Top Quark and BSM

At the LHC and beyond

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Top quark (discovery in 1995):

An elementary particle about 180 times heavier than the proton !
The only bare quark that decays before forming bound states, and therefore exposes its interactions with the other SM particles in a direct way.

Top quark being the heaviest elementary particle (so far) has the strongest interaction with the Higgs boson

It is crucial to know the top quark couplings precisely to know the details of Higgs couplings and thus to understand the Electroweak Symmetry Breaking

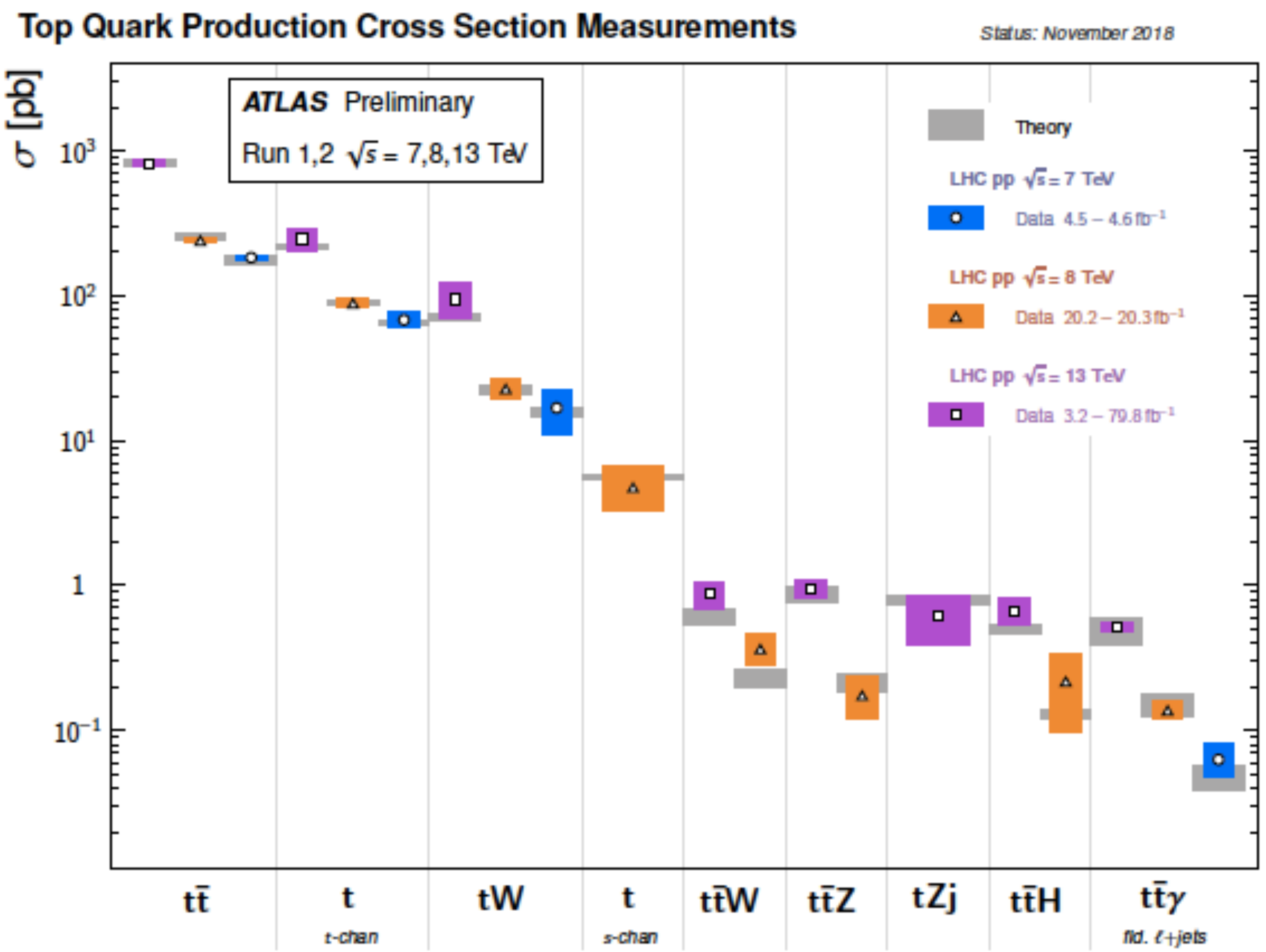
Top quark is produced at LCH in many processes

pair production

single top with a light jet
single top with W
single top with Z and jet

pair production along with H/Z/W

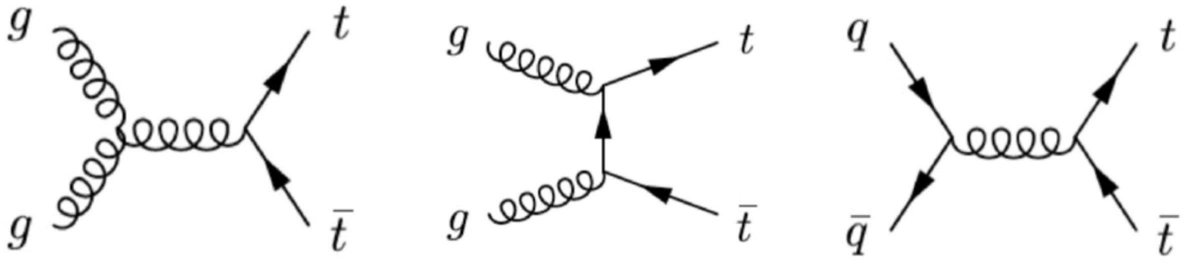
More than **80 X 10^6** top pairs
@ 13 TeV, 100 /fb

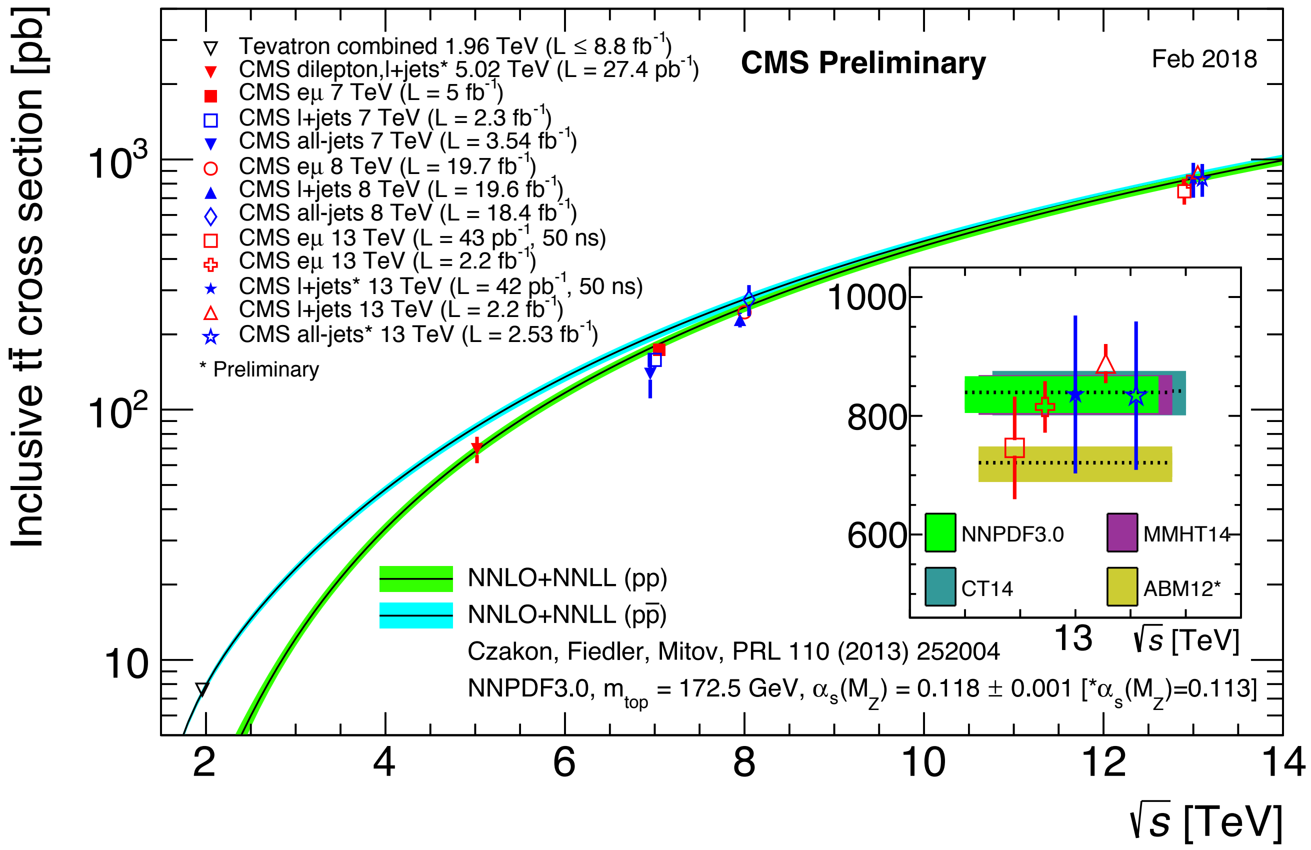


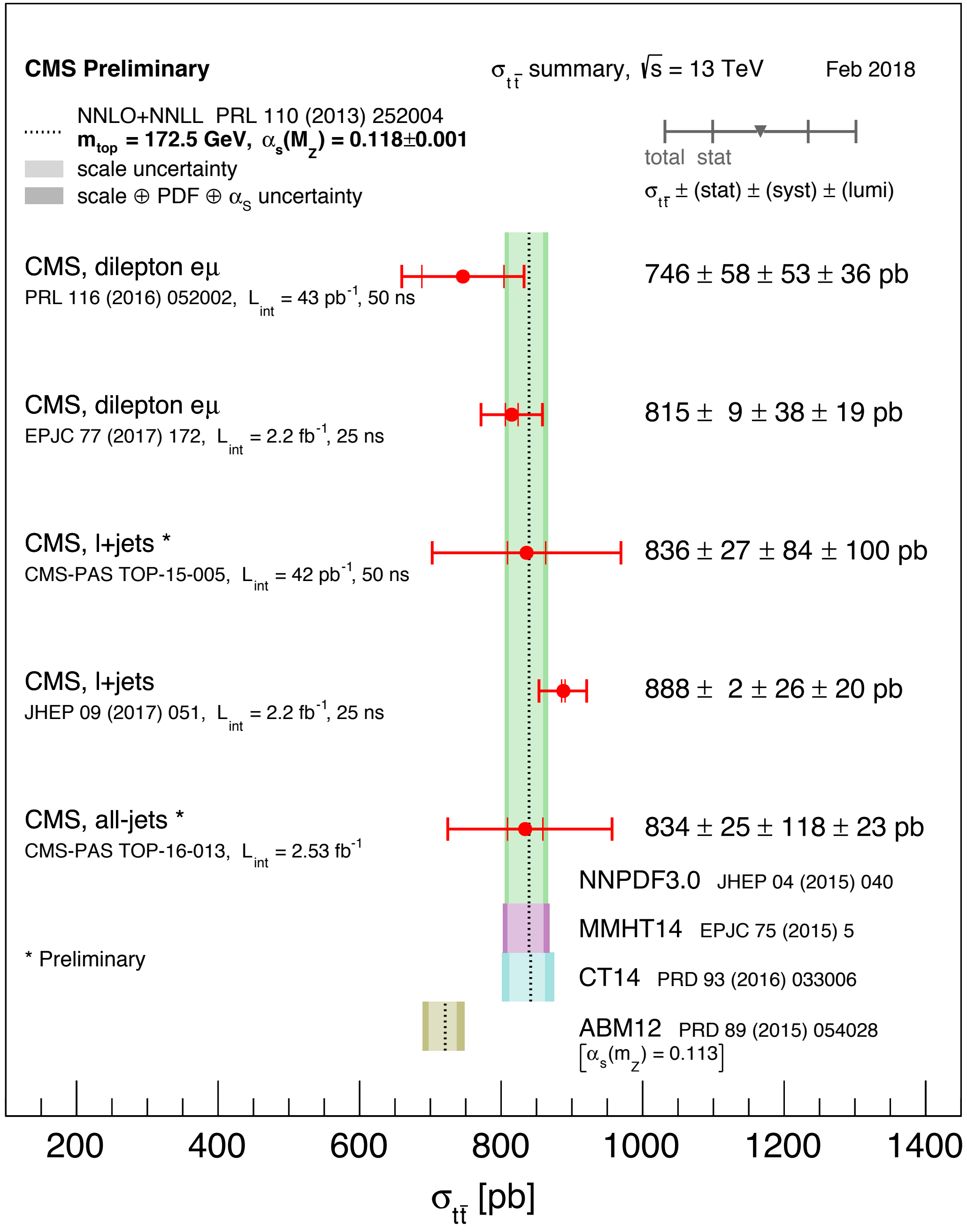
Top Working Group Summary Plots

ATL-PHYS-PUB-2018-034

Top quark pair production at the LHC

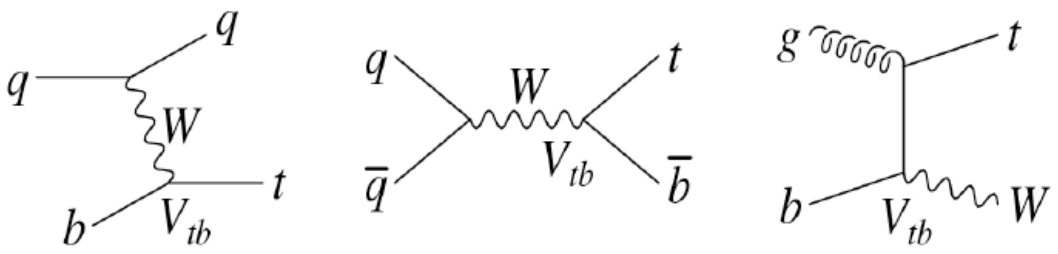


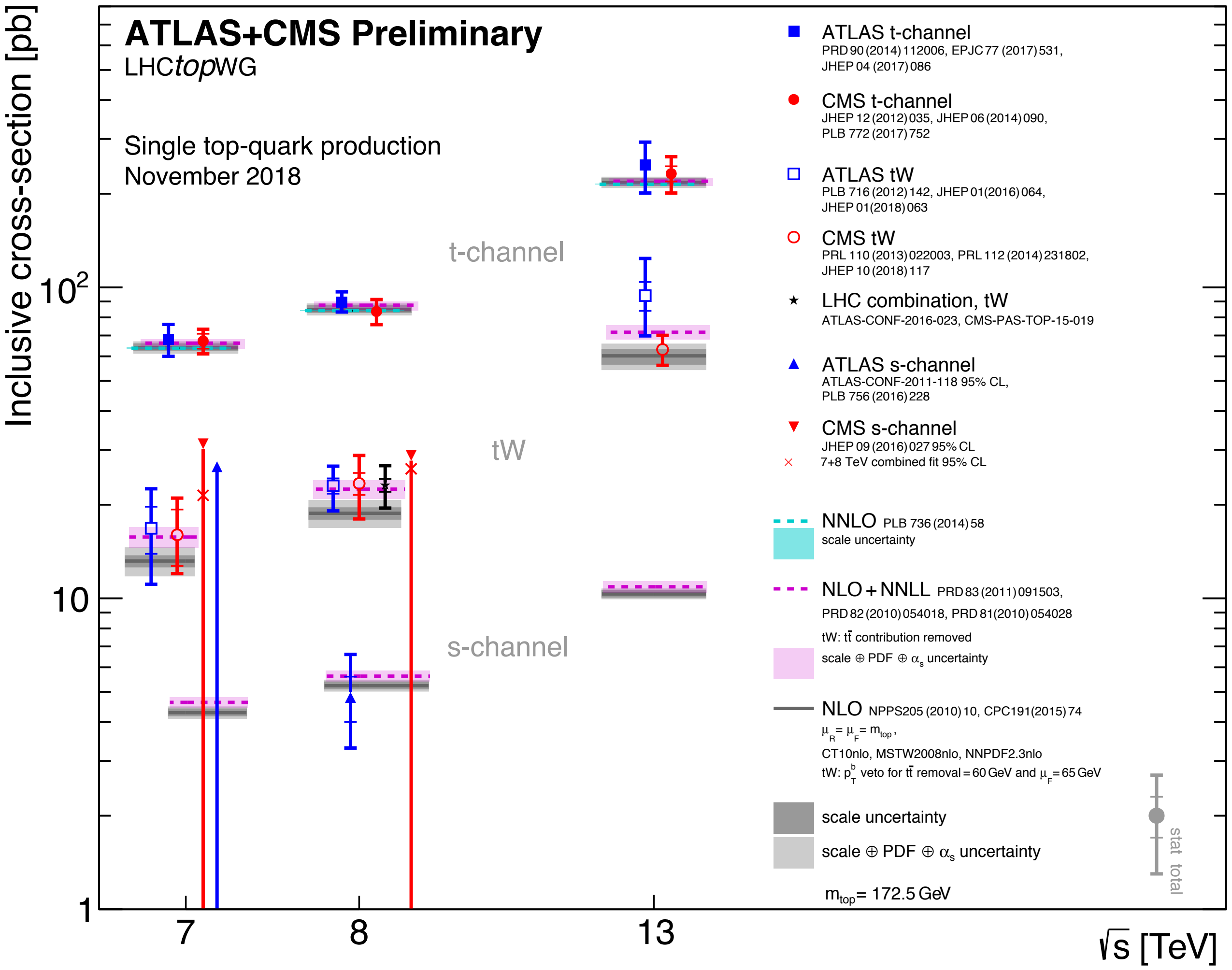


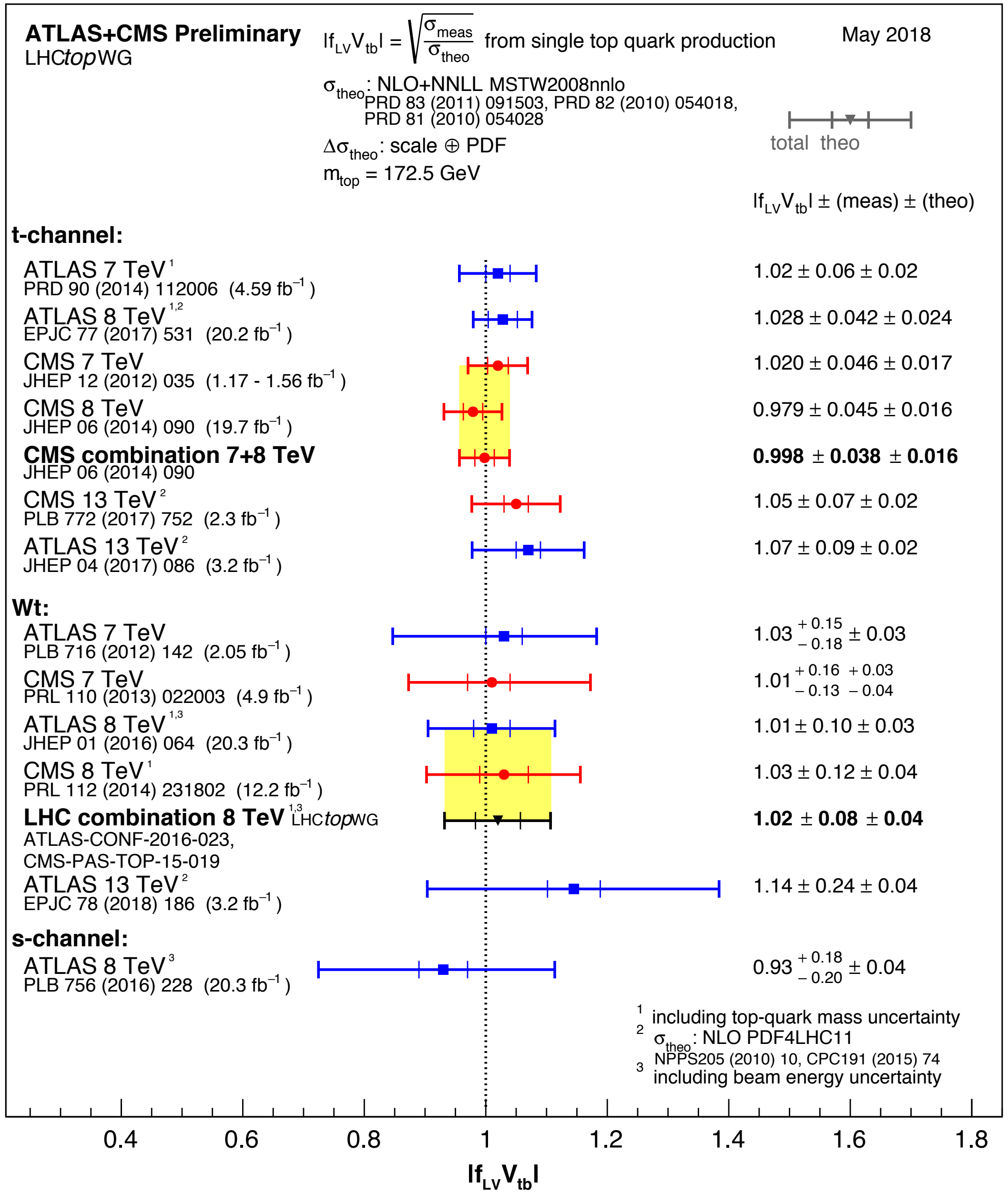


Single Top quark production at the LHC

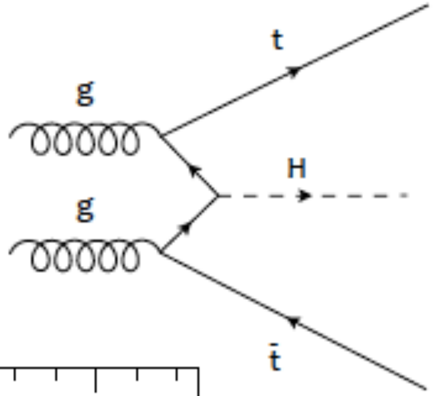
direct measurement of Vtb



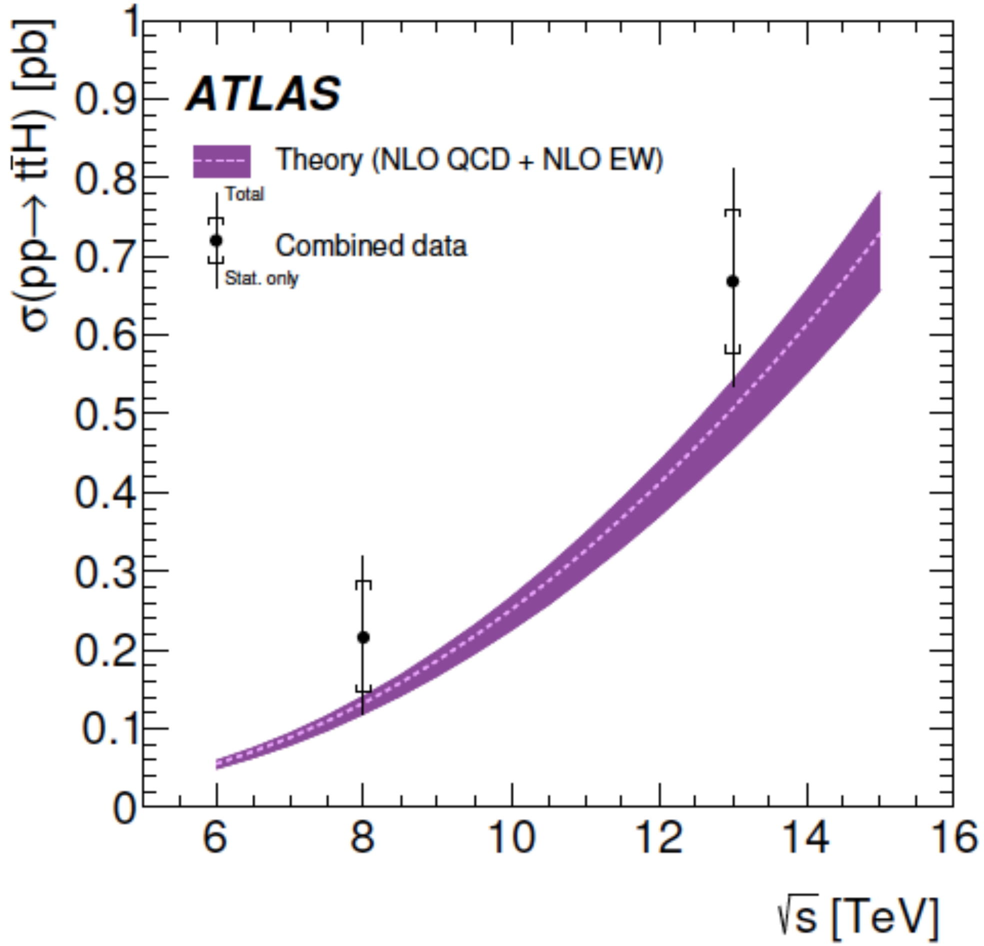


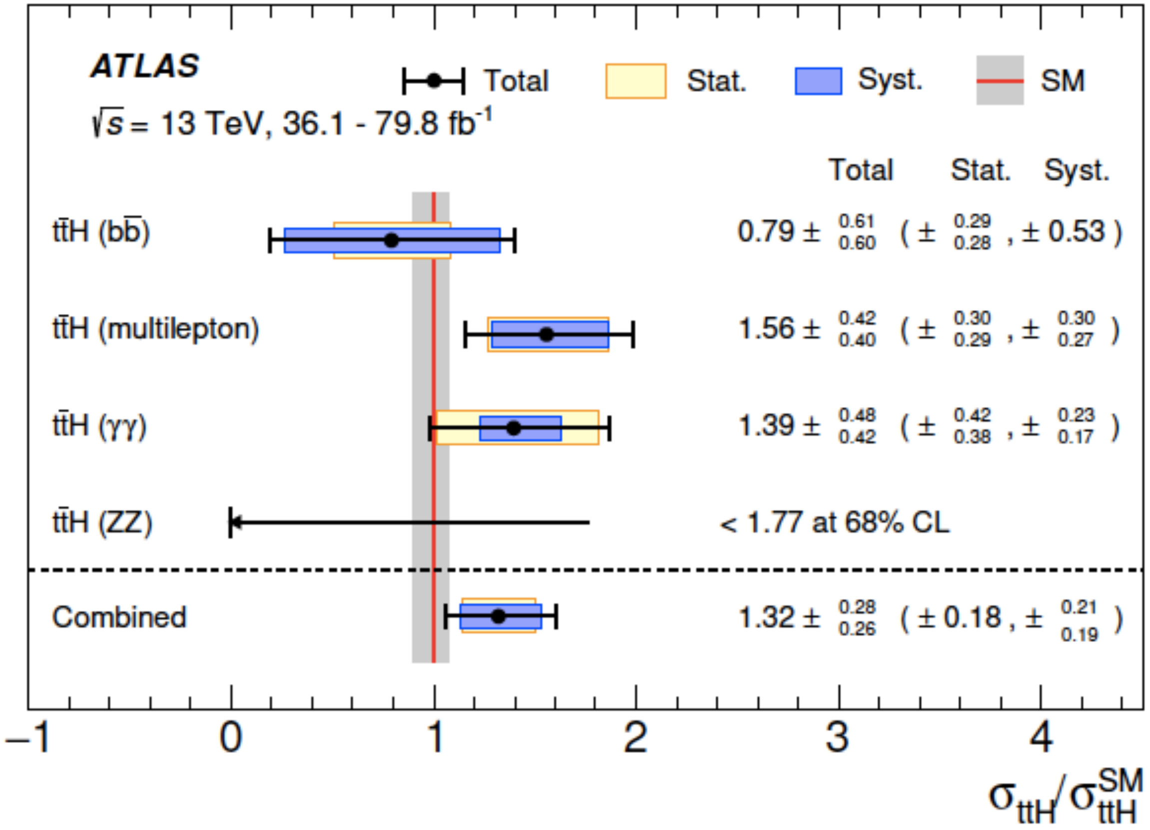


Top quark pair in association with Higgs



ATLAS, Phys. Lett. B 784 (2018) 173

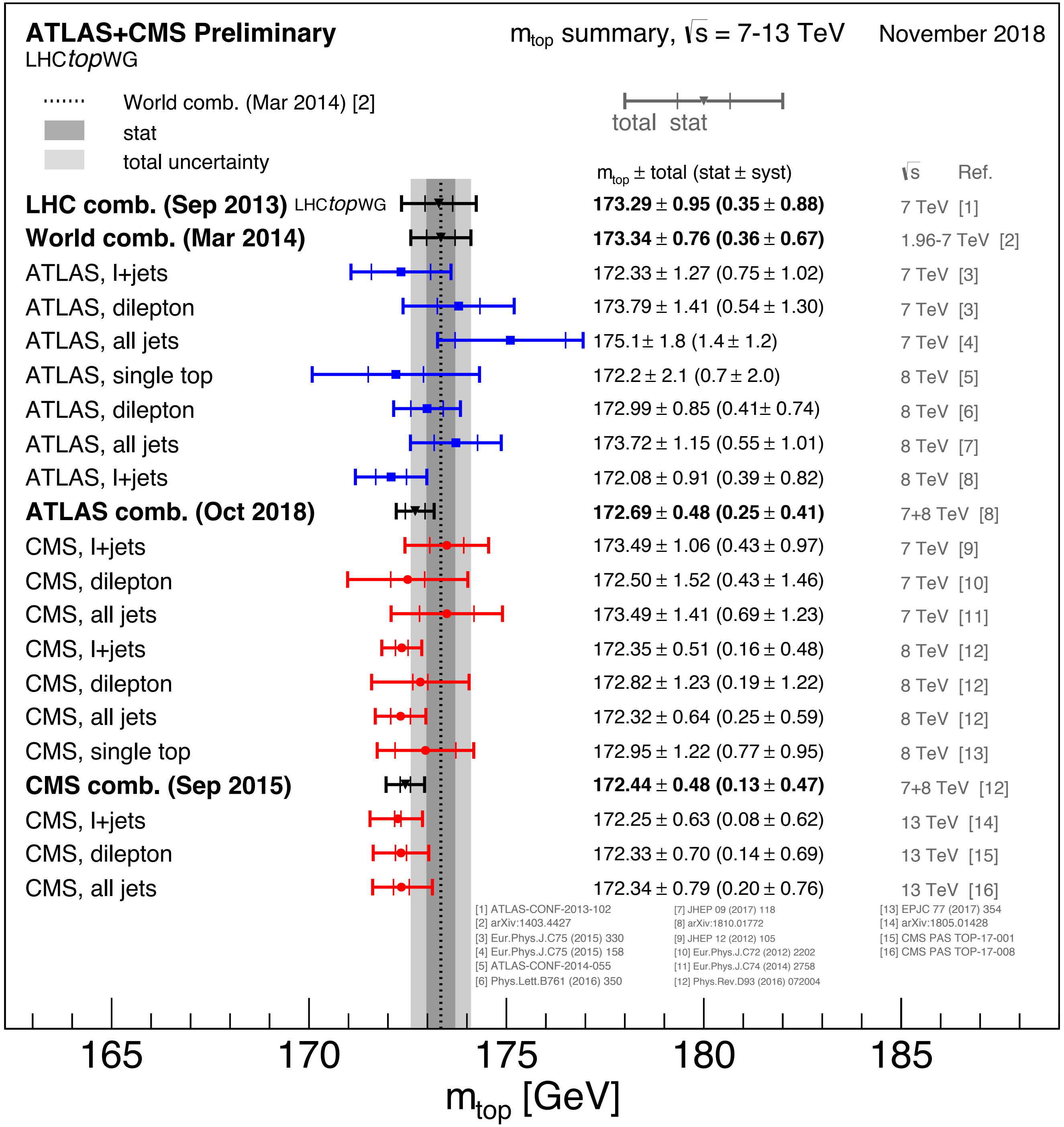




Direct measurement of Yukawa coupling

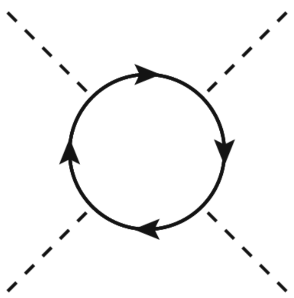
Top quark mass

Need to know precisely
to understand evolution of Higgs coupling.



Why is it important

$$V(\phi) = \mu^2 \phi^\dagger \phi + \lambda (\phi^\dagger \phi)^2$$



$$Y_d \bar{Q}_L \phi d_R - Y_u \bar{Q}_L \tilde{\phi} u_R$$

$y_t = g_{htt}$

Running of Higgs self coupling

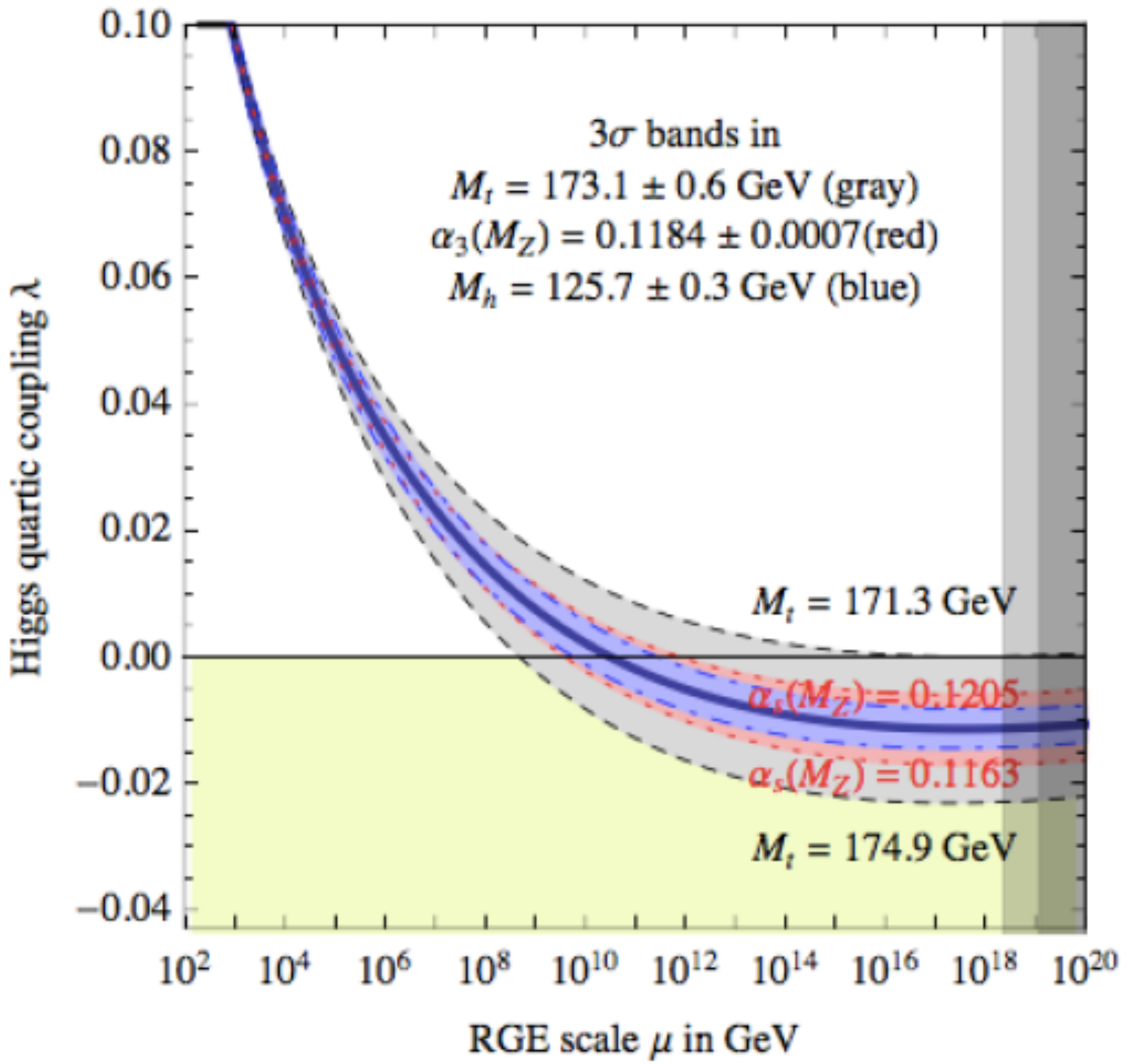
$$16\pi^2 \frac{d\lambda}{d\log\mu} = 24\lambda^2 + 12\lambda g_{htt}^2 - 9\lambda\left(g^2 + \frac{g'^2}{3}\right) - 6g_{htt}^4 + \frac{9g^4}{8} + \frac{3g'^4}{8} + \frac{3g^2 g'^2}{4}$$

In the SM, at tree level

$$g_{htt}^{SM} = \frac{\sqrt{2}\, m_t}{\upsilon} = \frac{\sqrt{2}\cdot(173.34 \pm 0.76)}{246} = 0.996 \pm 0.004$$

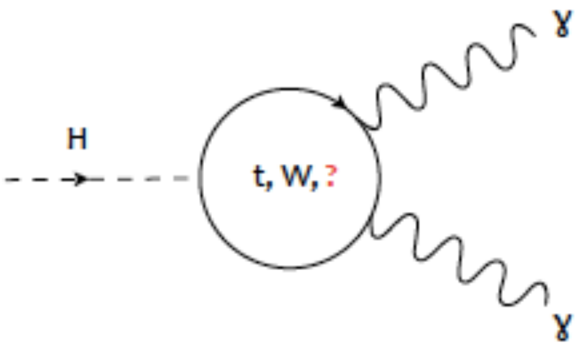
In 2HDM / MSSM $\quad g_{htt} = \frac{\sqrt{2}\, m_t}{\upsilon} \frac{\cos\alpha}{\sin\beta}$

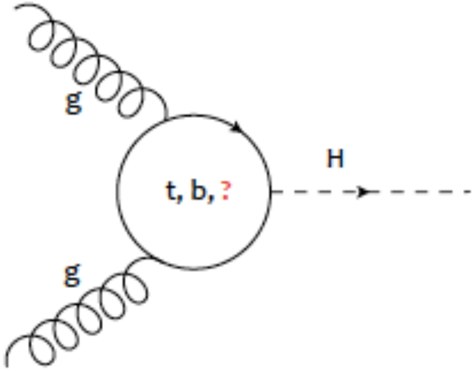
In general $\quad g_{htt} = c_t\, g_{htt}^{SM}$

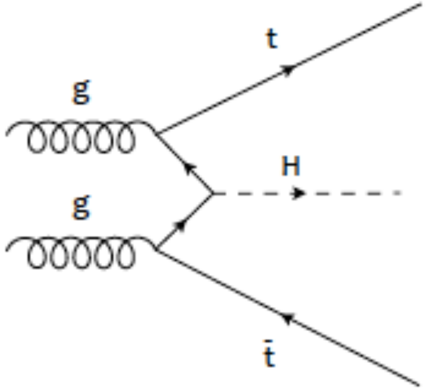


Degrassi, et al, JHEP08(2012)098 [1205.6497]

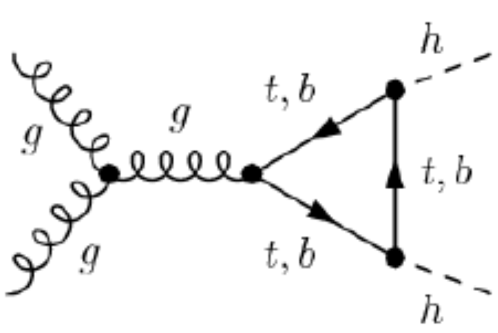
Top quark Yukawa influencing the production and decay of the Higgs boson at the LHC

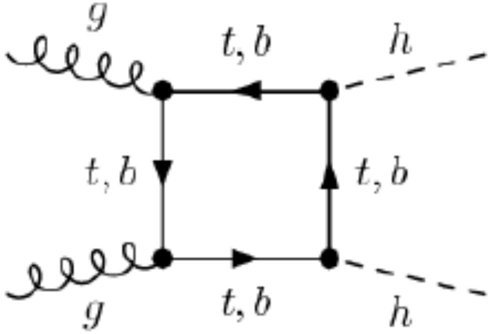


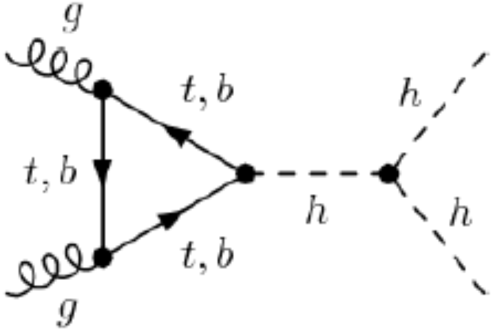


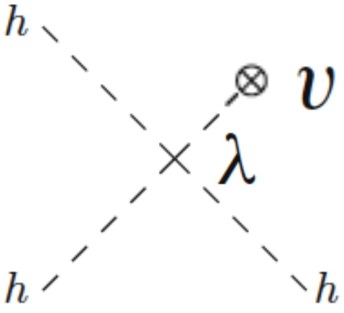


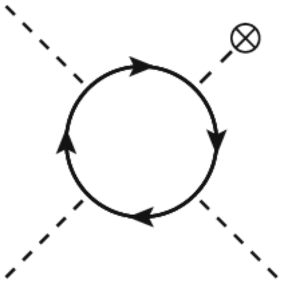
Also the measurement of Higgs trilinear coupling











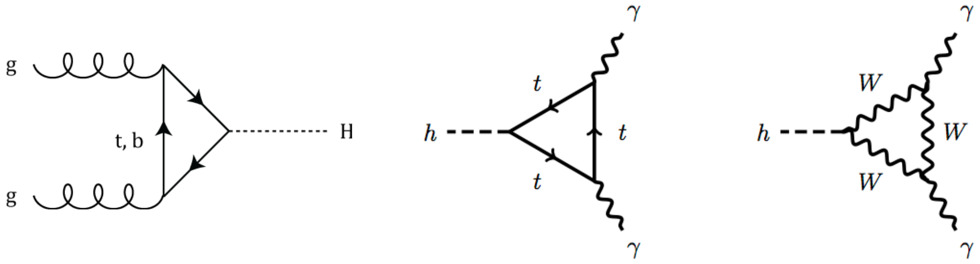
$$\mathcal{L}_{t\bar{t}H} = -\frac{m_t}{v}\bar{\psi}_t(\kappa_t + \tilde{\kappa}_t i\gamma_5)H\psi_t$$ SM => $\kappa_t = 1$ $\tilde{\kappa}_t = 0$

Measurements at LHC

JHEP 1608 (2016) 045, CERN-EP-2016-100, 1606.02266 ; ATLAS-CONF-2013-034; CERN-PH-TH-2012-284, ArXiv:1209.0040

Indirect measurements

$$pp(gg) \rightarrow H \rightarrow \gamma\gamma$$



$$\sigma \cdot \mathrm{BR}\,(\mathrm{gg} \to \mathrm{H} \to \gamma\gamma) \;=\; \sigma_{\mathrm{SM}}(\mathrm{gg} \to \mathrm{H}) \cdot \mathrm{BR}_{\mathrm{SM}}(\mathrm{H} \to \gamma\gamma) \cdot \frac{\kappa_g^2 \cdot \kappa_\gamma^2}{\kappa_H^2}$$

$$\kappa_j^2 = \sigma_j/\sigma_j^{\mathrm{SM}} \quad \text{or} \quad \kappa_j^2 = \Gamma^j/\Gamma^j_{\mathrm{SM}}$$

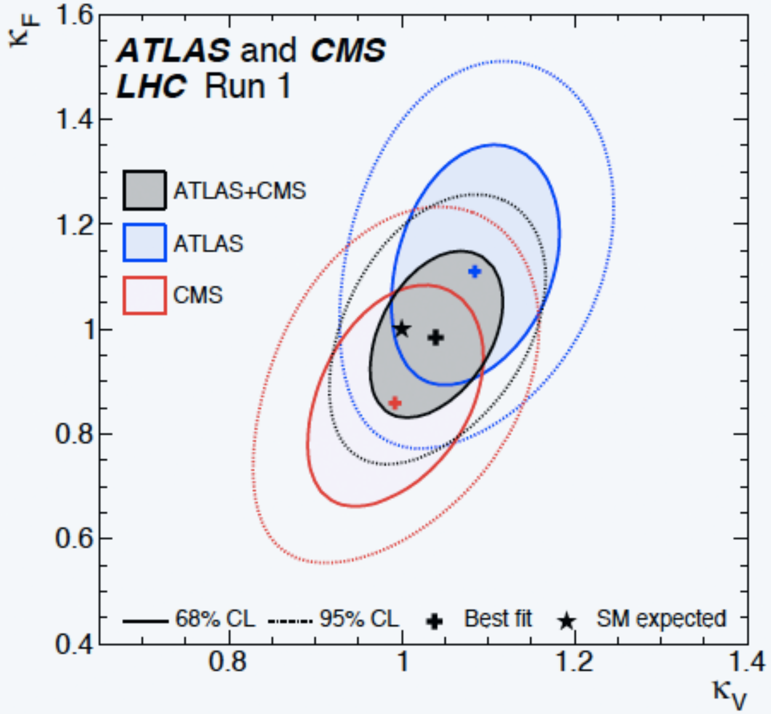
$$\sigma(gg \to H) * \mathrm{BR}(H \to \gamma\gamma) \;\sim\; \frac{\kappa_F^2 \cdot \kappa_\gamma^2(\kappa_F, \kappa_V)}{0.75 \cdot \kappa_F^2 + 0.25 \cdot \kappa_V^2}$$

$$\kappa_V = \kappa_W = \kappa_Z$$

$$\kappa_F = \kappa_t = \kappa_b = \kappa_\tau = \kappa_g$$

$$\kappa_\gamma^2(\kappa_F, \kappa_V) = 1.59 \cdot \kappa_V^2 - 0.66 \cdot \kappa_V \kappa_F + 0.07 \cdot \kappa_F^2$$

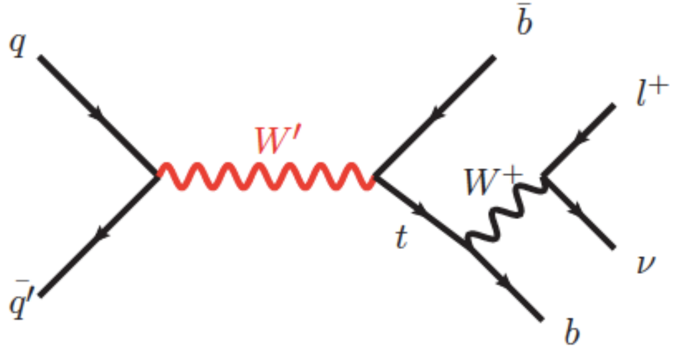
$$\kappa_H^2 = 0.57 \cdot \kappa_b^2 + 0.22 \cdot \kappa_W^2 + 0.09 \cdot \kappa_g^2 + 0.06 \cdot \kappa_\tau^2 + 0.03 \cdot \kappa_Z^2 + 0.03 \cdot \kappa_c^2 + 0.0023 \cdot \kappa_\gamma^2 + 0.0016 \cdot \kappa_{(Z\gamma)}^2 + 0.0001 \cdot \kappa_s^2 + 0.00022 \cdot \kappa_\mu^2$$

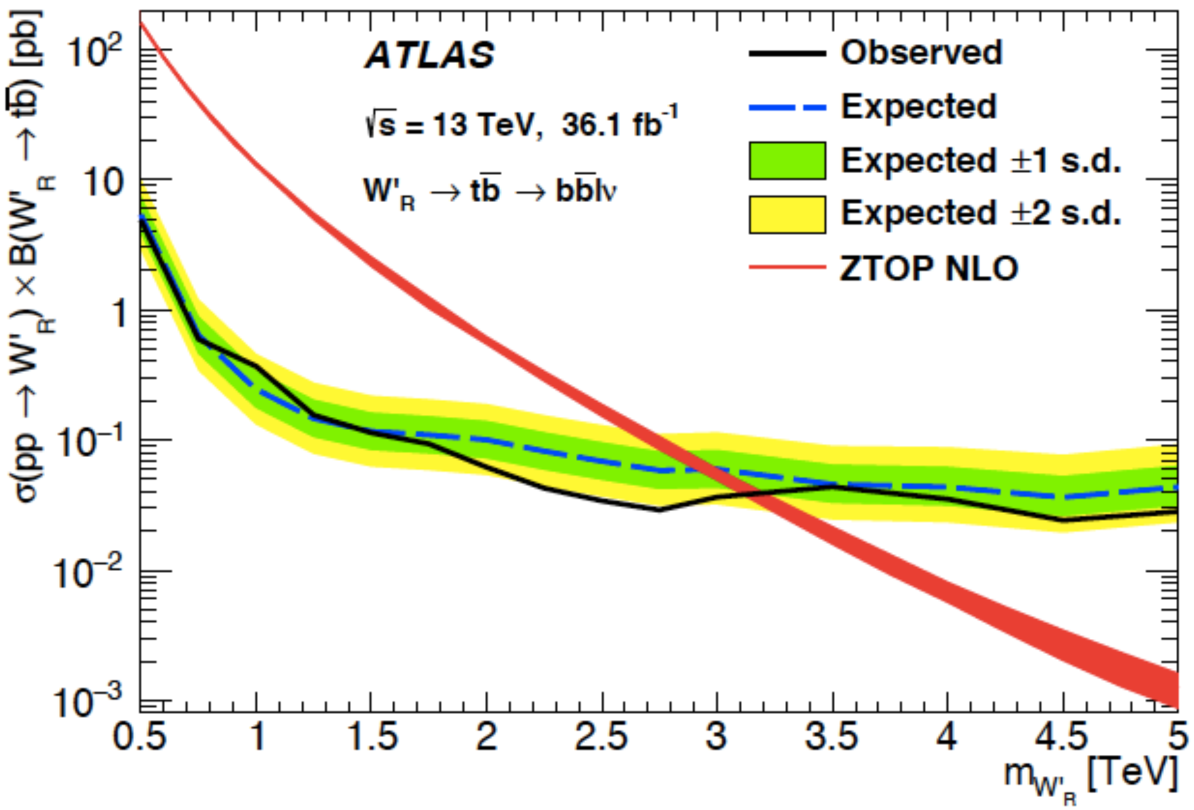


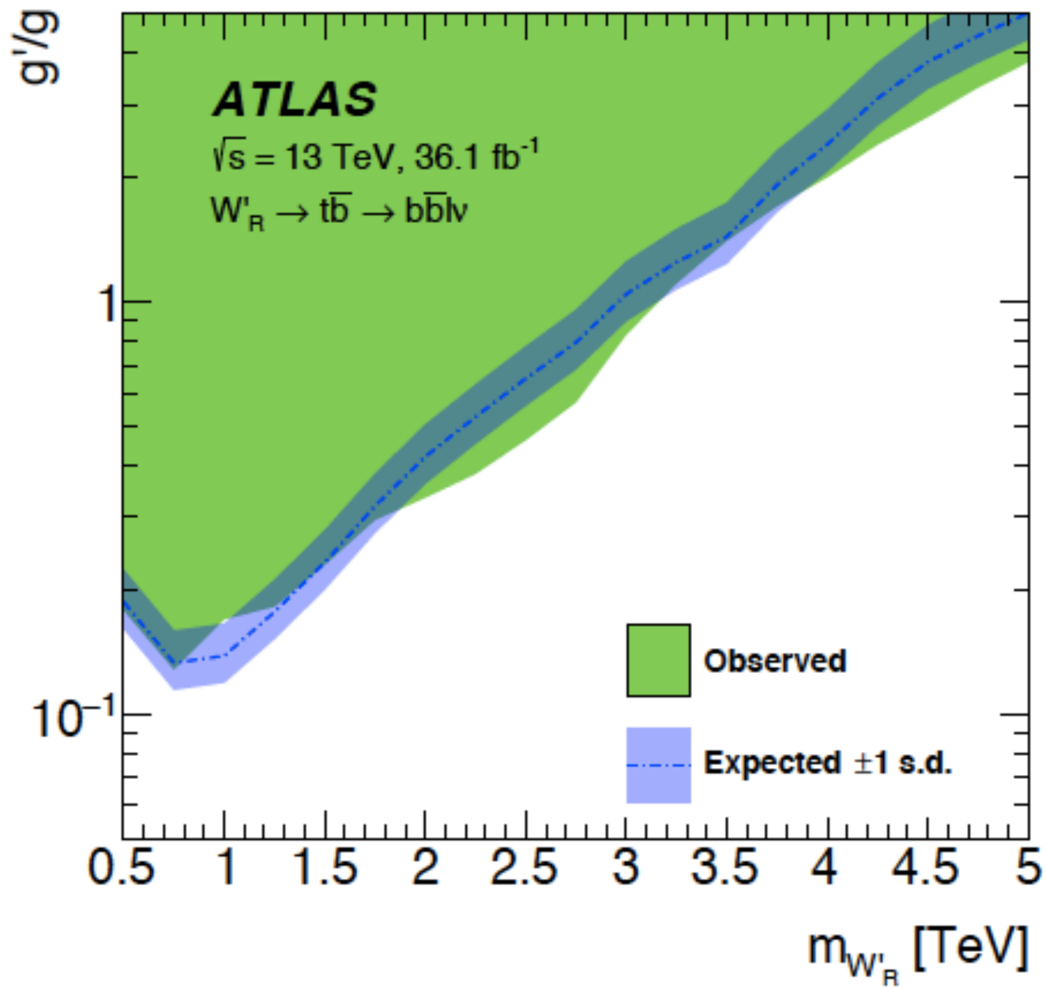
New Physics: Through heavy resonance

ATLAS, Phys.Lett. B788 (2019) 347

$W'^+ \to t\bar{b}$ and $W'^- \to \bar{t}b$







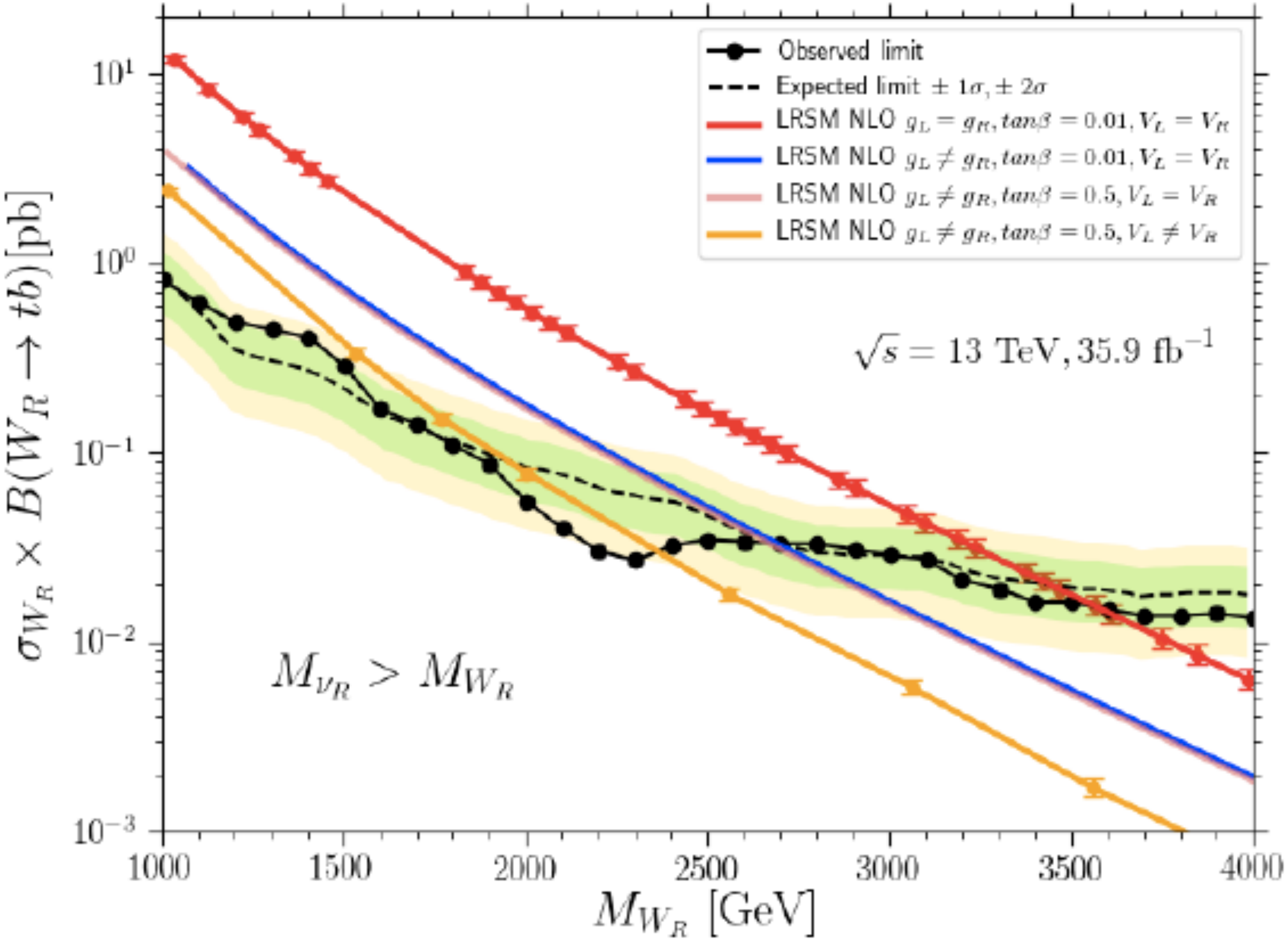
This can be relaxed considering

$g_R \neq g_L$

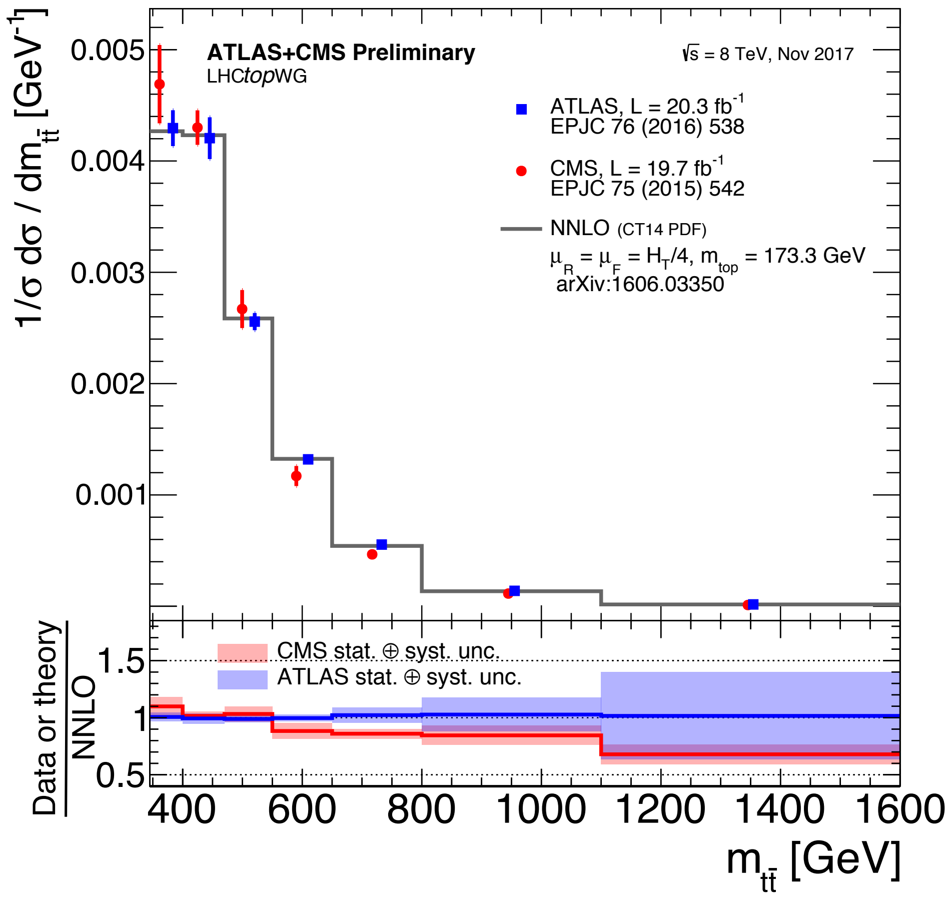
$V^L_{\rm CKM} \neq V^R_{\rm CKM}$

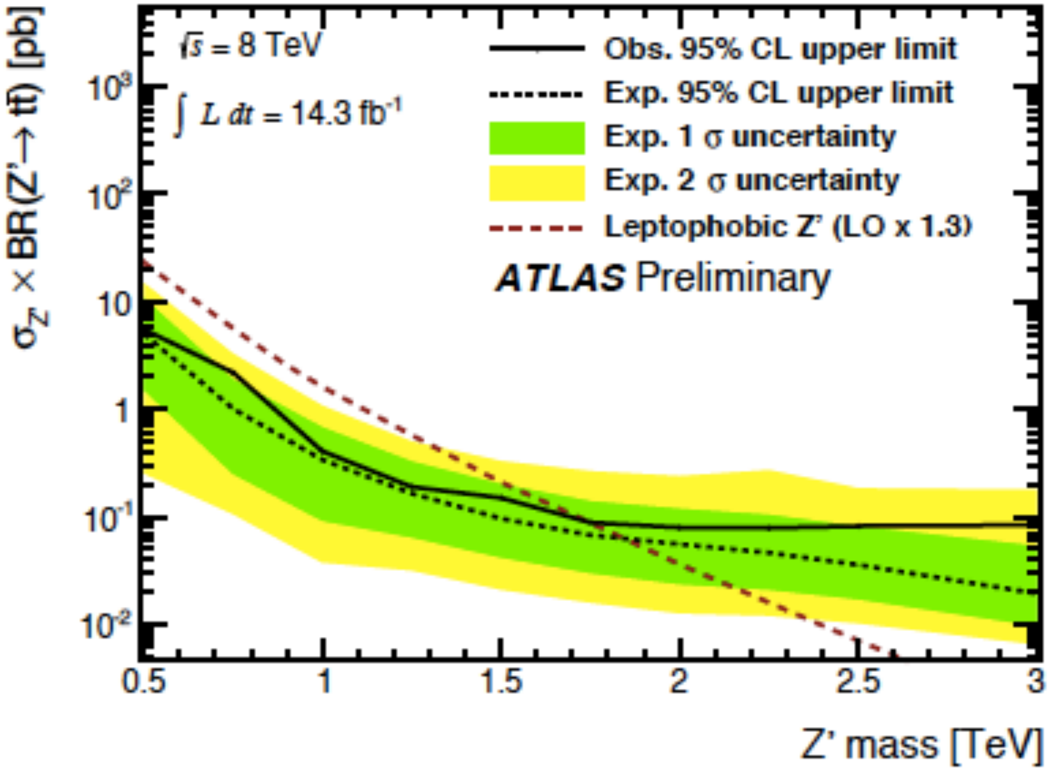
(respecting all constraints
including those from Flavour Sector)

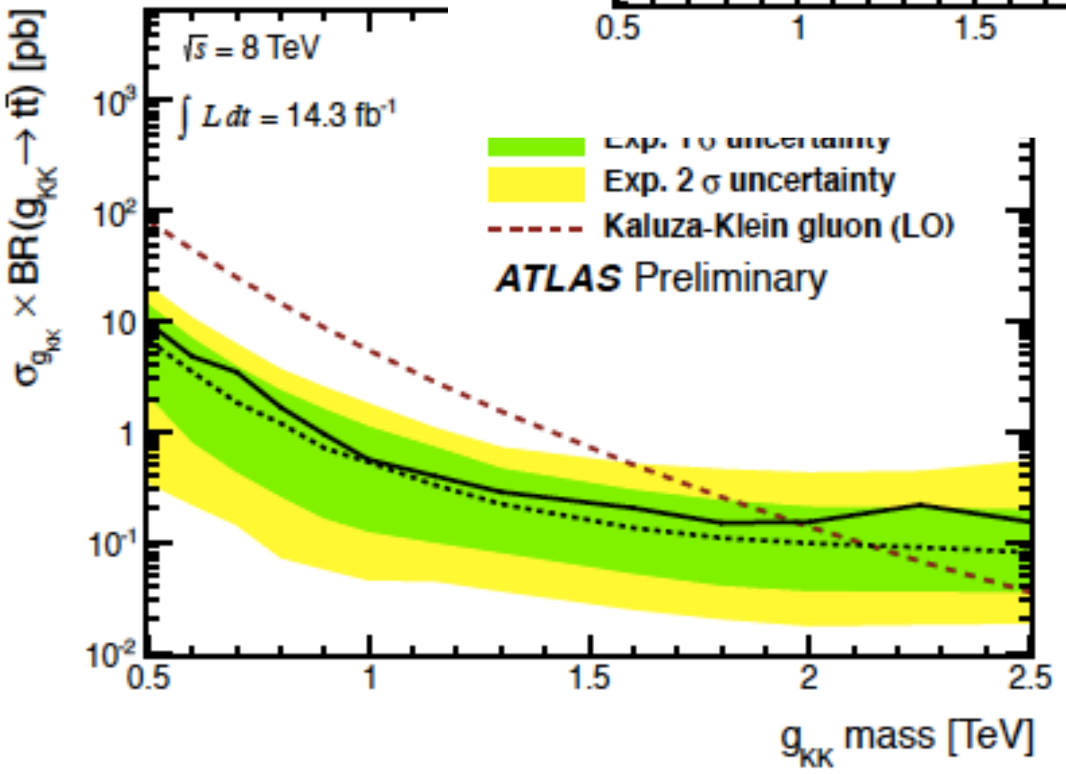
Frank, Ozdel, PP: arXiv:1812.05681



$Z' \to tt$ $G \to tt$



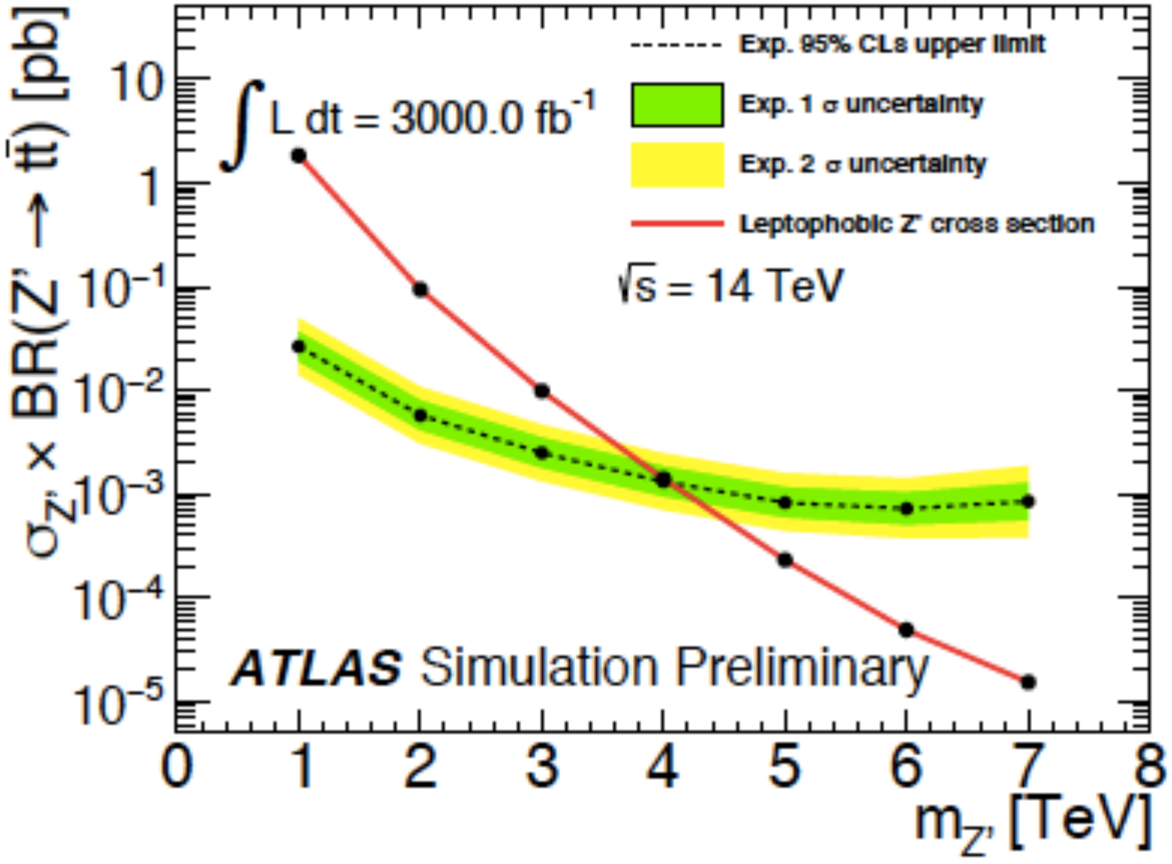


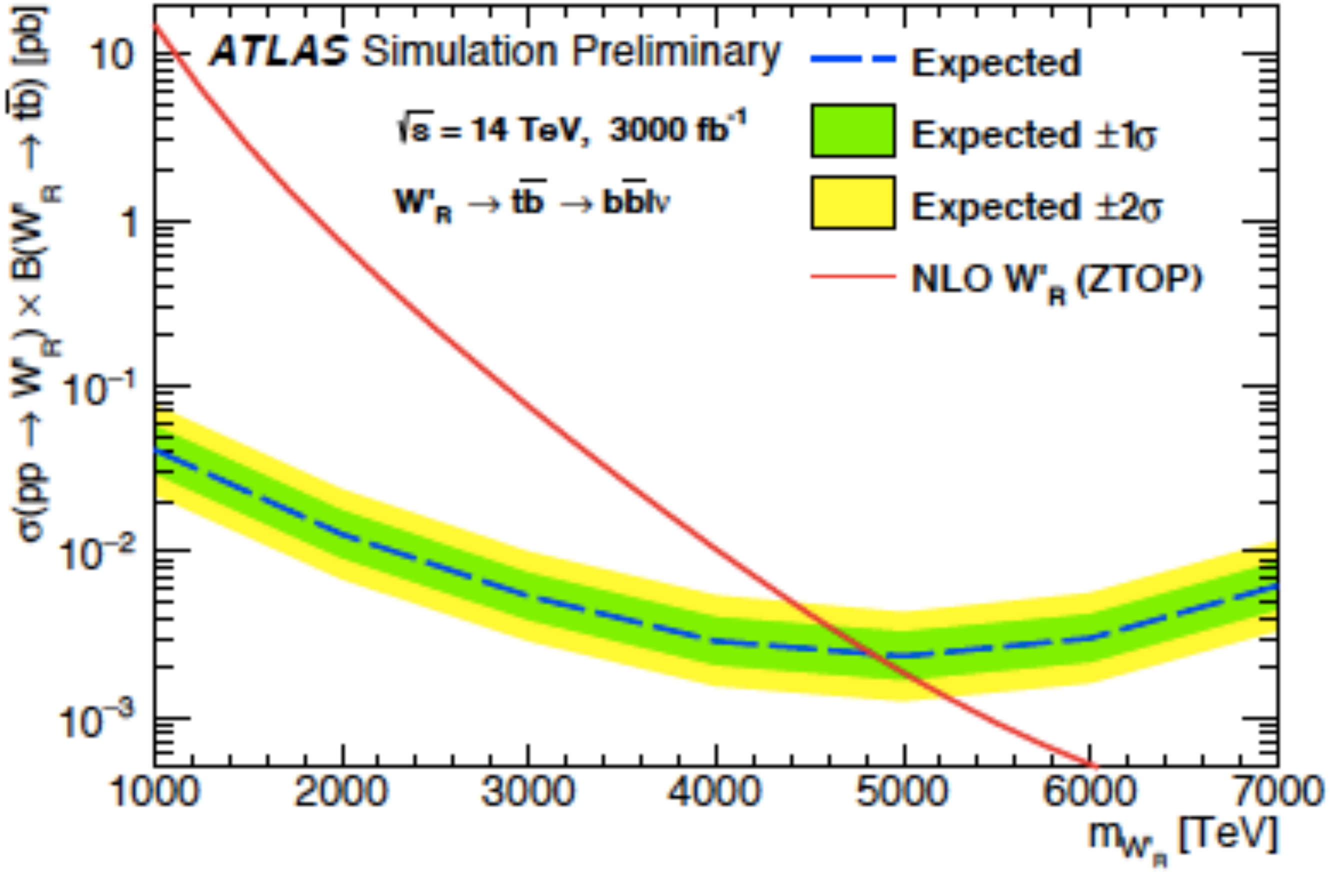


Limits are much weaker compared to di-jet and di-lepton channels

High Luminosity LHC expectations

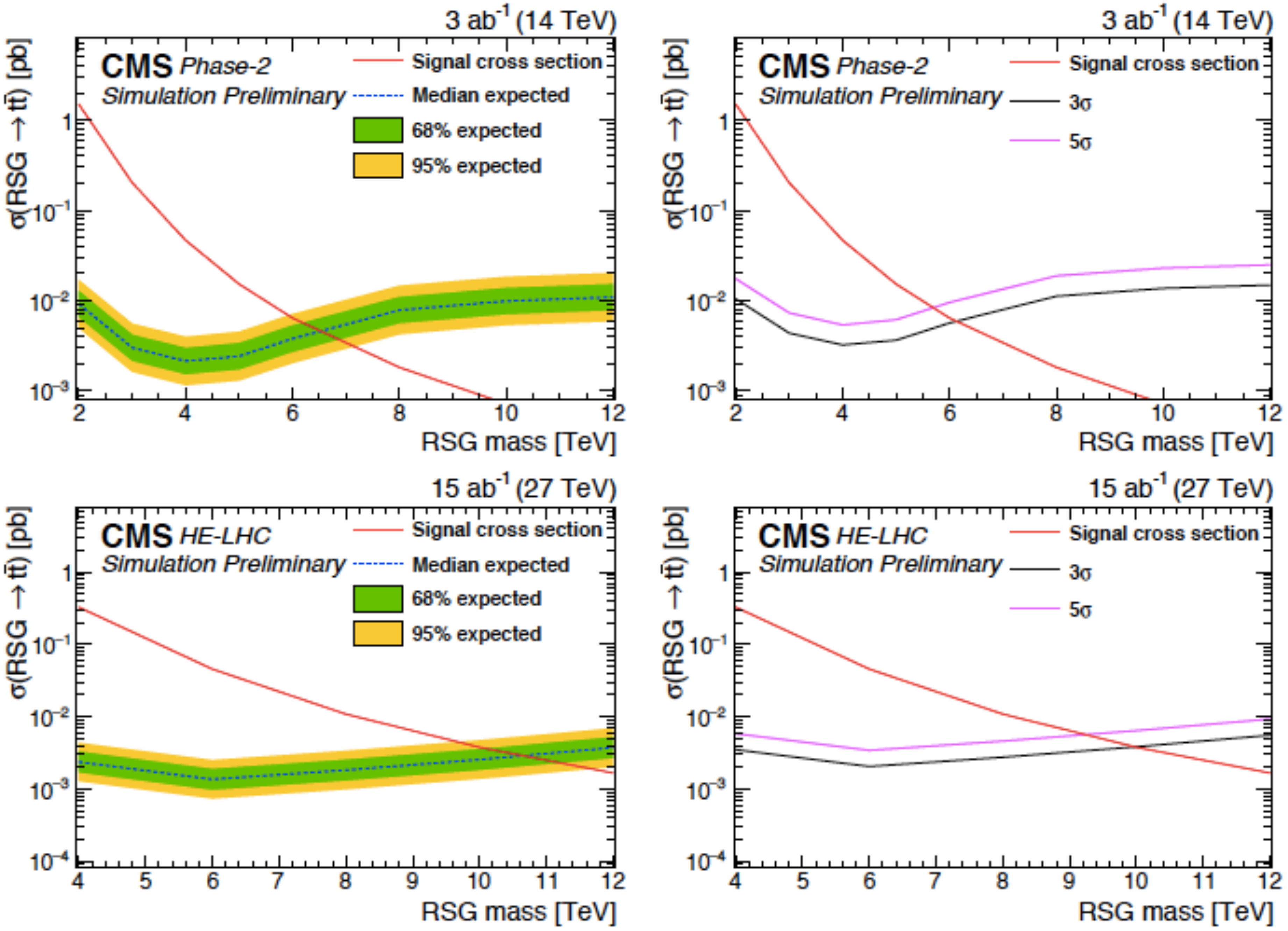
arXiv: 1812.07831





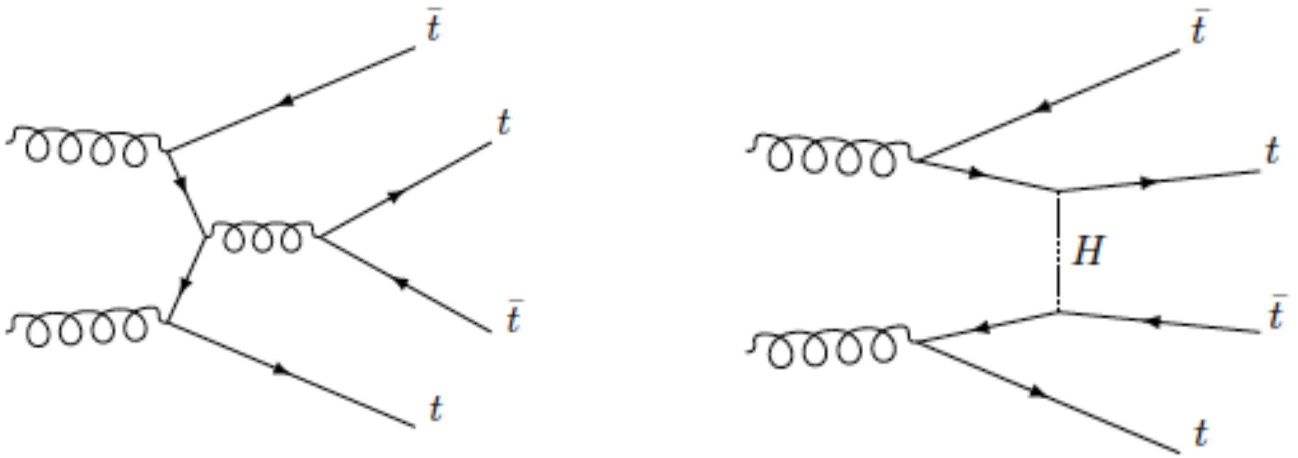
Spin-2 Resonance

at HL-LHC
and HE-LHC



Four Top production at the LHC

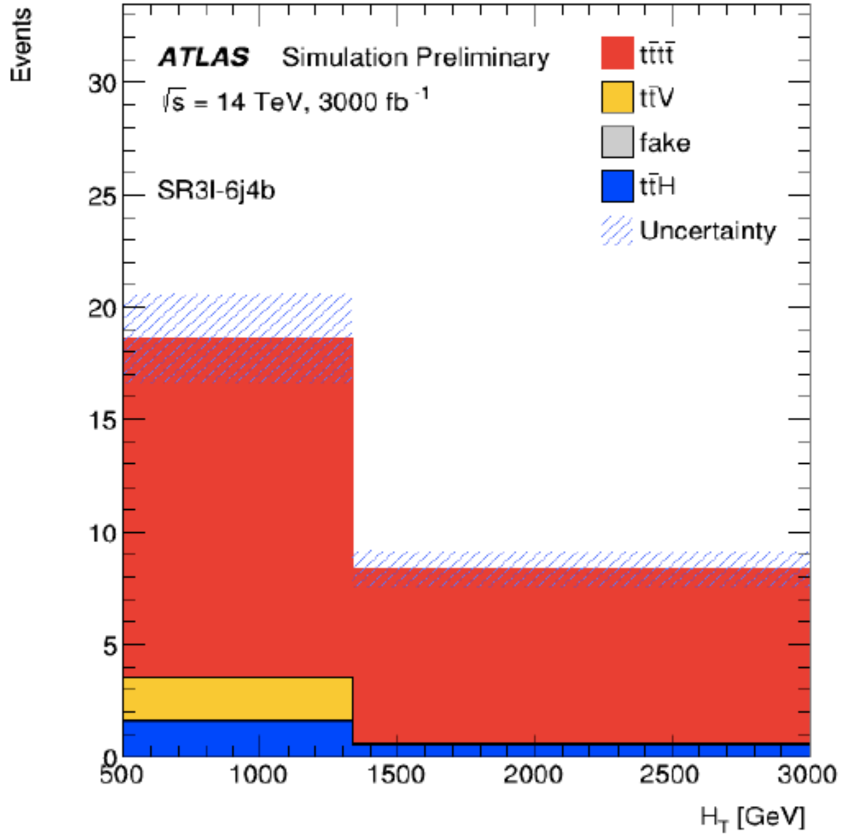
$$\sigma(pp \to t\bar{t}t\bar{t}) = 15.83^{+18\%}_{-21\%} \text{ fb at } 14 \text{ TeV}$$



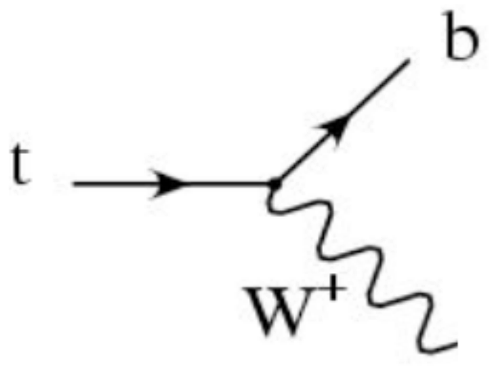
Explores top-top scattering

New physics possibilities

May be thought about for Working Group Activity (including QCD corrections and BSM)



Standard Decays of Top quark



/s / u

$$\Gamma_t = \frac{G_F\, M_{\rm top}^3}{8\,\pi\,\sqrt{2}} \left|V_{tb}\right|^2 \left(1 - \frac{M_W^2}{M_{\rm top}^2}\right)^2 \left(1 + 2\,\frac{M_W^2}{M_{\rm top}^2}\right)$$

$$|V_{tb}| = 1.019 \pm 0.028$$

$$|V_{ts}| = (39.4 \pm 2.3) \times 10^{-3}$$

$$|V_{td}| = (8.1 \pm 0.5) \times 10^{-3}$$

PDG, Phys.Rev. D98 (2018) no.3, 030001

Almost 100% decay to bW

Rare top decays

1) rare top decays (flavor changing neutral currents)

2 body decays: $t \to c\gamma$, $t \to cg$, $t \to cZ$, $t \to ch$

$t \to u\gamma$, $t \to ug$, $t \to uZ$, $t \to uh$

3 body decays: $t \to c\gamma h$, $t \to cgh$, $t \to c\ell^+\ell^-$, ...

$t \to u\gamma h$, $t \to ugh$, $t \to u\ell^+\ell^-$, ...

2) exotic top decays (into new physics particles)

light charged Higgs: $t \to H^\pm b$, $t \to H^\pm s$, $t \to H^\pm d$

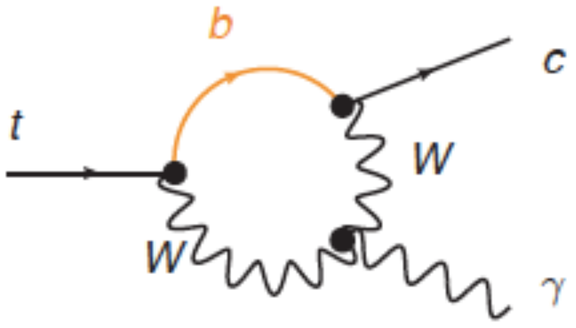
light neutral gauge boson: $t \to Z'c$, $t \to Z'u$

dark matter: $t \to \chi\chi c$, $t \to \chi\chi u$

$$\Gamma_t \simeq \frac{g_2^2}{64\pi}\left(\frac{m_t}{m_W}\right)^2 |V_{tb}|^2 m_t$$

Standard channel

top FCNCs are 1-loop suppressed, CKM suppressed and strongly GIM suppressed



$$\mathcal{A}_{t\to c\gamma} \propto \frac{e}{16\pi^2}\frac{G_F}{\sqrt{2}}\frac{m_b^2}{m_W^2}V_{tb}V_{cb}^*$$

$$\to \quad \mathrm{BR}(t\to c\gamma)_{\mathrm{SM}} \simeq 5\times 10^{-14}$$

(Aguilar-Saavedra hep-ph/0409342)

$$\mathrm{BR}(t\to c\gamma)\simeq 5\times 10^{-14} \quad , \quad \mathrm{BR}(t\to u\gamma)\simeq 4\times 10^{-16}$$

$$\mathrm{BR}(t\to cg)\simeq 5\times 10^{-12} \quad , \quad \mathrm{BR}(t\to ug)\simeq 4\times 10^{-14}$$

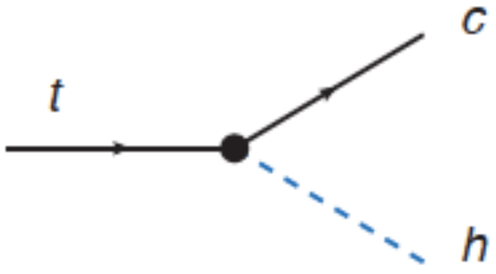
$$\mathrm{BR}(t\to cZ)\simeq 1\times 10^{-14} \quad , \quad \mathrm{BR}(t\to uZ)\simeq 8\times 10^{-17}$$

$$\mathrm{BR}(t\to ch)\simeq 3\times 10^{-15} \quad , \quad \mathrm{BR}(t\to uh)\simeq 2\times 10^{-17}$$

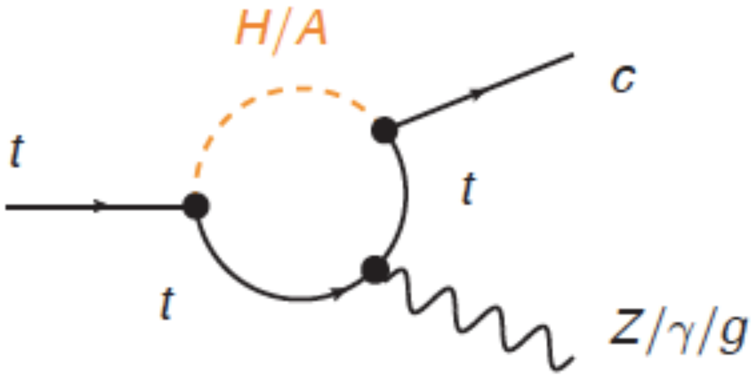
SM predictions

Beyond the SM

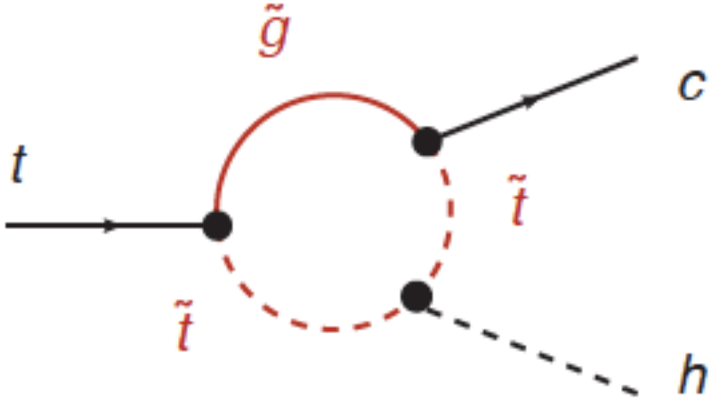
2HDM

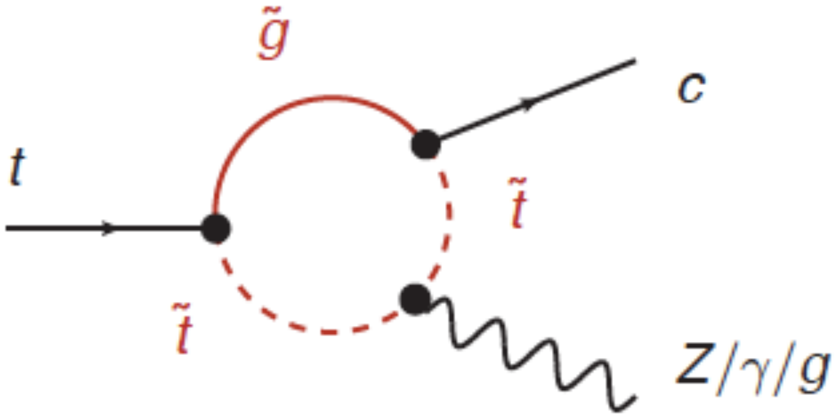


$t \to c\ Z/\gamma/g$ at the 1 loop level



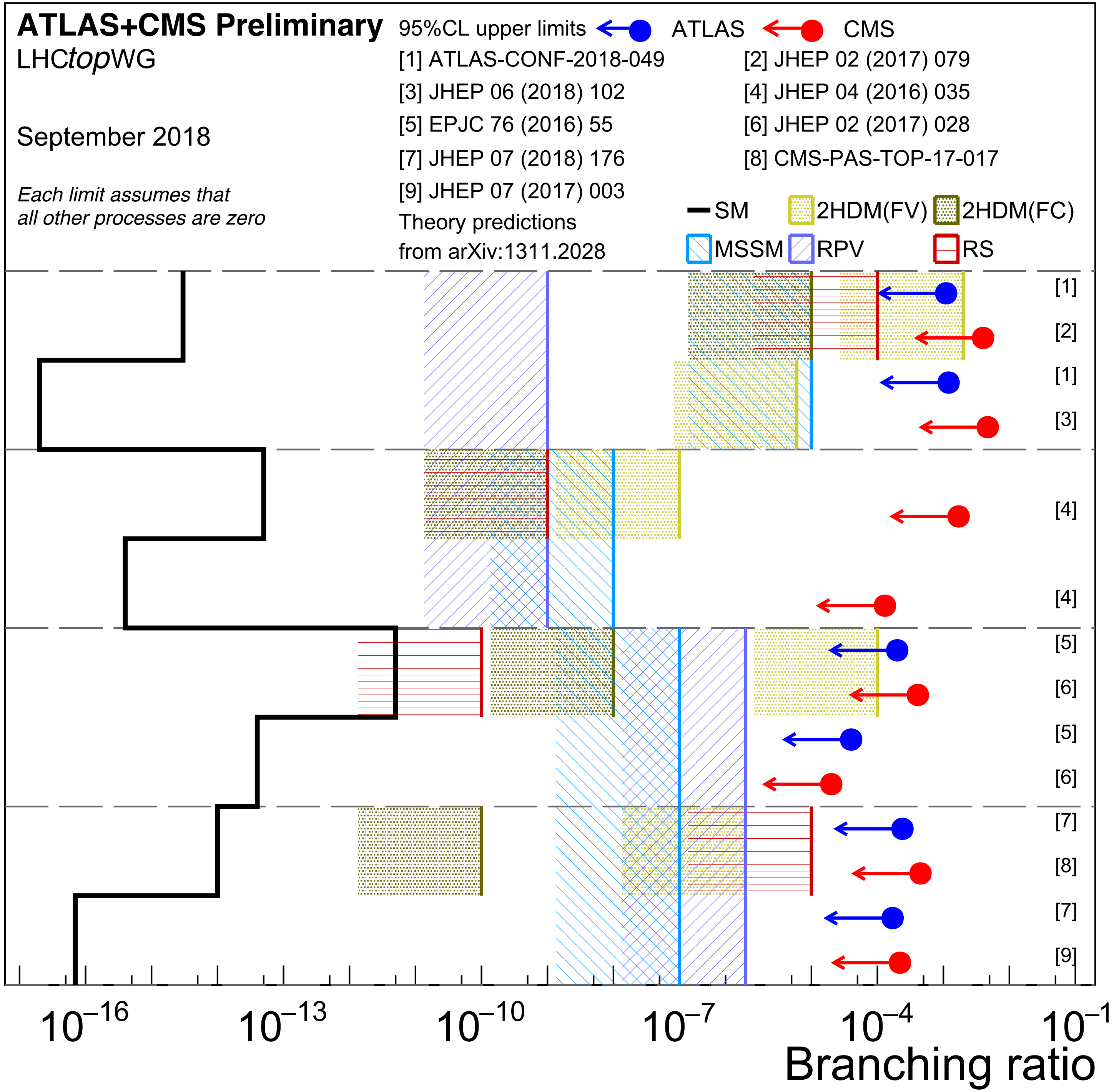
MSSM





Present Experimental status

and comparison with model predictions



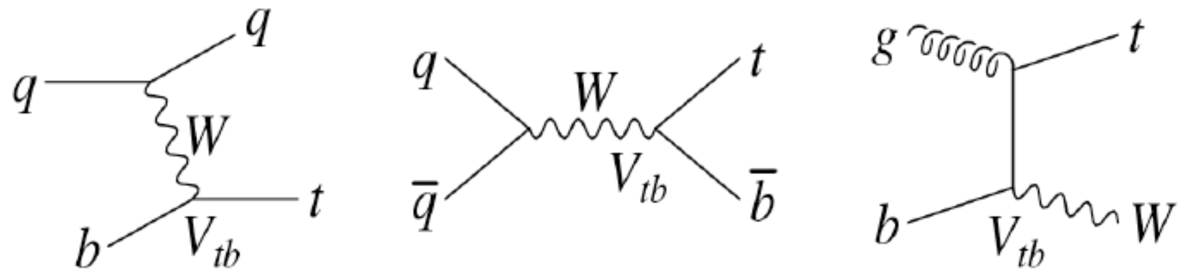
Assuming only one such coupling present at a time

Top Working Group Summary Plots

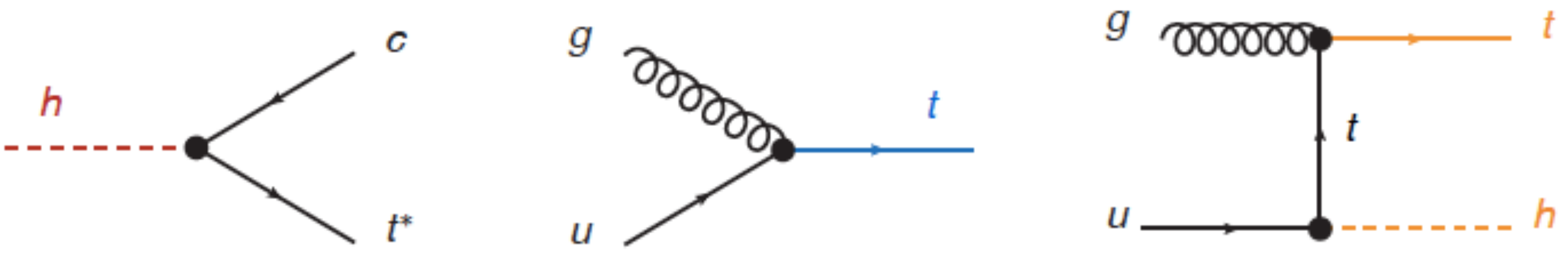
ATL-PHYS-PUB-2018-034

Apart from non-standard decays, large FCNC can invoke rare production channels

Standard Single top productions



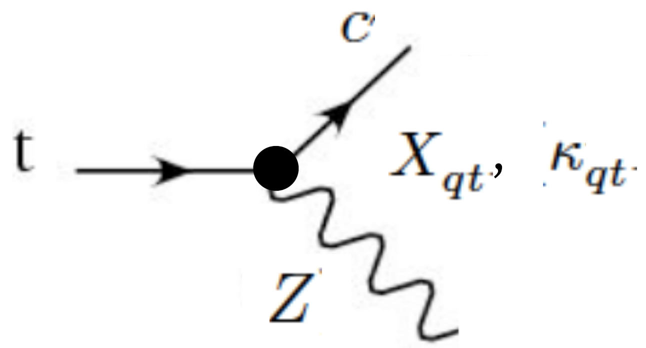
Non-Standard Single top productions include



Chen, Hou, Kao, Kohda 1304.8037; Atwood, Gupta, Soni 1305.2427

Greljo, Kamenik, Kopp 1404.1278; ...

Model Independent - Effective couplings



$$-\mathcal{L}_{\rm tqZ(\gamma)} = \frac{g}{2c_W}\bar{q}\gamma^\mu(X_{qt}^L P_L + X_{qt}^R P_R)tZ_\mu + \frac{g}{2c_W}\bar{q}\frac{i\sigma^{\mu\nu}q_\nu}{m_t}(\kappa_{qt}^L P_L + \kappa_{qt}^R P_R)tZ_\mu$$
$$+ e\bar{q}\frac{i\sigma^{\mu\nu}q_\nu}{m_t}(\kappa_{qt}^L(\gamma)P_L + \kappa_{qt}^R(\gamma)P_R)tA_\mu + \mathrm{H.c},$$

$$\Gamma(t\to qZ)_\gamma = \frac{\alpha}{32\, s_W^2 c_W^2}|X_{qt}|^2\frac{m_t^3}{M_Z^2}\left[1-\frac{M_Z^2}{m_t^2}\right]^2\left[1+2\frac{M_Z^2}{m_t^2}\right],$$
$$\Gamma(t\to qZ)_\sigma = \frac{\alpha}{16\, s_W^2 c_W^2}|\kappa_{qt}|^2 m_t\left[1-\frac{M_Z^2}{m_t^2}\right]^2\left[2+\frac{M_Z^2}{m_t^2}\right],$$
$$\Gamma(t\to q\gamma) = \frac{\alpha}{2}|\lambda_{qt}|^2 m_t,$$
$$\Gamma(t\to qg) = \frac{2\alpha_s}{3}|\zeta_{qt}|^2 m_t,$$
$$\Gamma(t\to qH) = \frac{\alpha}{32\, s_W^2}|g_{qt}|^2 m_t\left[1-\frac{M_H^2}{m_t^2}\right]^2.$$

$$\mathrm{Br}(t\to qZ)_\gamma = 0.472\, X_{qt}^2,$$
$$\mathrm{Br}(t\to qZ)_\sigma = 0.367\, \kappa_{qt}^2,$$
$$\mathrm{Br}(t\to q\gamma) = 0.428\, \lambda_{qt}^2,$$
$$\mathrm{Br}(t\to qg) = 7.93\, \zeta_{qt}^2,$$
$$\mathrm{Br}(t\to qH) = 3.88\times 10^{-2}\, g_{qt}^2$$

Current Limits:

$Br(t \to Zu(c)) < 1.7(2.4) \times 10^{-4}$	=> X_{qt}, κ^L_{qt} < 0.02	ATLAS	JHEP 07 (2018) 176
$\mathrm{BR}(t \to ug) \leq 4.0 \times 10^{-5}$	< 0.002	ATLAS	Eur.Phys. J.C. 76 (2016) 55
$\mathrm{BR}(t \to cg) \leq 2.0 \times 10^{-4}$	< 0.005		
$\mathrm{BR}(t \to u\gamma) \leq 1.3 \times 10^{-4}$	< 0.017	ATLAS	JHEP 04 (2016) 35
$\mathrm{BR}(t \to c\gamma) \leq 1.7 \times 10^{-3}$	< 0.063		
$\mathrm{BR}(t \to uH) \leq 2.4 \times 10^{-3}$	< 0.025	ATLAS	JHEP 1710 (2017) 120
$\mathrm{BR}(t \to cH) \leq 2.2 \times 10^{-3}$	< 0.024		

Expectations at HL-LHC (3 /ab)

$\mathrm{BR}(t \to cZ) \leq 5.8 \times 10^{-5}$ $\mathrm{BR}(t \to uZ) \leq 4.3 \times 10^{-5}$ $\mathrm{BR}(t \to q\gamma) \leq 2.5 \times 10^{-5}$

$t \to Hq < 1.2 \times 10^{-4}$ ATL-PHYS-PUB-2016-019 ATL-PHYS-PUB-2013-007

Expected reach on the BR

Top Quark Working Group 1311.2028

Process	Br Limit	Search	Dataset	Reference
$t \to Zq$	2.2×10^{-4}	ATLAS $t\bar{t} \to Wb + Zq \to \ell\nu b + \ell\ell q$	300 fb^{-1}, 14 TeV	[140]
$t \to Zq$	7×10^{-5}	ATLAS $t\bar{t} \to Wb + Zq \to \ell\nu b + \ell\ell q$	3000 fb^{-1}, 14 TeV	[140]
$t \to Zq$	$5\,(2) \times 10^{-4}$	ILC single top, γ_μ $(\sigma_{\mu\nu})$	500 fb^{-1}, 250 GeV	Extrap.
$t \to Zq$	$1.5\,(1.1) \times 10^{-4\,(-5)}$	ILC single top, γ_μ $(\sigma_{\mu\nu})$	500 fb^{-1}, 500 GeV	[141]
$t \to Zq$	$1.6\,(1.7) \times 10^{-3}$	ILC $t\bar{t}$, γ_μ $(\sigma_{\mu\nu})$	500 fb^{-1}, 500 GeV	[141]
$t \to \gamma q$	8×10^{-5}	ATLAS $t\bar{t} \to Wb + \gamma q$	300 fb^{-1}, 14 TeV	[140]
$t \to \gamma q$	2.5×10^{-5}	ATLAS $t\bar{t} \to Wb + \gamma q$	3000 fb^{-1}, 14 TeV	[140]
$t \to \gamma q$	6×10^{-5}	ILC single top	500 fb^{-1}, 250 GeV	Extrap.
$t \to \gamma q$	6.4×10^{-6}	ILC single top	500 fb^{-1}, 500 GeV	[141]
$t \to \gamma q$	1.0×10^{-4}	ILC $t\bar{t}$	500 fb^{-1}, 500 GeV	[141]
$t \to gu$	4×10^{-6}	ATLAS $qg \to t \to Wb$	300 fb^{-1}, 14 TeV	Extrap.
$t \to gu$	1×10^{-6}	ATLAS $qg \to t \to Wb$	3000 fb^{-1}, 14 TeV	Extrap.
$t \to gc$	1×10^{-5}	ATLAS $qg \to t \to Wb$	300 fb^{-1}, 14 TeV	Extrap.
$t \to gc$	4×10^{-6}	ATLAS $qg \to t \to Wb$	3000 fb^{-1}, 14 TeV	Extrap.
$t \to hq$	2×10^{-3}	LHC $t\bar{t} \to Wb + hq \to \ell\nu b + \ell\ell qX$	300 fb^{-1}, 14 TeV	Extrap.
$t \to hq$	5×10^{-4}	LHC $t\bar{t} \to Wb + hq \to \ell\nu b + \ell\ell qX$	3000 fb^{-1}, 14 TeV	Extrap.
$t \to hq$	5×10^{-4}	LHC $t\bar{t} \to Wb + hq \to \ell\nu b + \gamma\gamma q$	300 fb^{-1}, 14 TeV	Extrap.
$t \to hq$	2×10^{-4}	LHC $t\bar{t} \to Wb + hq \to \ell\nu b + \gamma\gamma q$	3000 fb^{-1}, 14 TeV	Extrap.

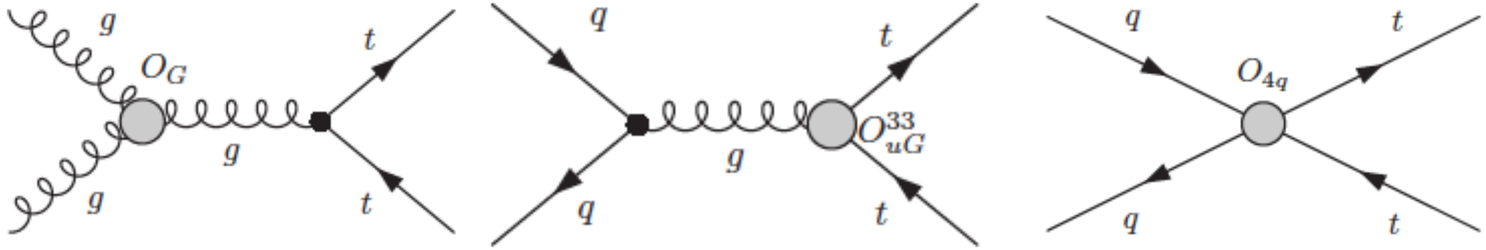
NP through Effective Lagrangian (SMEFT)
Anomalous Couplings

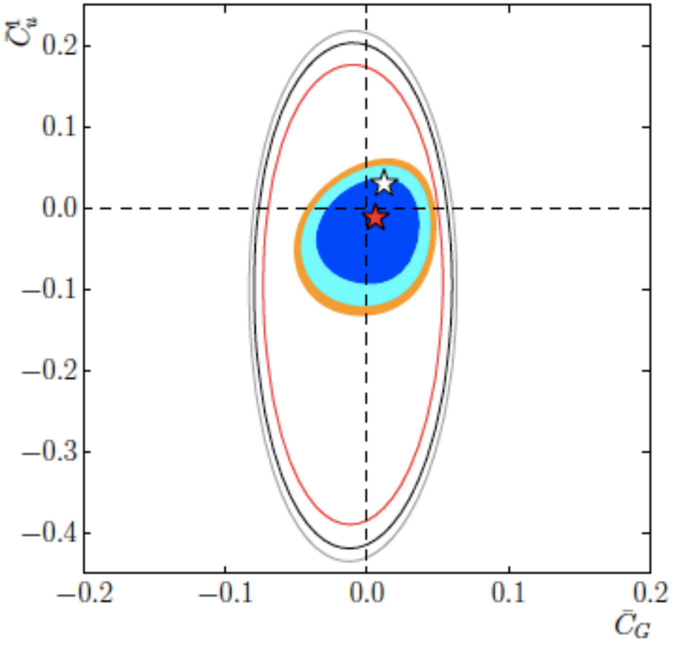
TopFitter Collaboration
1512.03360

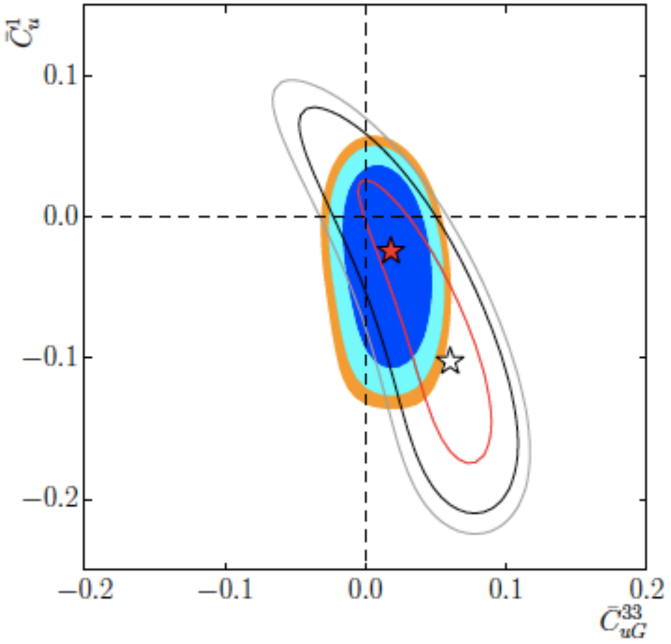
$$\mathcal{L} = \mathcal{L}^{SM} + \sum \frac{c_i}{\Lambda^2}\mathcal{O}_i + O\left(\frac{1}{\Lambda^4}\right)$$

$$\mathcal{L}_{D6} \supset \frac{C_{uG}}{\Lambda^2}(\bar{q}\sigma^{\mu\nu}T^A u)\tilde{\varphi}G^A_{\mu\nu} + \frac{C_G}{\Lambda^2} f_{ABC} G^{A\nu}_{\mu} G^{B\lambda}_{\nu} G^{C\mu}_{\lambda} + \frac{C_{\varphi G}}{\Lambda^2}(\varphi^\dagger\varphi) G^A_{\mu\nu} G^{A\mu\nu}$$
$$+ \frac{C^{(1)}_{qq}}{\Lambda^2}(\bar{q}\gamma_\mu q)(\bar{q}\gamma^\mu q) + \frac{C^{(3)}_{qq}}{\Lambda^2}(\bar{q}\gamma_\mu \tau^I q)(\bar{q}\gamma^\mu \tau^I q) + \frac{C_{uu}}{\Lambda^2}(\bar{u}\gamma_\mu u)(\bar{u}\gamma^\mu u)$$
$$+ \frac{C^{(8)}_{qu}}{\Lambda^2}(\bar{q}\gamma_\mu T^A q)(\bar{u}\gamma^\mu T^A u) + \frac{C^{(8)}_{qd}}{\Lambda^2}(\bar{q}\gamma_\mu T^A q)(\bar{d}\gamma^\mu T^A d) + \frac{C^{(8)}_{ud}}{\Lambda^2}(\bar{u}\gamma_\mu T^A u)(\bar{d}\gamma^\mu T^A d)$$

$$C^1_u = C^{(1)1331}_{qq} + C^{1331}_{uu} + C^{(3)1331}_{qq}$$







NP through Effective Lagrangian (SMEFT) Anomalous Couplings

$$\mathcal{L} = \mathcal{L}^{SM} + \sum \frac{c_i}{\Lambda^2}\mathcal{O}_i + O\left(\frac{1}{\Lambda^4}\right)$$

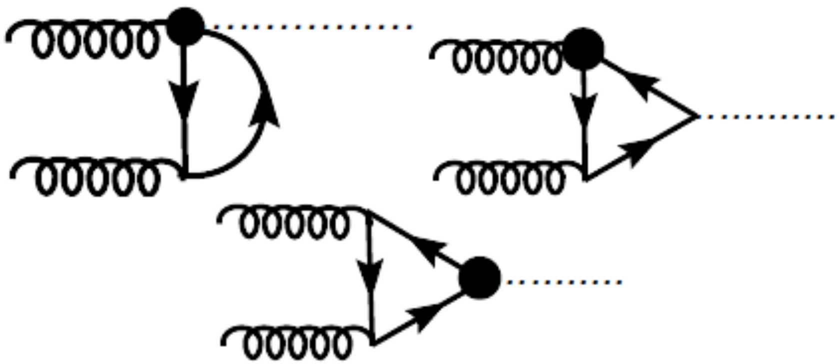
$$\mathcal{O}_{hg} = (\bar{Q}_L H)\,\sigma^{\mu\nu} T^a t_R G^a_{\mu\nu}, \qquad \mathcal{O}_{HG} = \frac{1}{2} H^\dagger H G^a_{\mu\nu} G^{\mu\nu}_a$$

$$\mathcal{O}_{Hy} = H^\dagger H\,(H\bar{Q}_L)\,t_R$$

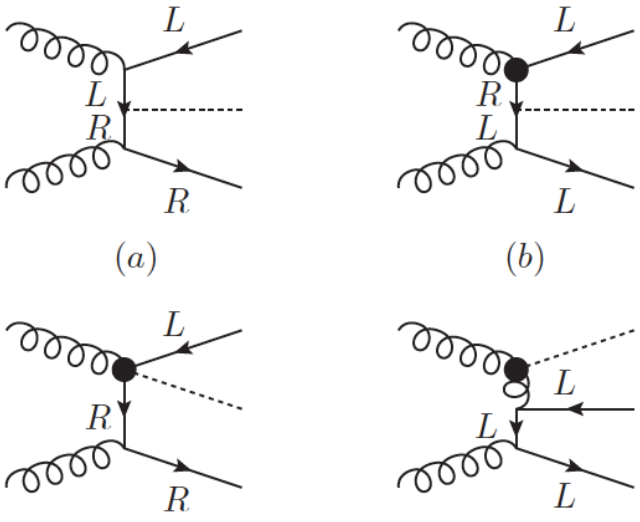
$$\mathcal{O}_{Ht} = H^\dagger D_\mu H \bar{t}_R \gamma^\mu t_R \qquad \mathcal{O}_{H\gamma} = \frac{1}{2} H^\dagger H F_{\mu\nu} F^{\mu\nu}$$

$$\mathcal{O}_{HQ} = H^\dagger D_\mu H \bar{Q}_L \gamma^\mu Q_L \qquad \mathcal{O}_H = \partial_\mu (H^\dagger H)\,\partial^\mu (H^\dagger H)$$

$$\mathcal{O}^{(3)}_{HQ} = H^\dagger \sigma^I D_\mu H \bar{Q}_L \sigma^I \gamma^\mu Q_L$$



$$\sigma(gg \to h) = \sigma(gg \to h)_{SM}\left(1 + \frac{c_{HG}}{\Lambda^2}\frac{6\pi v^2}{\alpha_s}\right)^2$$



C. Degrande, et al
JHEP 1207 (2012) 036,
1205.1065

$$\mathcal{L}^{ht\bar{t}} = \bar{t}t\frac{h}{\sqrt{2}}\left(y_t - \left(\frac{3}{2}\Re(c_{Hy}) + y_t c_H\right)\frac{v^2}{\Lambda^2}\right) = \bar{t}th\frac{m_t}{v}\left(1 - c_y\frac{v^2}{\Lambda^2}\right),$$

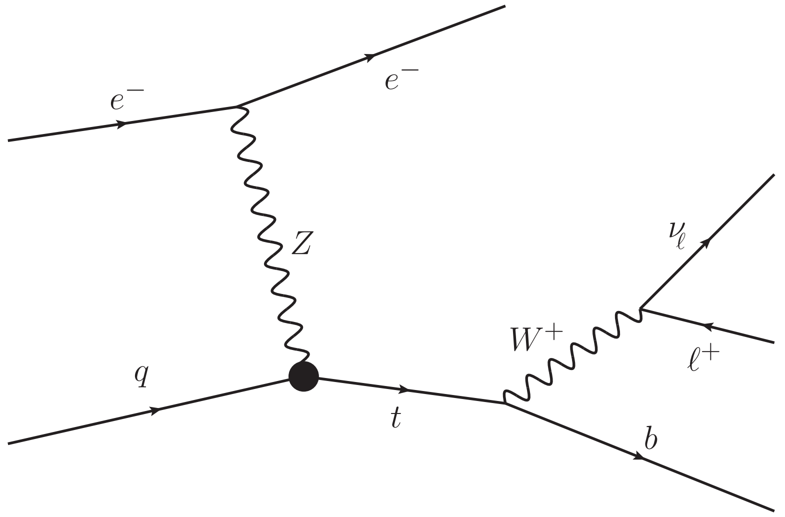
$\sqrt{s} = 14\ TeV$

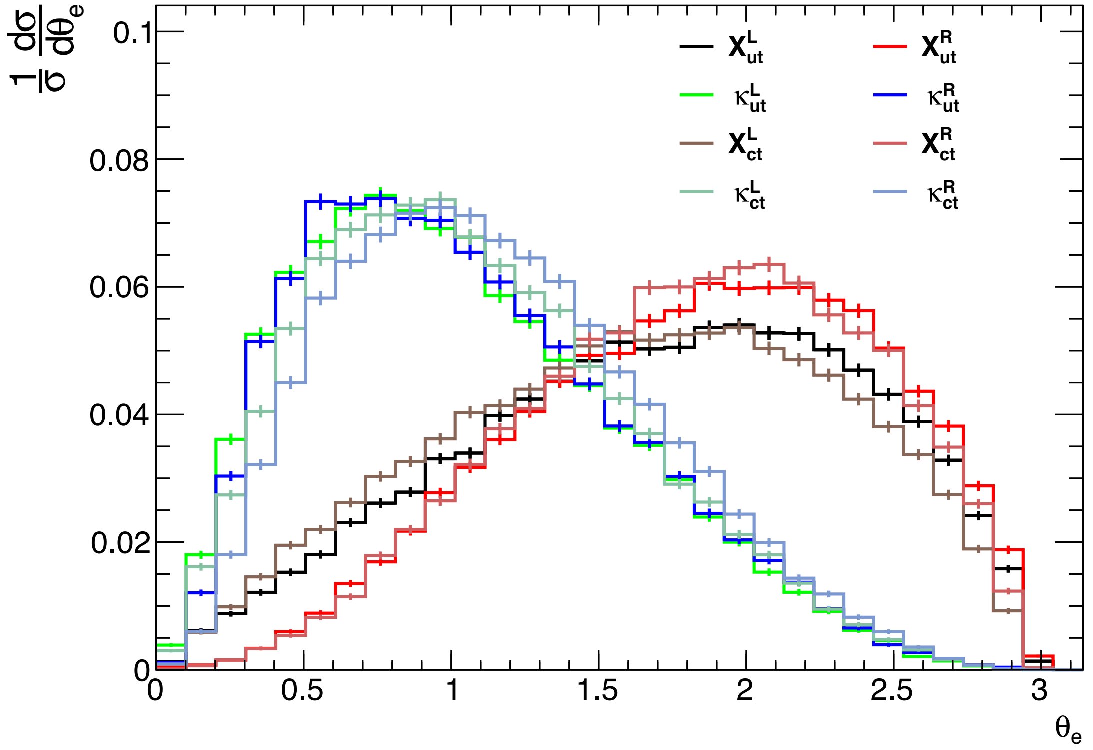
$$\begin{aligned}\frac{\sigma(pp \to t\bar{t}h)}{\text{fb}} &= 611^{+92}_{-110} + \Big[457^{+127}_{-91}\Re c_{hg} - 49^{+15}_{-10} c_G \\ &+ 147^{+55}_{-32} c_{HG} - 67^{+23}_{-16} c_y\Big]\left(\frac{\text{TeV}}{\Lambda}\right)^2 \\ &+ \Big[543^{+143}_{-123}(\Re c_{hg})^2 + 1132^{+323}_{-232} c_G^2 \\ &+ 85.5^{+73}_{-21} c_{HG}^2 + 2^{+0.7}_{-0.5} c_y^2 \\ &+ 233^{+81}_{-144}\Re c_{hg} c_{HG} - 50^{+16}_{-14}\Re c_{hg} c_y \\ &- 3.2^{+8}_{-8}\Re c_{Hy} c_{HG} - 1.2^{+8}_{-8} c_H c_{HG}\Big]\left(\frac{\text{TeV}}{\Lambda}\right)^4, \end{aligned} \qquad (18)$$

Top FCNC through ep > et

S. Behera, R. Rahqman, R. Islam, M. Kumar, PP, 1811.04681

$$-\mathcal{L}_{\rm tqZ(\gamma)} = \frac{g}{2c_W}\bar{q}\gamma^\mu(X^L_{qt}P_L + X^R_{qt}P_R)tZ_\mu + \frac{g}{2c_W}\bar{q}\frac{i\sigma^{\mu\nu}q_\nu}{m_t}(\kappa^L_{qt}P_L + \kappa^R_{qt}P_R)tZ_\mu + e\bar{q}\frac{i\sigma^{\mu\nu}q_\nu}{m_t}(\kappa^L_{qt}(\gamma)P_L + \kappa^R_{qt}(\gamma)P_R)tA_\mu + \text{H.c},$$



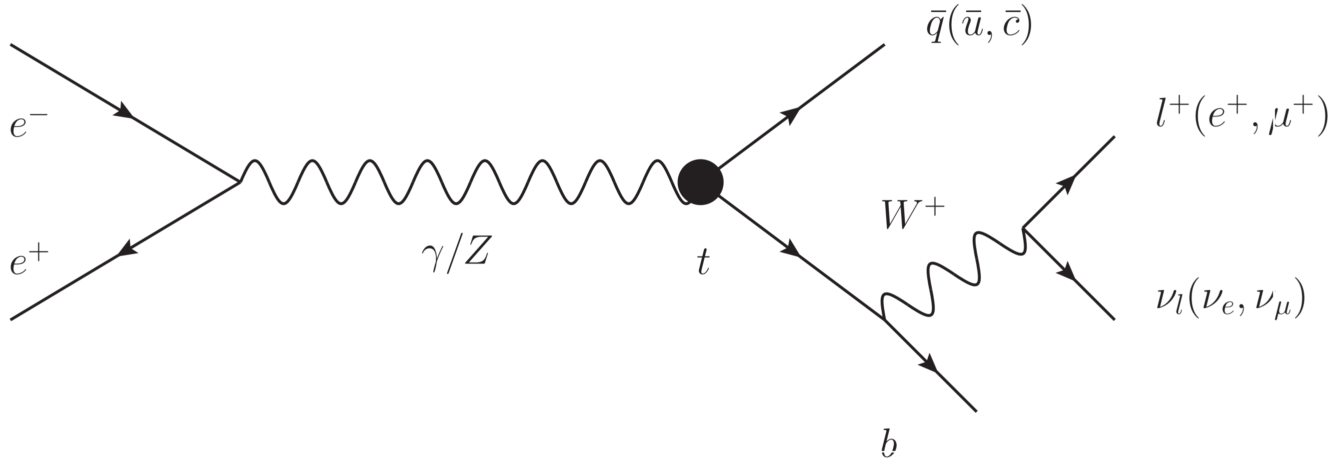


The scattered electron as a discriminator

Lorentz structure of the coupling can be probed.

Something quite hard at LHC

At the ILC250



Work under progress

Summary

Apart from probing resonant production of new physics particle, precise measurement
top quark couplings can provide information of physics beyond the Standard Model.

Good knowledge of the top quark couplings are essential to extract Higgs coupling information.

LHC producing plenty of top quark pairs, can perform precision measurements including rare top decays.

Other colliders like electron-proton collider, and the ILC can complement the LHC studies, and have the potential to provide additional informations like the Lorentz structure of the couplings, which are difficult to probe at the LHC.

Thank you

Top Quark Production Cross Section Measurements

ATLAS Preliminary

Run 1,2 $\sqrt{s}$ = 7, 8, 13

Status: November 2018

Model	E_{CM} [TeV]	$\int\mathcal{L}\,dt[fb^{-1}]$	Measurement	Theory	Reference
$t\bar{t}$	13	3.2	$\sigma = 818 \pm 8 \pm 35$ pb	$\sigma = 832^{+40}_{-46}$ pb (top++ NNLO+NLL)	PLB 761 (2016) 136
$t\bar{t}$	8	20.2	$\sigma = 242.9 \pm 1.7 \pm 8.6$ pb	$\sigma = 252.9^{+13.3}_{-14.5}$ pb (top++ NNLO+NNLL)	EPJC 74 (2014) 3109
$t\bar{t}$	7	4.6	$\sigma = 182.9 \pm 3.1 \pm 6.4$ pb	$\sigma = 177^{+10}_{-11}$ pb (top++ NNLO+NNLL)	EPJC 74 (2014) 3109
t_{t-chan}	13	3.2	$\sigma = 247 \pm 6 \pm 45$ pb	$\sigma = 217 \pm 10$ pb (NLO)	JHEP 04 (2017) 086
t_{t-chan}	8	20.2	$\sigma = 89.6 \pm 1.2^{+7}_{-6.2}$ pb	$\sigma = 87.8^{+3.4}_{-1.9}$ pb (NLO+NNLL)	EPJC 77 (2017) 531
t_{t-chan}	7	4.6	$\sigma = 68 \pm 2 \pm 8$ pb	$\sigma = 64.6^{+2.7}_{-2}$ pb (NLO+NNLL)	PRD 90 (2014) 112006
tW	13	3.2	$\sigma = 94 \pm 10^{+28}_{-22}$ pb	$\sigma = 71.7 \pm 3.9$ pb (NLO+NNLL)	JHEP 01 (2018) 63
tW	8	20.3	$\sigma = 23 \pm 1.3^{+3.4}_{-3.7}$ pb	$\sigma = 22.4 \pm 1.5$ pb (NLO+NNLL)	JHEP 01 (2016) 64
tW	7	2.0	$\sigma = 16.8 \pm 2.9 \pm 4.9$ pb	$\sigma = 15.7 \pm 1.1$ pb (NLO+NNLL)	PLB 716 (2012) 142
t_{s-chan}	8	20.3	$\sigma = 4.8 \pm 0.8^{+1.6}_{-1.3}$ pb	$\sigma = 5.61 \pm 0.22$ pb (NLO+NNLL)	PLB 756 (2016) 228

Top Quark Production Cross Section Measurements

ATLAS Preliminary

Run 1,2 $\sqrt{s}$ = 7, 8, 13

Status: November 2018

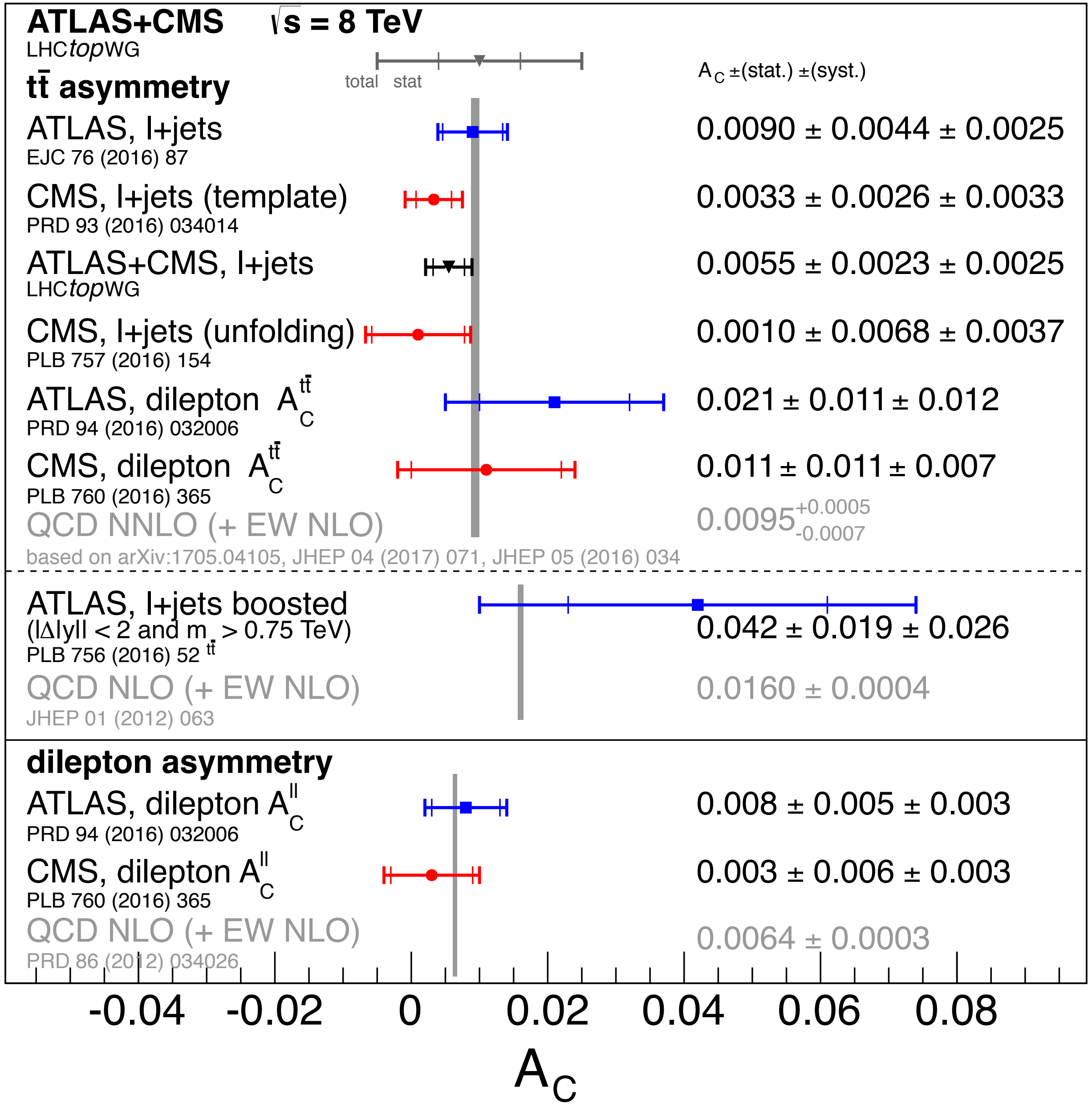
Model	E_{CM} [TeV]	$\int \mathcal{L}\, dt [fb^{-1}]$	Measurement	Theory	Reference
$t\bar{t}W$	13	36.1	$\sigma = 0.87 \pm 0.13 \pm 0.14$ pb	$\sigma = 0.6^{+0.08}_{-0.07}$ pb (Madgraph5 + aMCNLO)	ATLAS-CONF-2018-047
$t\bar{t}W$	8	20.3	$\sigma = 369^{+86}_{-79} \pm 44$ fb	$\sigma = 232 \pm 32$ fb (MCFM)	JHEP 11 (2015) 172
$t\bar{t}Z$	13	36.1	$\sigma = 0.95 \pm 0.08 \pm 0.1$ pb	$\sigma = 0.88^{+0.09}_{-0.11}$ pb (Madgraph5 + aMCNLO)	ATLAS-CONF-2018-047
$t\bar{t}Z$	8	20.3	$\sigma = 176^{+52}_{-48} \pm 24$ fb	$\sigma = 215 \pm 30$ fb (HELAC-NLO)	JHEP 11 (2015) 172
tZj	13	36.1	$\sigma = 620 \pm 170 \pm 160$ fb	$\sigma = 800^{+50}_{-60}$ fb (Madgraph5 + aMCNLO)	PLB 780 (2018) 557
$t\bar{t}H$	13	79.8	$\sigma = 670 \pm 90^{+110}_{-100}$ fb	$\sigma = 507^{+35}_{-50}$ fb (LHCHXSWG NLO QCD + NLO EW)	PLB 784 (2018) 173
$t\bar{t}H$	8	20.3	$\sigma = 220 \pm 100 \pm 70$ fb	$\sigma = 133^{+8}_{-13}$ fb (LHCHXSWG NLO QCD + NLO EW)	PLB 784 (2018) 173
$t\bar{t}\gamma$	13	36.1	$\sigma = 521 \pm 9 \pm 41$ fb	$\sigma = 495 \pm 99$ fb (MadGraph+PRD 83 (2011) 074013)	ATLAS-CONF-2018-048
$t\bar{t}\gamma$	8	20.2	$\sigma = 139 \pm 7 \pm 17$ fb	$\sigma = 151 \pm 25$ fb (MadGraph+PRD 83 (2011) 074013)	JHEP 11 (2017) 086
$t\bar{t}\gamma$	7	4.6	$\sigma = 63 \pm 8^{+17}_{-13}$ fb	$\sigma = 48 \pm 10$ fb (Whizard+NLO)	PRD 91 (2015) 072007

Top quark pair production: Charge Asymmetry

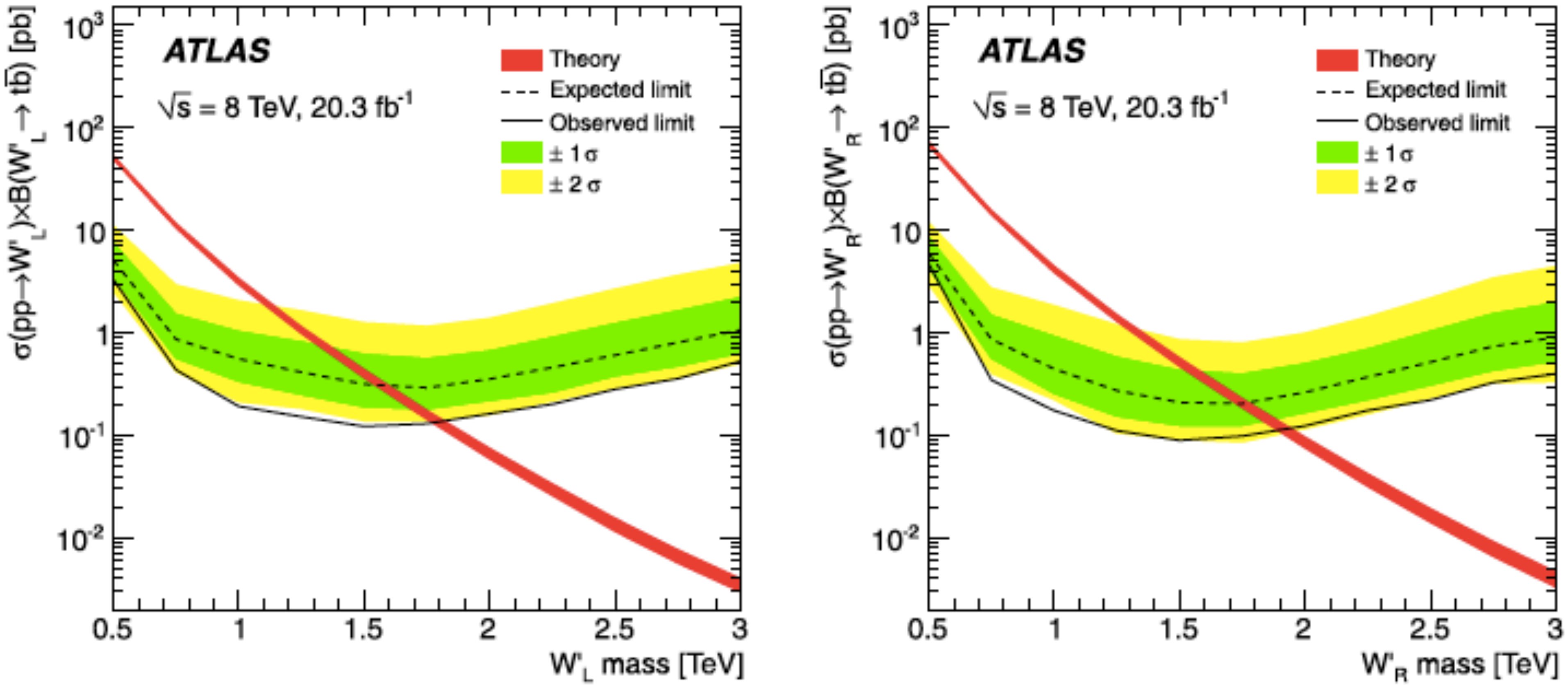
$$A_C^{\Delta|y|} = \frac{N(\Delta|y| > 0) - N(\Delta|y| < 0)}{N(\Delta|y| > 0) + N(\Delta|y| < 0)}$$

$$\Delta|y| = |y_t| - |y_{\bar{t}}|$$

Difference in the top anti-top rapidities



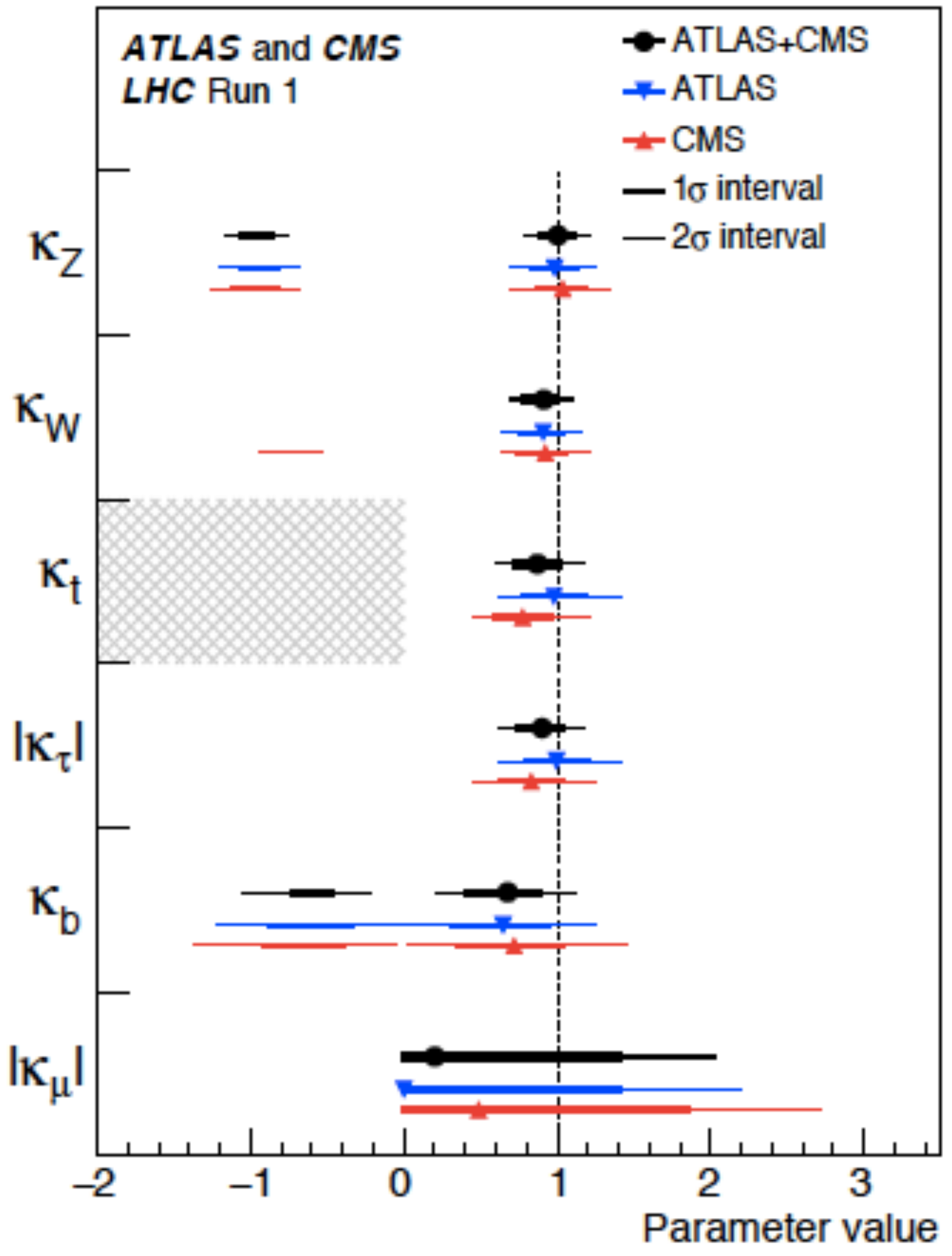
W’ -> tb by ATLAS Physics Letters B 743 (2015) 235–255

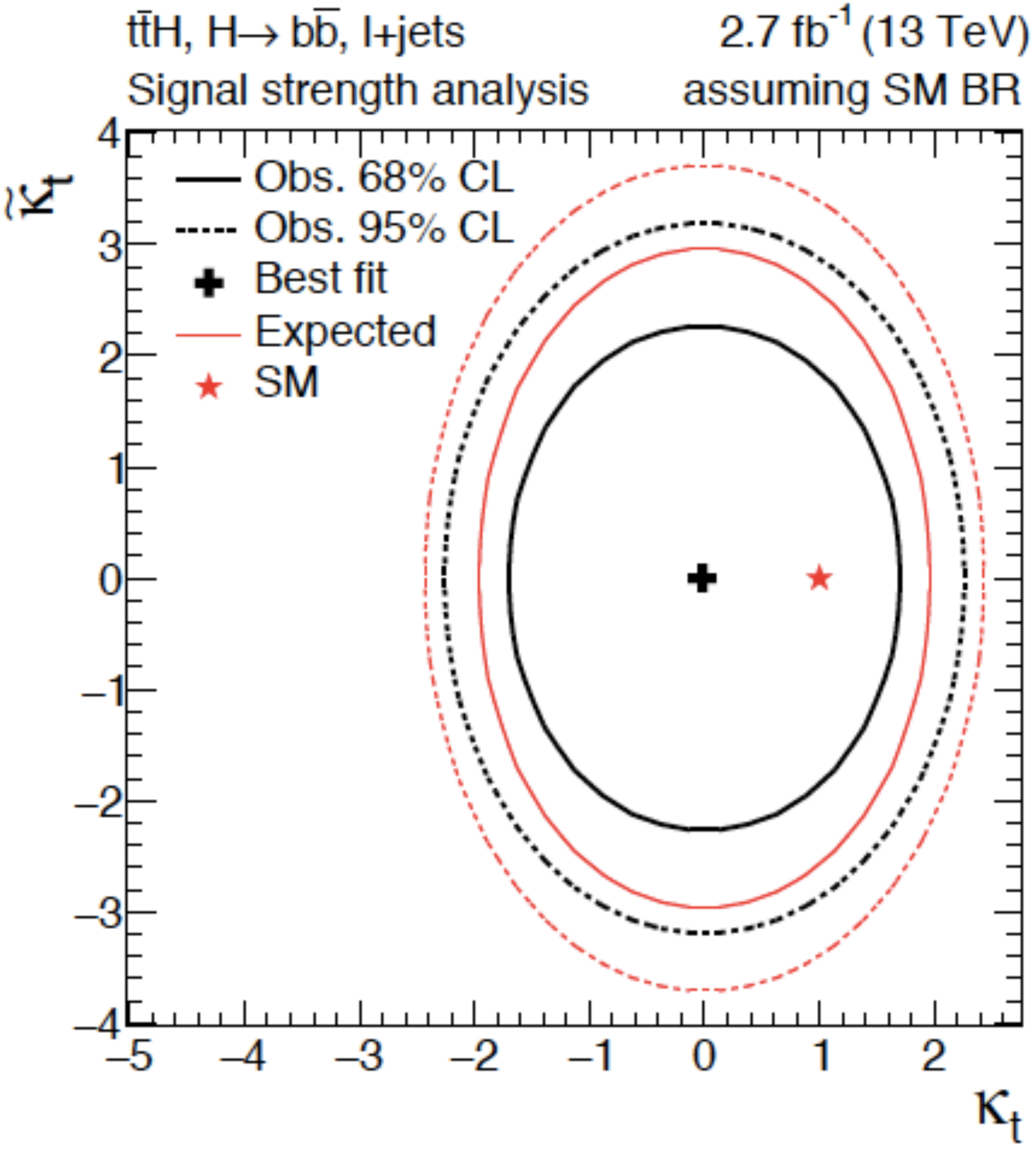


(a) (b)

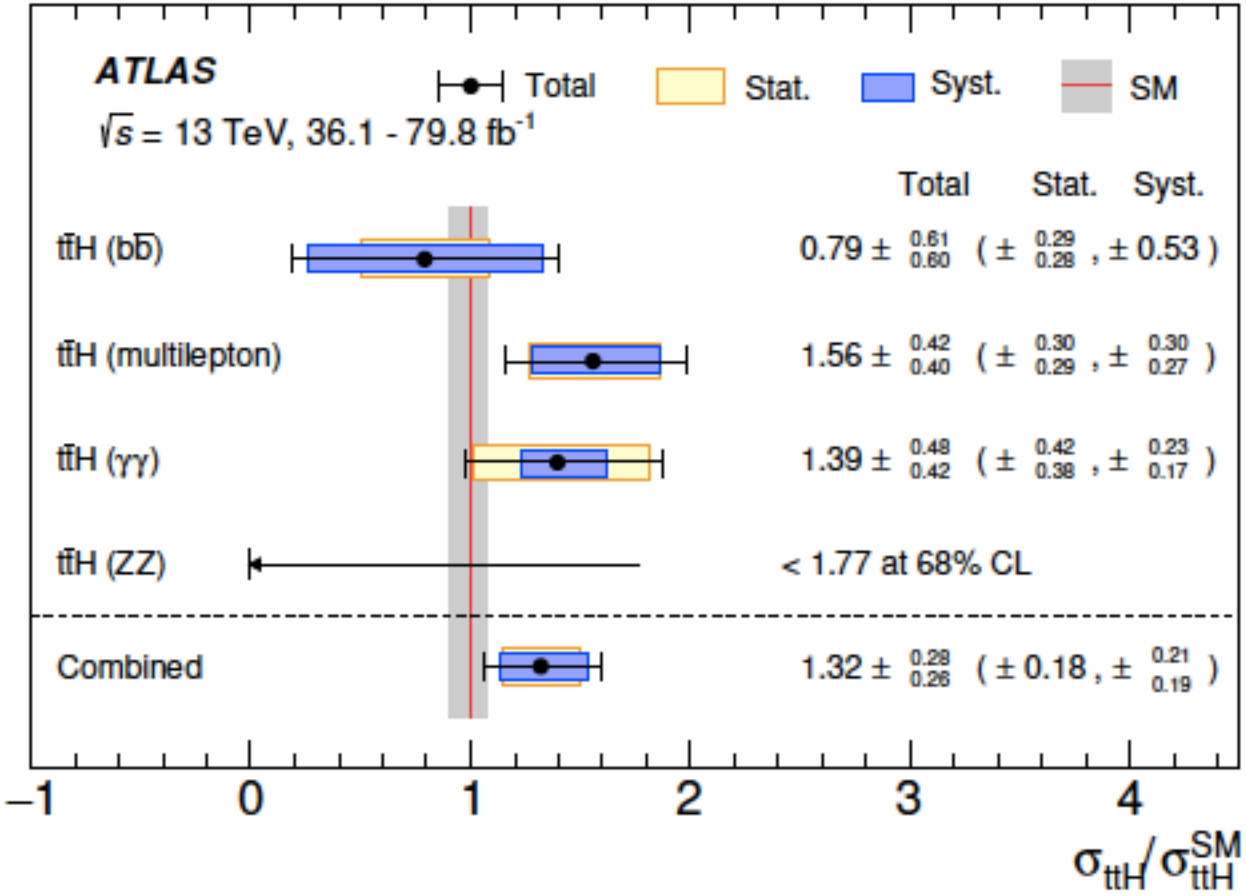
ATLAS and CMS, JHEP 1608 (2016) 045

Process	Resolved	Effective
σ_{ggH}	$1.06\kappa_t^2 + 0.01\kappa_b^2 - 0.07\kappa_t\kappa_b$	κ_g^2
σ_{VBF}	$0.74\kappa_W^2 + 0.26\kappa_Z^2$	
σ_{WH}	κ_W^2	
$\sigma_{q\bar{q}\to \mathrm{ZH}}$	κ_Z^2	
$\sigma_{gg\to \mathrm{ZH}}$	$2.27\kappa_Z^2 + 0.37\kappa_t^2 - 1.64\kappa_Z\kappa_t$	
$\sigma_{t\bar{t}\mathrm{H}}$	κ_t^2	
σ_{tHW}	$1.84\kappa_t^2 + 1.57\kappa_W^2 - 2.41\kappa_W\kappa_t$	
σ_{tHq}	$3.40\kappa_t^2 + 3.56\kappa_W^2 - 5.96\kappa_t\kappa_W$	
$\sigma_{b\bar{b}\mathrm{H}}$	κ_b^2	
Γ_{ZZ}	κ_Z^2	
Γ_{WW}	κ_W^2	
$\Gamma_{b\bar{b}}$	κ_b^2	
$\Gamma_{\tau\tau}$	κ_τ^2	
$\Gamma_{\gamma\gamma}$	$1.59\kappa_W^2 + 0.07\kappa_t^2 - 0.66\kappa_W\kappa_t$	κ_γ^2

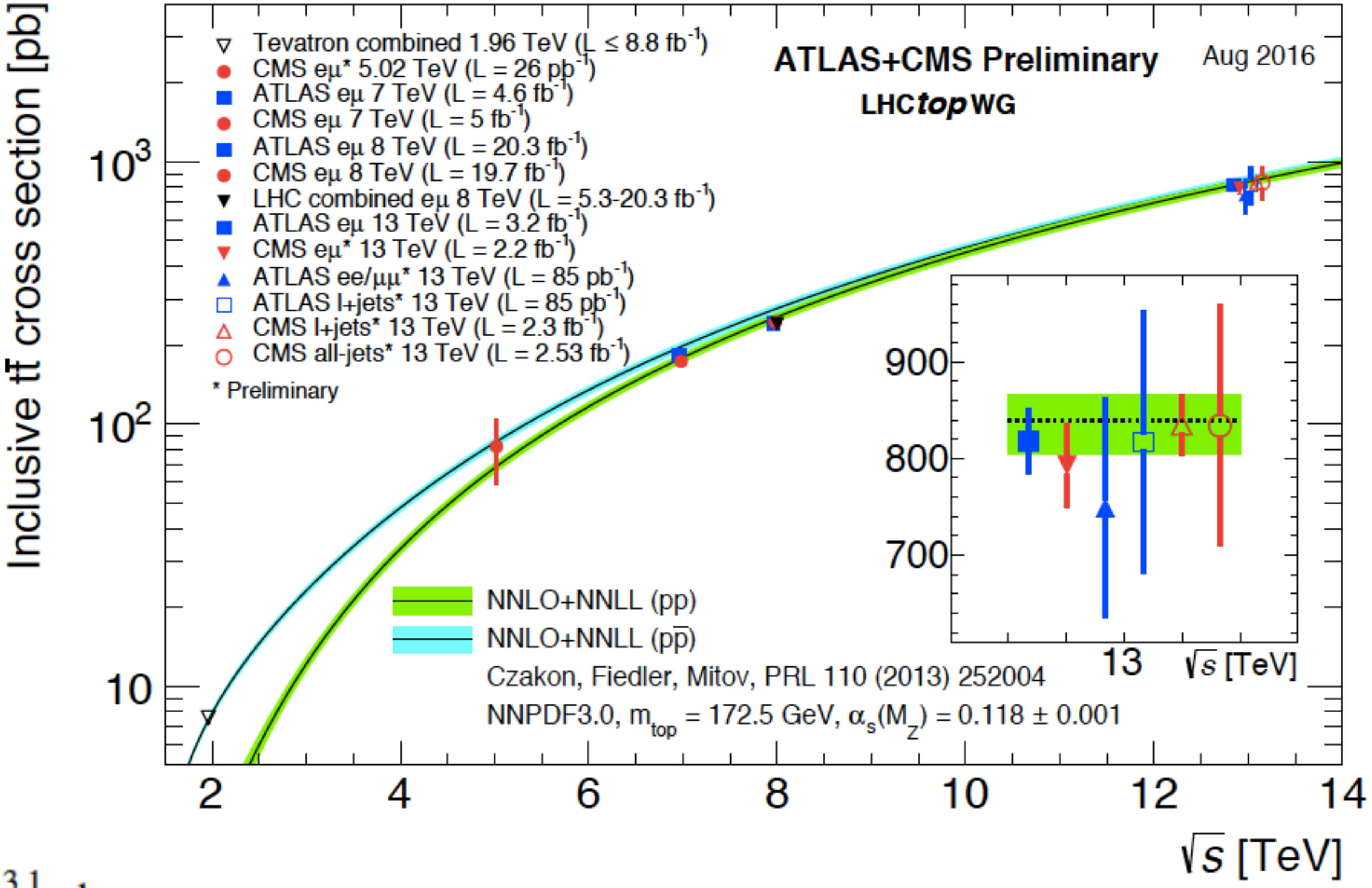




ATLAS, Phys.Lett. B784 (2018) 173-191



Top production at LHC

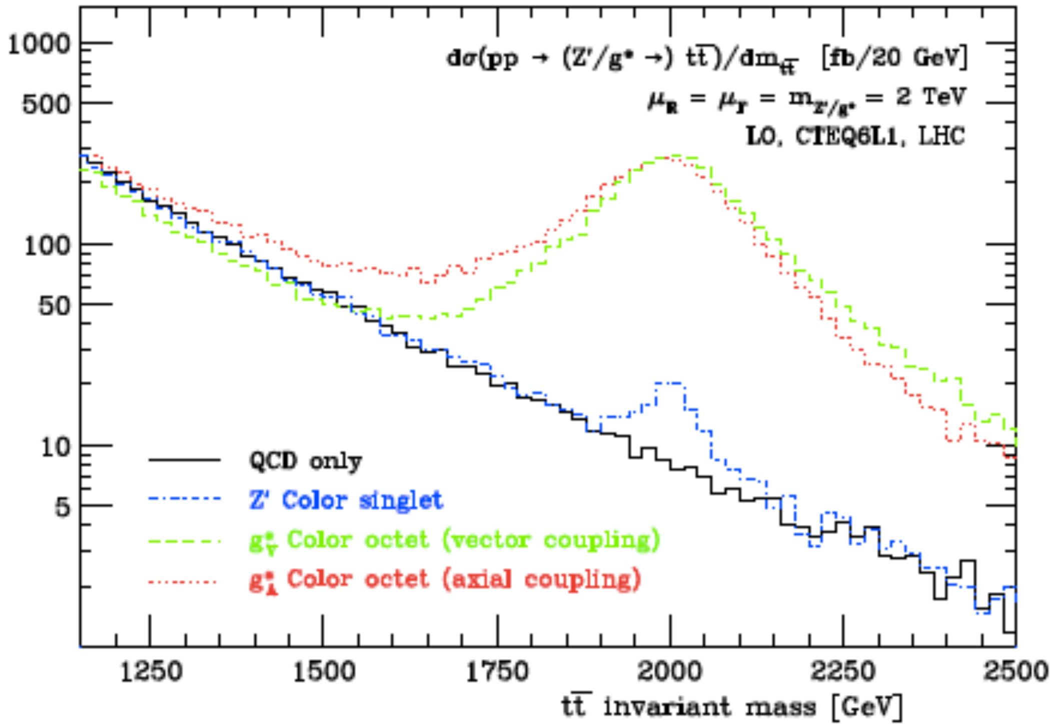


$$\sigma_{t\bar{t}}(8\ \text{TeV}) = 247.7^{+13.1}_{-14.3}\ \text{pb}$$

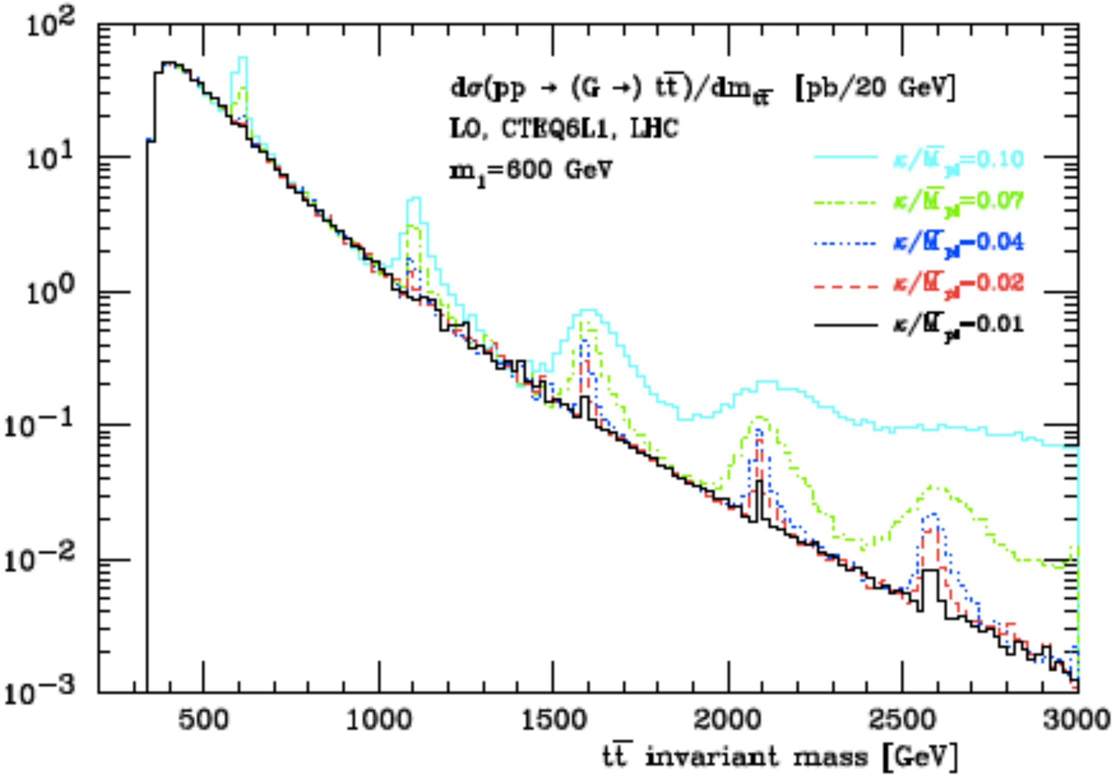
$$\sigma_{t\bar{t}}(13\ \text{TeV}) = 816.0^{+39.5}_{-44.7}\ \text{pb}$$

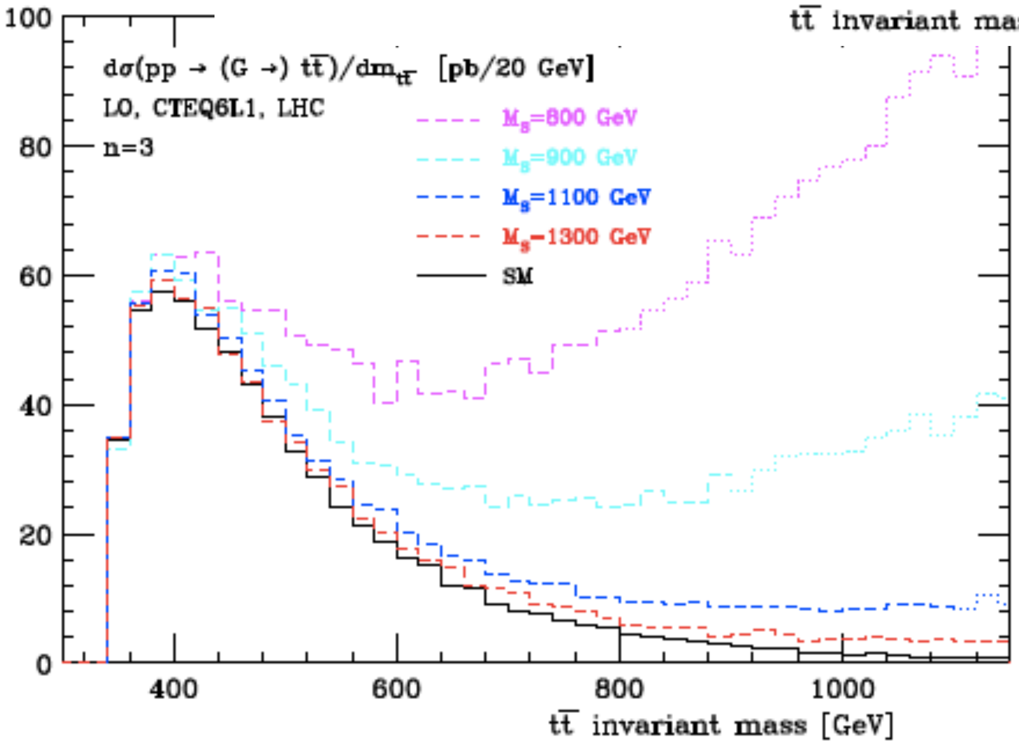
=> 81600000 events @ 100 /fb Luminosity

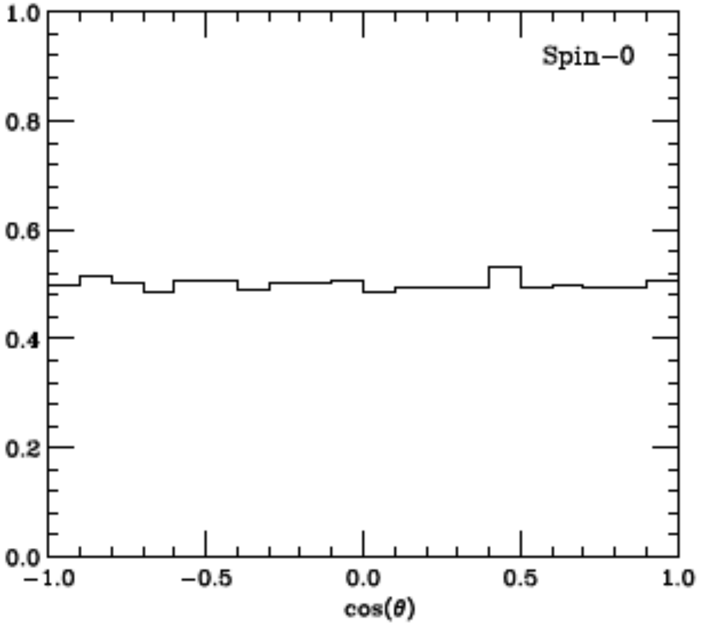
Top pair invariant mass distribution: a window on new physics



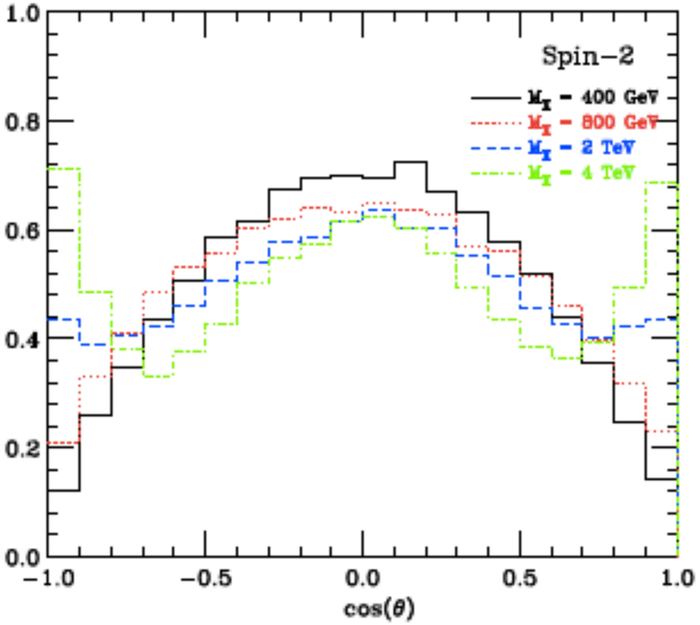
Frederix and Matloni JHEP 01 (2009) 047



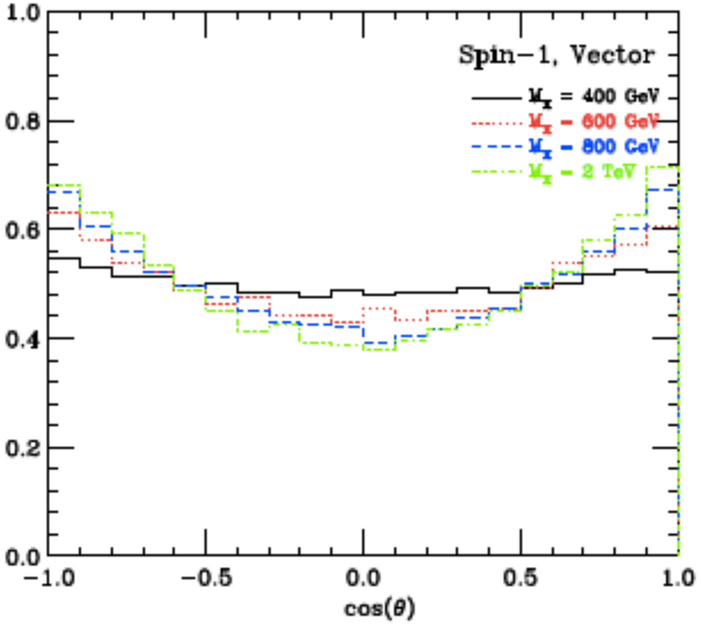


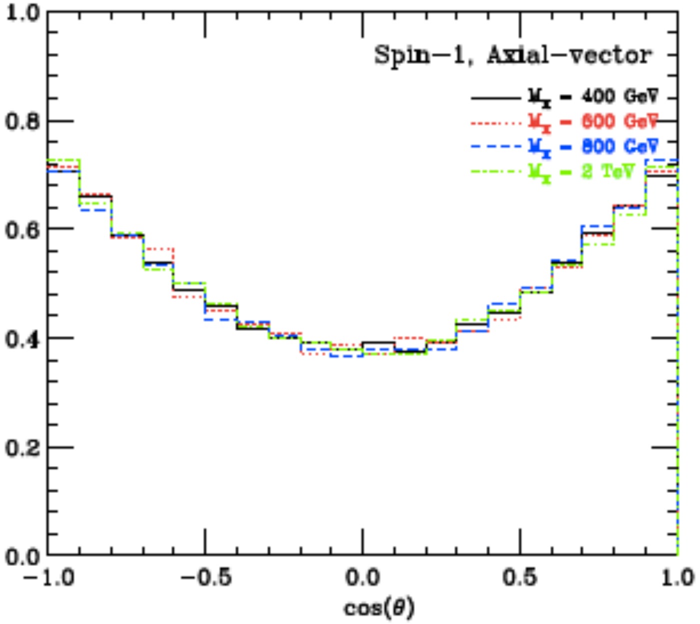

Spin−0
cos(θ)

(a)

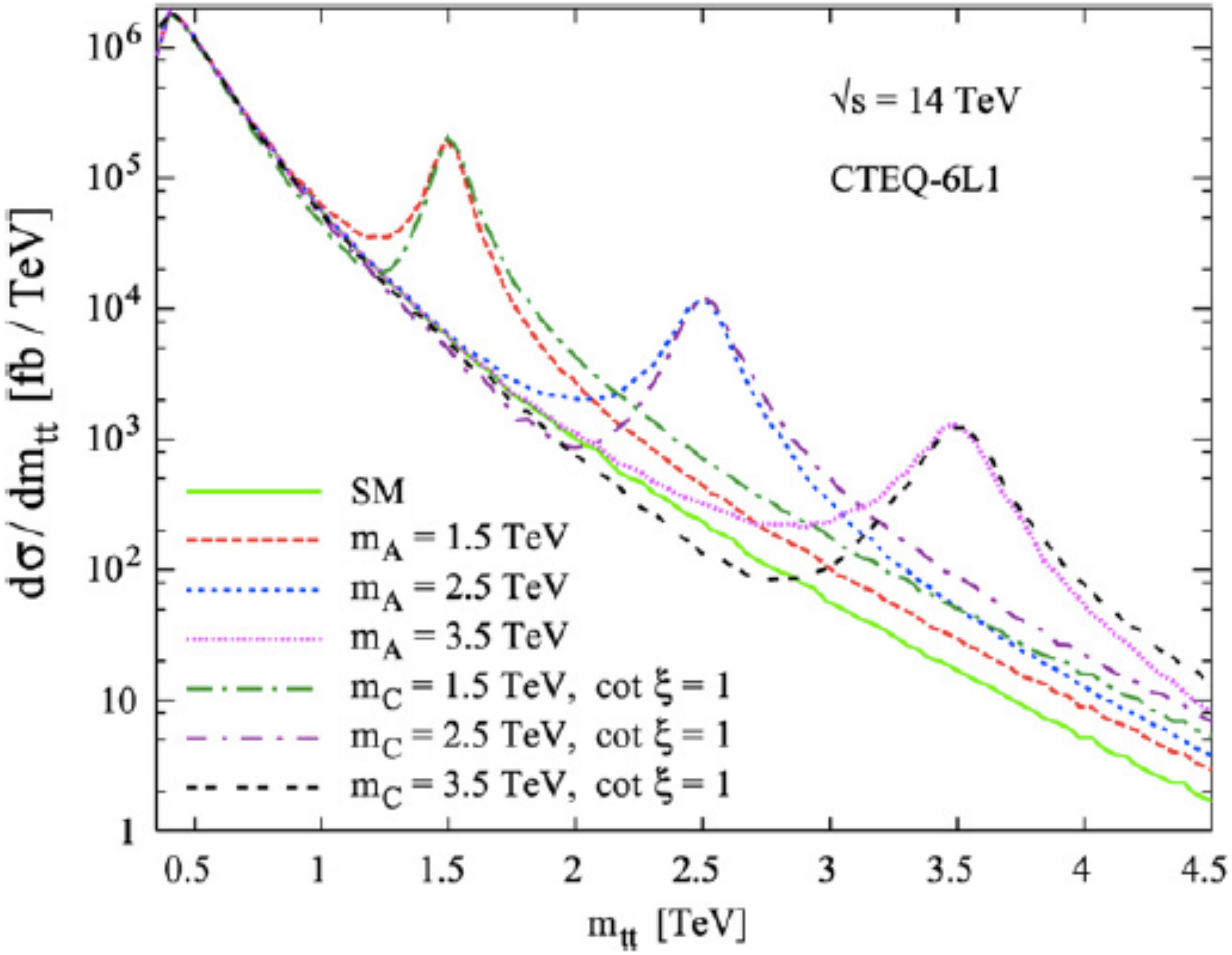

Spin−2
M_X = 400 GeV
M_X = 800 GeV
M_X = 2 TeV
M_X = 4 TeV
cos(θ)

(b)


Spin−1, Vector
M_X = 400 GeV
M_X = 600 GeV
M_X = 800 GeV
M_X = 2 TeV
cos(θ)


Spin−1, Axial−vector
M_X = 400 GeV
M_X = 600 GeV
M_X = 800 GeV
M_X = 2 TeV
cos(θ)

Axigluons and Colorons



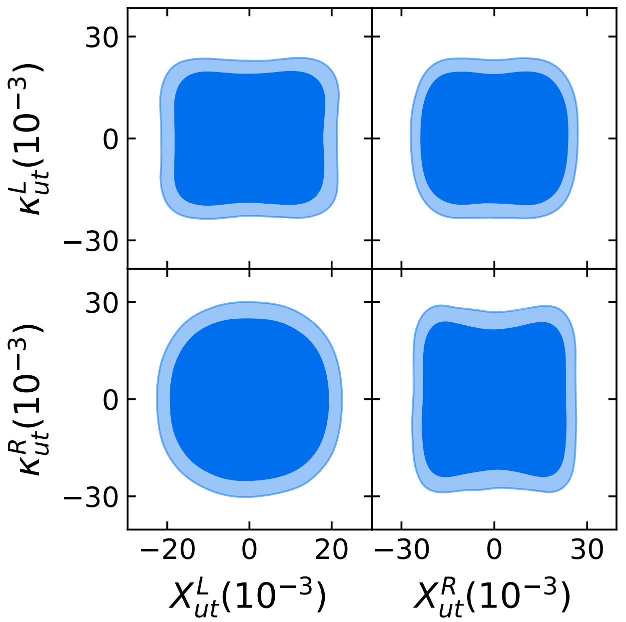
Choudhury, Godbole, Singh, Wagh, PLB 657 (2007) 69

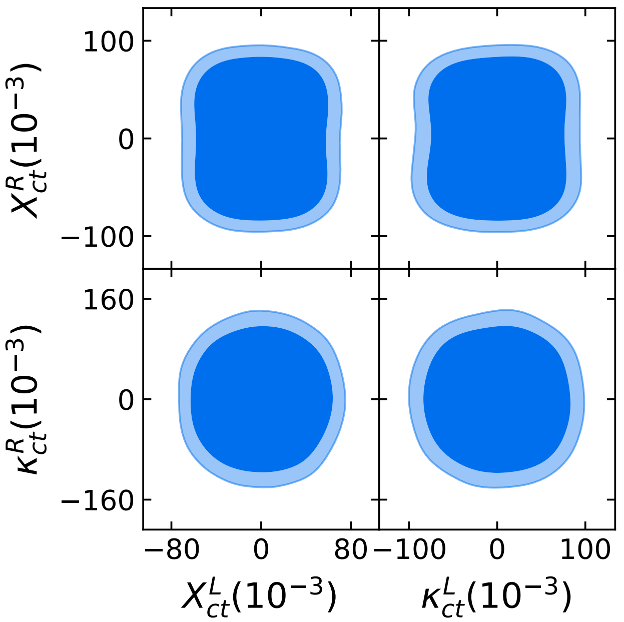
Present Experimental status

Process	Br Limit	Search	Dataset
$t \to Zq$	5×10^{-4}	CMS $t\bar{t} \to Wb + Zq \to \ell\nu b + \ell\ell q$	19.7 fb^{-1}, 8 TeV
$t \to Zq$	7.3×10^{-3}	ATLAS $t\bar{t} \to Wb + Zq \to \ell\nu b + \ell\ell q$	2.1 fb^{-1}, 7 TeV
$t \to gu$	3.1×10^{-5}	ATLAS $qg \to t \to Wb$	14.2 fb^{-1}, 8 TeV
$t \to gc$	1.6×10^{-4}	ATLAS $qg \to t \to Wb$	14.2 fb^{-1}, 8 TeV
$t \to \gamma u$	1.6×10^{-4}	CMS $qg \to t\gamma \to Wb\gamma$	19.1 fb^{-1}, 8 TeV
$t \to \gamma c$	1.8×10^{-3}	CMS $qg \to t\gamma \to Wb\gamma$	19.1 fb^{-1}, 8 TeV
$t \to hq$	7.9×10^{-3}	ATLAS $t\bar{t} \to Wb + hq \to \ell\nu b + \gamma\gamma q$	20 fb^{-1}, 8 TeV
$t \to hq$	5.6×10^{-3}	CMS $t\bar{t} \to Wb + hq \to \ell\nu b + \ell\ell qX$	19.5 fb^{-1}, 8 TeV

Process	SM	2HDM(FV)	2HDM(FC)	MSSM	RPV	RS
$t \to Zu$	7×10^{-17}	–	–	$\leq 10^{-7}$	$\leq 10^{-6}$	–
$t \to Zc$	1×10^{-14}	$\leq 10^{-6}$	$\leq 10^{-10}$	$\leq 10^{-7}$	$\leq 10^{-6}$	$\leq 10^{-5}$
$t \to gu$	4×10^{-14}	–	–	$\leq 10^{-7}$	$\leq 10^{-6}$	–
$t \to gc$	5×10^{-12}	$\leq 10^{-4}$	$\leq 10^{-8}$	$\leq 10^{-7}$	$\leq 10^{-6}$	$\leq 10^{-10}$
$t \to \gamma u$	4×10^{-16}	–	–	$\leq 10^{-8}$	$\leq 10^{-9}$	–
$t \to \gamma c$	5×10^{-14}	$\leq 10^{-7}$	$\leq 10^{-9}$	$\leq 10^{-8}$	$\leq 10^{-9}$	$\leq 10^{-9}$
$t \to hu$	2×10^{-17}	6×10^{-6}	–	$\leq 10^{-5}$	$\leq 10^{-9}$	–
$t \to hc$	3×10^{-15}	2×10^{-3}	$\leq 10^{-5}$	$\leq 10^{-5}$	$\leq 10^{-9}$	$\leq 10^{-4}$

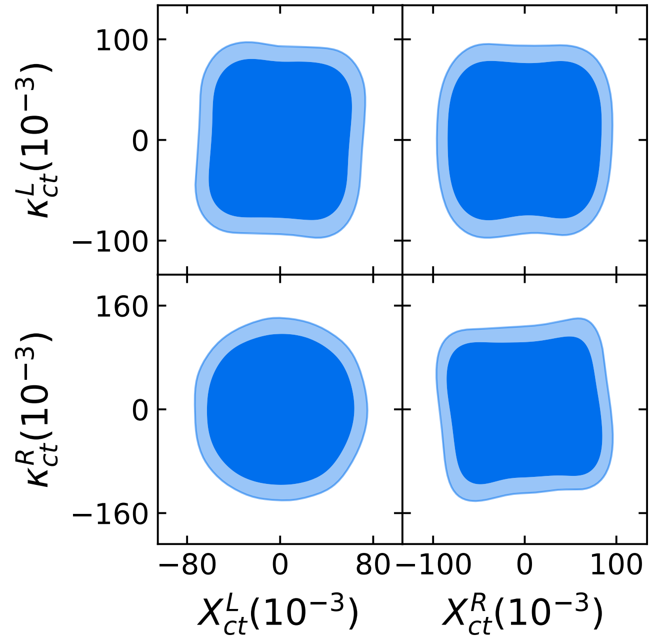
Top Quark Working Group **1311.2028**

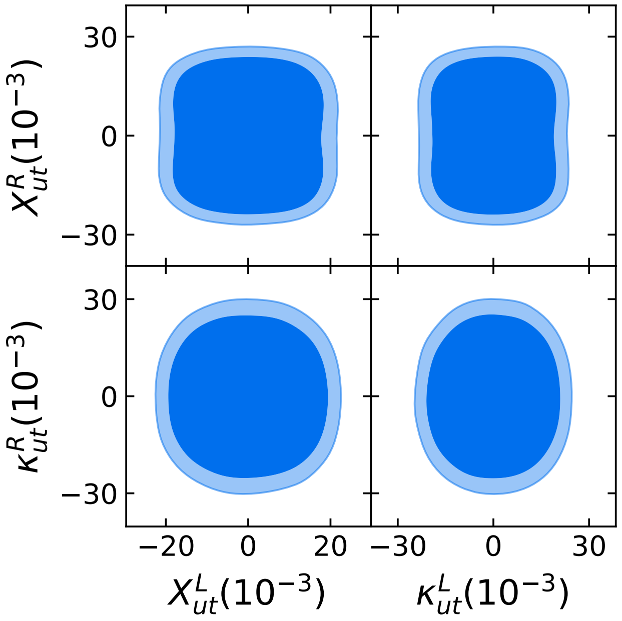




2D planes of the hyperspace of all the parameters considered together.

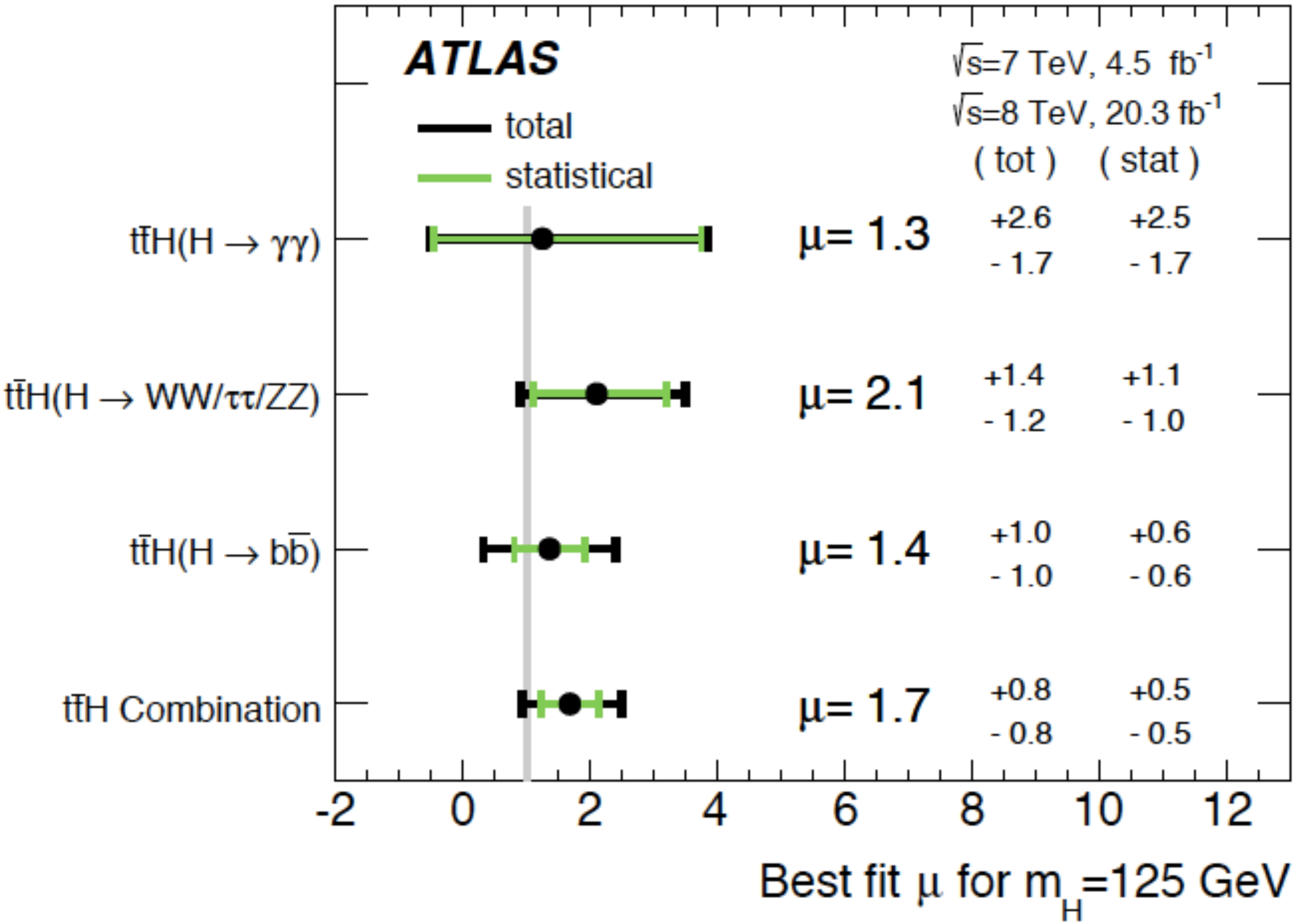
Luminosity: 2 /ab

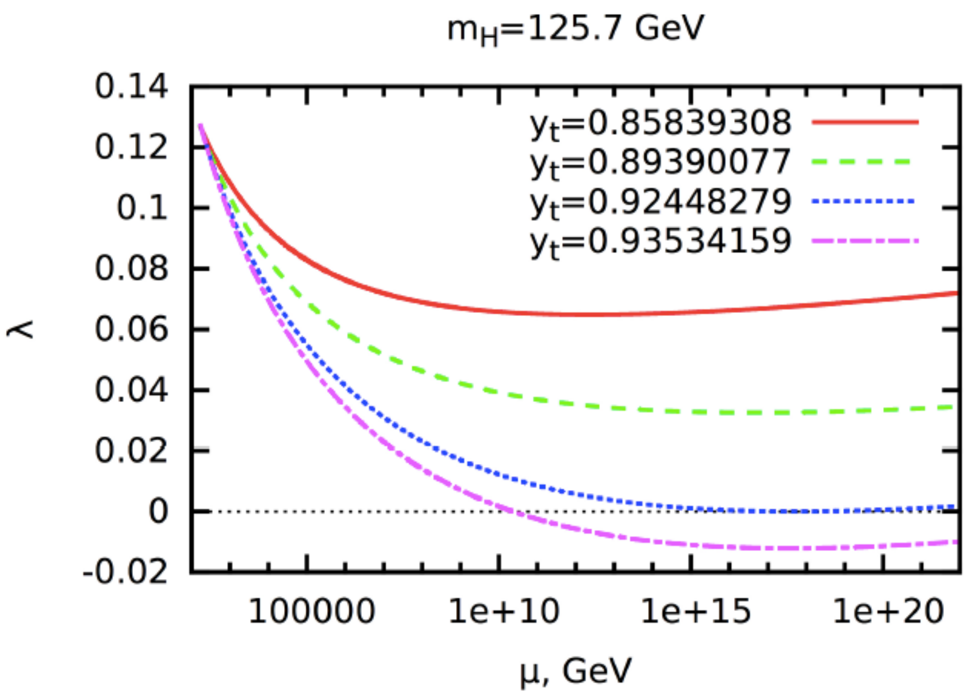




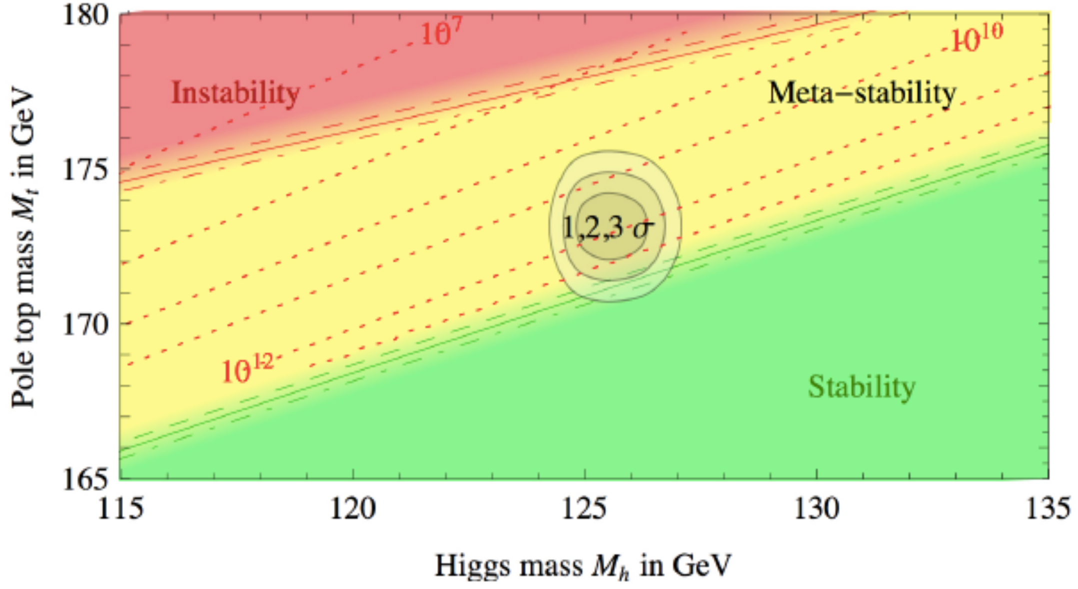
Backup

ATLAS, JHEP 1605 (2016) 160

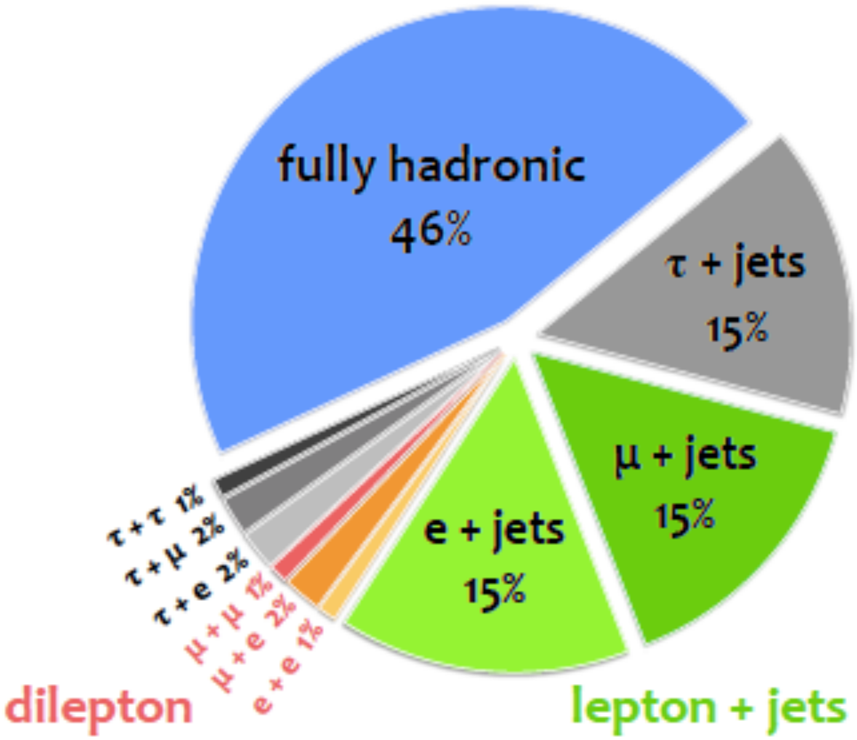


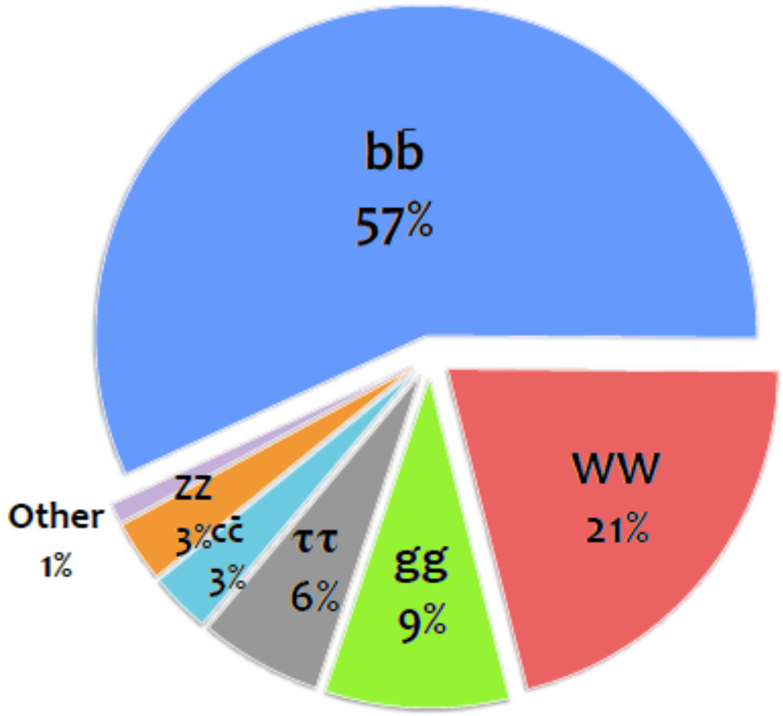


mH=125.7 GeV
yt=0.85839308
yt=0.89390077
yt=0.92448279
yt=0.93534159
λ
μ, GeV



Instability
Meta-stability
Stability
1,2,3 σ
Pole top mass Mt in GeV
Higgs mass Mh in GeV

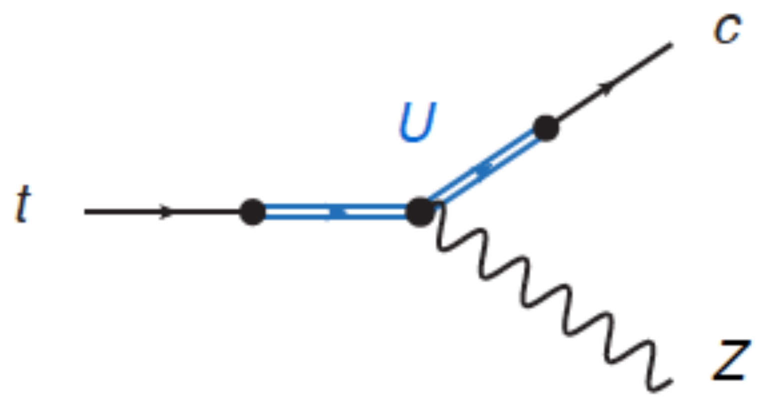


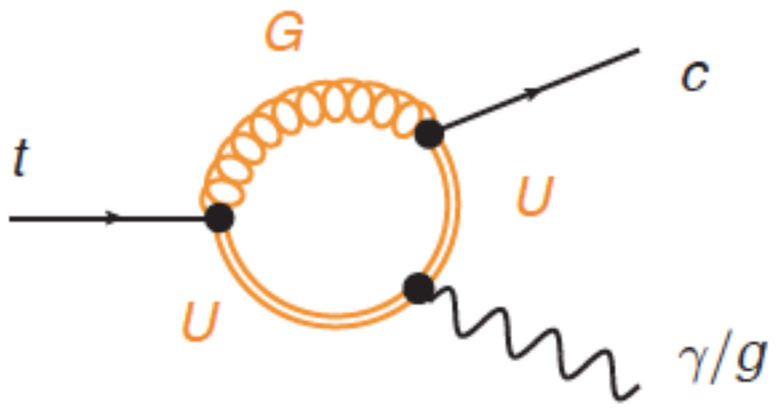


125 GeV Higgs decays

tt —> final states

Compositeness models / Warped Extra Dim





	2HDM[1)]	MSSM[2)]	RS[3)]
$t \to cZ$	$\lesssim 10^{-6}$	$\lesssim 10^{-7}$	$\lesssim 10^{-5}$
$t \to c\gamma$	$\lesssim 10^{-7}$	$\lesssim 10^{-8}$	$\lesssim 10^{-9}$
$t \to cg$	$\lesssim 10^{-5}$	$\lesssim 10^{-7}$	$\lesssim 10^{-10}$
$t \to ch$	$\lesssim 10^{-2}$	$\lesssim 10^{-5}$	$\lesssim 10^{-4}$

[1)] Atwood, Reina, Soni hep-ph/9609279 [2)] Cao et al. hep-ph/0702264

[3)] Agashe, Contino 0906.1542; Azatov et al. 0906.1990; Casagrande et al. 1005.4315

see also Snowmass Top Quark Working Group Report 1311.2028

Constraints from EDM