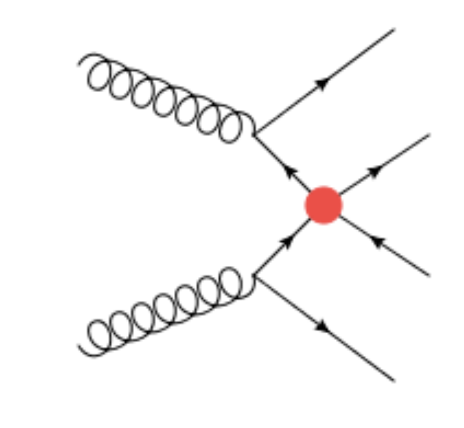


Four top signal has a long history, starting from [Tait et al, 2008]. SM signal known at NLO accuracy [Bevilacqua and Worek, 2012] and available NLO+PS [Maltoni et al. 2015]. BSM scenarios range from gluino gluino production and deca to 4t+Etmiss, to 4F interactions. Dedicated searches as well model independent ones have been undertaken.

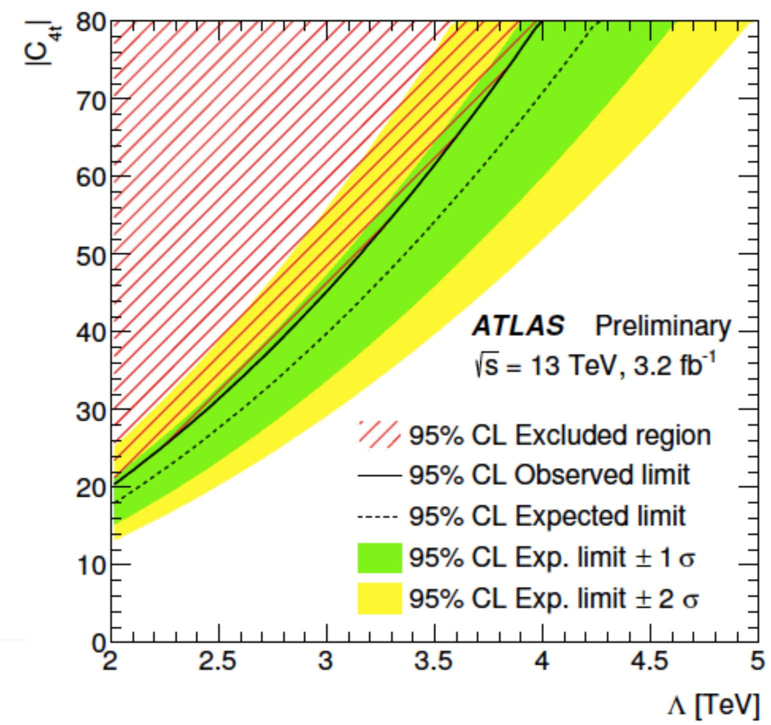
[CMS 2016]



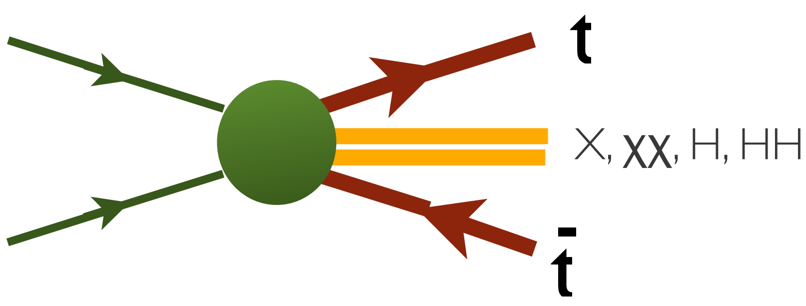




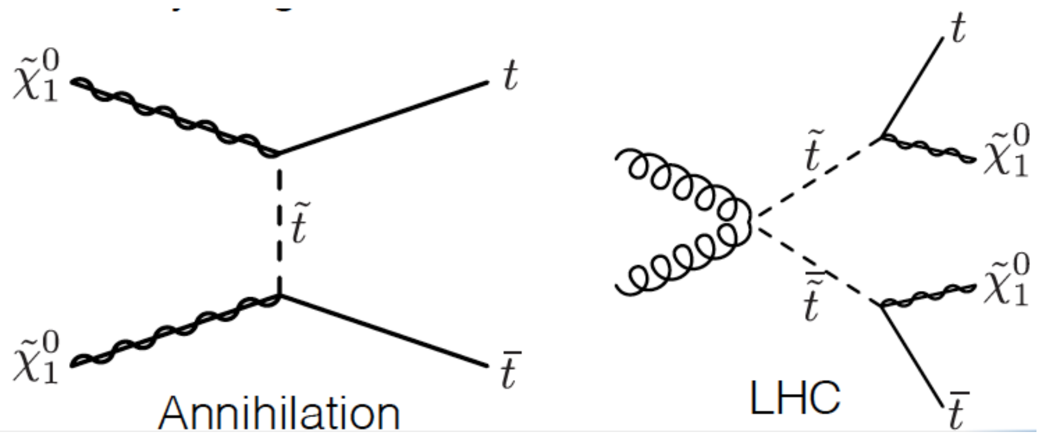
[ATLAS 2016]



Exotic top-quark signatures

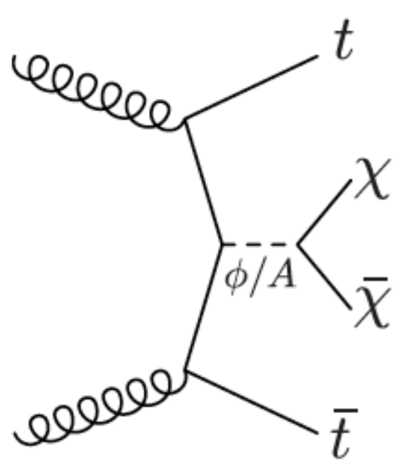


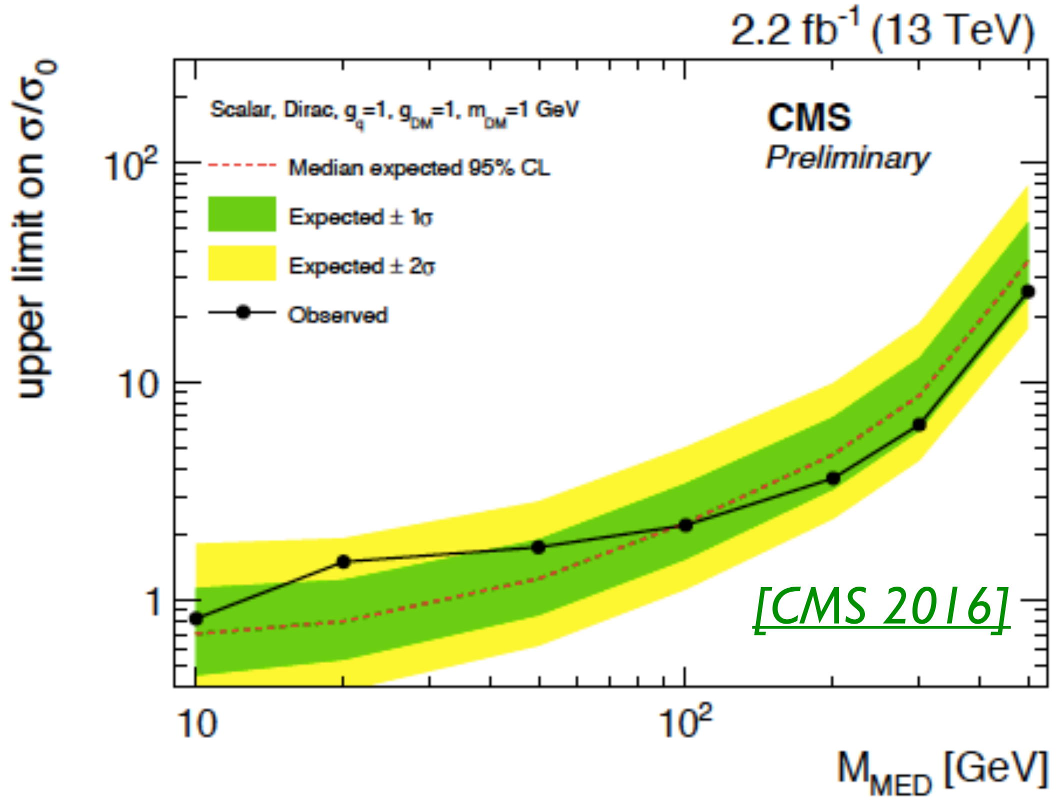
This signature is very popular, for SUSY and top-partner searches.



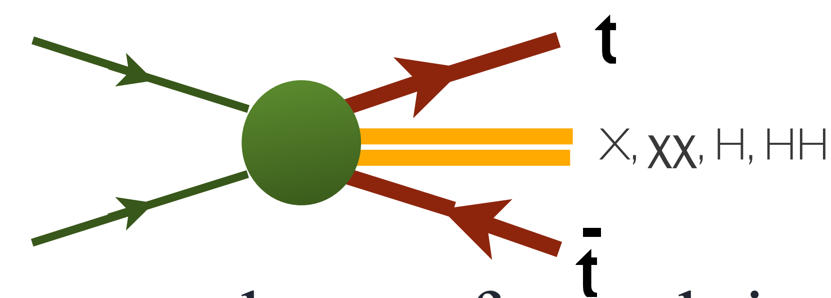
Lately also for DM searches in the s-channel.

$$\mathcal{L}_{t,X}^{Y_0} = -\left(g_t \frac{y_t}{\sqrt{2}}\bar{t}t + g_X \bar{X}X\right)Y_0$$



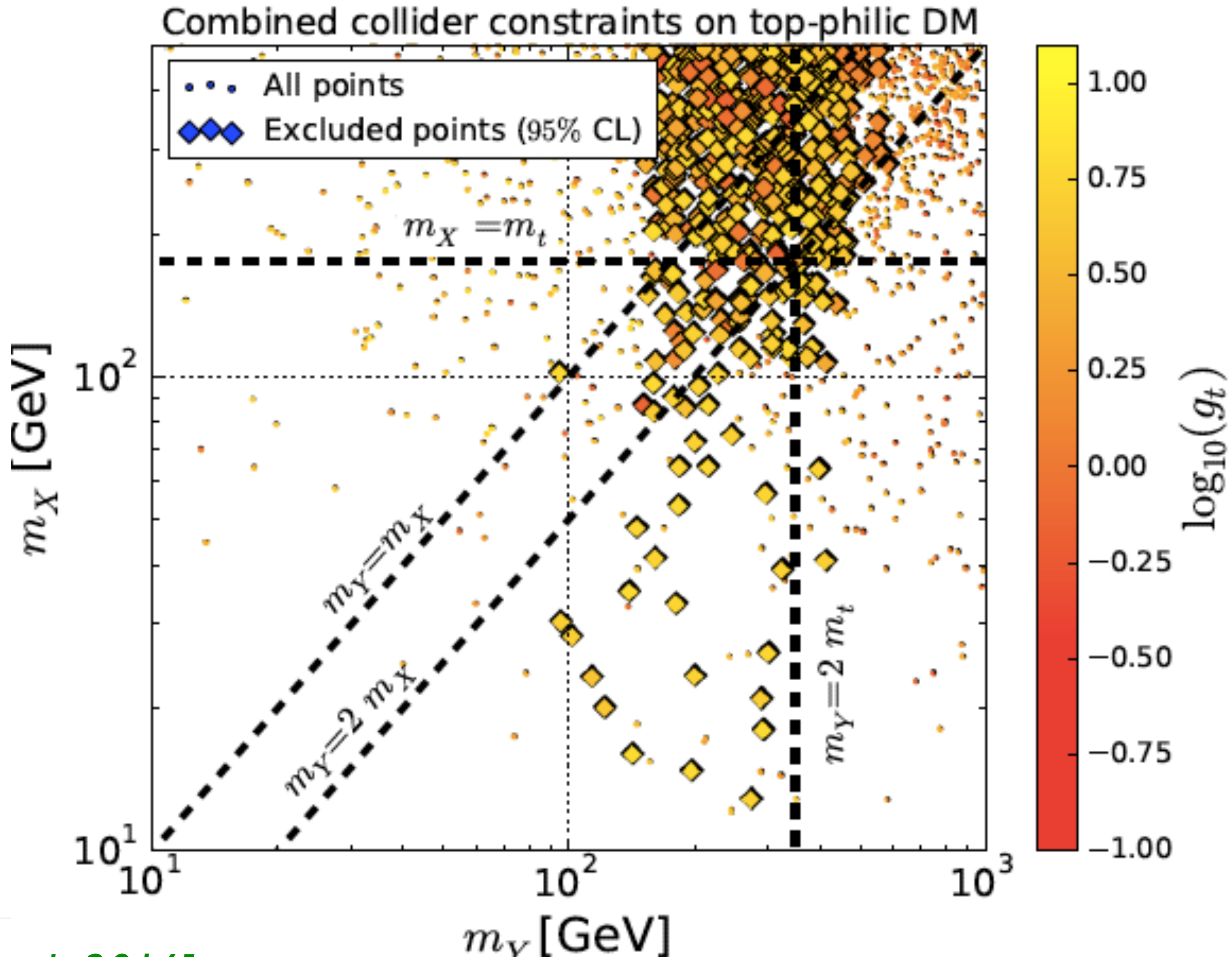


Exotic top-quark signatures



Simplified model searches for a top-philic mediator can be performed in different channels [Haisch et al., 2013] [Haisch et al., 2013] [Haisch et al., 2014] [Crivellin et al., 2015] [Haisch and Re, 2015] [Buckley and Gonsalves, 2015]

Cosmology	relic indirect	$m_X > m_t$	Planck, FermiLAT
		$m_X < m_t$	
Astrophysics		$m_X > m_Y$	
	direct	$m_X > 1$ GeV	LUX, CDMSLite
Colliders	$\not{E}_T$	$m_Y > 2m_X$	$+t\bar{t}$
		$m_Y > 2m_X$	$+j$, $+Z$, $+h$
	no $\not{E}_T$	$m_Y > 2m_t$	$4t$
		$m_Y > 2m_t$	$t\bar{t}$
		$m_Y < 2m_X, 2m_t$	jj, $\gamma\gamma$

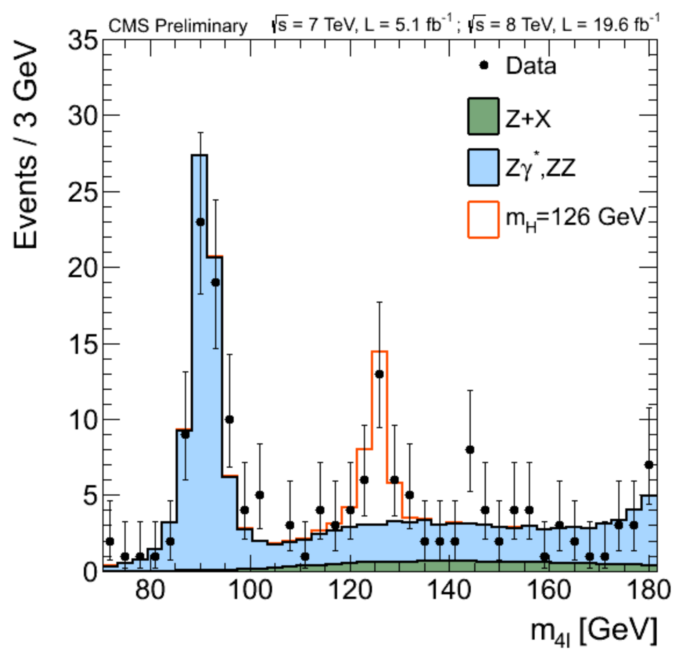


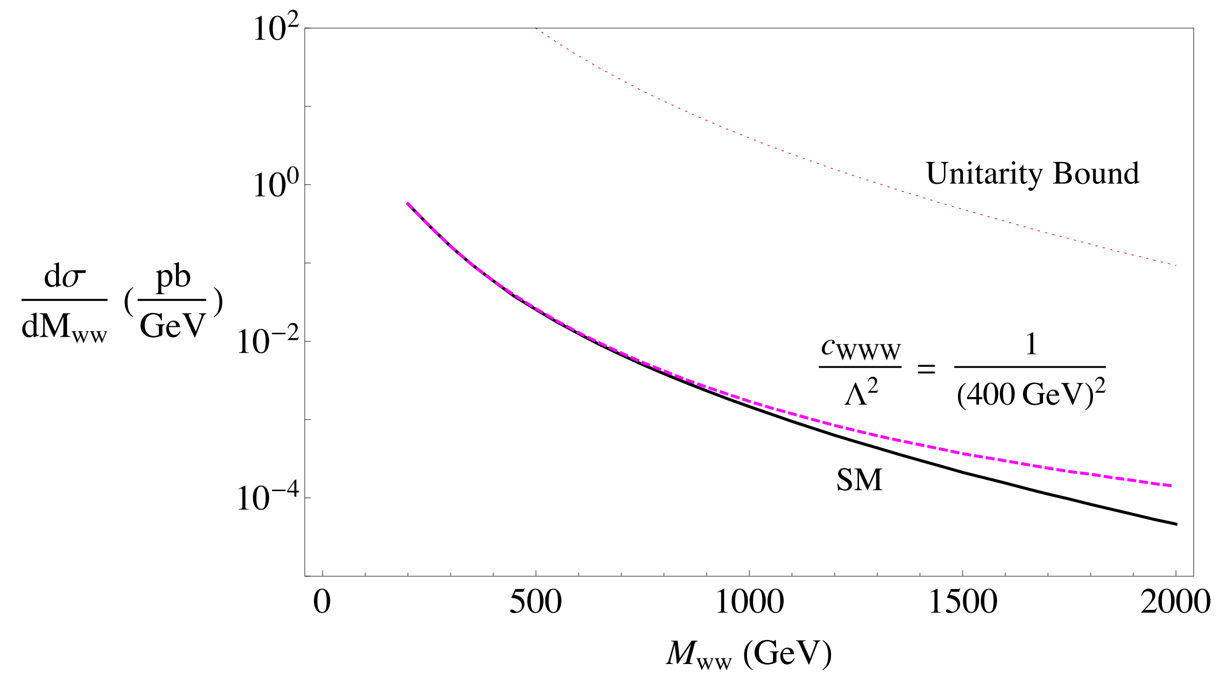
[Arina et al., 2016]

Search for New Physics at the LHC

Two main strategies for searching new physics

Search for new states ⟷ Search for new interactions





"Peak" or more complicated structures searches. Need for **descriptive MC** for discovery = Discovery is data driven. Later need precision for characterisation.

Deviations are expected to be small. Intrinsically a precision measurement. Needs for **predictive MC** and accurate predictions for SM and EFT.

Search for New Physics at the LHC

Two main strategies for searching new physics

Search for new states ⟷ Search for new interactions

The matter content of SM has been experimentally verified and evidence for light states is not present. SM measurements can always be seen as searches for deviations from the dim=4 SM Lagrangian predictions.

$$\mathcal{L}_{SM}^{(6)} = \mathcal{L}_{SM}^{(4)} + \sum_i \frac{c_i}{\Lambda^2}\mathcal{O}_i + \dots$$

BSM goal of the SM LHC program:

determination of the couplings of the SM lagrangian at DIM=6

Dim=6 SM Lagrangian

[Grzadkowski et al, 10]

X^3		φ^6 and $\varphi^4 D^2$		$\psi^2\varphi^3$	
Q_G	$f^{ABC} G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$	Q_φ	$(\varphi^\dagger\varphi)^3$	$Q_{e\varphi}$	$(\varphi^\dagger\varphi)(\bar l_p e_r \varphi)$
$Q_{\widetilde G}$	$f^{ABC} \widetilde G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$	$Q_{\varphi\Box}$	$(\varphi^\dagger\varphi)\Box(\varphi^\dagger\varphi)$	$Q_{u\varphi}$	$(\varphi^\dagger\varphi)(\bar q_p u_r \widetilde\varphi)$
Q_W	$\varepsilon^{IJK} W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$	$Q_{\varphi D}$	$\left(\varphi^\dagger D^\mu\varphi\right)^\star \left(\varphi^\dagger D_\mu\varphi\right)$	$Q_{d\varphi}$	$(\varphi^\dagger\varphi)(\bar q_p d_r \varphi)$
$Q_{\widetilde W}$	$\varepsilon^{IJK} \widetilde W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$				
$X^2\varphi^2$		$\psi^2 X\varphi$		$\psi^2\varphi^2 D$	
$Q_{\varphi G}$	$\varphi^\dagger\varphi\, G^A_{\mu\nu} G^{A\mu\nu}$	Q_{eW}	$(\bar l_p \sigma^{\mu\nu} e_r)\tau^I\varphi W^I_{\mu\nu}$	$Q_{\varphi l}^{(1)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar l_p \gamma^\mu l_r)$
$Q_{\varphi\widetilde G}$	$\varphi^\dagger\varphi\, \widetilde G^A_{\mu\nu} G^{A\mu\nu}$	Q_{eB}	$(\bar l_p \sigma^{\mu\nu} e_r)\varphi B_{\mu\nu}$	$Q_{\varphi l}^{(3)}$	$(\varphi^\dagger i\overleftrightarrow{D}^I_\mu \varphi)(\bar l_p \tau^I \gamma^\mu l_r)$
$Q_{\varphi W}$	$\varphi^\dagger\varphi\, W^I_{\mu\nu} W^{I\mu\nu}$	Q_{uG}	$(\bar q_p \sigma^{\mu\nu} T^A u_r)\widetilde\varphi\, G^A_{\mu\nu}$	$Q_{\varphi e}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar e_p \gamma^\mu e_r)$
$Q_{\varphi\widetilde W}$	$\varphi^\dagger\varphi\, \widetilde W^I_{\mu\nu} W^{I\mu\nu}$	Q_{uW}	$(\bar q_p \sigma^{\mu\nu} u_r)\tau^I\widetilde\varphi\, W^I_{\mu\nu}$	$Q_{\varphi q}^{(1)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar q_p \gamma^\mu q_r)$
$Q_{\varphi B}$	$\varphi^\dagger\varphi\, B_{\mu\nu} B^{\mu\nu}$	Q_{uB}	$(\bar q_p \sigma^{\mu\nu} u_r)\widetilde\varphi\, B_{\mu\nu}$	$Q_{\varphi q}^{(3)}$	$(\varphi^\dagger i\overleftrightarrow{D}^I_\mu \varphi)(\bar q_p \tau^I \gamma^\mu q_r)$
$Q_{\varphi\widetilde B}$	$\varphi^\dagger\varphi\, \widetilde B_{\mu\nu} B^{\mu\nu}$	Q_{dG}	$(\bar q_p \sigma^{\mu\nu} T^A d_r)\varphi\, G^A_{\mu\nu}$	$Q_{\varphi u}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar u_p \gamma^\mu u_r)$
$Q_{\varphi WB}$	$\varphi^\dagger\tau^I\varphi\, W^I_{\mu\nu} B^{\mu\nu}$	Q_{dW}	$(\bar q_p \sigma^{\mu\nu} d_r)\tau^I\varphi\, W^I_{\mu\nu}$	$Q_{\varphi d}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar d_p \gamma^\mu d_r)$
$Q_{\varphi\widetilde WB}$	$\varphi^\dagger\tau^I\varphi\, \widetilde W^I_{\mu\nu} B^{\mu\nu}$	Q_{dB}	$(\bar q_p \sigma^{\mu\nu} d_r)\varphi\, B_{\mu\nu}$	$Q_{\varphi ud}$	$i(\widetilde\varphi^\dagger D_\mu\varphi)(\bar u_p \gamma^\mu d_r)$

$(\bar LL)(\bar LL)$		$(\bar RR)(\bar RR)$		$(\bar LL)(\bar RR)$	
Q_{ll}	$(\bar l_p\gamma_\mu l_r)(\bar l_s\gamma^\mu l_t)$	Q_{ee}	$(\bar e_p\gamma_\mu e_r)(\bar e_s\gamma^\mu e_t)$	Q_{le}	$(\bar l_p\gamma_\mu l_r)(\bar e_s\gamma^\mu e_t)$
$Q_{qq}^{(1)}$	$(\bar q_p\gamma_\mu q_r)(\bar q_s\gamma^\mu q_t)$	Q_{uu}	$(\bar u_p\gamma_\mu u_r)(\bar u_s\gamma^\mu u_t)$	Q_{lu}	$(\bar l_p\gamma_\mu l_r)(\bar u_s\gamma^\mu u_t)$
$Q_{qq}^{(3)}$	$(\bar q_p\gamma_\mu\tau^I q_r)(\bar q_s\gamma^\mu\tau^I q_t)$	Q_{dd}	$(\bar d_p\gamma_\mu d_r)(\bar d_s\gamma^\mu d_t)$	Q_{ld}	$(\bar l_p\gamma_\mu l_r)(\bar d_s\gamma^\mu d_t)$
$Q_{lq}^{(1)}$	$(\bar l_p\gamma_\mu l_r)(\bar q_s\gamma^\mu q_t)$	Q_{eu}	$(\bar e_p\gamma_\mu e_r)(\bar u_s\gamma^\mu u_t)$	Q_{qe}	$(\bar q_p\gamma_\mu q_r)(\bar e_s\gamma^\mu e_t)$
$Q_{lq}^{(3)}$	$(\bar l_p\gamma_\mu\tau^I l_r)(\bar q_s\gamma^\mu\tau^I q_t)$	Q_{ed}	$(\bar e_p\gamma_\mu e_r)(\bar d_s\gamma^\mu d_t)$	$Q_{qu}^{(1)}$	$(\bar q_p\gamma_\mu q_r)(\bar u_s\gamma^\mu u_t)$
		$Q_{ud}^{(1)}$	$(\bar u_p\gamma_\mu u_r)(\bar d_s\gamma^\mu d_t)$	$Q_{qu}^{(8)}$	$(\bar q_p\gamma_\mu T^A q_r)(\bar u_s\gamma^\mu T^A u_t)$
		$Q_{ud}^{(8)}$	$(\bar u_p\gamma_\mu T^A u_r)(\bar d_s\gamma^\mu T^A d_t)$	$Q_{qd}^{(1)}$	$(\bar q_p\gamma_\mu q_r)(\bar d_s\gamma^\mu d_t)$
				$Q_{qd}^{(8)}$	$(\bar q_p\gamma_\mu T^A q_r)(\bar d_s\gamma^\mu T^A d_t)$
$(\bar LR)(\bar RL)$ and $(\bar LR)(\bar LR)$		B-violating			
Q_{ledq}	$(\bar l_p^j e_r)(\bar d_s q_t^j)$	Q_{duq}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(q_s^{\gamma j})^T C l_t^k\right]$		
$Q_{quqd}^{(1)}$	$(\bar q_p^j u_r)\varepsilon_{jk}(\bar q_s^k d_t)$	Q_{qqu}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(u_s^\gamma)^T C e_t\right]$		
$Q_{quqd}^{(8)}$	$(\bar q_p^j T^A u_r)\varepsilon_{jk}(\bar q_s^k T^A d_t)$	$Q_{qqq}^{(1)}$	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\varepsilon_{mn}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(q_s^{\gamma m})^T C l_t^n\right]$		
$Q_{lequ}^{(1)}$	$(\bar l_p^j e_r)\varepsilon_{jk}(\bar q_s^k u_t)$	$Q_{qqq}^{(3)}$	$\varepsilon^{\alpha\beta\gamma}(\tau^I\varepsilon)_{jk}(\tau^I\varepsilon)_{mn}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(q_s^{\gamma m})^T C l_t^n\right]$		
$Q_{lequ}^{(3)}$	$(\bar l_p^j \sigma_{\mu\nu} e_r)\varepsilon_{jk}(\bar q_s^k \sigma^{\mu\nu} u_t)$	Q_{duu}	$\varepsilon^{\alpha\beta\gamma}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(u_s^\gamma)^T C e_t\right]$		

- Based on all the symmetries of the SM
- New physics is heavier than the resonance itself : $\Lambda > M_X$
- QCD and EW renormalizable (order by order in $1/\Lambda$)
- Number of extra couplings reduced by symmetries and dimensional analysis
- Extends the reach of searches for NP beyond the collider energy.
- Valid only up to the scale Λ

The EFT approach: managing unknown unknowns

- Very powerful approach.
- Note, however, that it only makes sense if a **global constraining strategy** is used to extract information from the data:
  - assume all couplings might not be zero at the EW scale.
  - identify the operators entering each observable.
  - find enough observables (cross sections, BR's, distributions,…) to constrain all operators.
  - solve the (linear+quadratic) system.
  - hierarchical approach on the couplings.

Top-quark operators and processes

[Willenbrock and Zhang 2011, Aguilar-Saavedra 2011, Degrande et al. 2011]

$$O_{\varphi Q}^{(3)} = i\frac{1}{2}y_t^2\left(\varphi^\dagger \overleftrightarrow{D}^I_\mu \varphi\right)(\bar{Q}\gamma^\mu\tau^I Q)$$

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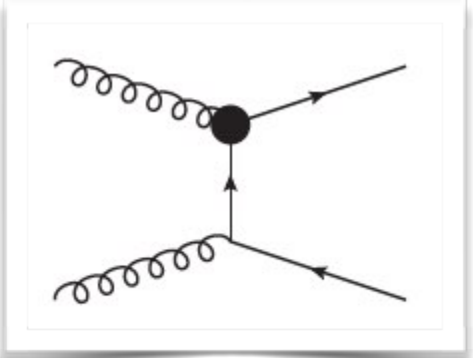
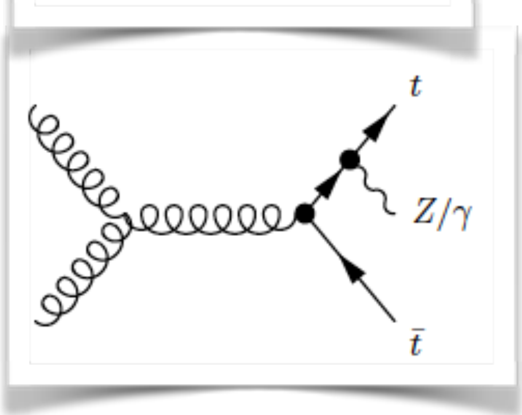
$$O_{tG} = y_t g_s(\bar{Q}\sigma^{\mu\nu}T^A t)\tilde{\varphi}G^A_{\mu\nu}\,,$$

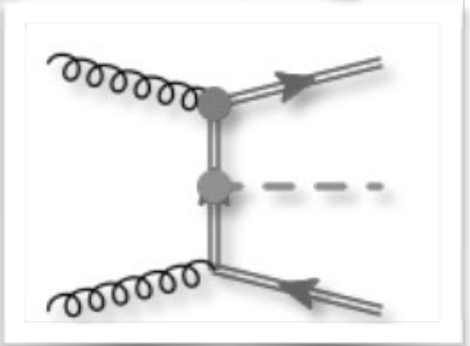
$$O_{t\varphi} = y_t^3(\varphi^\dagger\varphi)\bar{Q}\tilde{\varphi}t$$

+four-fermion operators

+ operators that do not feature a top, but contribute to the procs…







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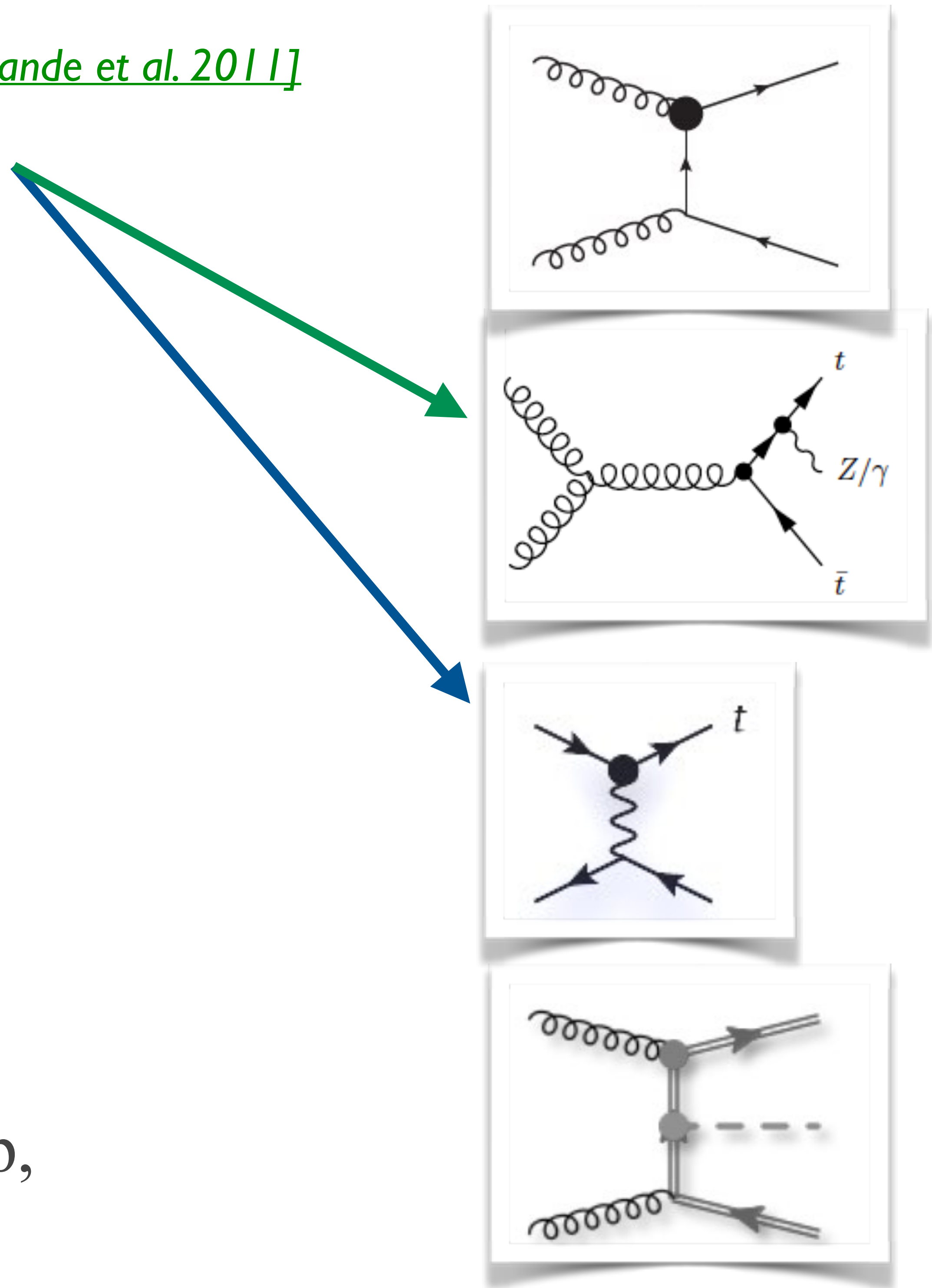

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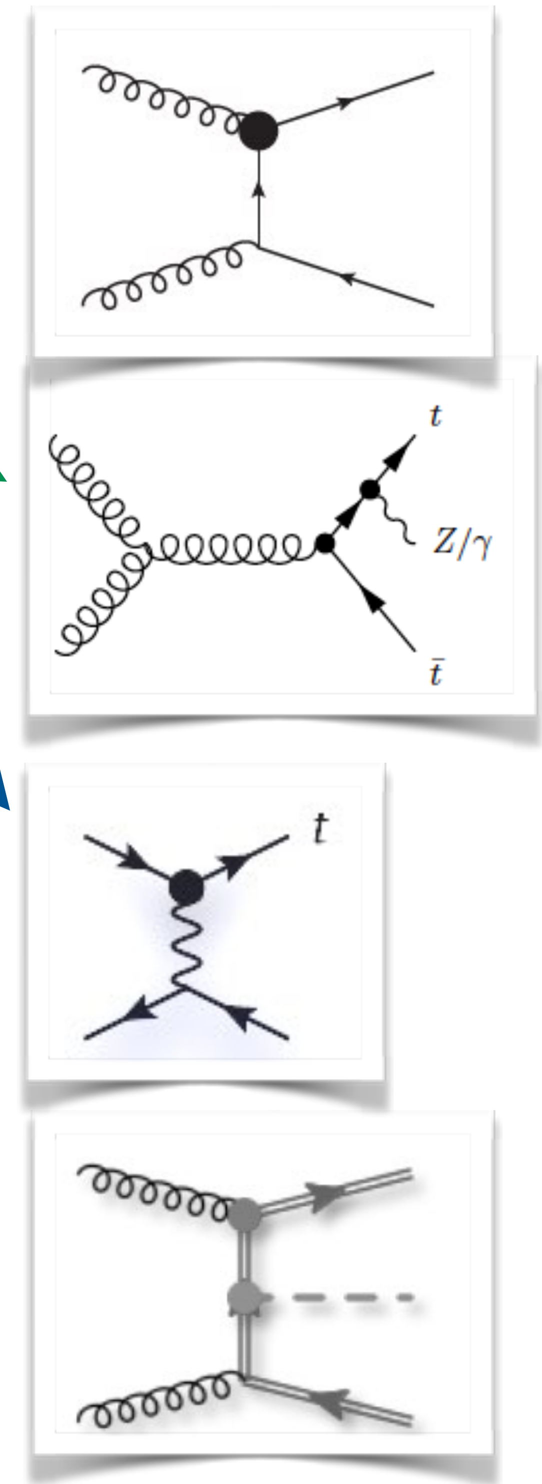

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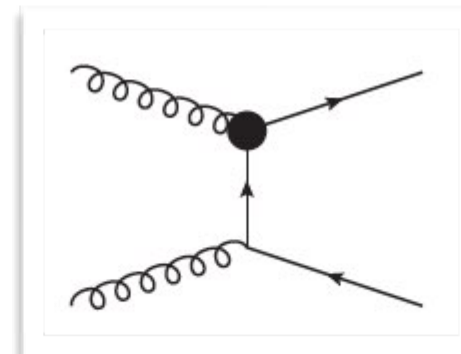

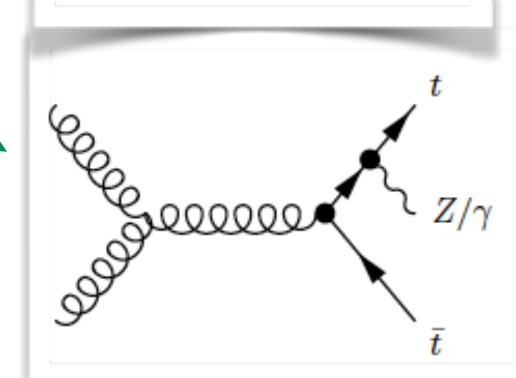

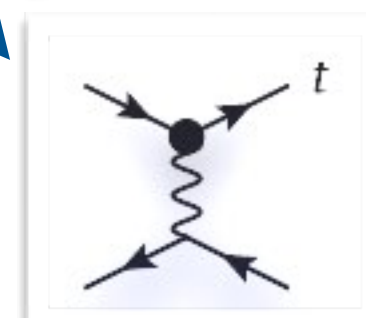

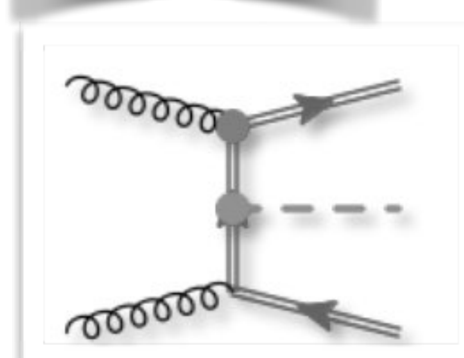

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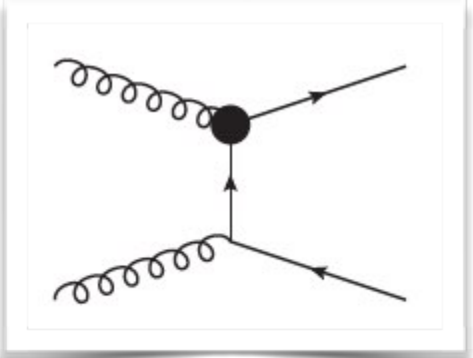

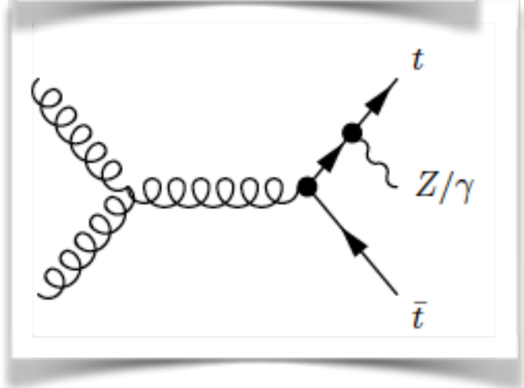

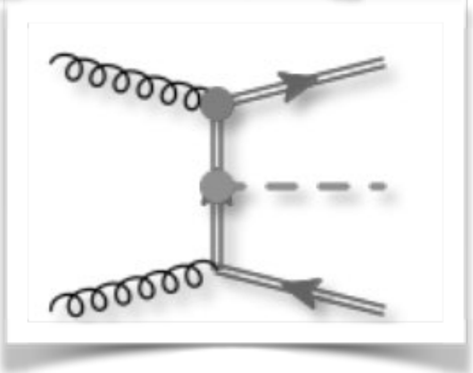

Top-quark operators and processes

[Willenbrock and Zhang 2011, Aguilar-Saavedra 2011, Degrande et al. 2011]

$$O_{\varphi Q}^{(3)} = i\frac{1}{2}y_t^2\left(\varphi^\dagger \overleftrightarrow{D}^I_\mu \varphi\right)(\bar{Q}\gamma^\mu\tau^I Q)$$

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$$O_{tG} = y_t g_s(\bar{Q}\sigma^{\mu\nu}T^A t)\tilde{\varphi}G^A_{\mu\nu}\,,$$

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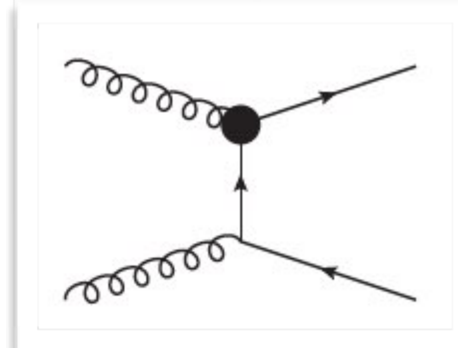

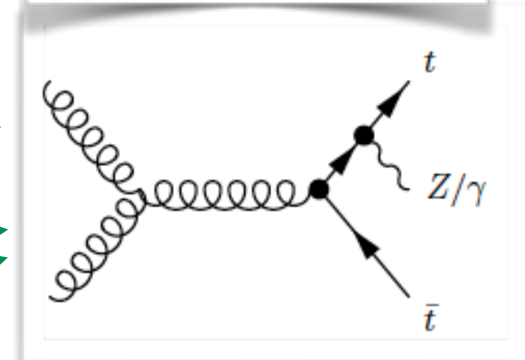

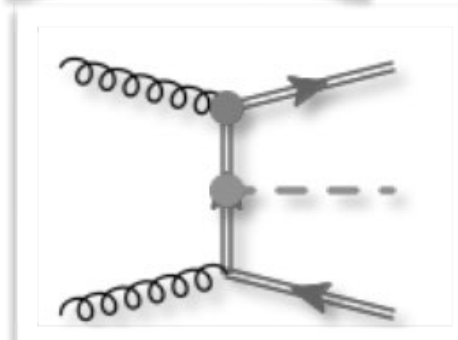

+four-fermion operators

+ operators that do not feature a top, but contribute to the procs…

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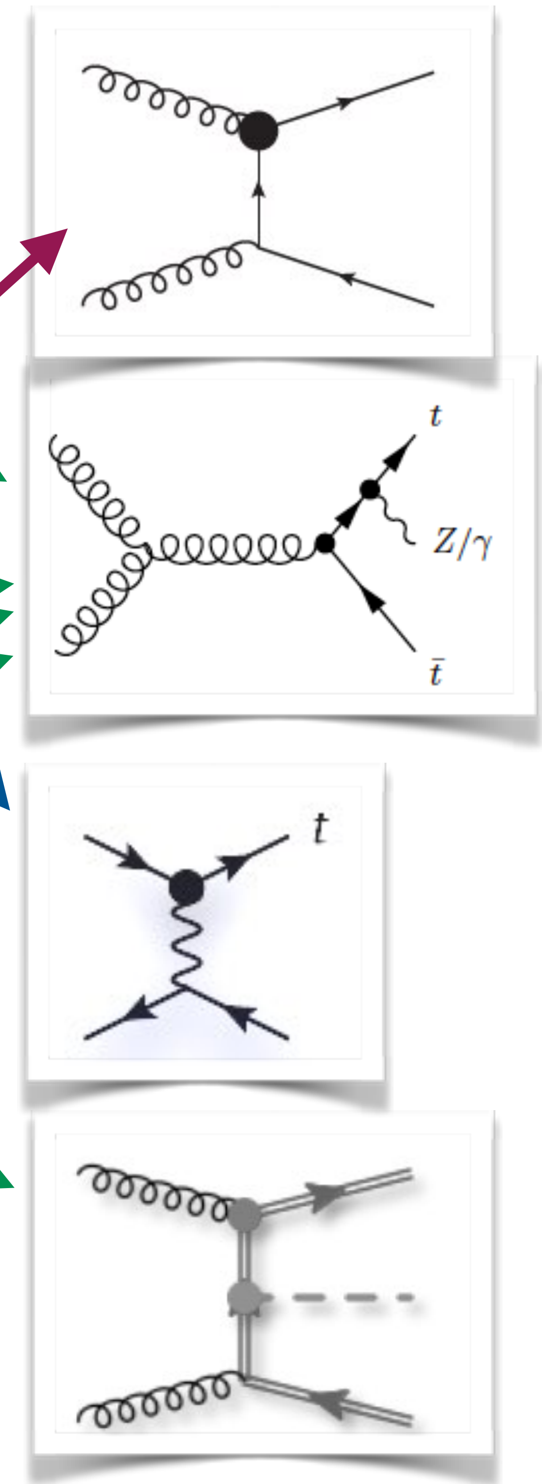

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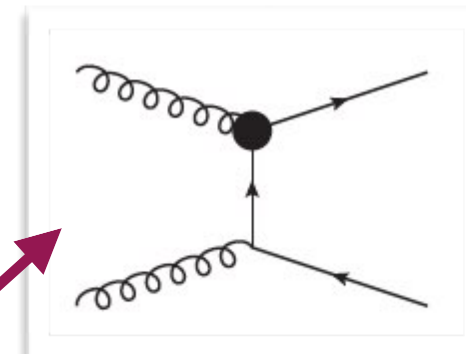
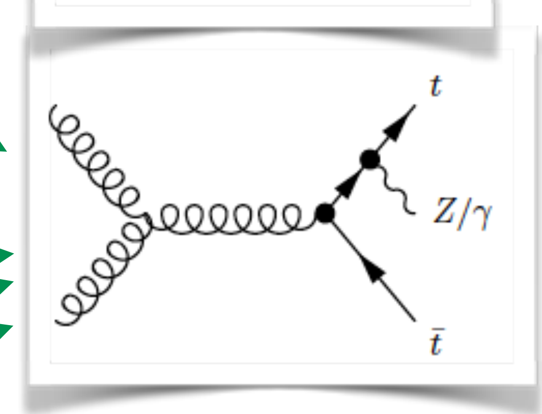
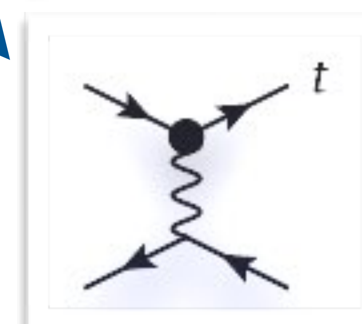
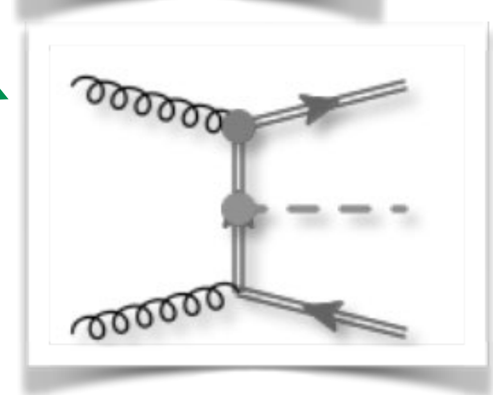








+four-fermion operators

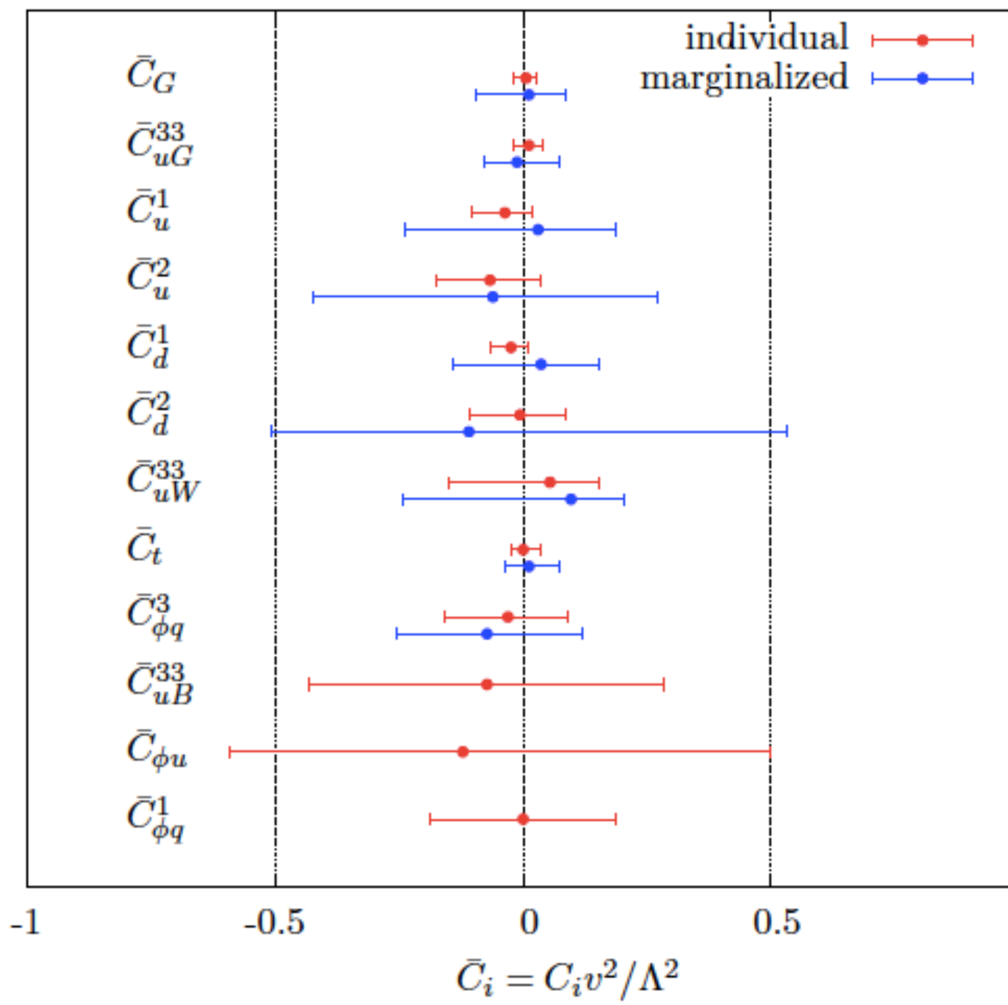
+ operators that do not feature a top, but contribute to the procs…

Towards a global fit at the LHC

4-fermion operators		Non 4-fermion operators	
O_{qq}^1	$(\bar{q}\gamma_\mu q)(\bar{q}\gamma^\mu q)$	$O_{\phi q}^3$	$i(\phi^\dagger \tau^I D_\mu \phi)(\bar{q}\gamma^\mu \tau^I q)$
O_{qq}^3	$(\bar{q}\gamma_\mu \tau^I q)(\bar{q}\gamma^\mu \tau^I q)$	O_{tW}	$(\bar{q}\sigma^{\mu\nu}\tau^I t)\tilde{\phi}W_{\mu\nu}^I$
O_{uu}	$(\bar{u}\gamma_\mu u)(\bar{u}\gamma^\mu u)$	O_{tG}	$(\bar{q}\sigma^{\mu\nu}\lambda^A t)\tilde{\phi}G_{\mu\nu}^A$
O_{qu}^8	$(\bar{q}\gamma_\mu T^A q)(\bar{u}\gamma^\mu T^A u)$	O_G	$f_{ABC}\, G_\mu^{A\nu} G_\nu^{B\lambda} G_\lambda^{C\mu}$
O_{qd}^8	$(\bar{q}\gamma_\mu T^A q)(\bar{d}\gamma^\mu T^A d)$	$O_{\tilde{G}}$	$f_{ABC}\, \tilde{G}_\mu^{A\nu} G_\nu^{B\lambda} G_\lambda^{C\mu}$
O_{ud}^8	$(\bar{u}\gamma_\mu T^A u)(\bar{d}\gamma^\mu T^A d)$	$O_{\phi G}$	$(\phi^\dagger \phi) G_{\mu\nu}^A G^{A\mu\nu}$
		$O_{\phi\tilde{G}}$	$(\phi^\dagger \phi) \tilde{G}_{\mu\nu}^A G^{A\mu\nu}$

TABLE I: All dimension-six operators relevant to top quark production, in the notation of Ref. [12]. Details of each are included in the text. We do not include explicit flavor indices here. 13 operators are shown, but O_{tW} and O_{tG} have both real and imaginary parts which should be considered as independent operators; the latter produce $\mathcal{CP}$-violating effects.

[Buckley et al.,2015] [Buckley et al.,2015]



- EFT based, fit on Tevatron and LHC data: total as well as differential information from ttbar and t-channel single-top.
- SM at NLO (or NNLO) and EFT at LO in QCD (Feynrules+MadGraph).

The need for NLO in QCD

- A global approach with constraints on top couplings coming from a wide set of observables is the (only) way to go.
- A precision physics effort needs accurate predictions not only for the SM but also for the EFT.
- This is because the top is coloured and the LHC is a hadron collider.
- In fact, the structure of the EFT for the top becomes non trivial at NLO in QCD, with operator mixings.

Towards a global fit at the LHC

However, the only consistent/useful way of making progress is to consider constraints coming from different processes at the same time and do this at NLO in QCD. One has to pay attention to which operators contribute for a given process, LO and NLO.

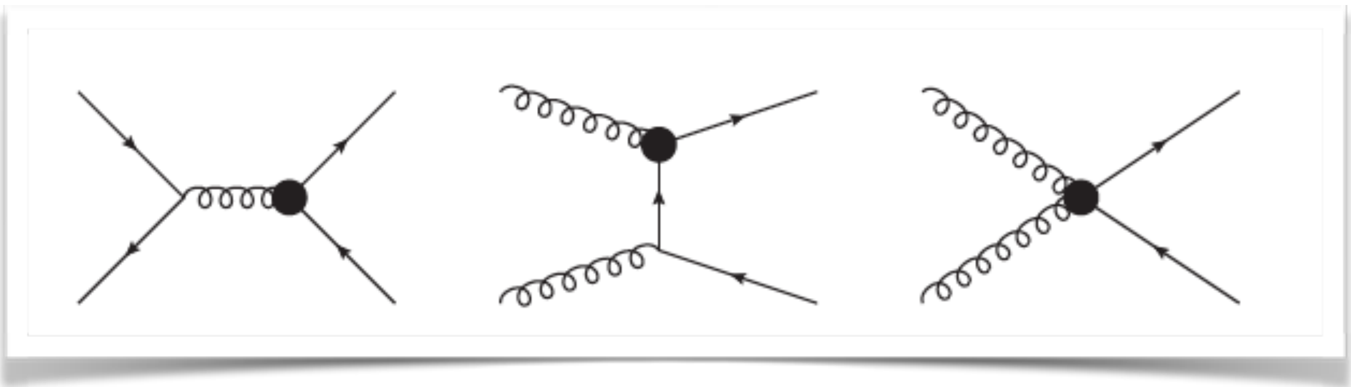
Process	O_{tG}	O_{tB}	O_{tW}	$O^{(3)}_{\varphi Q}$	$O^{(1)}_{\varphi Q}$	$O_{\varphi t}$	$O_{t\varphi}$	O_{4f}	O_G	$O_{\varphi G}$
$t \to bW \to bl^+\nu$	N		L	L				L		
$pp \to t\bar{q}$	N		L	L				L		
$pp \to tW$	L		L	L				N	N	N
$pp \to t\bar{t}$	L						N	L	L	L
$pp \to t\bar{t}\gamma$	L	L	L				N	L	L	L
$pp \to t\bar{t}Z$	L	L	L	L	L	L	N	L	L	L
$pp \to t\bar{t}h$	L						L	L	L	L
$gg \to H, H \to \gamma\gamma$	N						N			L

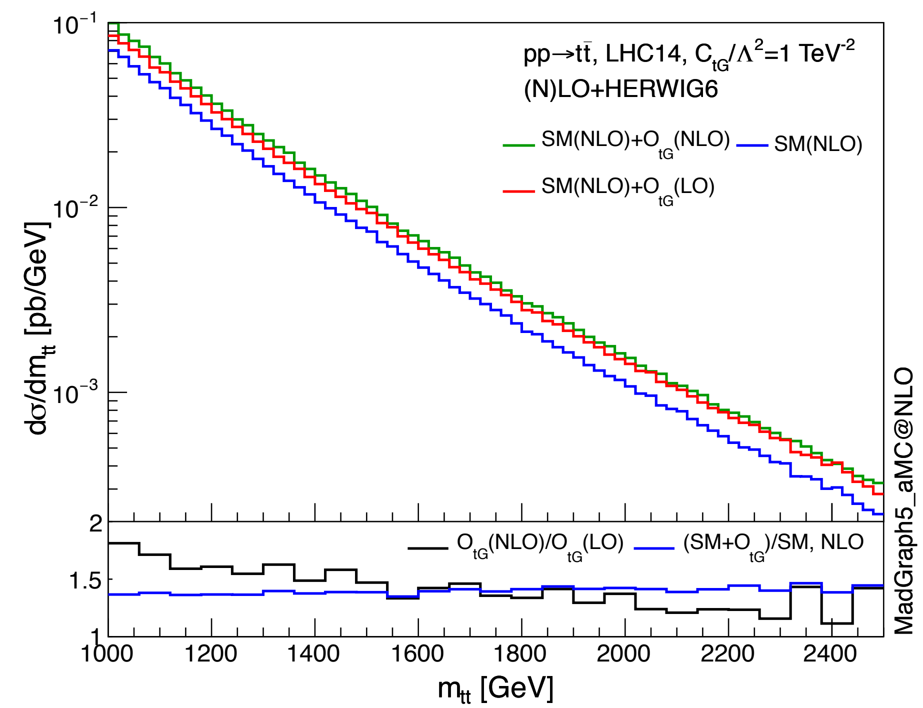
$O_G = g_s f^{ABC} G^{A\nu}_{\mu} G^{B\rho}_{\nu} G^{C\mu}_{\rho}$ and $O_{\varphi G} = g_s^2 \left(\varphi^\dagger \varphi\right) G^A_{\mu\nu} G^{A\mu\nu}$ are included because they mix with other top-quark operators and play a role in NLO calculations.

[Cen Zhang]

Bounding OtG at NLO from ttbar

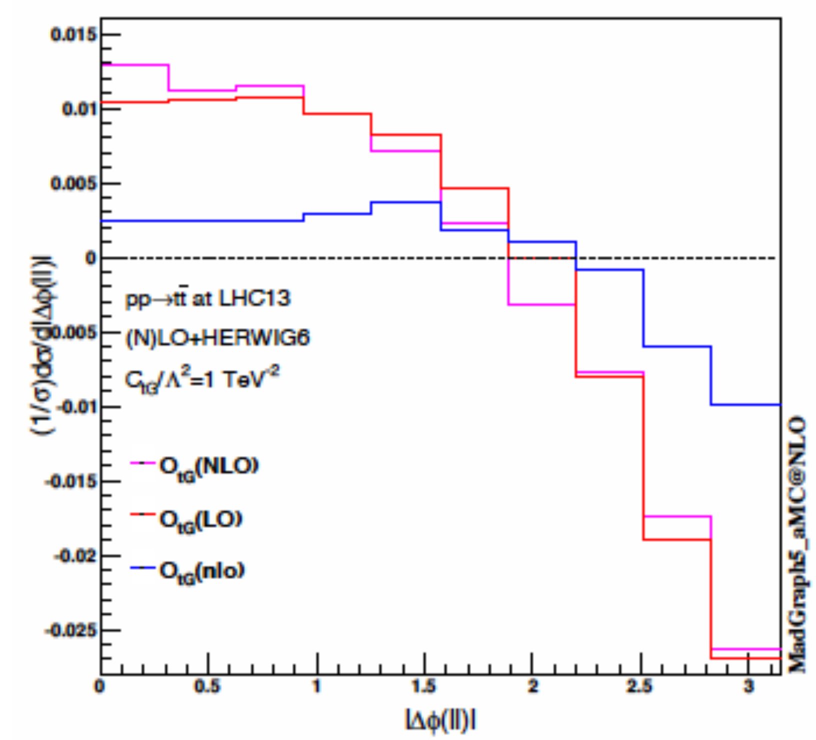
[Franzosi and Zhang, 2015]





Recent analysis at NLO in QCD

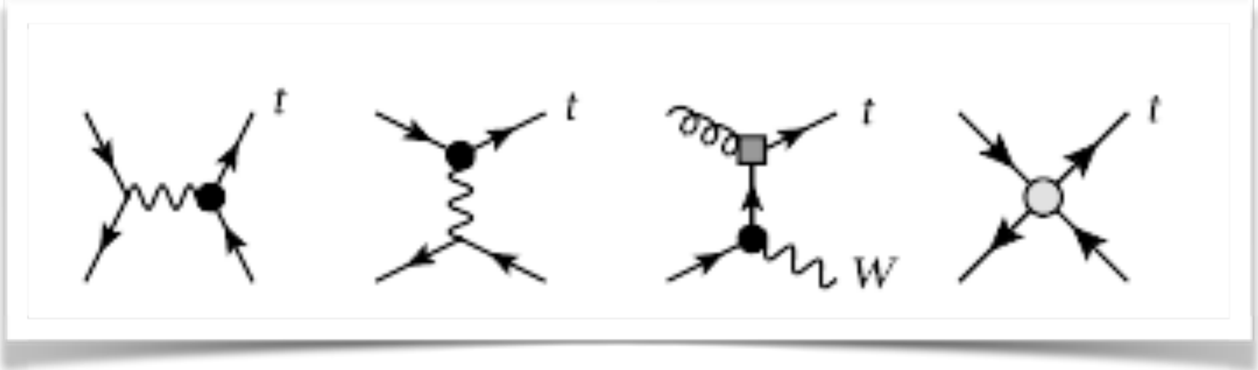
$$\sigma = \sigma_{\rm SM} + \frac{C_{tG}}{\Lambda^2}\beta_1 + \left(\frac{C_{tG}}{\Lambda^2}\right)^2 \beta_2$$



Limits on ctG from LHC8

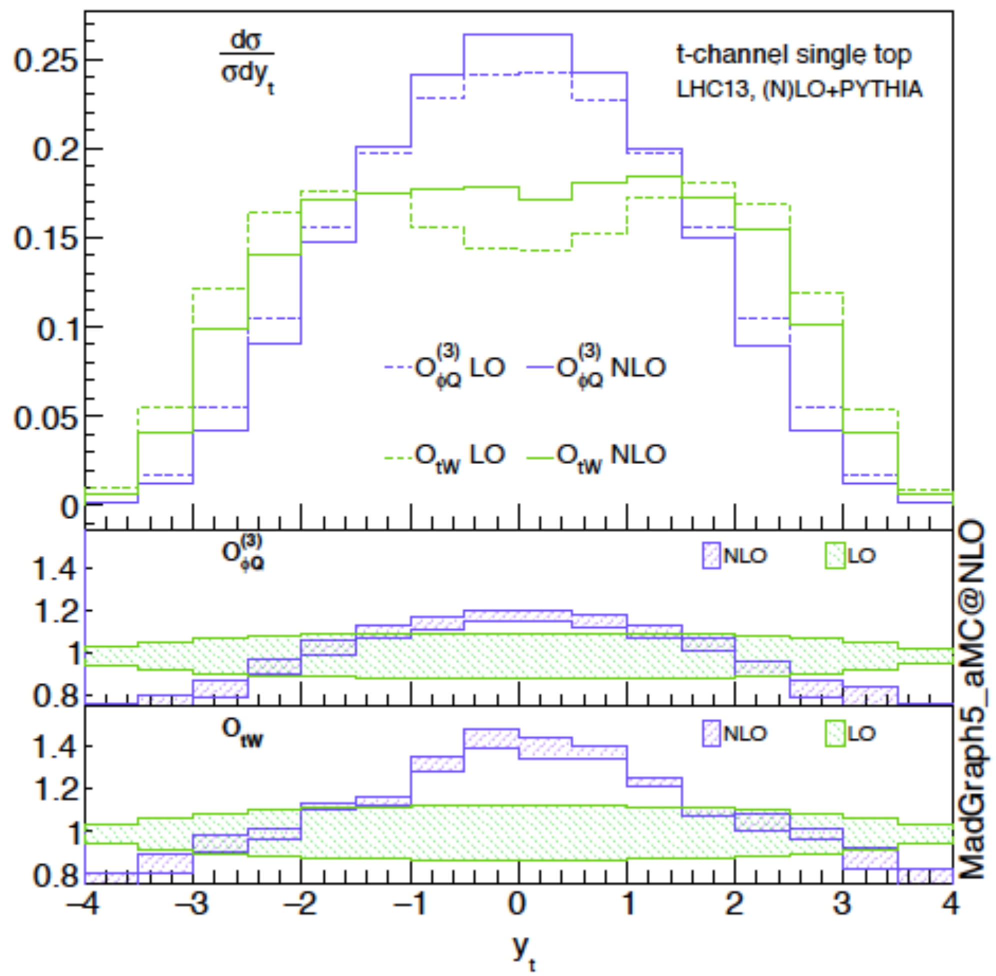
	LO [TeV^{-2}]	NLO [TeV^{-2}]
Tevatron	[-0.33, 0.75]	[-0.32, 0.73]
LHC8	[-0.56, 0.41]	[-0.42, 0.30]
LHC14	[-0.56, 0.61]	[-0.39, 0.43]

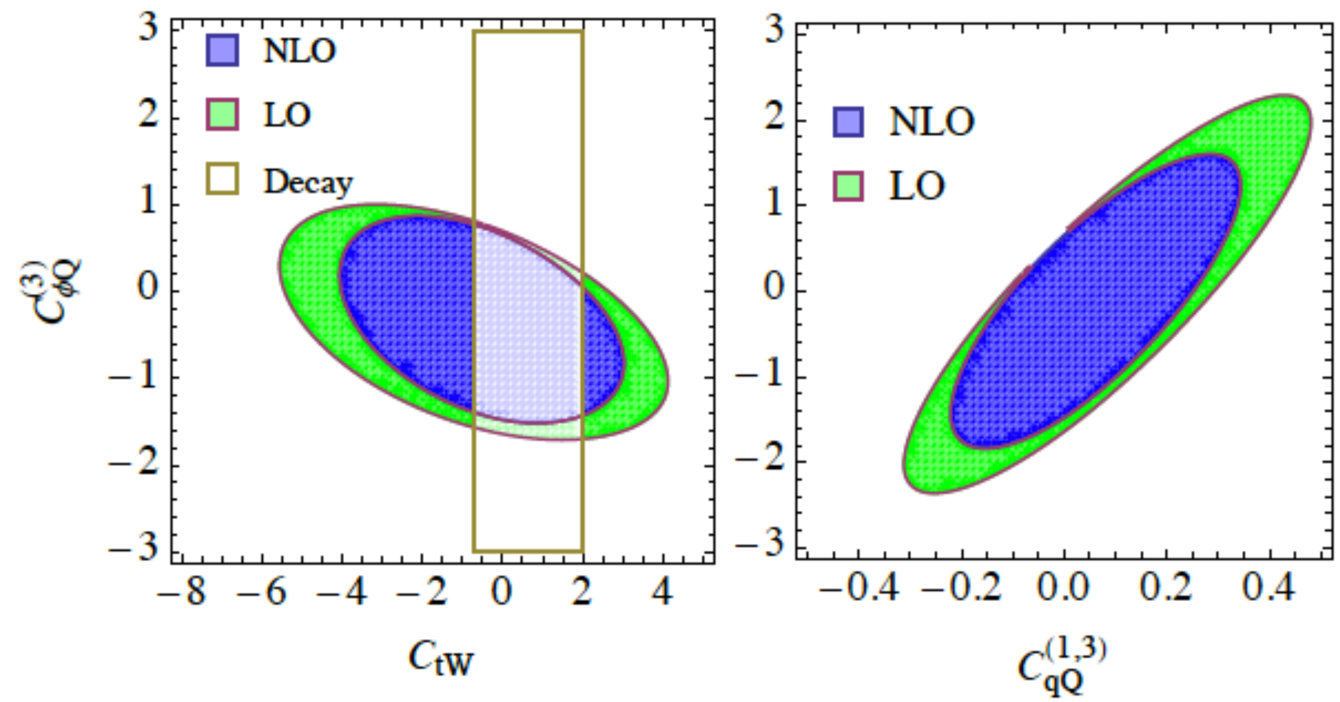
Single-top in the EFT at NLO



[Cen Zhang, 2016]

4F operator can also be included (on-going).





NLO corrections distort LO distributions, they impact the limits in accuracy and precision.

ttV in the EFT at NLO

[Bylund, FM, Tsinikos, Vryonidou, Zhang, 2016]

$$\sigma = \sigma_{SM} + \sum_i \frac{C_i}{(\Lambda/1\mathrm{TeV})^2}\sigma_i^{(1)} + \sum_{i<j} \frac{C_i C_j}{(\Lambda/1\mathrm{TeV})^4}\sigma_{ij}^{(2)}$$

13TeV	$\mathcal{O}_{tG}$	$\mathcal{O}_{\phi Q}^{(3)}$	$\mathcal{O}_{\phi t}$	$\mathcal{O}_{tW}$
$\sigma_{i,LO}^{(1)}$	$286.7^{+38.2\%}_{-25.5\%}$	$78.3^{+40.4\%}_{-26.6\%}$	$51.6^{+40.1\%}_{-26.4\%}$	$-0.20(3)^{+88.0\%}_{-230.0\%}$
$\sigma_{i,NLO}^{(1)}$	$310.5^{+5.4\%}_{-9.7\%}$	$90.6^{+7.1\%}_{-11.0\%}$	$57.5^{+5.8\%}_{-10.3\%}$	$-1.7(2)^{+31.3\%}_{-49.1\%}$
K-factor	1.08	1.16	1.11	8.5
$\sigma_{ii,LO}^{(2)}$	$258.5^{+49.7\%}_{-30.4\%}$	$2.8(1)^{+39.7\%}_{-26.9\%}$	$2.9(1)^{+39.7\%}_{-26.7\%}$	$20.9^{+44.3\%}_{-28.3\%}$
$\sigma_{ii,NLO}^{(2)}$	$244.5^{+4.2\%}_{-8.1\%}$	$3.8(3)^{+13.2\%}_{-14.4\%}$	$3.9(3)^{+13.8\%}_{-14.6\%}$	$24.2^{+6.2\%}_{-11.2\%}$

$$O_{\varphi Q}^{(3)} = i\frac{1}{2}y_t^2\left(\varphi^\dagger \overleftrightarrow{D}^I_\mu \varphi\right)(\bar{Q}\gamma^\mu \tau^I Q)$$

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$$O_{tG} = y_t g_s(\bar{Q}\sigma^{\mu\nu}T^A t)\tilde{\varphi}G^A_{\mu\nu},$$

Small contribution from OtW and OtB at $O(1/\Lambda^2)$ but large at $O(1/\Lambda^4)$

How should we treat $O(1/\Lambda^4)$ terms?

$$C_i^2\frac{E^4}{\Lambda^4} > C_i\frac{E^2}{\Lambda^2} > 1 > \frac{E^2}{\Lambda^2}$$

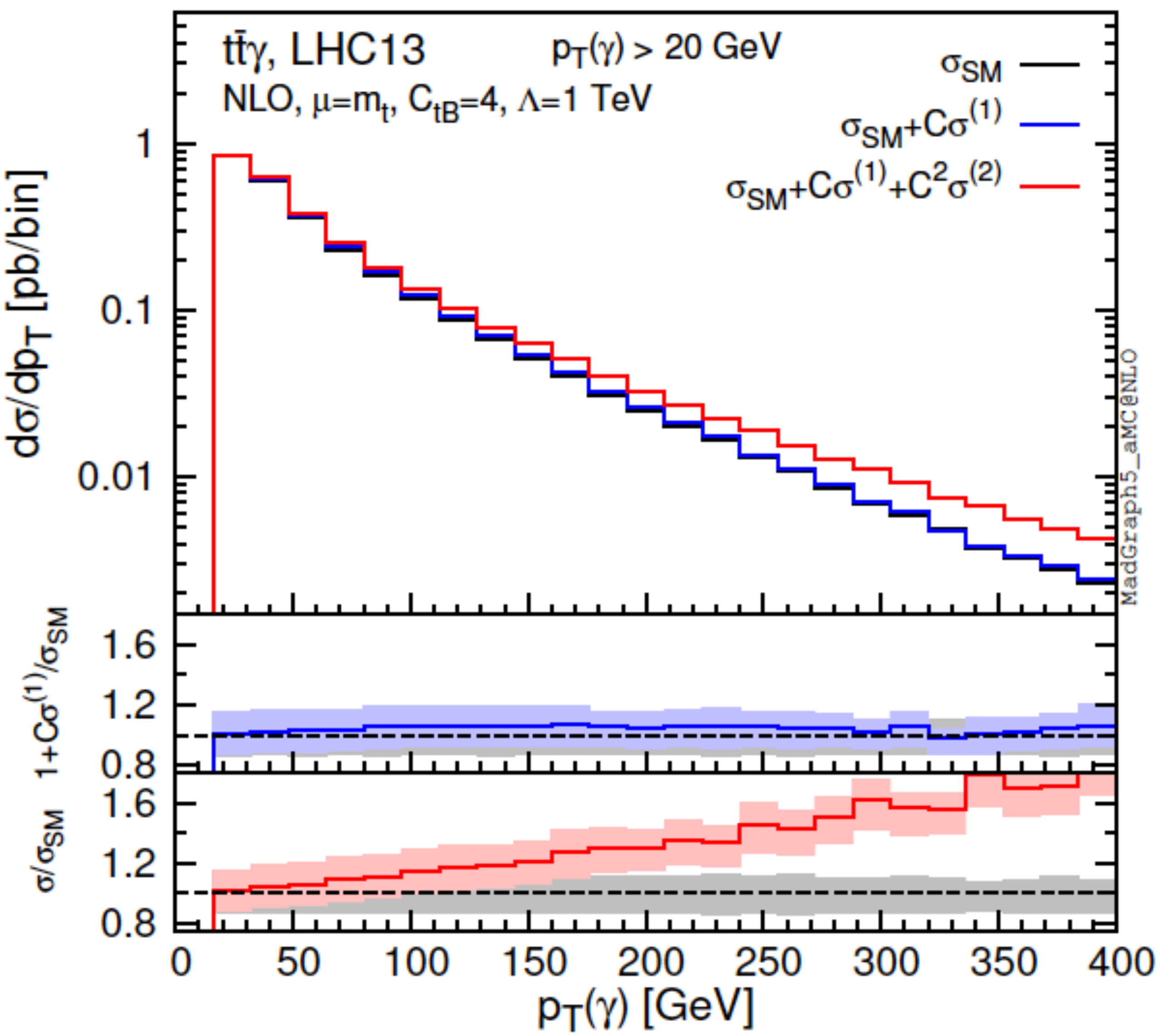
EFT condition satisfied (see Sasha's intro to EFT)

$$\gamma = \frac{2\alpha_s}{\pi}\begin{pmatrix} \frac{1}{6} & 0 & 0 \\ \frac{1}{3} & \frac{1}{3} & 0 \\ \frac{5}{9} & 0 & \frac{1}{3} \end{pmatrix}$$

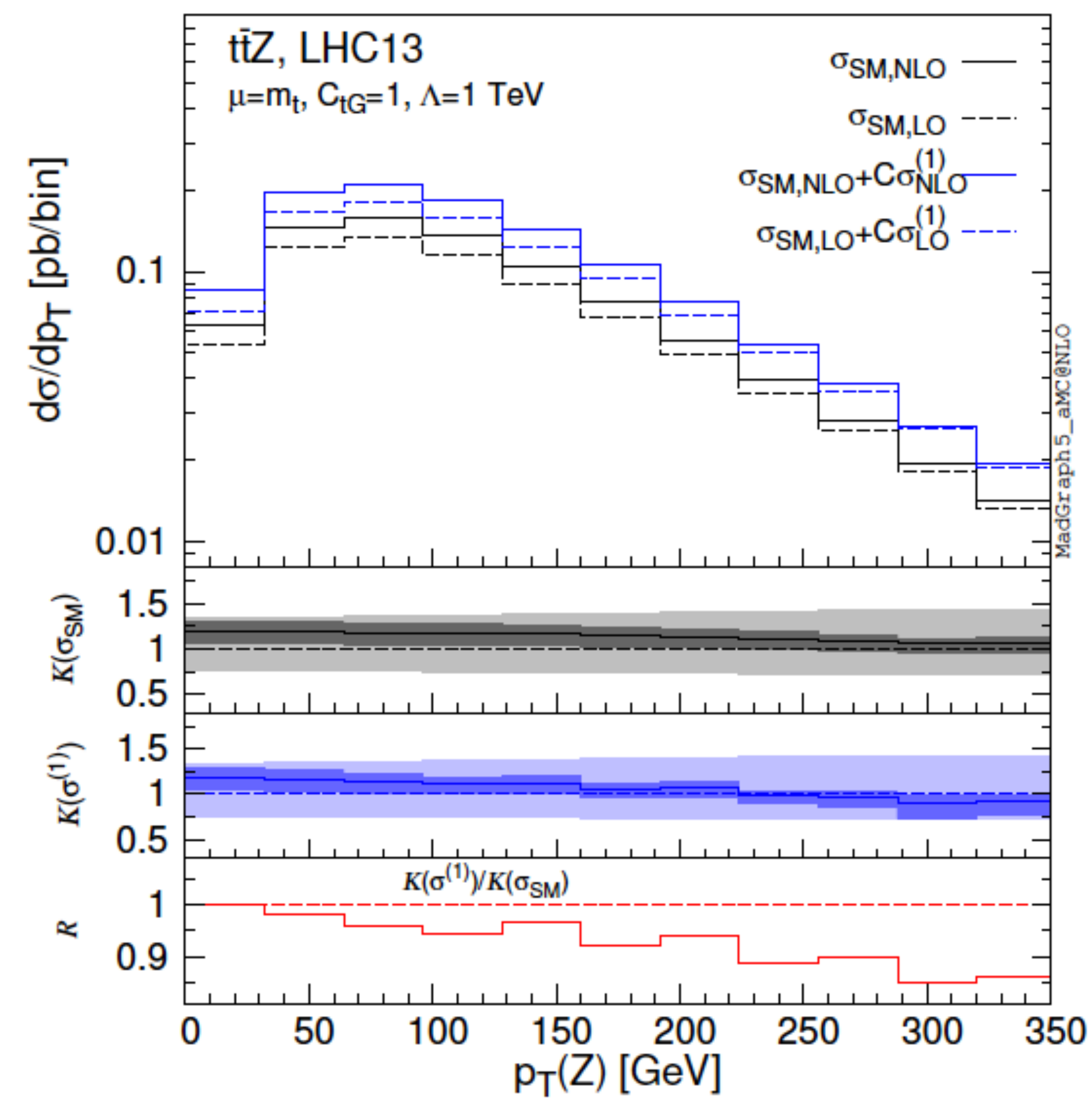
Anom. dim. matrix: O_{tW}, O_{tB}, O_{tG}

ttV in the EFT at NLO

[Bylund, FM, Tsinikos, Vryonidou, Zhang, 2016]



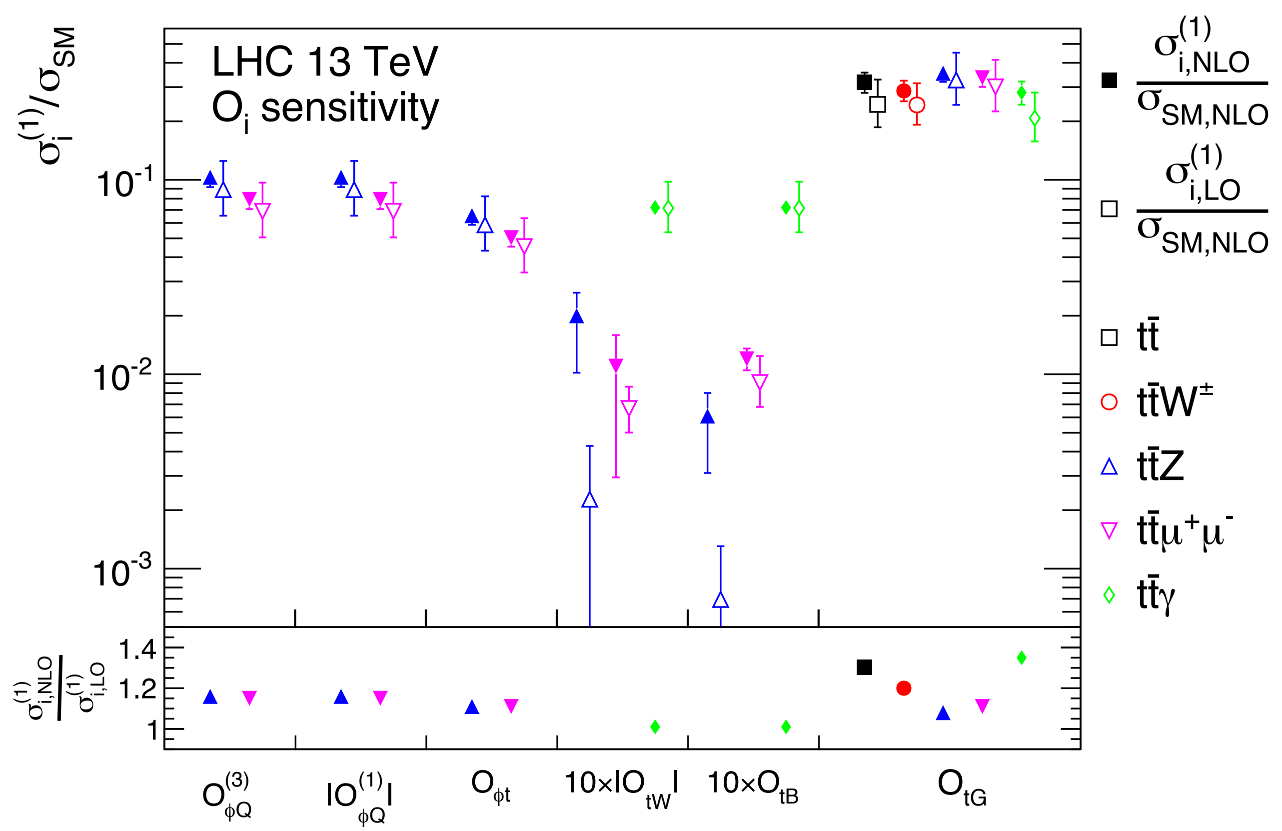
Large contribution at $O(1/\Lambda^4)$ rising with energy

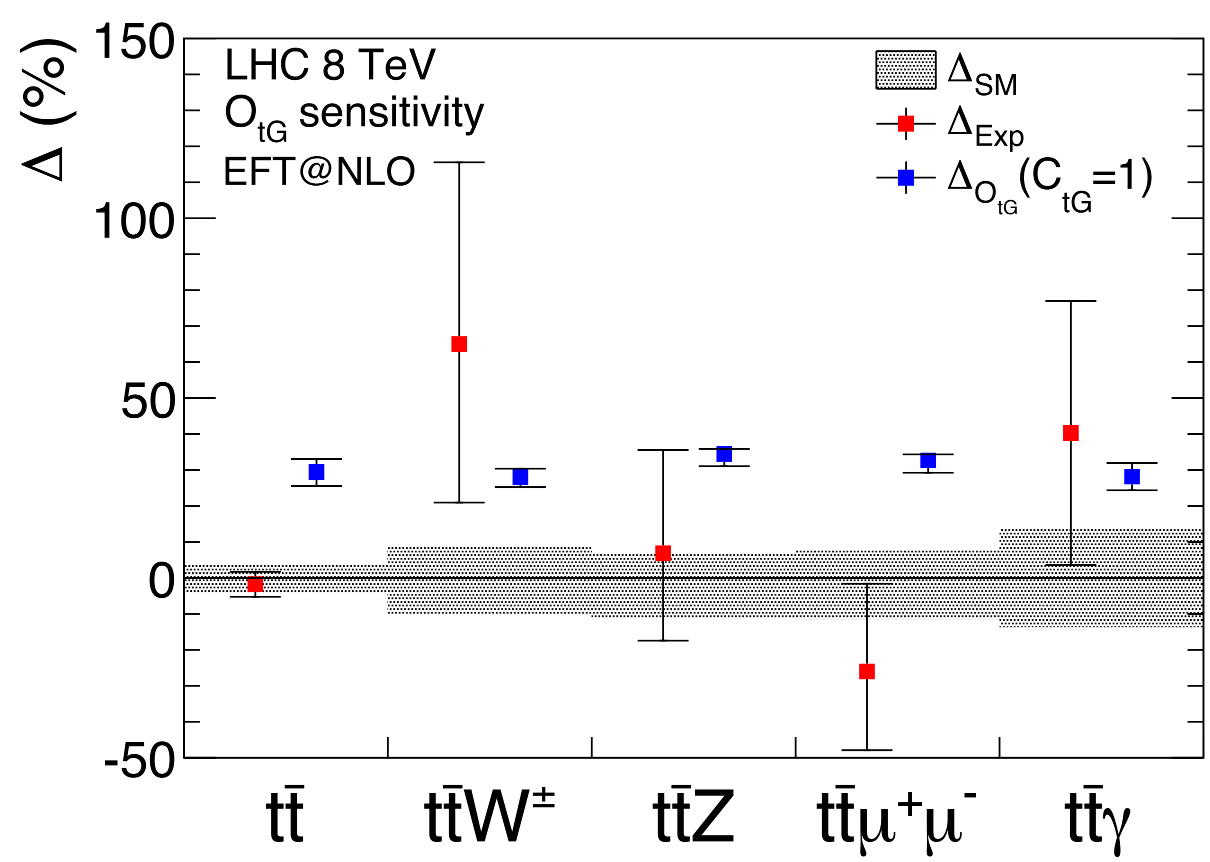


Using SM k-factors is not enough

ttV in the EFT at NLO

[Bylund, FM, Tsinikos, Vryonidou, Zhang, 2016]





Chromomagnetic operator affecting all processes in the same way.

LHC measurements of ttV processes can set constraints on the Wilson coefficients See also: [Rontsch and Schulze et al. 2014, 2015] and [Schulze 2016] in the anomalous coupling framework.

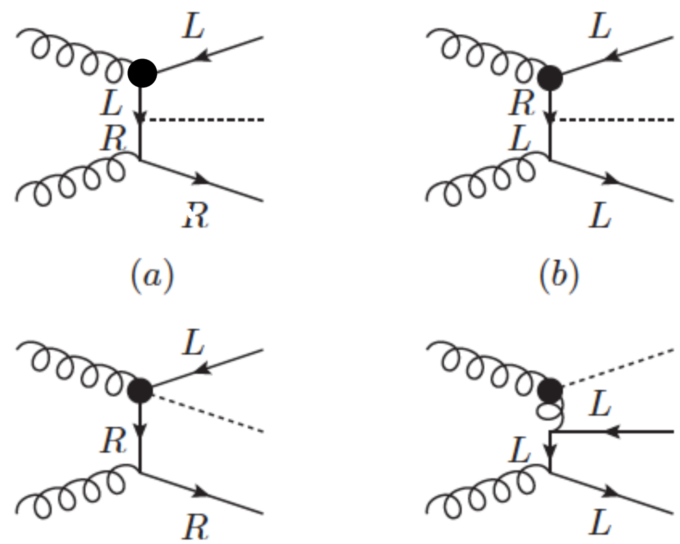
Top-Higgs interactions

[FM, Vryonidou, Zhang, 2016]

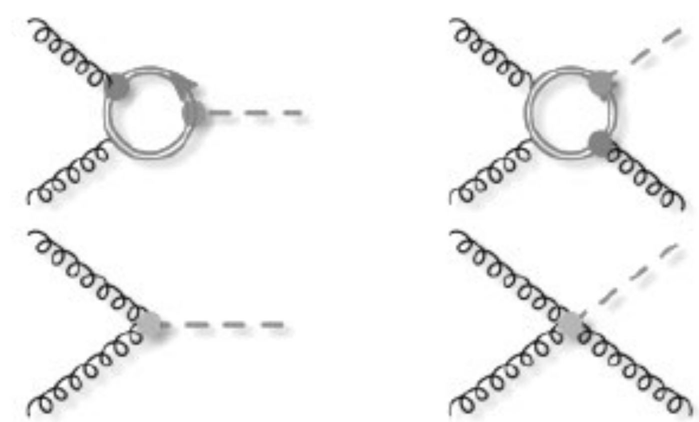
$$O_{t\phi} = y_t^3 \left(\phi^\dagger \phi\right) \left(\bar{Q} t\right) \tilde{\phi}$$

$$O_{\phi G} = y_t^2 \left(\phi^\dagger \phi\right) G^A_{\mu\nu} G^{A\mu\nu}$$

$$O_{tG} = y_t g_s (\bar{Q} \sigma^{\mu\nu} T^A t) \tilde{\phi} G^A_{\mu\nu}$$



ttH



H, H+j

$$\gamma = \frac{2\alpha_s}{\pi} \begin{pmatrix} \frac{1}{6} & 0 & 0 \\ 4 & -1 & 4 \\ \frac{1}{4} & 0 & -\frac{7}{4} \end{pmatrix}$$

See also
[Degrande et al. 2012]
[Grojean et al. 2013]

Use with 1) ttH and 2) H+j to break degeneracy between operators and extract maximal information

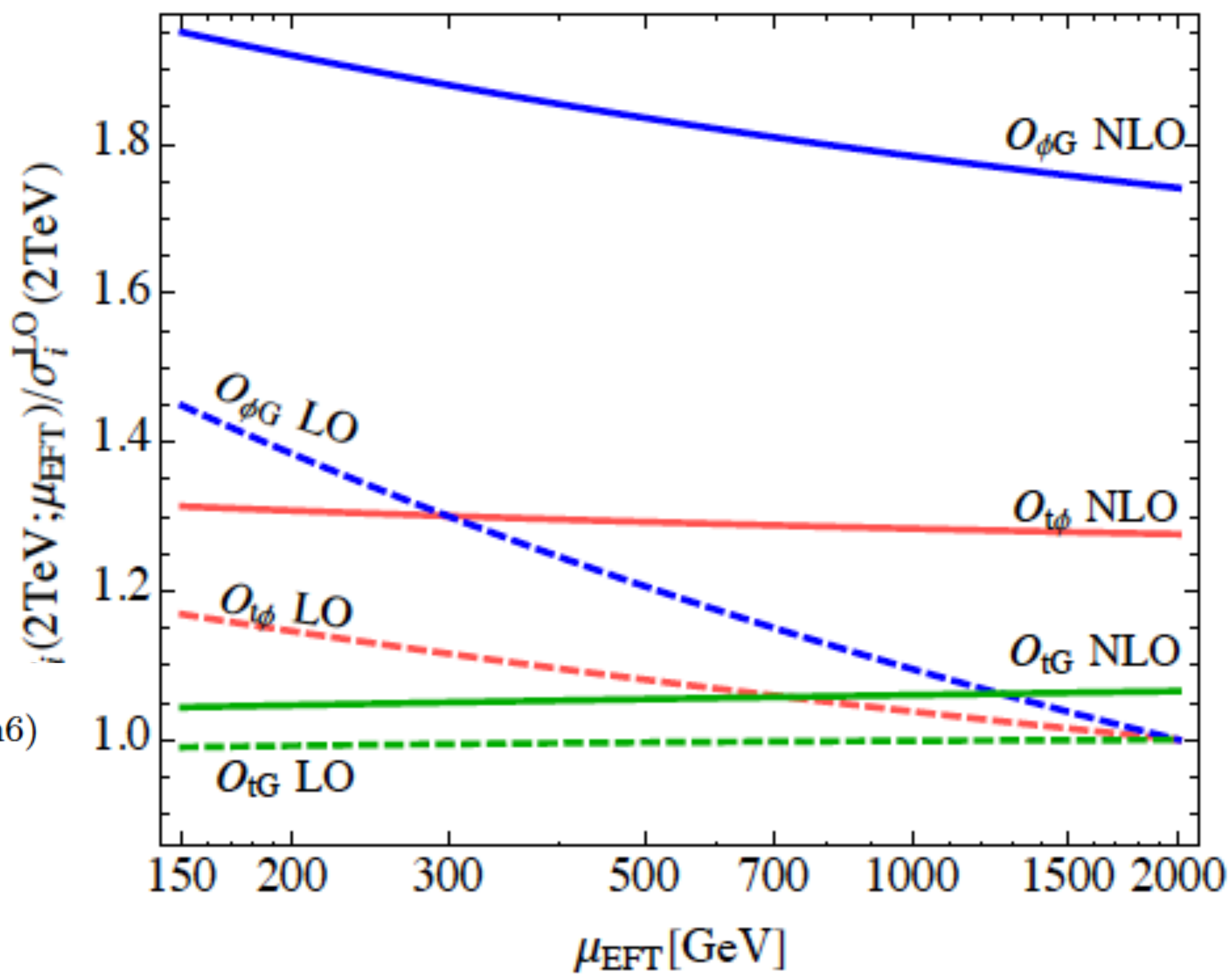
Top-Higgs at NLO

[FM, Vryonidou, Zhang, 2016]

13 TeV	σ NLO	K
σ_{SM}	$0.507^{+0.030+0.000+0.007}_{-0.048-0.000-0.008}$	1.09
$\sigma_{t\phi}$	$-0.062^{+0.006+0.001+0.001}_{-0.004-0.001-0.001}$	1.13
$\sigma_{\phi G}$	$0.872^{+0.131+0.037+0.013}_{-0.123-0.035-0.016}$	1.39
σ_{tG}	$0.503^{+0.025+0.001+0.007}_{-0.046-0.003-0.008}$	1.07
$\sigma_{t\phi,t\phi}$	$0.0019^{+0.0001+0.0001+0.0000}_{-0.0002-0.0000-0.0000}$	1.17
$\sigma_{\phi G,\phi G}$	$1.021^{+0.204+0.096+0.024}_{-0.178-0.085-0.029}$	1.58
$\sigma_{tG,tG}$	$0.674^{+0.036+0.004+0.016}_{-0.067-0.007-0.019}$	1.04
$\sigma_{t\phi,\phi G}$	$-0.053^{+0.008+0.003+0.001}_{-0.008-0.004-0.001}$	1.42
$\sigma_{t\phi,tG}$	$-0.031^{+0.003+0.000+0.000}_{-0.002-0.000-0.000}$	1.10
$\sigma_{\phi G,tG}$	$0.859^{+0.127+0.021+0.017}_{-0.126-0.020-0.022}$	1.37

First systematic study of uncertainties:

- Scale and PDF uncertainties
- EFT scale uncertainties

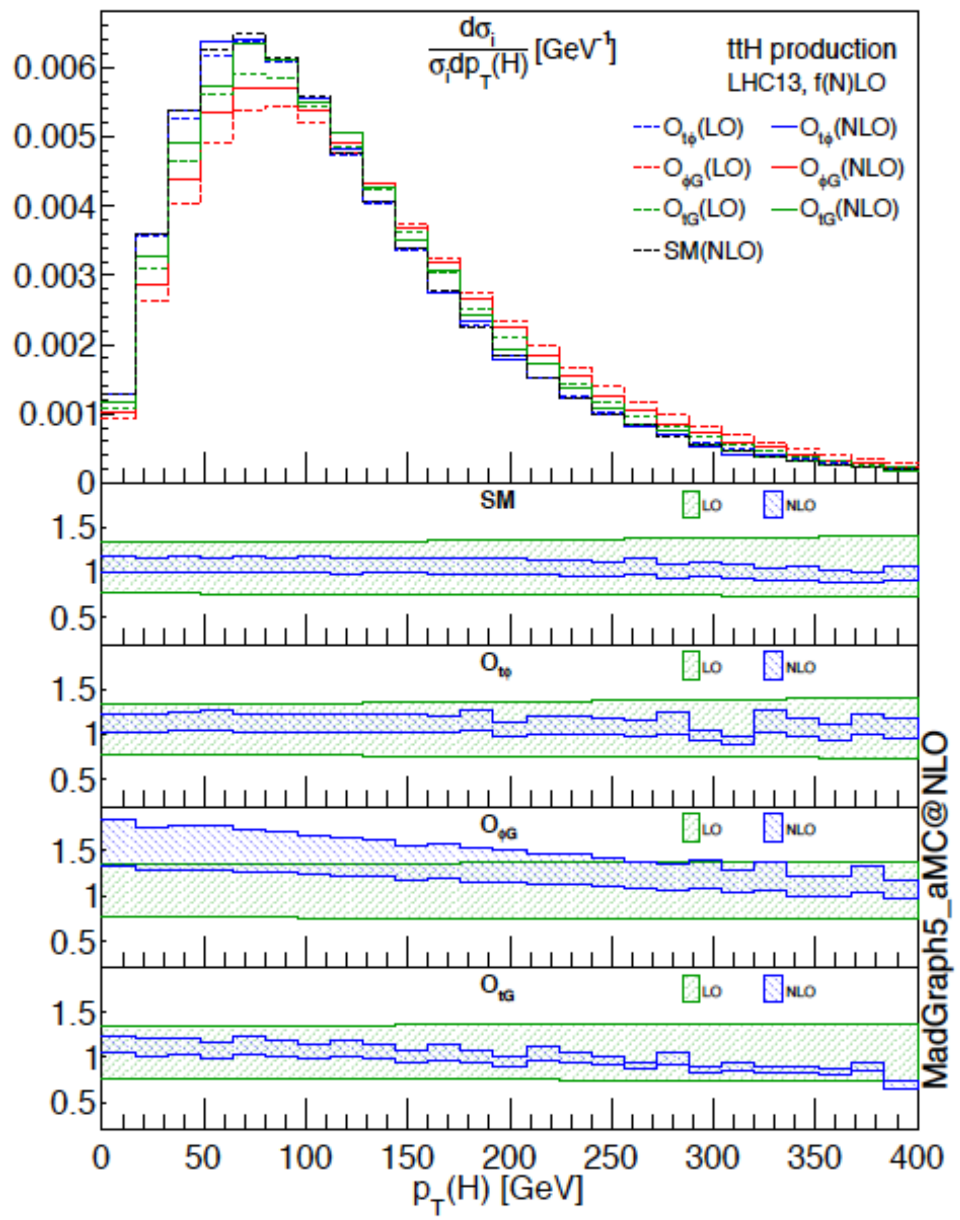


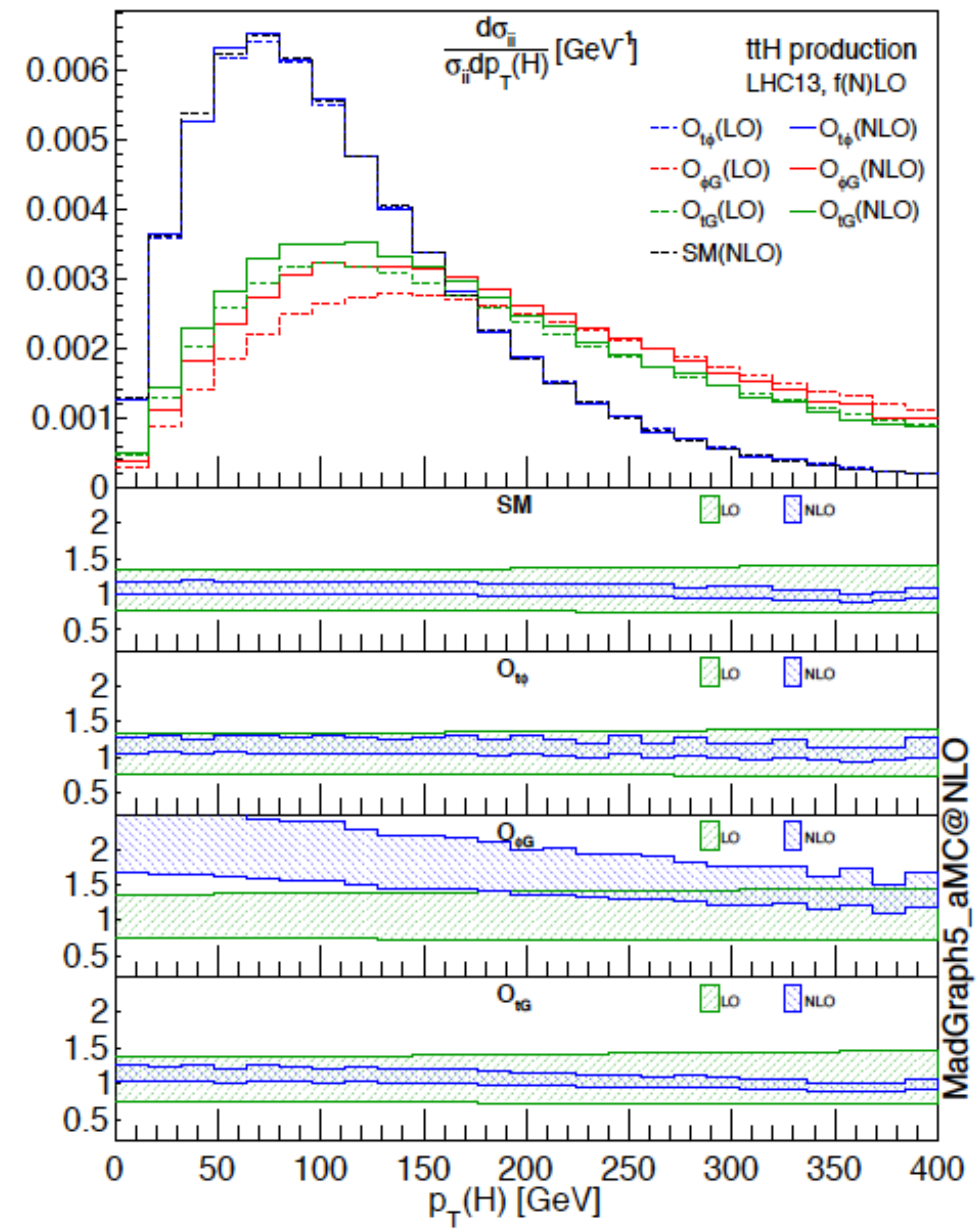
- Missing higher order terms in $1/\Lambda$ expansion: squared terms computed

$$\sigma = \sigma_{SM} + \sum_i \frac{C_i^{\rm dim6}}{(\Lambda/1{\rm TeV})^2}\sigma_i^{\rm (dim6)} + \sum_{i\le j} \frac{C_i^{\rm dim6}C_j^{\rm dim6}}{(\Lambda/1{\rm TeV})^4}\sigma_{ij}^{\rm (dim6)} + \sum_i \frac{C_i^{\rm dim8}}{(\Lambda/1{\rm TeV})^4}\sigma_i^{\rm (dim8)} + \mathcal{O}(\Lambda^{-6})\ .$$

Differential distributions for ttH

[FM,Vryonidou, Zhang, 2016]





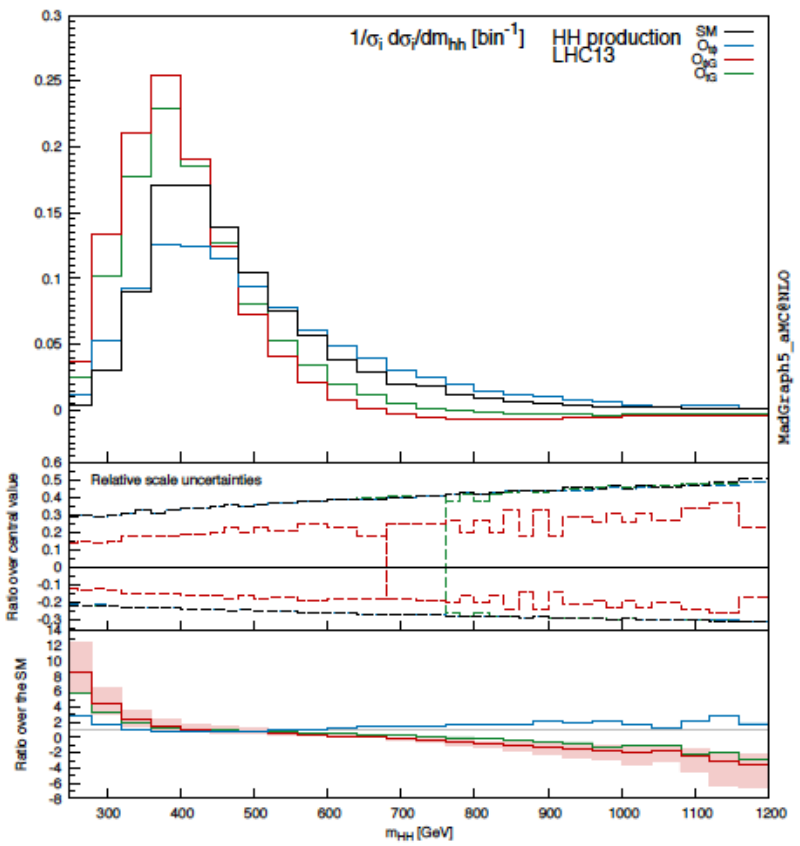
NLO: smaller uncertainties, non-flat K-factors

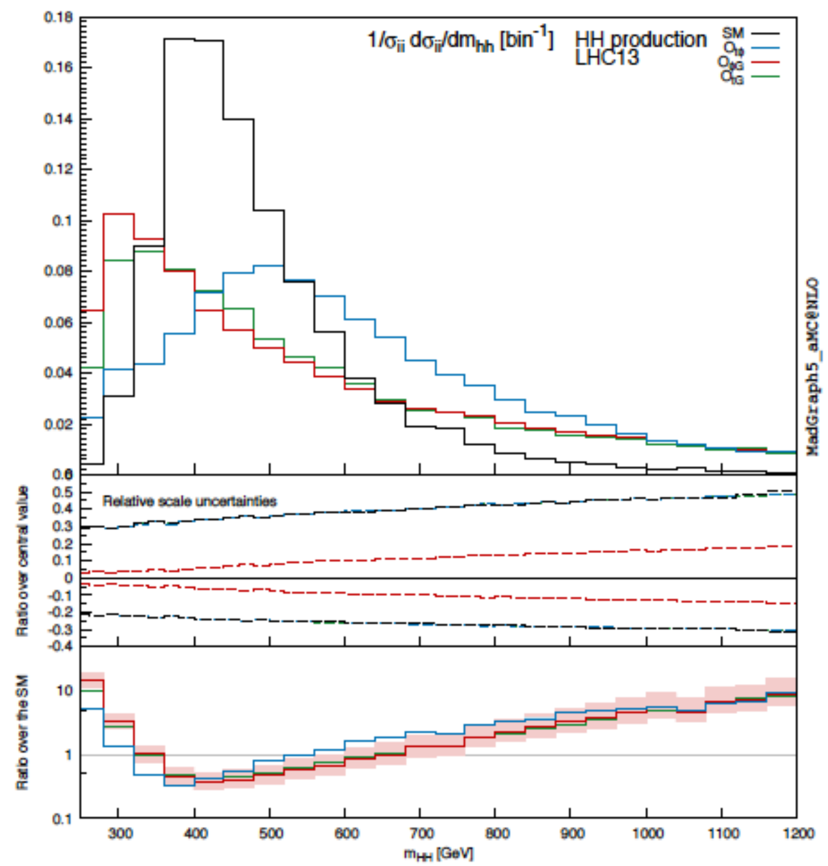
Different shapes for different operators for the squared terms

HH in the EFT

[FM,Vryonidou, Zhang, 2016]

Contribution of the chromomagnetic operator to HH computed for the first time



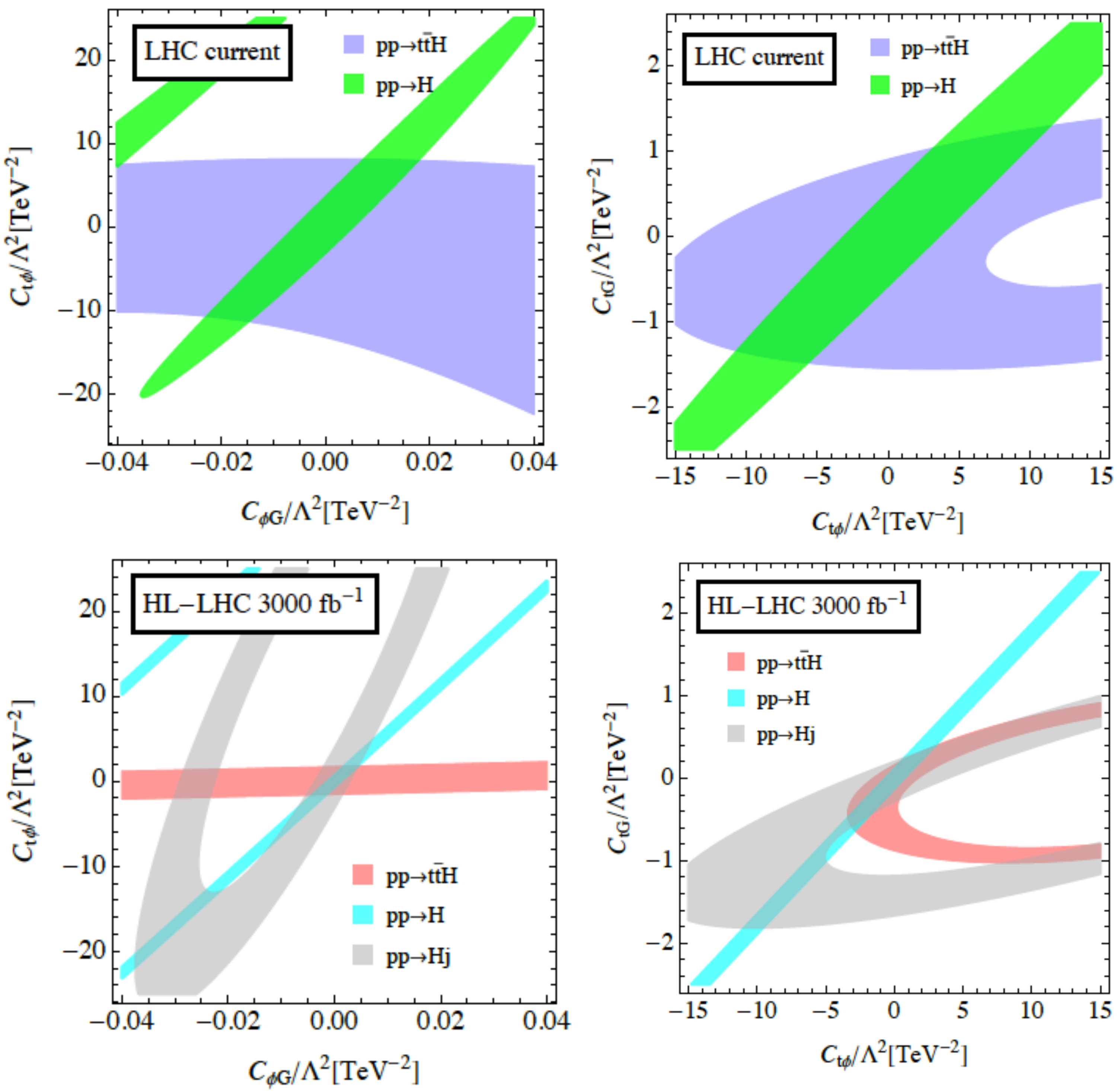


13 TeV	σ/σ_{SM} LO
σ_{SM}	$1.000^{+0.000+0.000}_{-0.000-0.000}$
$\sigma_{t\phi}$	$0.227^{+0.00114+0.0116}_{-0.000918-0.0101}$
$\sigma_{\phi G}$	$-47.3^{+6.18+3.707}_{-6.14-4.42}$
σ_{tG}	$-1.356^{+0.0271+0.161}_{-0.0225-0.051}$
$\sigma_{t\phi,t\phi}$	$0.0293^{+0.000727+0.0031}_{-0.000584-0.0026}$
$\sigma_{\phi G,\phi G}$	$2856.2^{+743.3+552}_{-628.5-425}$
$\sigma_{tG,tG}$	$1.940^{+0.0650+0.198}_{-0.0477-0.493}$
$\sigma_{t\phi,\phi G}$	$-11.83^{+1.39+1.42}_{-1.41-1.77}$
$\sigma_{t\phi,tG}$	$-0.340^{+0.000238+0.064}_{-0.000438-0.047}$
$\sigma_{\phi G,tG}$	$147.5^{+20.83+20.7}_{-18.86-31.4}$

To be investigated: the impact of the chromomagnetic operator in EFT analyses that focus on the extraction of the triple Higgs coupling λ (e.g. arXiv:1502.00539 and arXiv:1410.3471)

Constraints from ttH and Higgs production

[FM, Vryonidou, Zhang, 2016]



Current limits using LHC measurements

$$O_{t\phi} = y_t^3 \left(\phi^\dagger\phi\right)\left(\bar{Q}t\right)\tilde{\phi}$$
$$O_{\phi G} = y_t^2 \left(\phi^\dagger\phi\right) G^A_{\mu\nu} G^{A\mu\nu}$$
$$O_{tG} = y_t g_s (\bar{Q}\sigma^{\mu\nu} T^A t)\tilde{\phi} G^A_{\mu\nu}$$

14TeV projection

3000 fb-1

Constraints from ttH and Higgs production

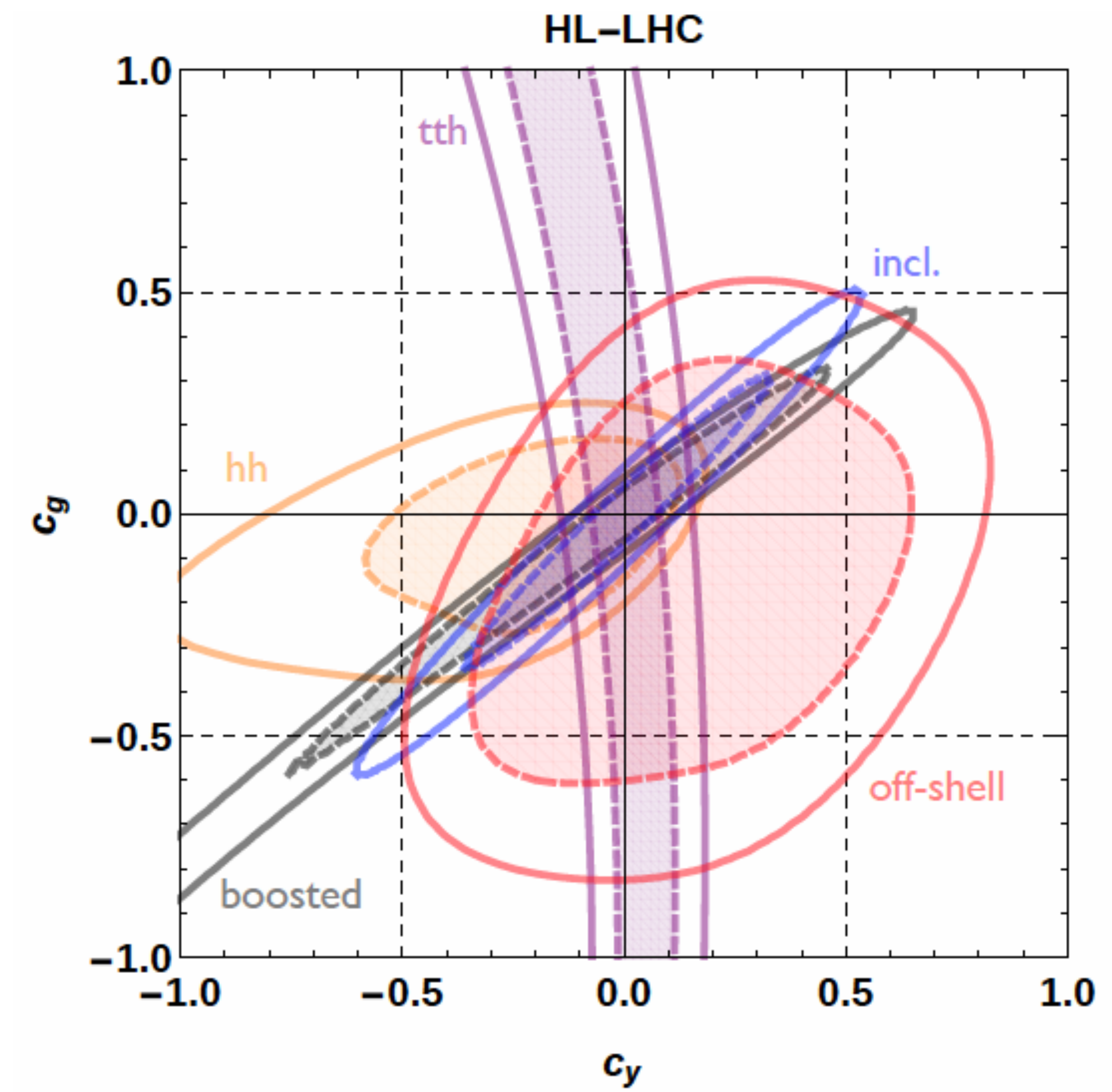
[Azatov et al, 2016]

$$O_{t\phi} = y_t^3 \left(\phi^\dagger \phi\right) \left(\bar{Q} t\right) \tilde{\phi}$$

$$O_{\phi G} = y_t^2 \left(\phi^\dagger \phi\right) G^A_{\mu\nu} G^{A\mu\nu}$$

Combination:

- inclusive H
- boosted Higgs
- ttH
- HH
- off-shell Higgs



Conclusions

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- The discovery of a scalar boson has opened a new realm of possibilities for searching new physics, especially connected to the top quark.

- The most beaten paths for searching new physics at the LHC involve top-down (or simplified models) approach to detecting new resonances.

A complementary and far reaching approach is that of searching for new interactions employing an EFT.

- The EFT approach provides a consistent QFT to work with. Predictions can be obtained and systematically improved. To be fully meaningful and useful, predictions have to be available at NLO accuracy in QCD (and EW) and constraints need to be obtained in a global way.

- TH results and MC tools to put in action this strategy and first results becoming available.

Credits and further reading

This talk is based on material extracted from papers and notes (which are hyper ref to the corresponding documents on the web) and from a selection of recent (and less recent) talks given by colleagues.

For the EFT top, major contributions come from **Cen Zhang**'s and **Eleni Vryonidou**'s talks (see for example the **HP2** agenda).

Please have a look at the recent talks given at **TOP2016**, in particular those of **Thursday**. If interested on the general picture, start with

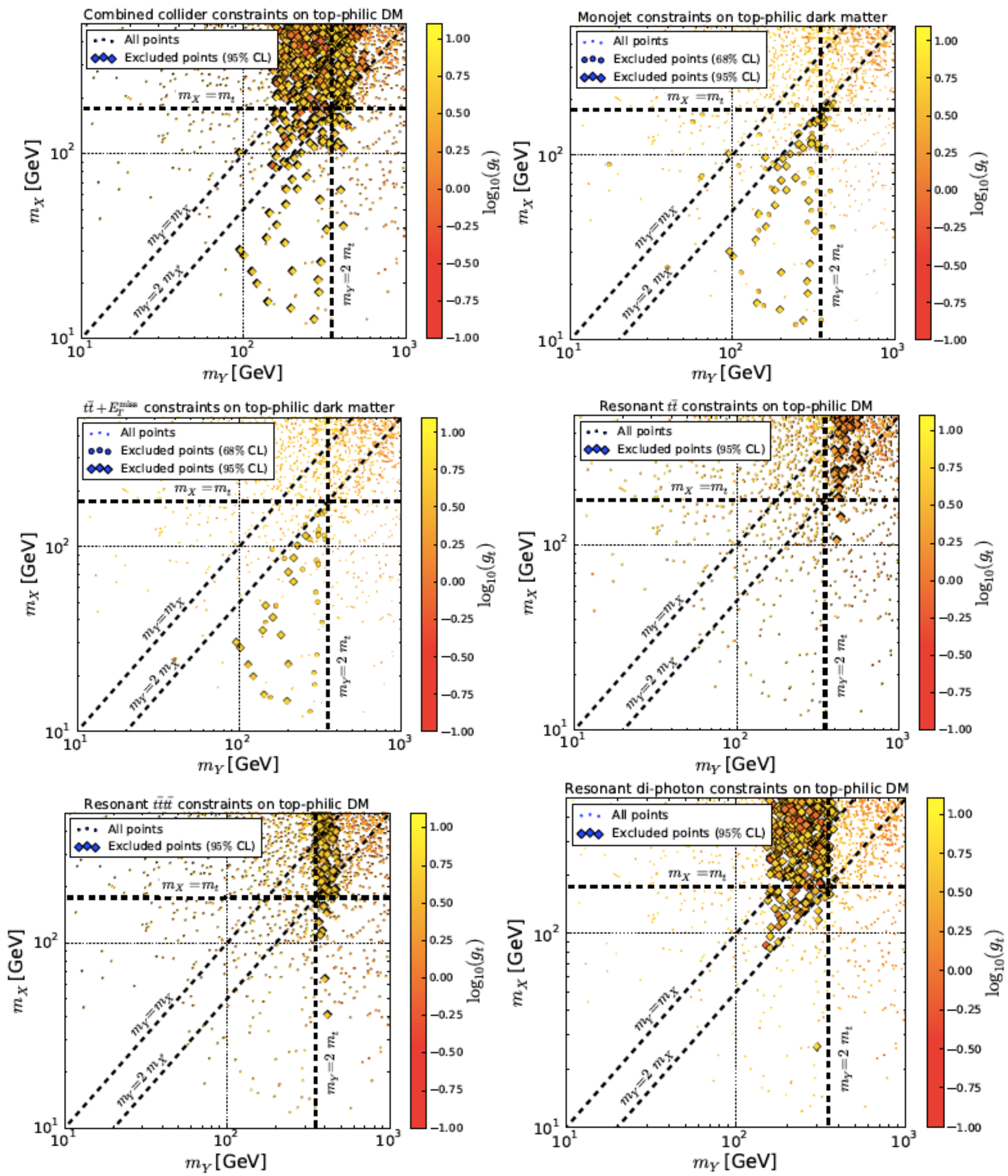
* The **Keynote** by **Andi Weiler**, which gives a very stimulating overview on top physics through the eyes of a BSM specialist.

* **Top and Naturalness**, by **Matthew Maccullough**, a compact and illuminating review on the BSM scenarios that naturalness lead to, including a discussion on the new proposal on Hyperfolded SUSY with an electrically charged -4/3 scalar partner of the top.

and then go to the more dedicated talks, such as:

* **Top physics and BSM**, by **Roberto Franceschini**, which contains a thorough discussion on the stop searches in the funnels and points to possible new directions.

* **Global approach to top flavour violation**, by **Gauthier Durieux**. A very rich and promising activity from TH and EXP point of views, which unfortunately, I had no time to cover.

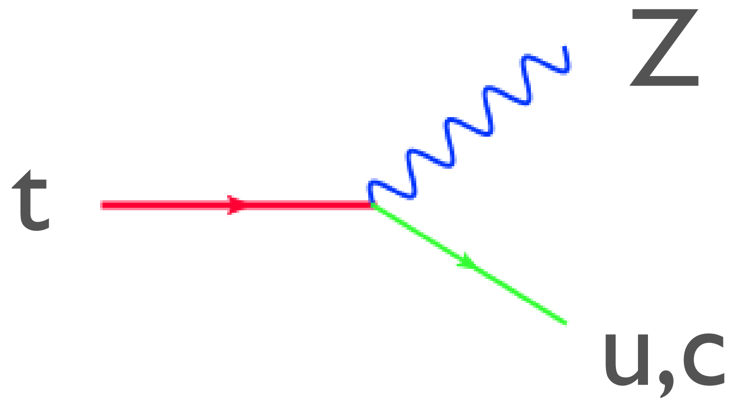


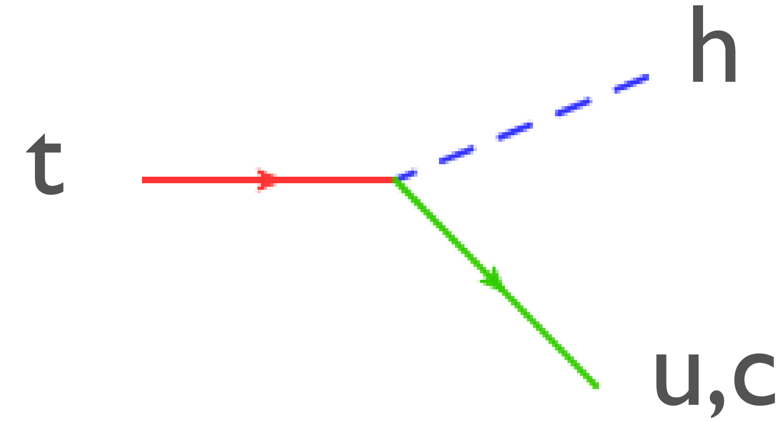
Combined collider constraints on top-philic DM
All points
Excluded points (95% CL)
Monojet constraints on top-philic dark matter
All points
Excluded points (68% CL)
Excluded points (95% CL)
$t\bar{t}+E_T^{miss}$ constraints on top-philic dark matter
All points
Excluded points (68% CL)
Excluded points (95% CL)
Resonant $t\bar{t}$ constraints on top-philic DM
All points
Excluded points (95% CL)
Resonant $t\bar{t}t\bar{t}$ constraints on top-philic DM
All points
Excluded points (95% CL)
Resonant di-photon constraints on top-philic DM
All points
Excluded points (95% CL)
$m_X = m_t$
$m_Y = m_X$
$m_Y = 2\ m_X$
$m_Y = 2\ m_t$
m_X [GeV]
m_Y [GeV]
$\log_{10}(g_t)$

Top-quark FCNC

The study of FCNC couplings can bring new information:

[Kao et al. 2011 , Kai-Feng et al 2013] [Zhang FM, 2013]





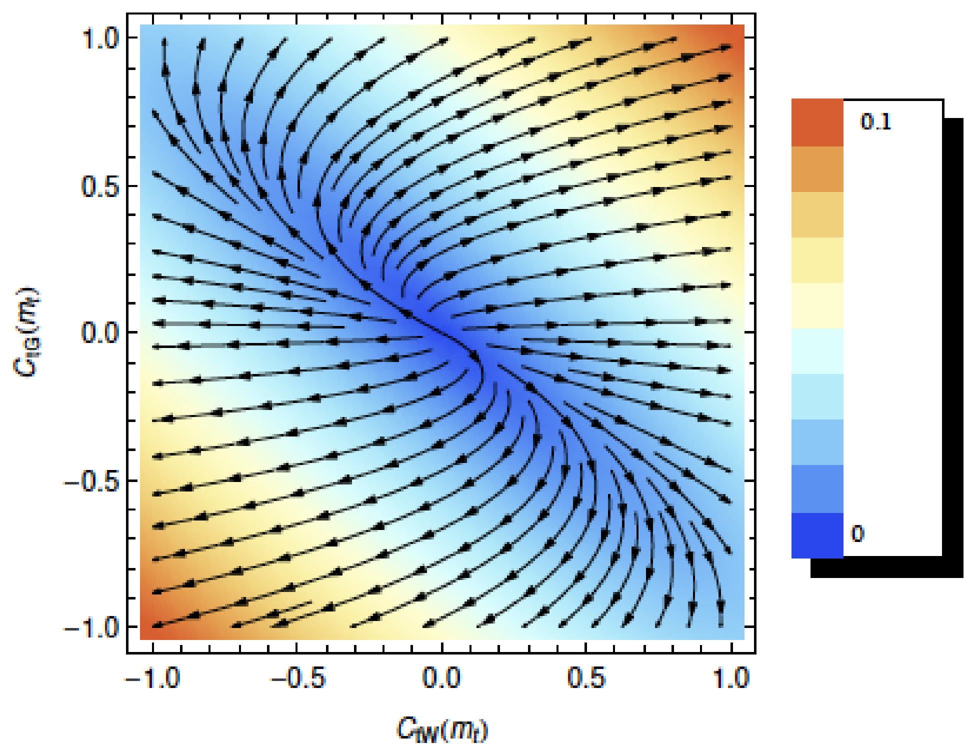
While the exp searches are completely different, one has to remember that the decay rates will depend on several operators that are linked by gauge symmetry. For example:

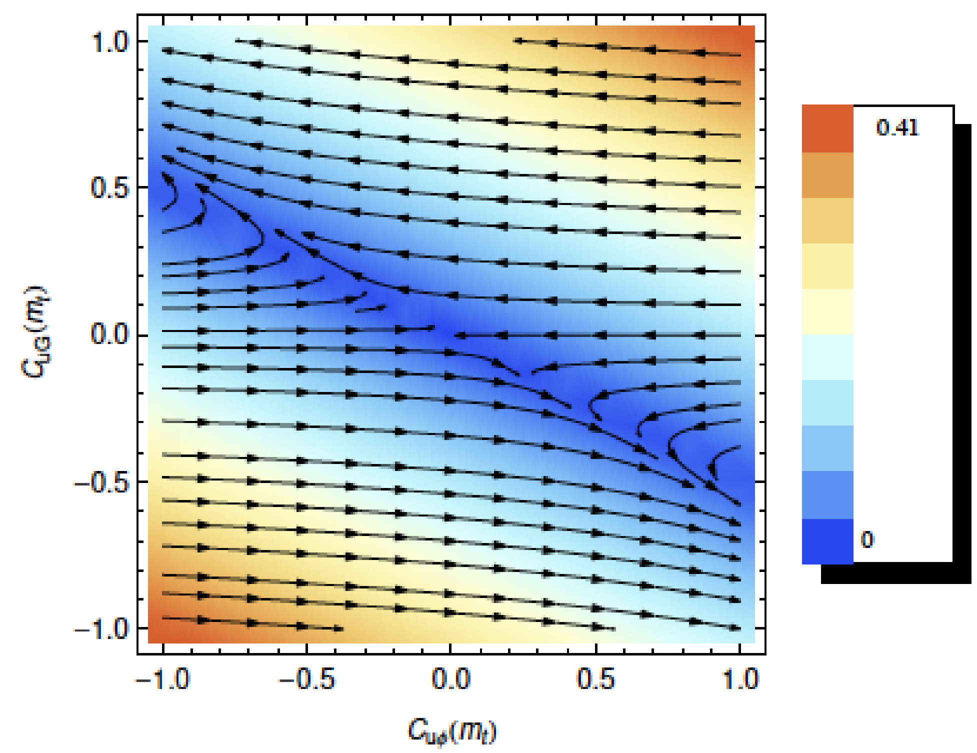
$$O_{uB}^{(13)} = y_t g_Y (\bar{q}\sigma^{\mu\nu}t)\tilde{\varphi}B_{\mu\nu}$$
$$O_{uW}^{(13)} = y_t g_W (\bar{q}\sigma^{\mu\nu}\tau^I t)\tilde{\varphi}W_{\mu\nu}^I$$
$$O_{uG}^{(13)} = y_t g_s (\bar{q}\sigma^{\mu\nu}T^A t)\tilde{\varphi}G_{\mu\nu}^A$$
$$O_{u\varphi}^{(13)} = -y_t^3 (\varphi^\dagger\varphi)(\bar{q}t)\tilde{\varphi}$$

$$\gamma = \frac{2\alpha_s}{\pi}\begin{pmatrix} \frac{1}{6} & 0 & 0 & 0 \\ \frac{1}{3} & \frac{1}{3} & 0 & 0 \\ \frac{5}{9} & 0 & \frac{1}{3} & 0 \\ -2 & 0 & 0 & -1 \end{pmatrix}$$

Top FCNC at NLO

[Durieux, FM, Zhang 2014]





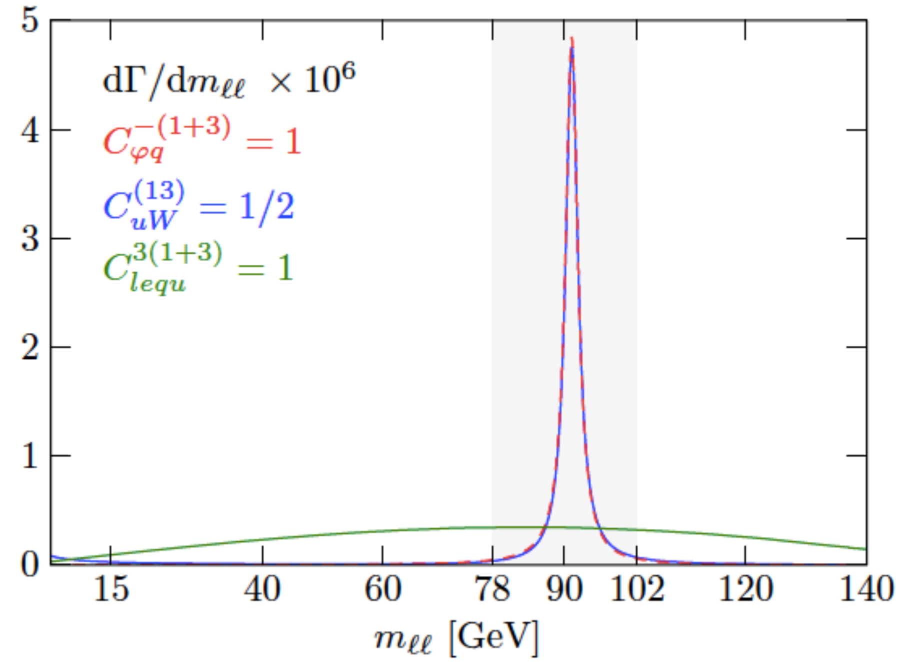
$$
\begin{aligned}
O_{tG} &= y_t g_s (\bar{Q}\sigma^{\mu\nu}T^A t)\tilde{\varphi}G^A_{\mu\nu} \\
O_{tW} &= y_t g_W (\bar{Q}\sigma^{\mu\nu}\tau^I t)\tilde{\varphi}W^I_{\mu\nu} \\
O_{tB} &= y_t g_Y (\bar{Q}\sigma^{\mu\nu} t)\tilde{\varphi}B_{\mu\nu} \\
O_{t\varphi} &= -y_t^3 (\varphi^\dagger\varphi)(\bar{Q}t)\tilde{\varphi}\ .
\end{aligned}
\qquad
\gamma = \frac{2\alpha_s}{\pi}\begin{pmatrix} \frac{1}{6} & 0 & 0 & 0 \\ \frac{1}{3} & \frac{1}{3} & 0 & 0 \\ \frac{5}{9} & 0 & \frac{1}{3} & 0 \\ -4 & 0 & 0 & -1 \end{pmatrix}
$$

$$
\begin{aligned}
O^{(13)}_{uG} &= y_t g_s (\bar{q}\sigma^{\mu\nu}T^A t)\tilde{\varphi}G^A_{\mu\nu} \\
O^{(13)}_{uW} &= y_t g_W (\bar{q}\sigma^{\mu\nu}\tau^I t)\tilde{\varphi}W^I_{\mu\nu} \\
O^{(13)}_{uB} &= y_t g_Y (\bar{q}\sigma^{\mu\nu} t)\tilde{\varphi}B_{\mu\nu} \\
O^{(13)}_{u\varphi} &= -y_t^3 (\varphi^\dagger\varphi)(\bar{q}t)\tilde{\varphi}\ .
\end{aligned}
\qquad
\gamma = \frac{2\alpha_s}{\pi}\begin{pmatrix} \frac{1}{6} & 0 & 0 & 0 \\ \frac{1}{3} & \frac{1}{3} & 0 & 0 \\ \frac{5}{9} & 0 & \frac{1}{3} & 0 \\ -2 & 0 & 0 & -1 \end{pmatrix}
$$

$$
\begin{cases} C^{(13)}_{uG}(1\ \text{TeV}) = 1, \\ C^{(13)}_{u\varphi}(1\ \text{TeV}) = 0, \end{cases}
\longrightarrow
\begin{cases} C^{(13)}_{uG}(m_t) = 0.98, \\ C^{(13)}_{u\varphi}(m_t) = 0.23. \end{cases}
$$

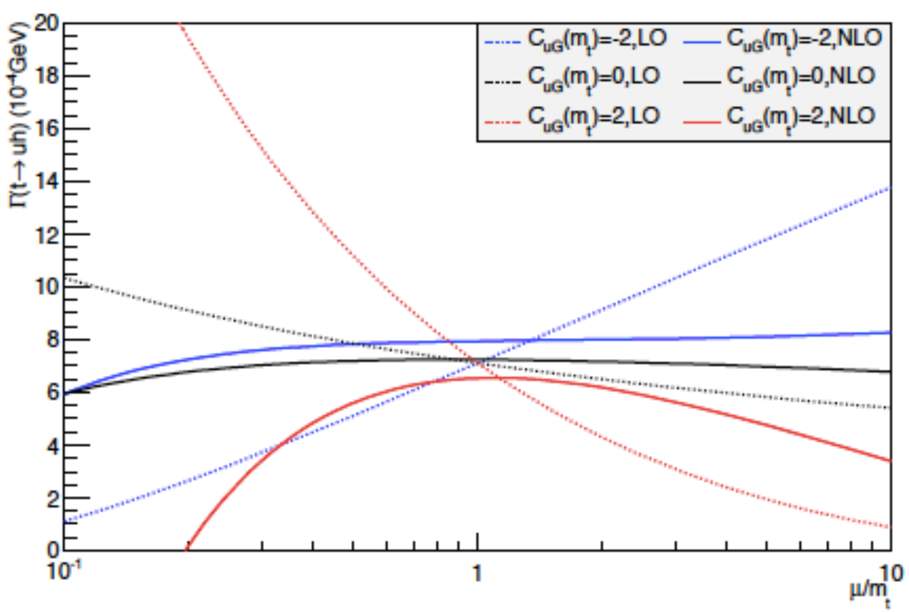
Top FCNC at NLO : decays

[Durieux, FM, Zhang 2014]



$$\Gamma^{\text{on-peak}}_{t\to u\, e^+e^-} \;/10^{-5}\ \text{GeV}\ \times (\Lambda/1\,\text{TeV})^4$$
$$= 1.7\,|C_{\varphi q}^{-(1+3)}|^2 + 6.6\,|C_{uW}^{(13)}|^2 + 0.81\,|C_{lequ}^{3(13)}|^2$$

$$\Gamma^{\text{off-peak}}_{t\to u\, e^+e^-} \;/10^{-5}\ \text{GeV}\ \times (\Lambda/1\,\text{TeV})^4$$
$$= 0.2\,|C_{\varphi q}^{-(1+3)}|^2 + 1.0\,|C_{uW}^{(13)}|^2 + 2.7\,|C_{lequ}^{3(13)}|^2$$



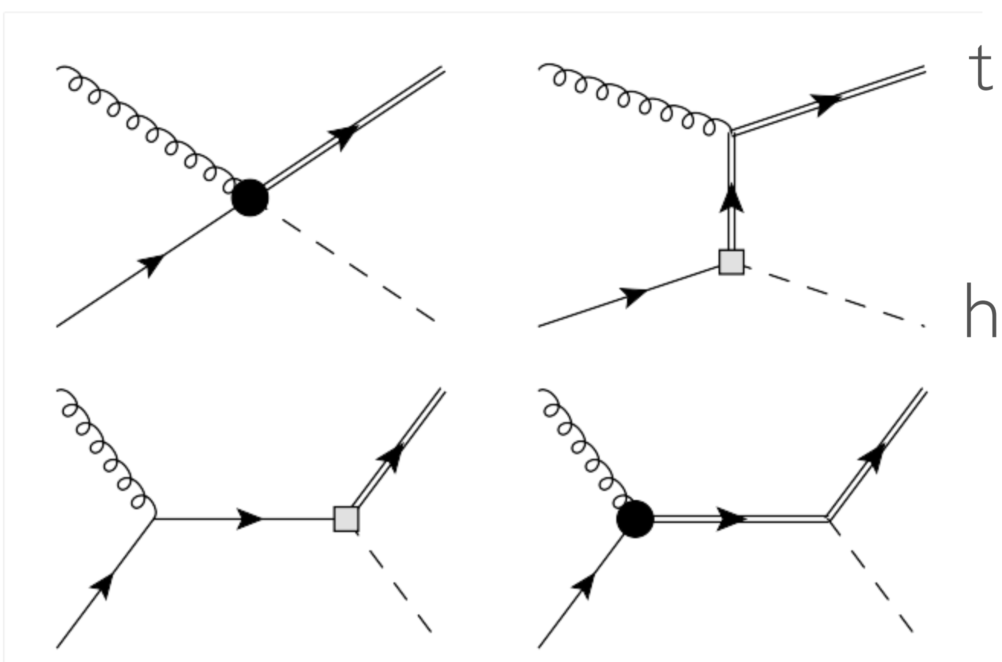
$$\Gamma(t \to u_i h) = \Gamma^{(0)} + \alpha_s \Gamma^{(1)}$$

$$\Gamma^{(0)} = 7.11|C_{u\varphi}(\mu)|^2 \;\times 10^{-4}\,\text{GeV}\,,$$
$$\Gamma^{(1)} = \left\{ \left[1.19 - 9.05 \log\left(\frac{m_t}{\mu}\right)\right] |C_{u\varphi}(\mu)|^2 - \left[3.26 + 18.1 \log\left(\frac{m_t}{\mu}\right)\right] \text{Re}C_{uG}(\mu)C^*_{u\varphi} + 9.33\times 10^{-5}|C_{uG}(\mu)|^2 \right\} \times 10^{-4}\,\text{GeV}\,. \quad (48)$$

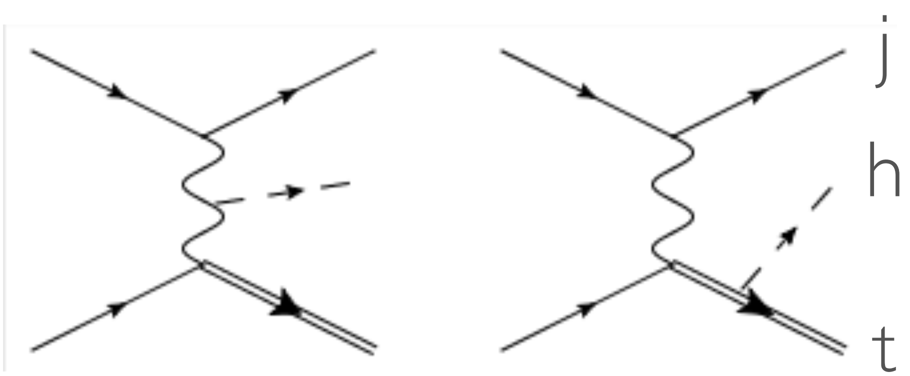
Top FCNC at NLO : production

[Degrande, FM, Wang, Zhang, 2014]

pp → th



pp → thj (SM)



Contributions appear at LO from Otφ and one from OtG..

At NLO in QCD OtG mixes with all the other operators so it has always to be included.

It also means that if a specific (arbitrary) choice of coefficient operators is made at high scales (where one can imagine a full theory to live) many operators become active when evolved to lower scales.

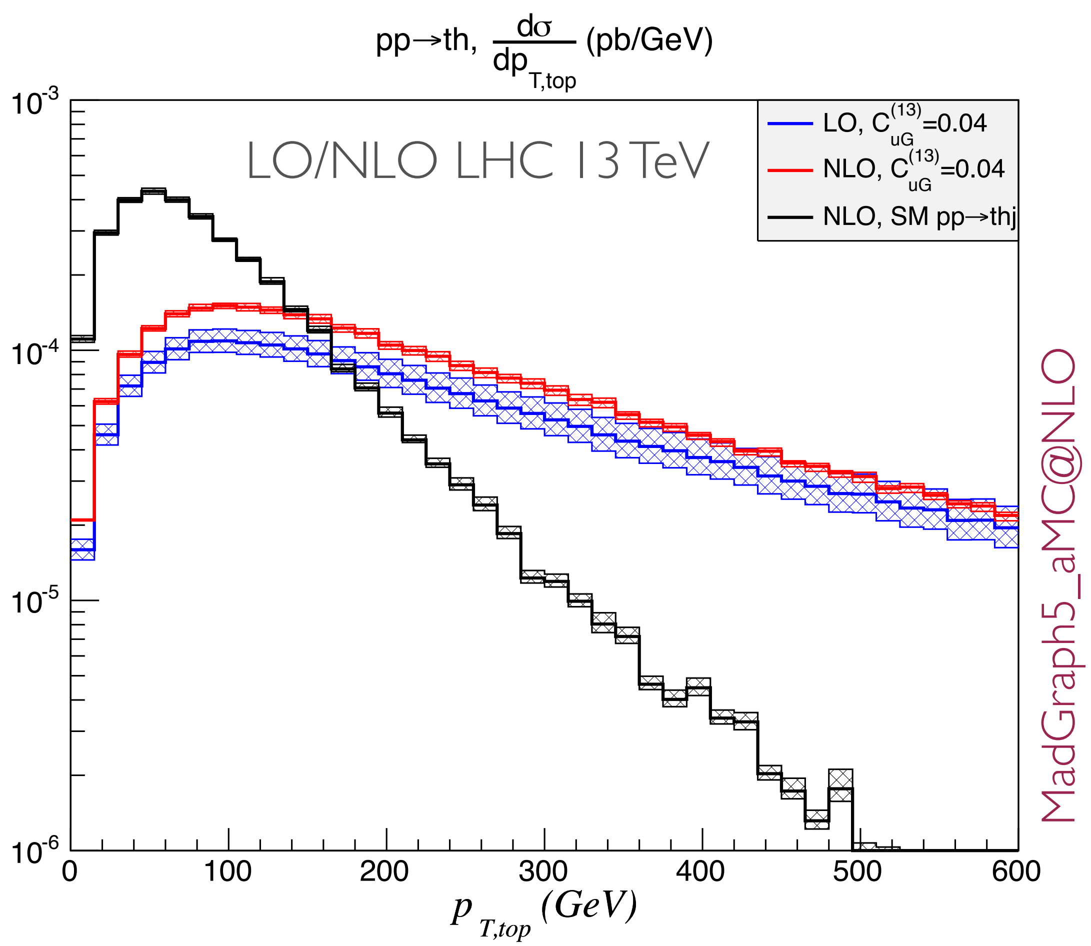
Only a global/fit approach on constraining such operators at the same time can be useful strategy and it has to be at least NLO in QCD.

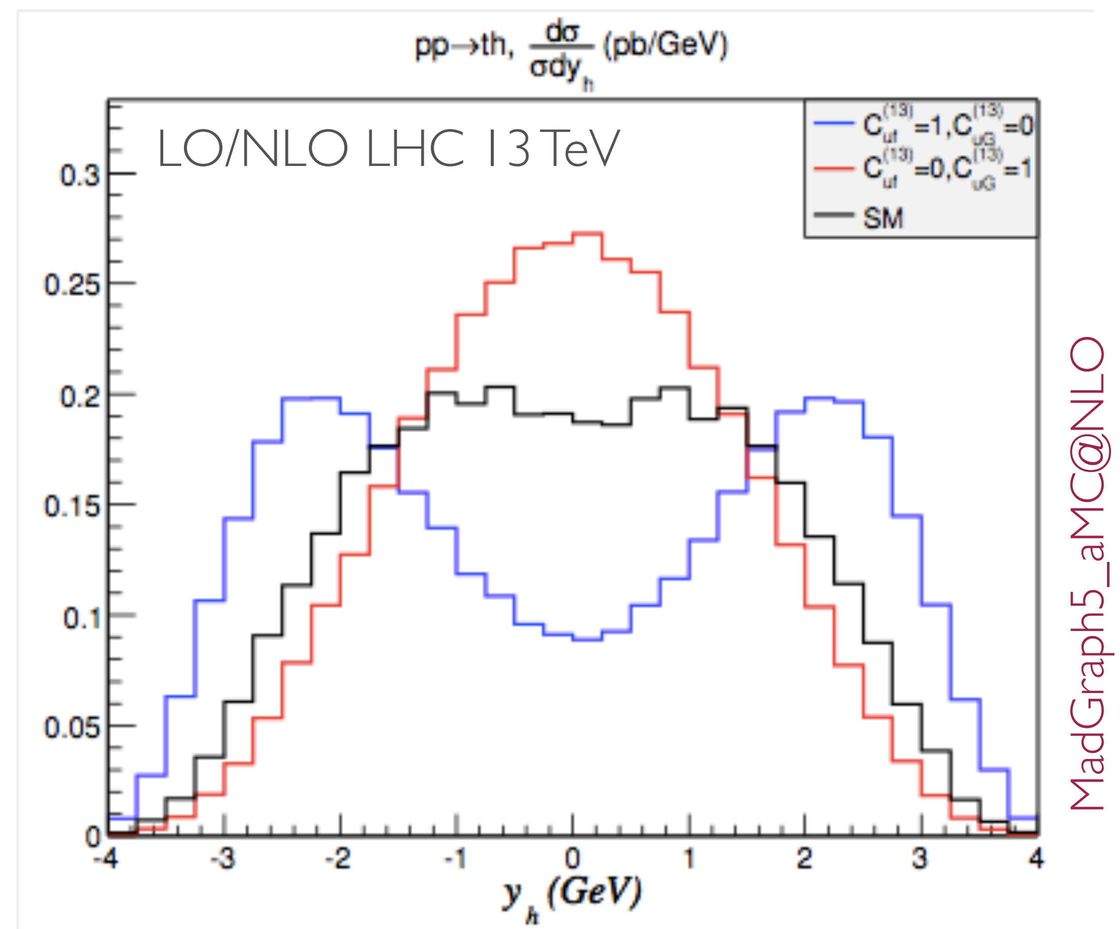
Top FCNC at NLO : production

[Degrande, FM, Wang, Zhang, 2014]

The operators have been implemented in FeynRules, the model was upgraded to NLO automatically and then passed to MG5_aMC.

Results shown here at NLO. The pp →thj interesting process by itself...





Complete implementation of all operators of dim=6 at NLO (including four fermion operators) in QCD is on going.

Top-quark FCNC at NLO : global fit

[Durieux, FM, Zhang 2014]

$$\mathrm{Br}(t \to j\, e^+e^-) + \mathrm{Br}(t \to j\, \mu^+\mu^-) \lesssim 0.0017\%$$ CMS

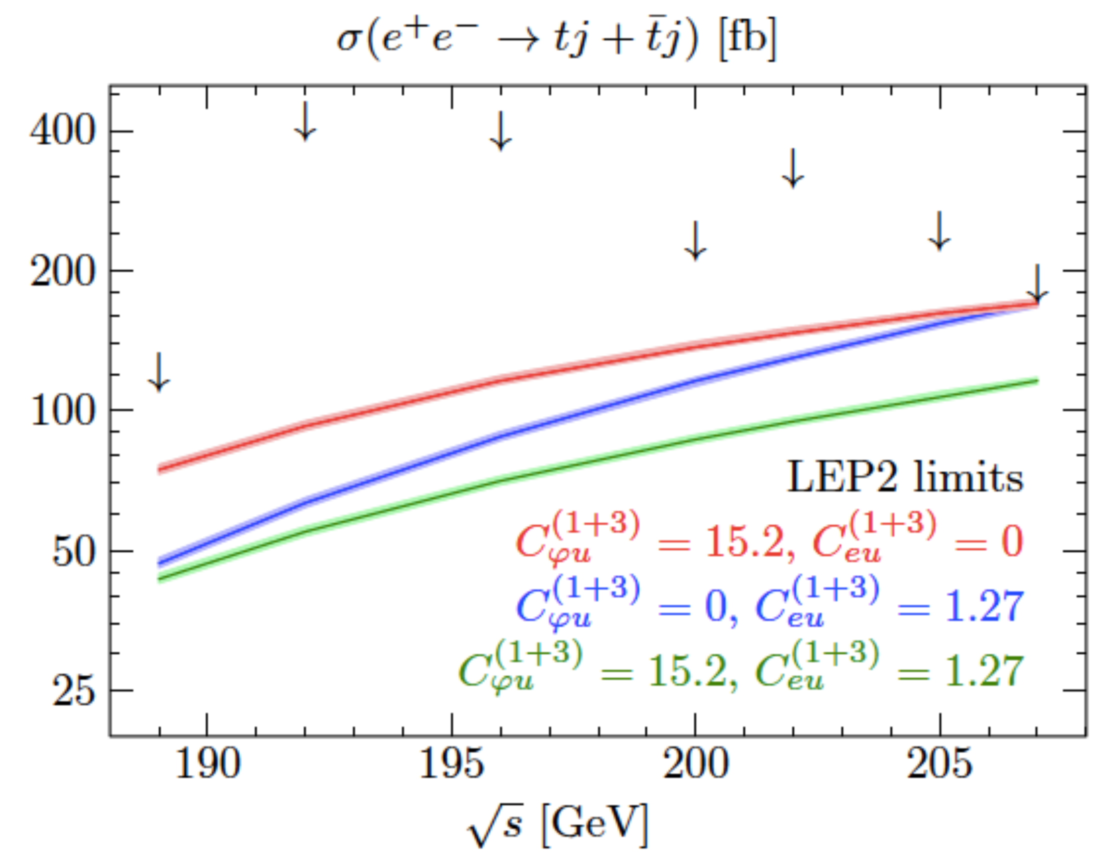
$$\mathrm{Br}(t \to j\gamma) < 3.2\%$$ CDF

$$\mathrm{Br}(t \to j\, \gamma\gamma) < 0.0016\%$$ CMS

$$\sigma(pp \to t) + \sigma(pp \to \bar{t}) < 2.5 \text{ pb} \quad \text{at } \sqrt{s} = 8 \text{ TeV}$$ ATLAS

$$\sigma(ug \to t\gamma) + \sigma(ug \to \bar{t}\gamma) + 0.778\, [\sigma(cg \to t\gamma) + \sigma(cg \to \bar{t}\gamma)] < 0.0670 \text{ pb} \quad \text{at } \sqrt{s_{pp}} = 8 \text{ TeV}$$ CMS

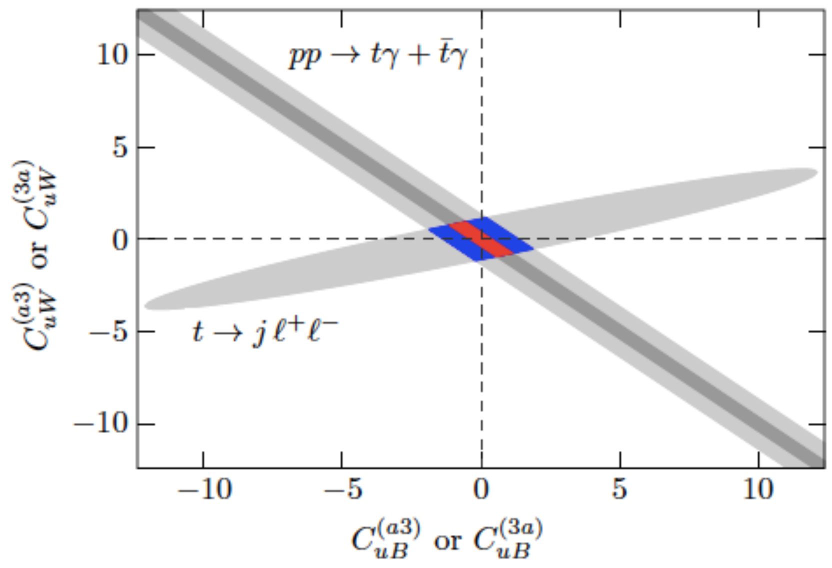
$$\sigma(e^+e^- \to tj + \bar{t}j) < 176 \text{ fb} \quad \text{at } \sqrt{s} = 207 \text{ GeV}$$ LEPII

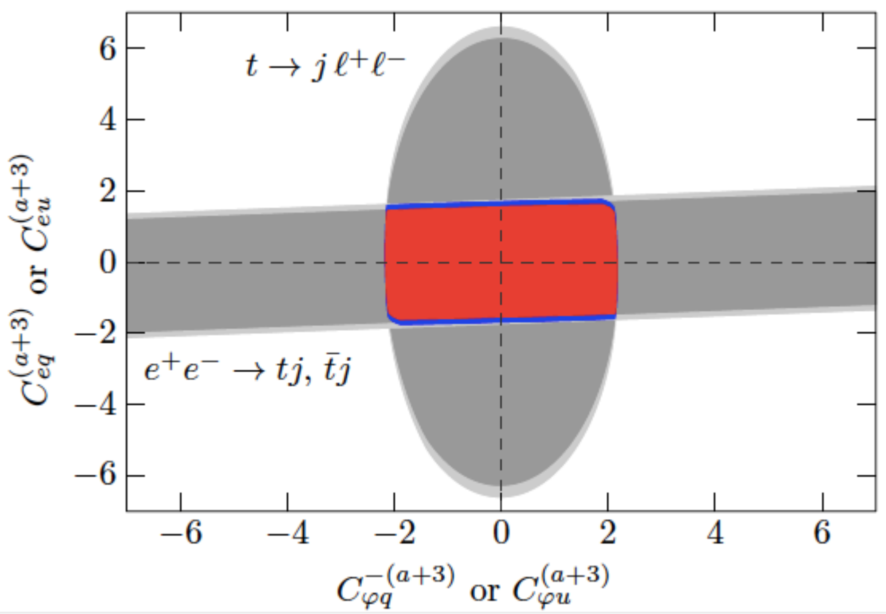


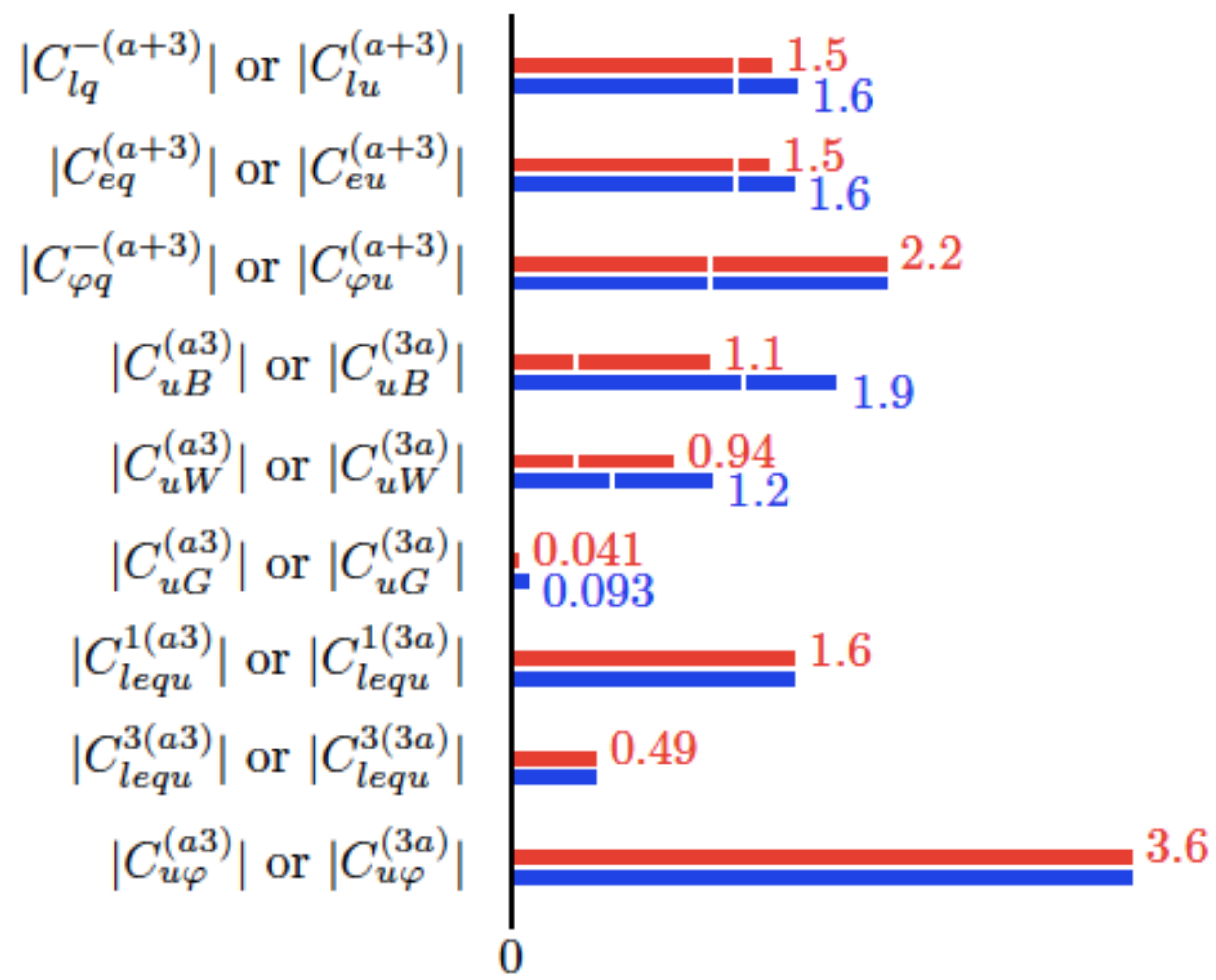
For the sake of illustration and simplicity, we only consider the most constraining observables. This suffices to set significant bounds on all two-quark operators as well as on a subset of the two-quark–two-lepton ones.

Top-quark FCNC at NLO : global fit

[Durieux, FM, Zhang 2014]







First proof of principle that a complete global fitting strategy in a self-contained sector of the top EFT is possible with the available measurements. The red (blue) are for 1st (2nd) generation. ticks = one on at the time.