Top Quark at the LHC

Exploring Beyond the Standard Model

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Top quark is special in many ways

Heaviest elementary particle, about 180 times heavier than the proton !

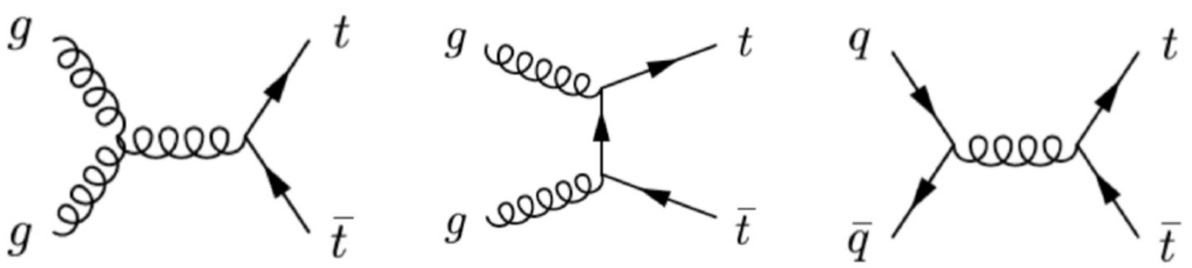
The only bare quark that decays before forming bound states, and therefore exposes its interactions with the other SM particles in a direct way.

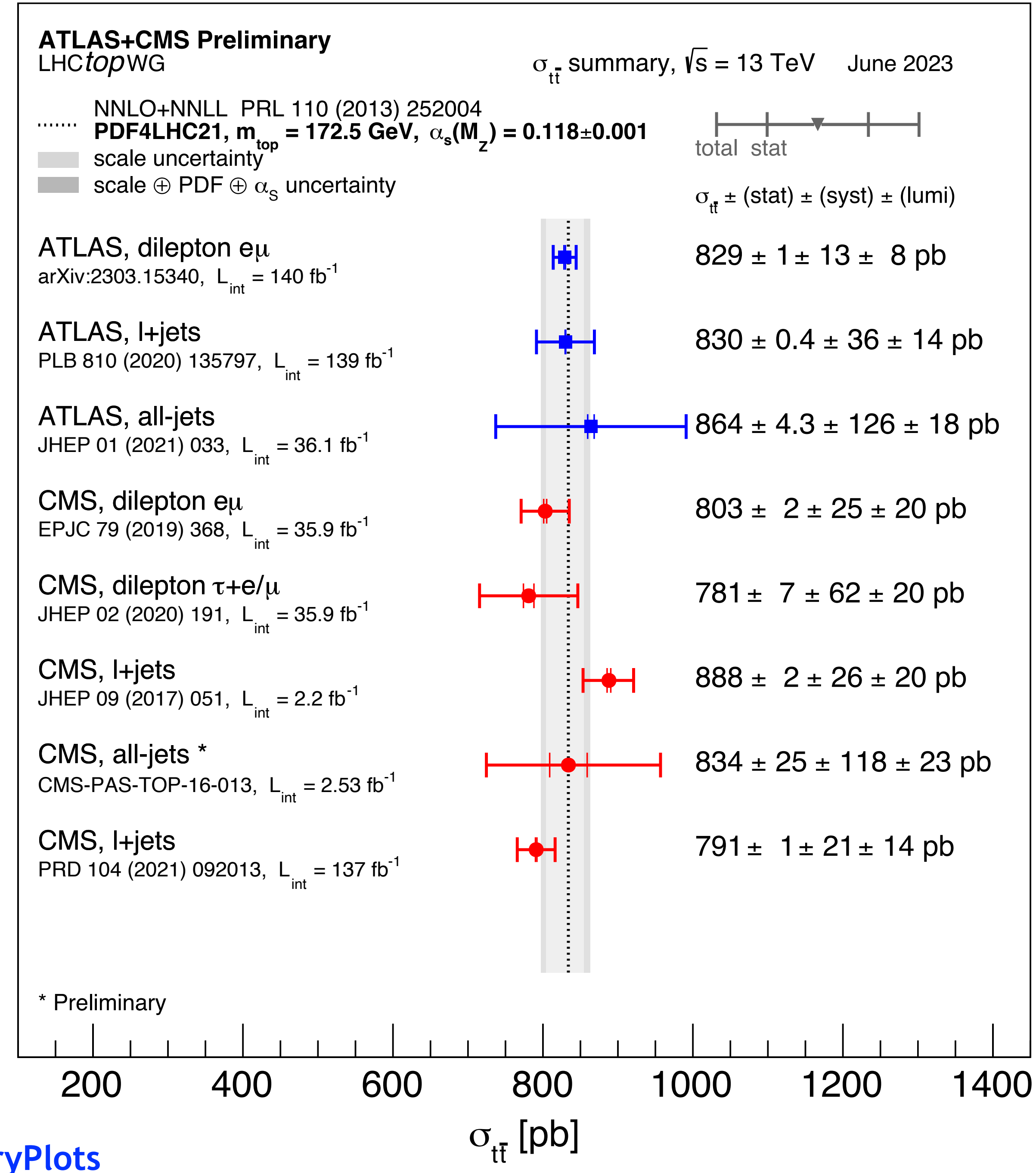
Having strongest interaction with the Higgs boson
it is crucial to know the top quark couplings precisely to know the details of Higgs couplings and thus to understand the Electroweak Symmetry Breaking

In general, top quark can potentially probe dynamics beyond the SM

Top quark pair production at the LHC

Mostly strong process





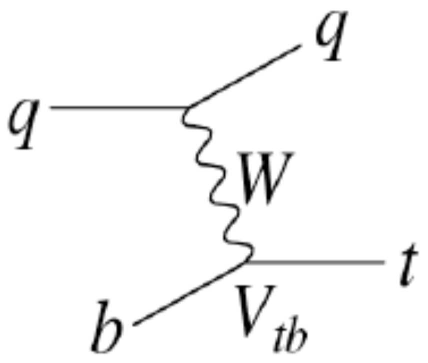
More than **80 X 10^6** top pairs
@ 13 TeV, 100 /fb

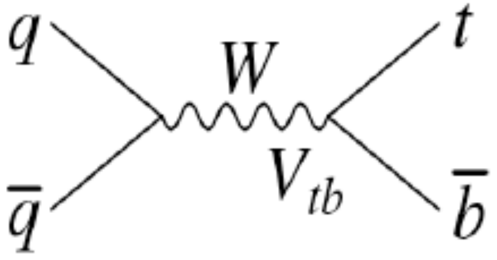
Top Working Group Summary Plots

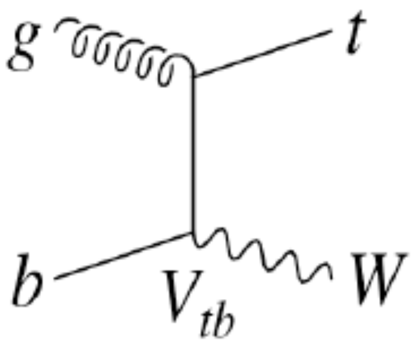
https://twiki.cern.ch/twiki/bin/view/LHCPhysics/LHCTopWGSummaryPlots

Single Top quark production at the LHC

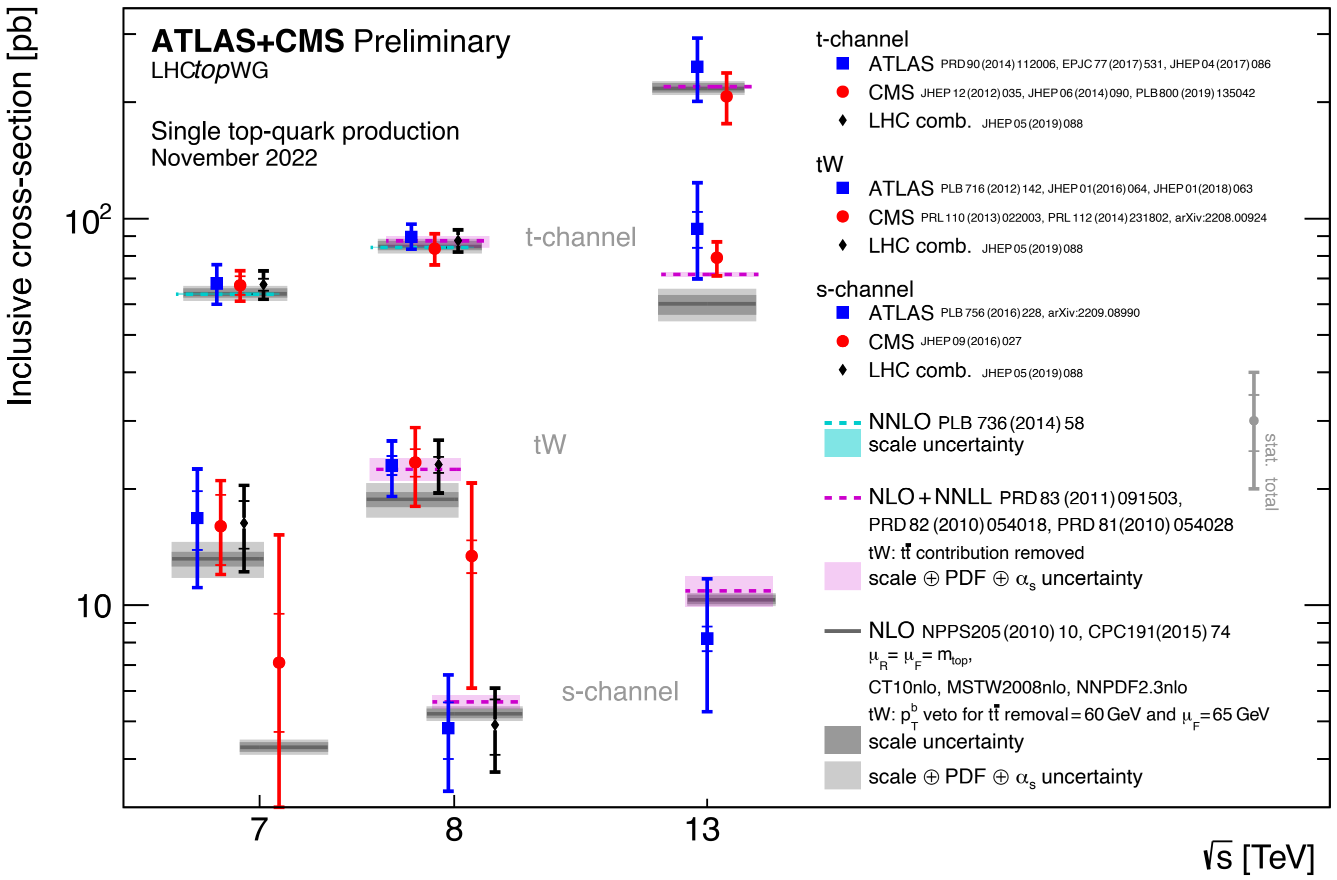
weak process

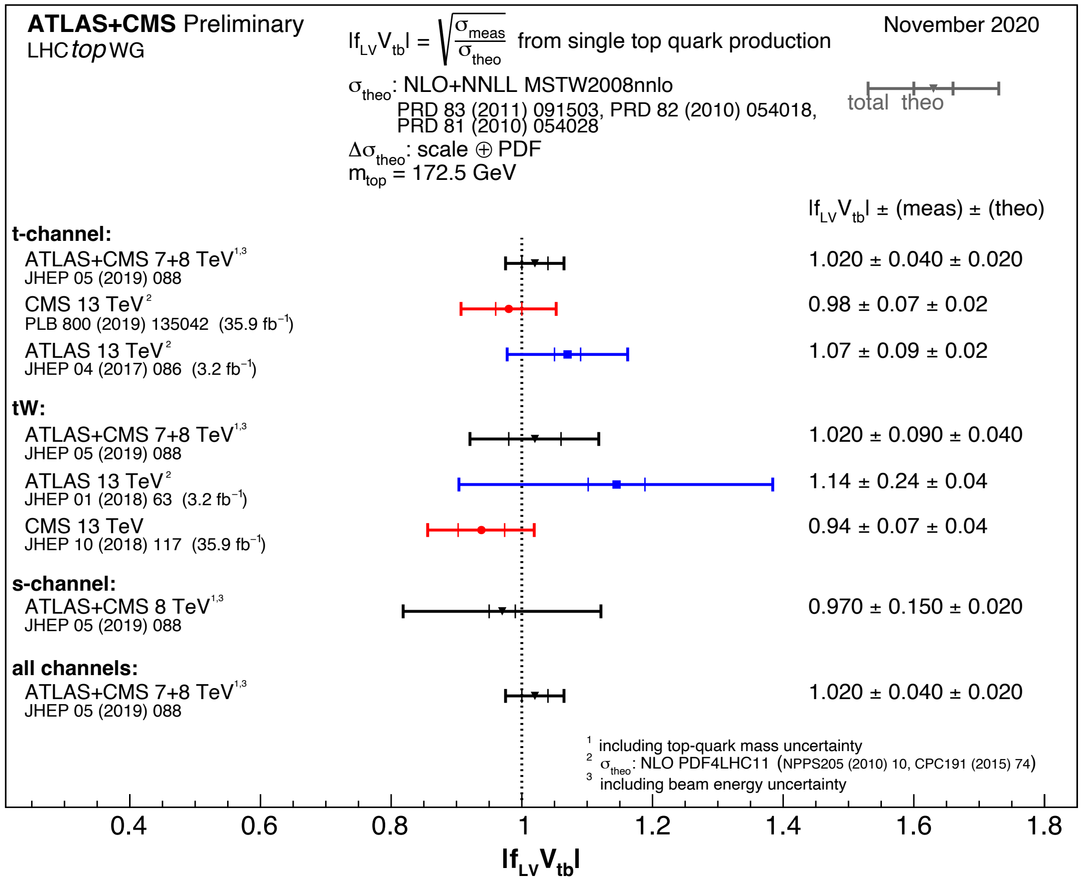






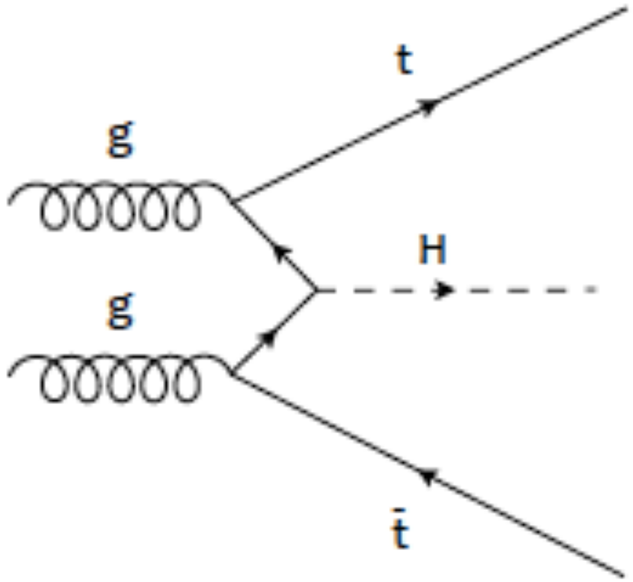
direct measurement of V_{tb}

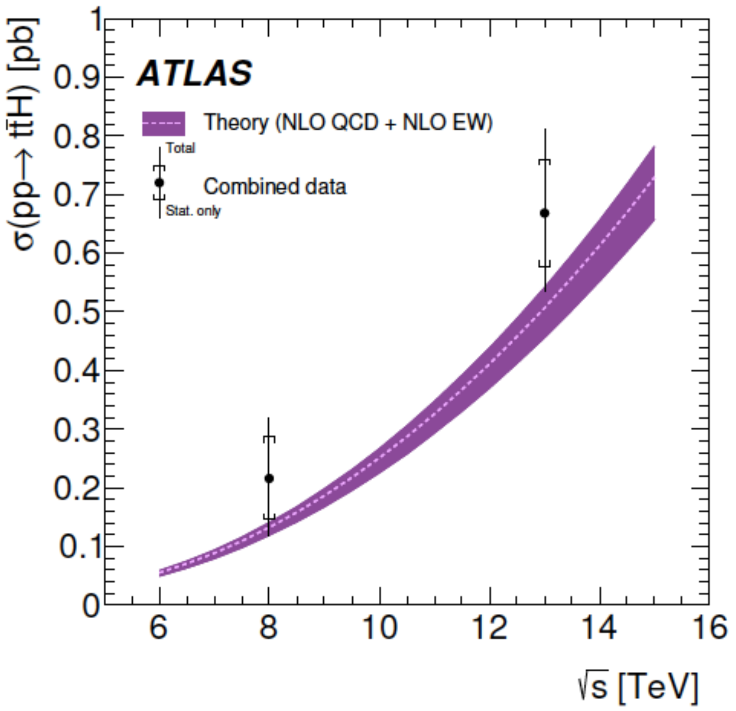


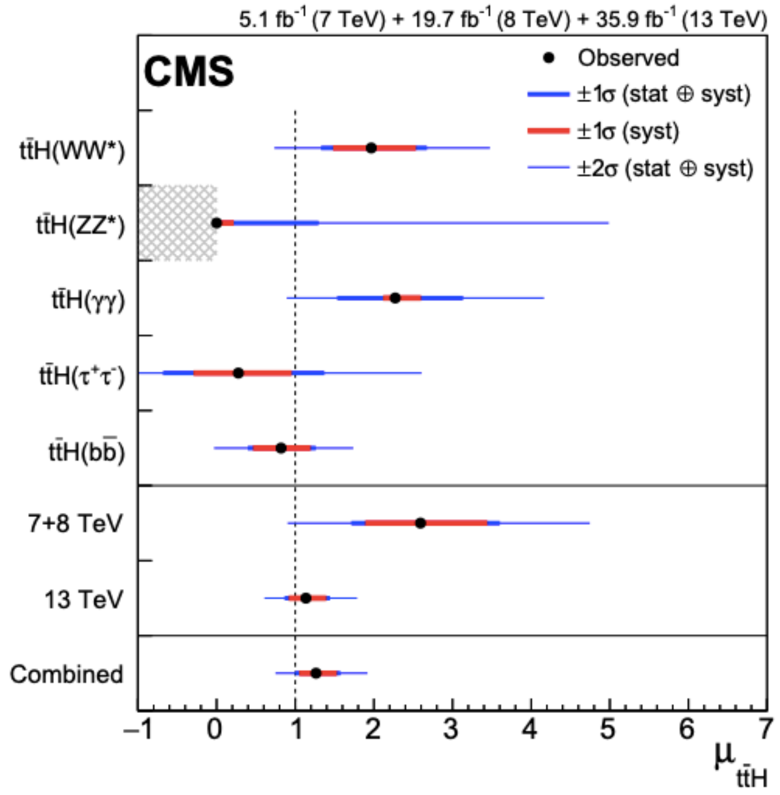


Top quark pair in association with Higgs

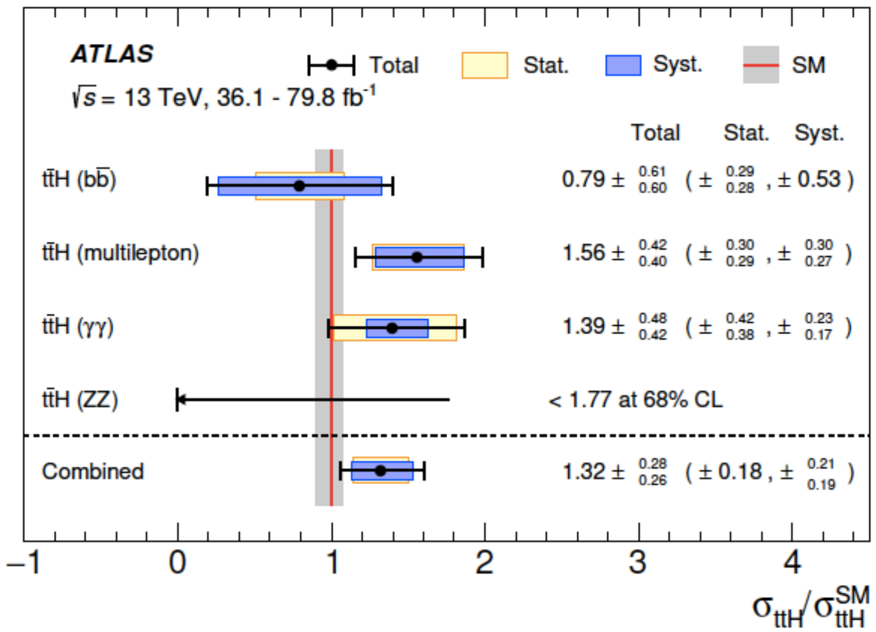
ATLAS, Phys. Lett. B 784 (2018) 173



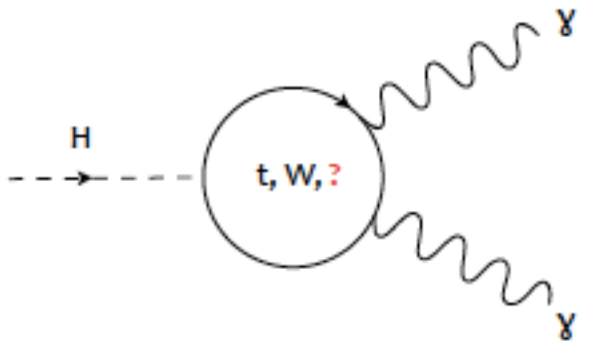


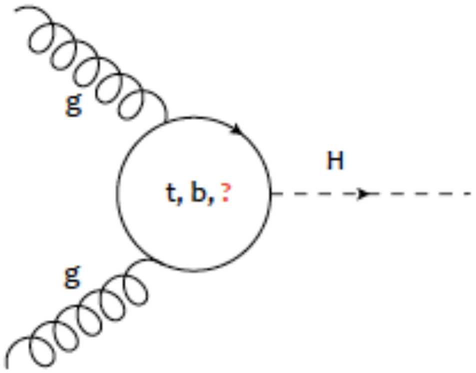


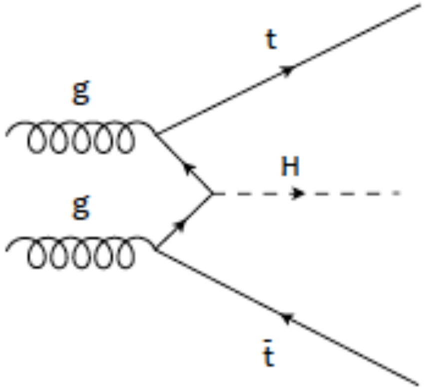
Direct measurement of Yukawa coupling



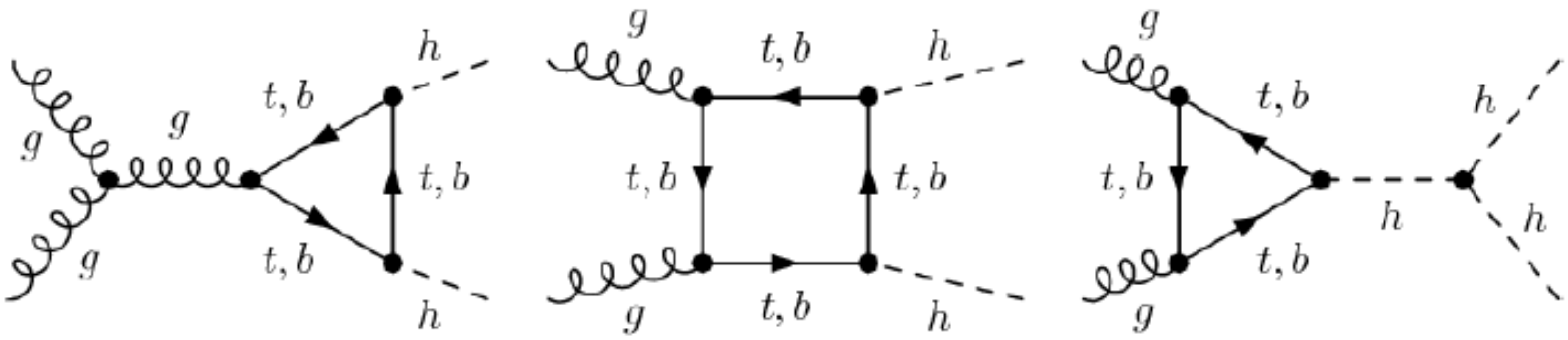
Top quark Yukawa influencing the production and decay of the Higgs boson at the LHC

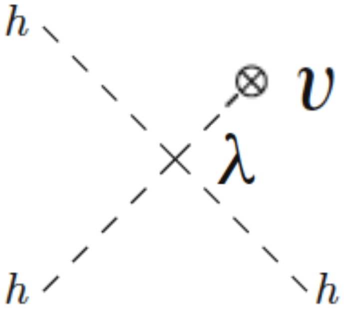


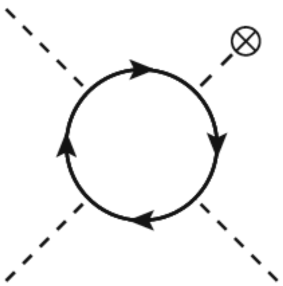




Also the measurement of Higgs trilinear coupling







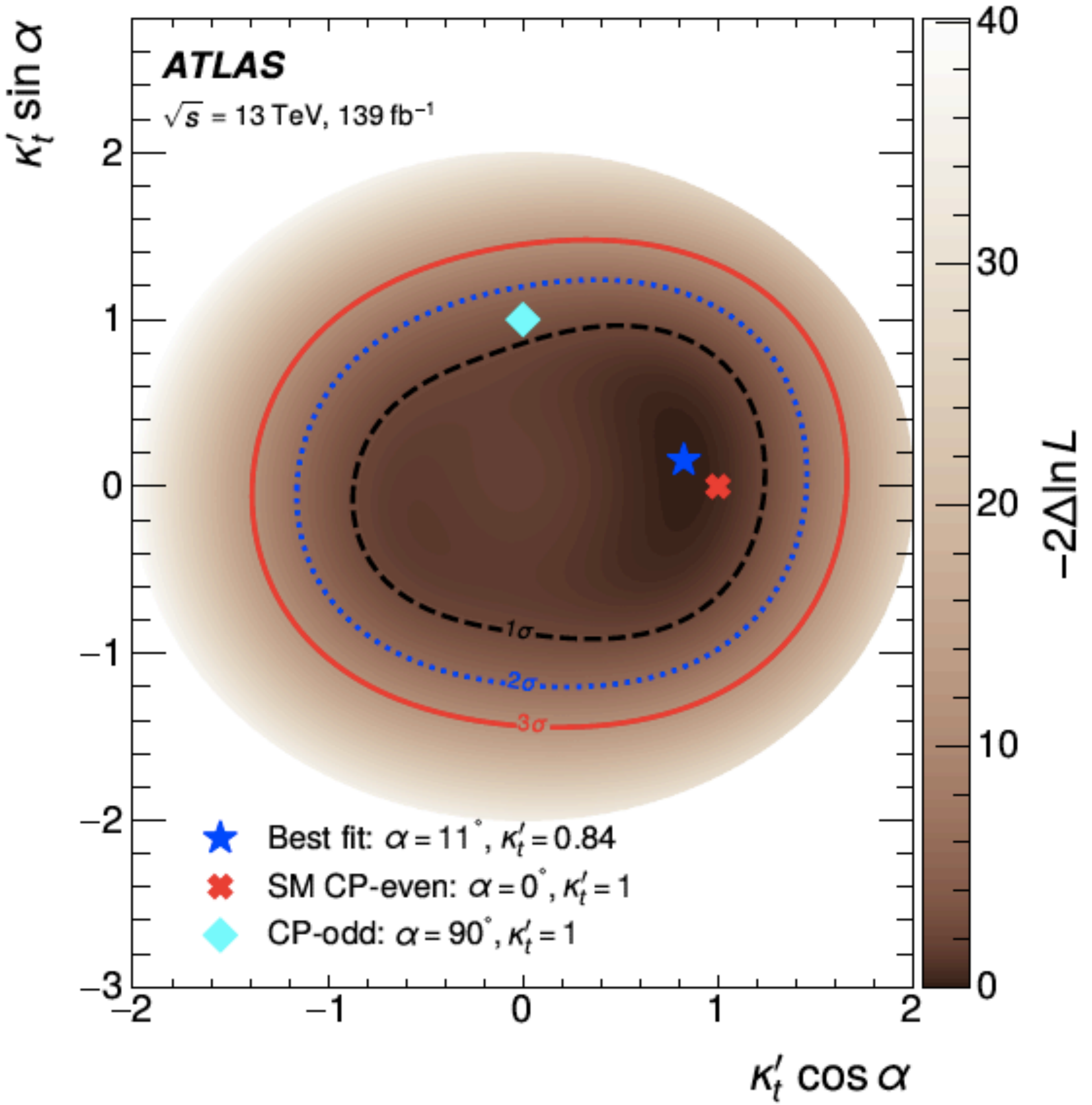
$$\mathcal{L}_{t\bar{t}H} = -\frac{m_t}{v}\bar{\psi}_t(\kappa_t + \tilde{\kappa}_t i\gamma_5)H\psi_t \qquad \text{SM} \Rightarrow \qquad \kappa_t = 1 \qquad \tilde{\kappa}_t = 0$$

Measure of CP violation

CP - violation in top Yukawa

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

$$\kappa_t = K_t' \cos\alpha \qquad \tilde{\kappa}_t = K_t' \sin\alpha$$

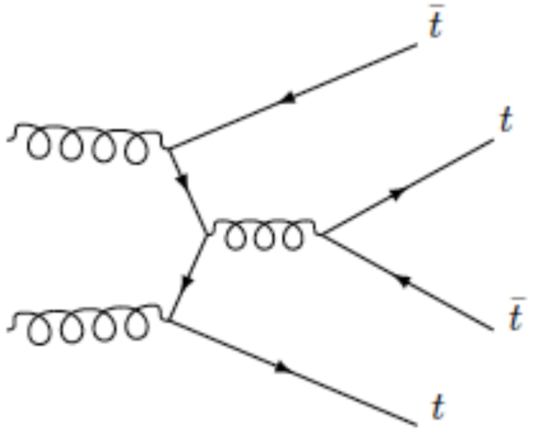


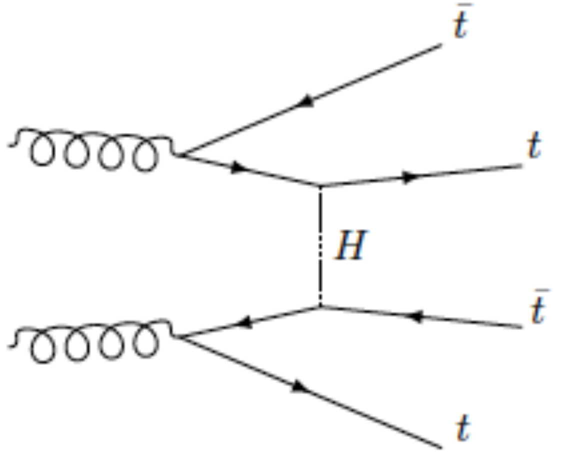
CERN-EP-2022-208, arXiv:2303.05974

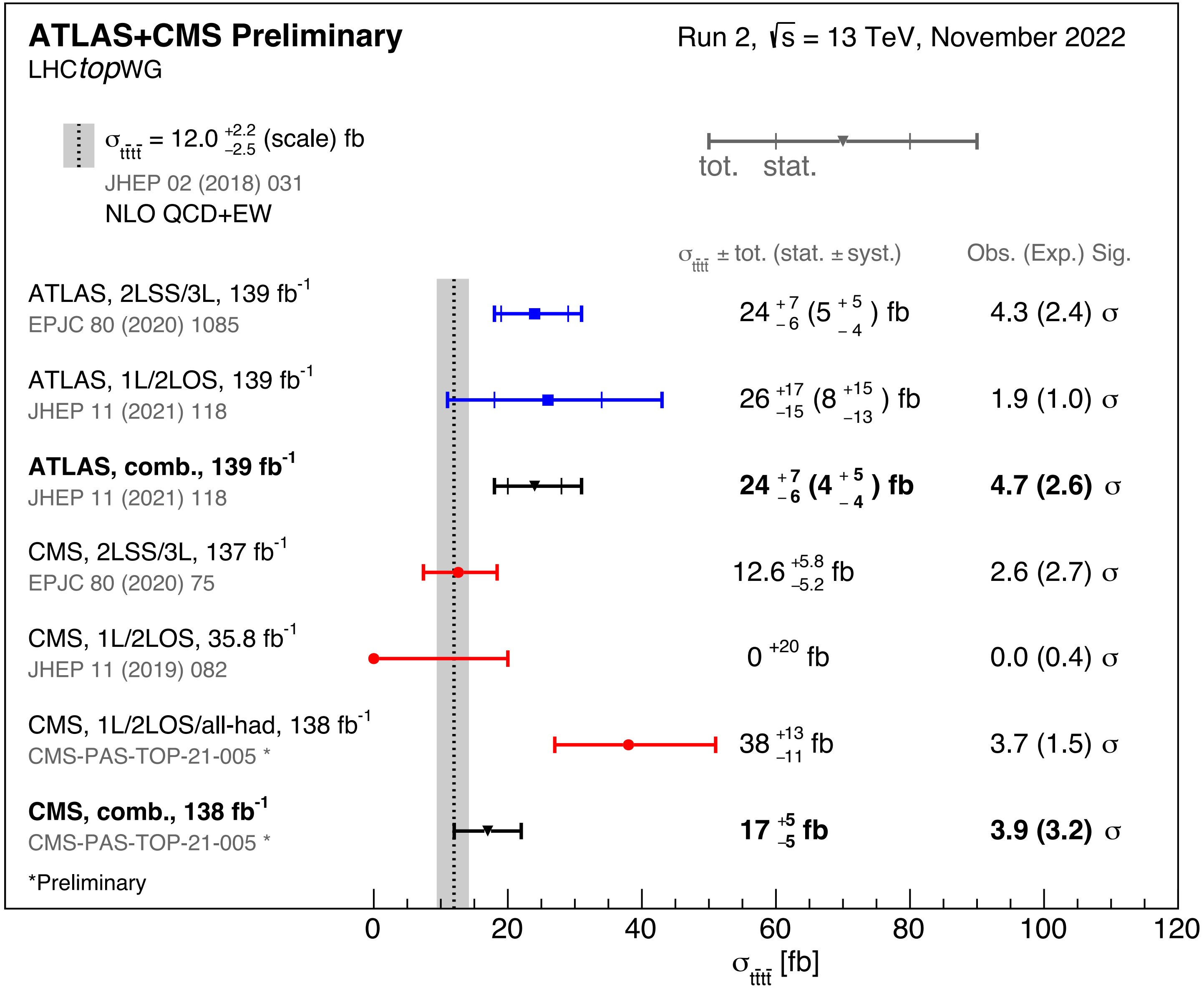
Four Top production at the LHC

$$\sigma(pp \to t\bar{t}t\bar{t}) = 12.0^{+2.2}_{-2.5} \quad fb \quad @ \sqrt{s} = 13\ \text{TeV}$$

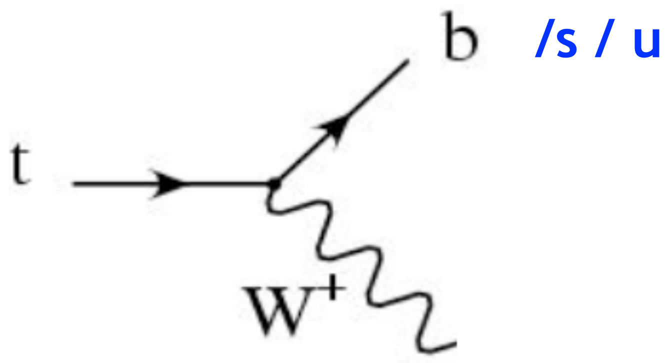
Explores top-top scattering







Standard Decays of Top quark



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

$$V_{tb} = 1.014 \pm 0.029$$

$$V_{td} = (8.6 \pm 0.2) \times 10^{-3}$$

$$V_{ts} = (41.5 \pm 0.9) \times 10^{-3}$$

PDG, Prog. There. Exp. Phys. 2022.083C01 (2022)

Almost 100% decay to bW

Rare top decays - Neutral current

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

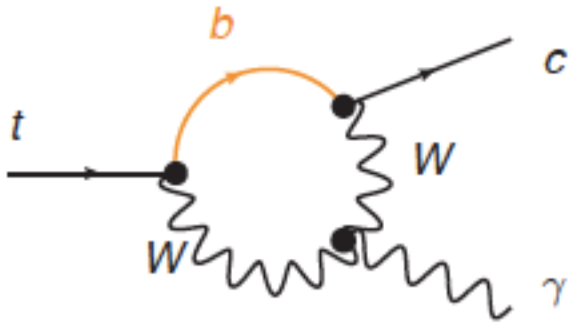
light neutral gauge boson: $t \to Z'c$, $t \to Z'u$

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)

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

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

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

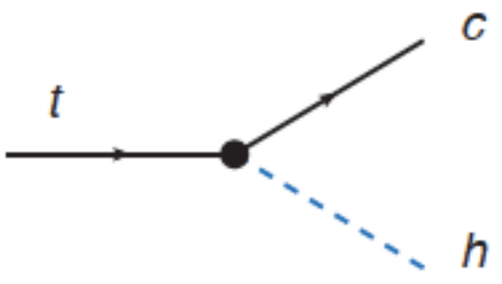
$$\mathrm{BR}(t\to ch) \simeq 3\times 10^{-15} \quad , \quad \mathrm{BR}(t\to uh) \simeq 2\times 10^{-17}$$

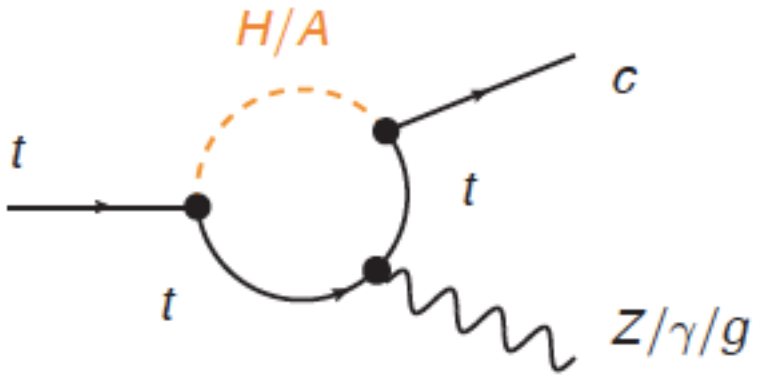
SM predictions

Beyond the SM

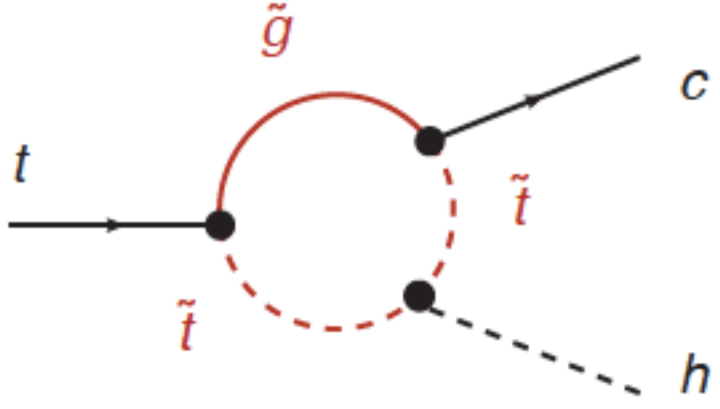
$t \to c\ Z/\gamma/g$ at the 1 loop level

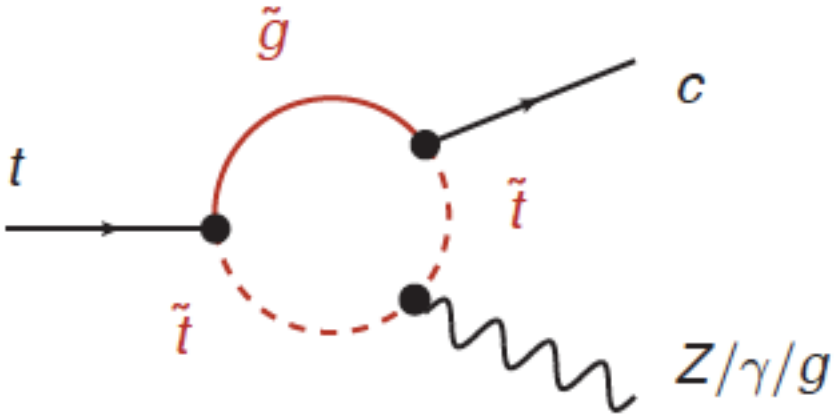
2HDM





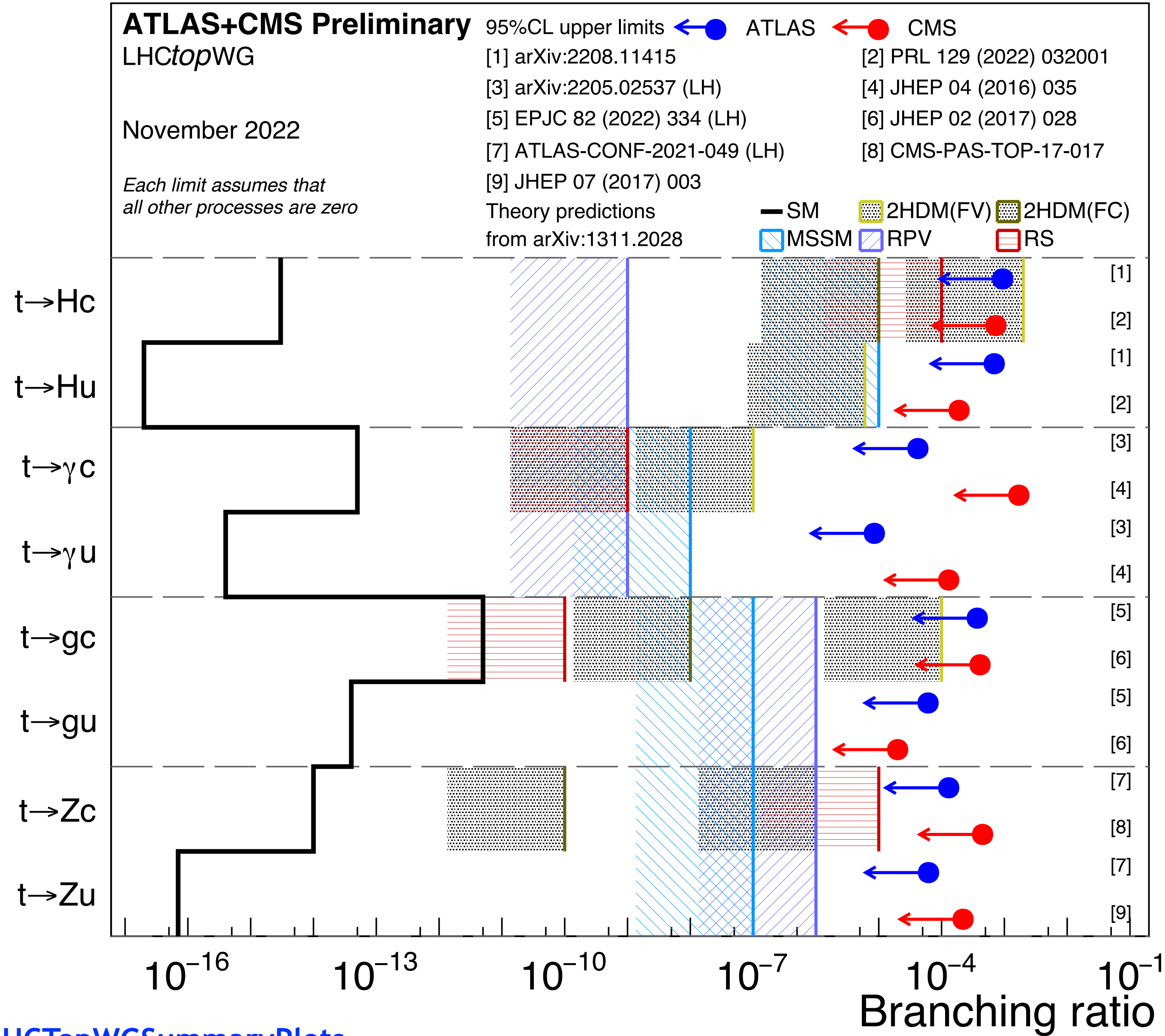
MSSM





Present Experimental status

and comparison with model predictions



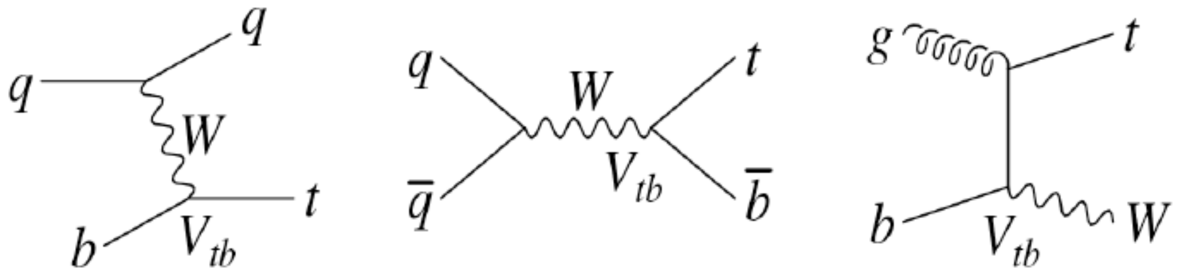
Assuming only one such coupling present at a time

Top Working Group Summary Plots

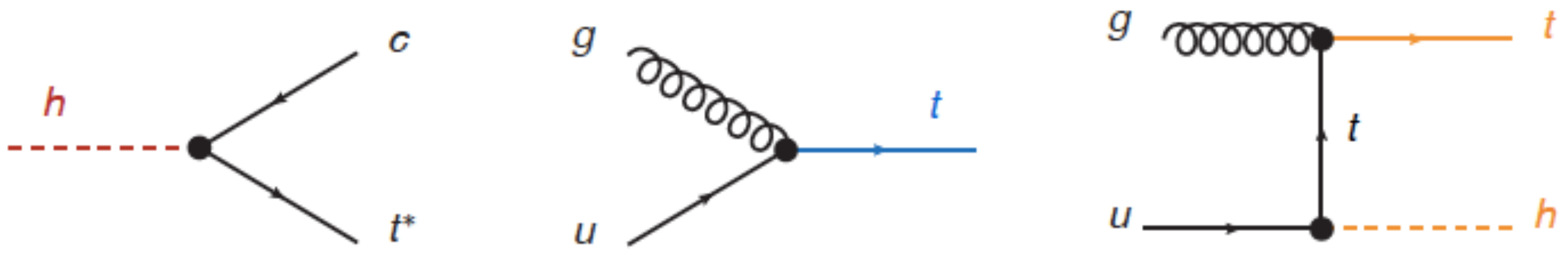
https://twiki.cern.ch/twiki/bin/view/LHCPhysics/LHCTopWGSummaryPlots

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

Standard Single top productions

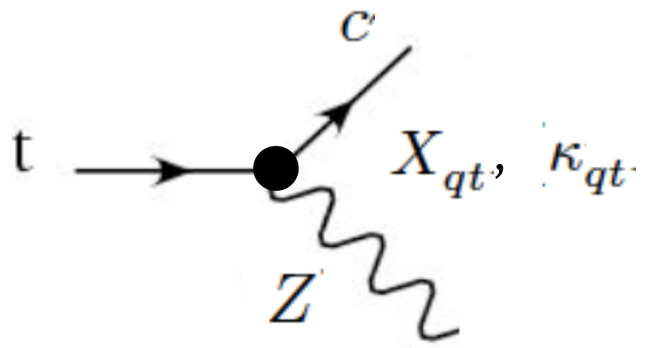


Non-Standard Single top productions include



Chen, Hou, Kao, Kohda 1304.8037; Atwood, Gupta, Soni 1305.2427
Greljo, Kamenik, Kopp 1404.1278; ...

Model Independent - Effective couplings



$$-\mathscr{L}_{qt} = \frac{g}{2c_W}\bar{q}\gamma^\mu\left(X^L_{qt}P_L + X^R_{qt}P_R\right) t\ Z_\mu + \frac{g}{2c_W\ m_t}\ \bar{q}\ i\sigma^{\mu\nu}\left(\kappa^L_{qt}P_L + \kappa^R_{qt}P_R\right) t\ Z_{\mu\nu}$$

$$+\frac{e}{m_t}\ \bar{q}\ i\sigma^{\mu\nu}\left(\lambda^L_{qt}P_L + \lambda^R_{qt}P_R\right) t\ F_{\mu\nu} + \frac{g_s\lambda^a}{m_t}\ \bar{q}\ i\sigma^{\mu\nu}\left(\zeta^L_{qt}P_L + \zeta^R_{qt}P_R\right) t\ G^a_{\mu\nu}$$

$$+g\ \bar{q}\ \left(g^L_{qt}P_L + g^R_{qt}P_R\right) t\ H + \quad h.c.$$

$$\Gamma(t \to qZ)_\gamma = \frac{\alpha}{32\, s_W^2 c_W^2}|X_{qt}|^2\frac{m_t^3}{M_Z^2}\left[1 - \frac{M_Z^2}{m_t^2}\right]^2\left[1 + 2\frac{M_Z^2}{m_t^2}\right],$$

$$\Gamma(t \to qZ)_\sigma = \frac{\alpha}{16\, s_W^2 c_W^2}|\kappa_{qt}|^2 m_t\left[1 - \frac{M_Z^2}{m_t^2}\right]^2\left[2 + \frac{M_Z^2}{m_t^2}\right],$$

$$\Gamma(t \to q\gamma) = \frac{\alpha}{2}|\lambda_{qt}|^2 m_t\,,$$

$$\Gamma(t \to qg) = \frac{2\alpha_s}{3}|\zeta_{qt}|^2 m_t\,,$$

$$\Gamma(t \to qH) = \frac{\alpha}{32\, s_W^2}|g_{qt}|^2 m_t\left[1 - \frac{M_H^2}{m_t^2}\right]^2.$$

$$|X_{qt}|^2 = |X^L_{qt}|^2 + |X^R_{qt}|^2$$

$$|\kappa_{qt}|^2 = |\kappa^L_{qt}|^2 + |\kappa^R_{qt}|^2$$

$$|\lambda_{qt}|^2 = |\lambda^L_{qt}|^2 + |\lambda^R_{qt}|^2, \quad etc.$$

Nucl.Phys.B 812 (2009)181; 812 (2009)215; 944 (2019) 114640

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

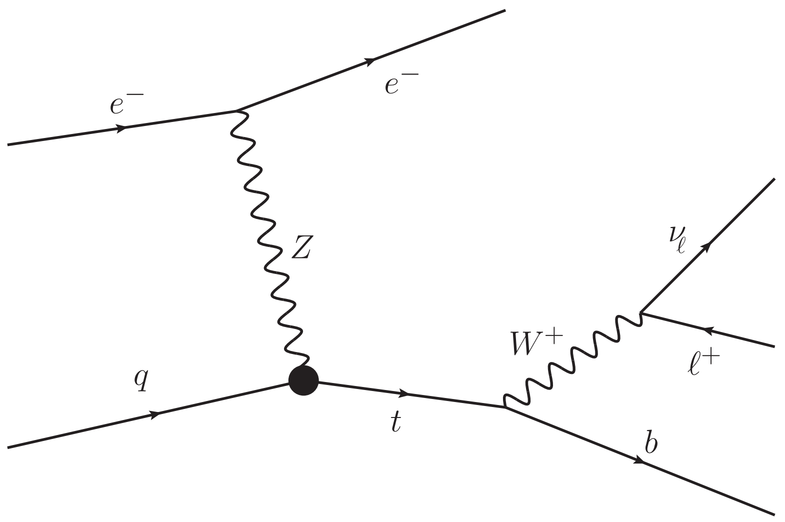
Top Quark Working Group **1311.2028**

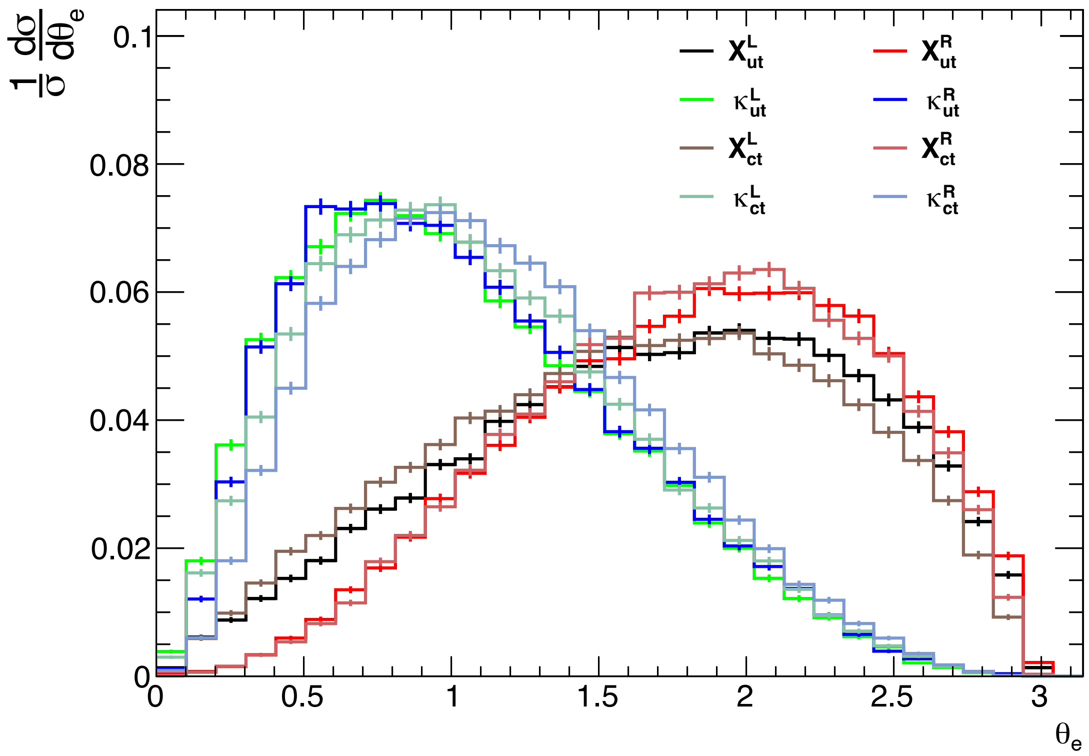
Process	Br Limit	Search	Dataset	Reference
$t \to Zq$	2.2×10^{-4}	ATLAS $t\bar{t} \to Wb + Zq \to \ell\nu b + \ell\ell q$	300 fb^{-1}, 14 TeV	[140]
$t \to Zq$	7×10^{-5}	ATLAS $t\bar{t} \to Wb + Zq \to \ell\nu b + \ell\ell q$	3000 fb^{-1}, 14 TeV	[140]
$t \to Zq$	$5\,(2) \times 10^{-4}$	ILC single top, 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.

Top FCNC through ep > et

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

$$-\mathscr{L}_{qtZ} = \frac{g}{2c_W}\bar{q}\gamma^{\mu}\left(X^L_{qt}P_L + X^R_{qt}P_R\right) t\ Z_{\mu} + \frac{g}{2c_W\ m_t}\ \bar{q}\ i\sigma^{\mu\nu}\left(\kappa^L_{qt}P_L + \kappa^R_{qt}P_R\right) t\ Z_{\mu\nu} + \quad h.c.$$





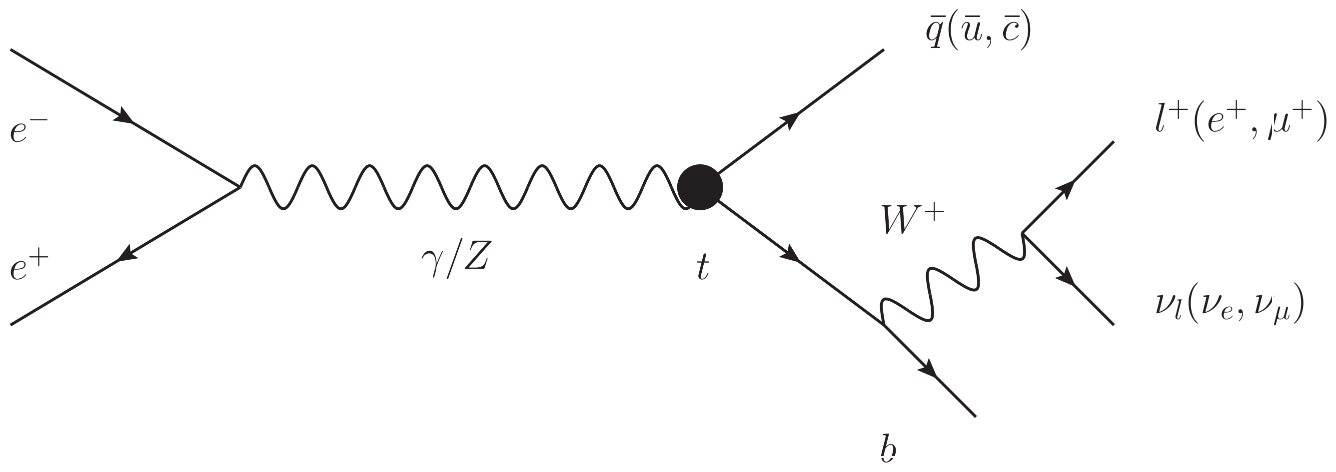
The scattered electron as a discriminator

Lorentz structure of the coupling can be probed.

Something quite hard at LHC

Left-Right Models

with Subhasish Behera, Daniel Jeans



Coopling	$\kappa^L_{ut}(\gamma)$	$\kappa^R_{ut}(\gamma)$	X^L_{ut}	X^R_{ut}	κ^L_{ut}	κ^R_{ut}	$\kappa^L_{ct}(\gamma)$	$\kappa^R_{ct}(\gamma)$	X^L_{ct}	X^R_{ct}	κ^L_{ct}	κ^R_{ct}
σ_{unpol} (fb)	126.66	127.23	53.97	53.88	89.37	89.49	126.84	127.29	53.99	53.91	89.45	89.39
$\sigma(-80\%, +30\%)$ (fb)	156.5	156.3	77.97	78.09	131.8	131.7	156.5	156.3	77.97	78.09	131.8	131.7
$\sigma(+80\%, -30\%)$ (fb)	157.06	157.89	53.63	54.01	89.18	89.61	157.19	157.75	54.02	53.78	89.50	89.59

at $\sqrt{s} = 250$ GeV

At the ILC250

$$A_x = \frac{1}{\sigma_{\rm tot}} \int_{-1}^{1} d c_{\theta_\ell} \left[\int_{-\frac{\pi}{2}}^{\frac{\pi}{2}} d\phi_\ell \frac{d\sigma}{d c_{\theta_\ell} d\phi_\ell} - \int_{\frac{\pi}{2}}^{\frac{3\pi}{2}} d\phi_\ell \frac{d\sigma}{d c_{\theta_\ell} d\phi_\ell} \right]$$
$$= \frac{\sigma(c_{\phi_\ell} > 0) - \sigma(c_{\phi_\ell} < 0)}{\sigma(c_{\phi_\ell} > 0) + \sigma(c_{\phi_\ell} < 0)} \equiv \frac{1}{2} P_x,$$

$$A_y = \frac{1}{\sigma_{\rm tot}} \int_{-1}^{1} d c_{\theta_\ell} \left[\int_{0}^{\pi} d\phi_\ell \frac{d\sigma}{d c_{\theta_\ell} d\phi_\ell} - \int_{\pi}^{2\pi} d\phi_\ell \frac{d\sigma}{d c_{\theta_\ell} d\phi_\ell} \right]$$
$$= \frac{\sigma(s_{\phi_\ell} > 0) - \sigma(s_{\phi_\ell} < 0)}{\sigma(s_{\phi_\ell} > 0) + \sigma(s_{\phi_\ell} < 0)} \equiv \frac{1}{2} P_y,$$

$$A_z = \frac{1}{\sigma_{\rm tot}} \int_{0}^{2\pi} d\phi_\ell \left[\int_{0}^{1} d c_{\theta_\ell} \frac{d\sigma}{d c_{\theta_\ell} d\phi_\ell} - \int_{-1}^{0} d c_{\theta_\ell} \frac{d\sigma}{d c_{\theta_\ell} d\phi_\ell} \right]$$
$$= \frac{\sigma(c_{\theta_\ell} > 0) - \sigma(c_{\theta_\ell} < 0)}{\sigma(c_{\theta_\ell} > 0) + \sigma(c_{\theta_\ell} < 0)} \equiv \frac{1}{2} P_z.$$

A_z	A_j^{FB}	Coupling
$-$ve	$-$ve	X_{qt}^L
$+$ve	$+$ve	X_{qt}^R
[-0.10,0.10]∼0	$+$ve	$\kappa_{qt}^L(\gamma), \kappa_{qt}^L$
	$-$ve	$\kappa_{qt}^R(\gamma), \kappa_{qt}^R$

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

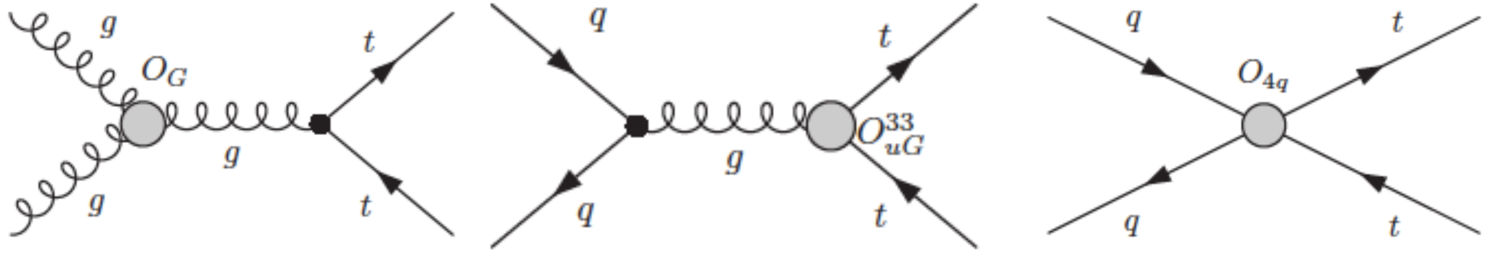
NP through Effective Lagrangian (SMEFT)
Anomalous Couplings

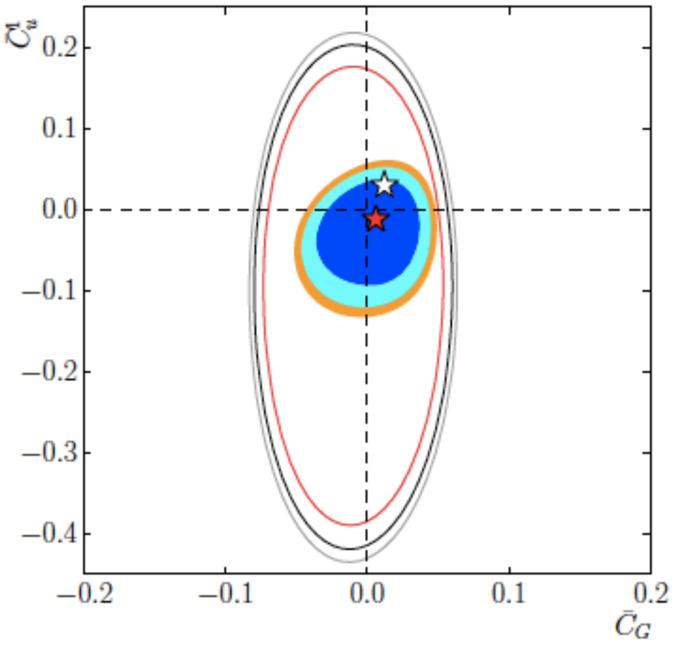
TopFitter Collaboration
1512.03360

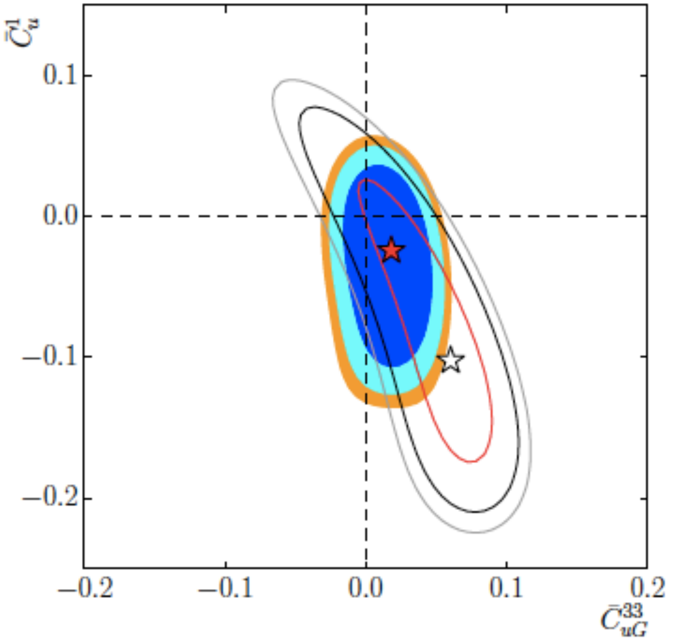
$$\mathcal{L} = \mathcal{L}^{SM} + \sum \frac{c_i}{\Lambda^2}\mathcal{O}_i + O\left(\frac{1}{\Lambda^4}\right)$$

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

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







NP through Effective Lagrangian (SMEFT)
Anomalous Couplings

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

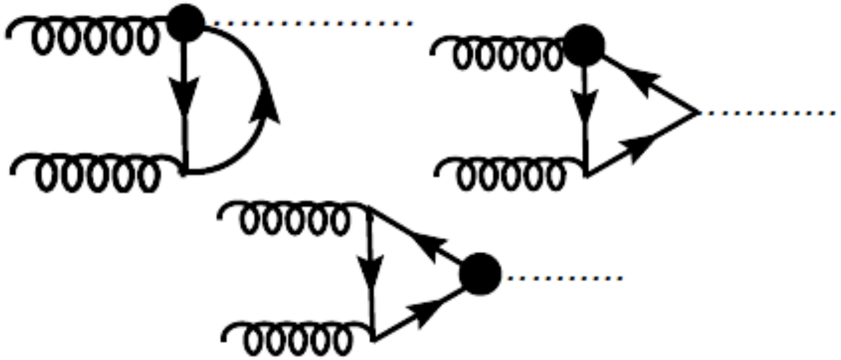
$$\mathcal{O}_{hg} = \left(\bar{Q}_L H\right)\sigma^{\mu\nu}T^a t_R G^a_{\mu\nu}, \qquad \mathcal{O}_{HG} = \frac{1}{2}H^\dagger H G^a_{\mu\nu}G^{\mu\nu}_a$$

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

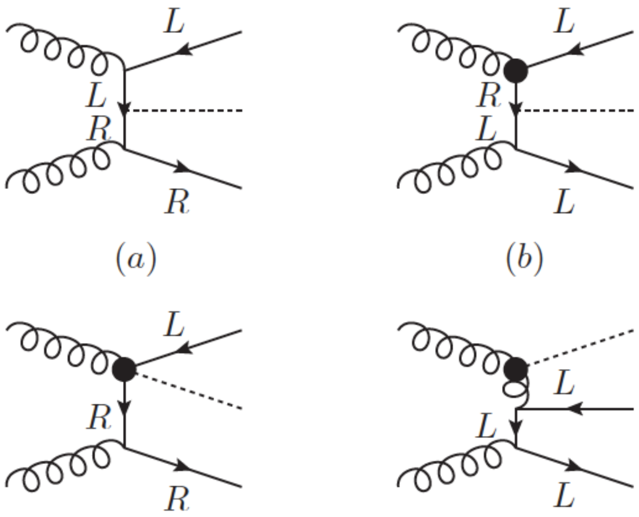
$$\mathcal{O}_{Ht} = H^\dagger D_\mu H \bar{t}_R\gamma^\mu t_R \qquad \mathcal{O}_{H\gamma} = \frac{1}{2}H^\dagger H F_{\mu\nu}F^{\mu\nu}$$

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

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



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



(a) (b)

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

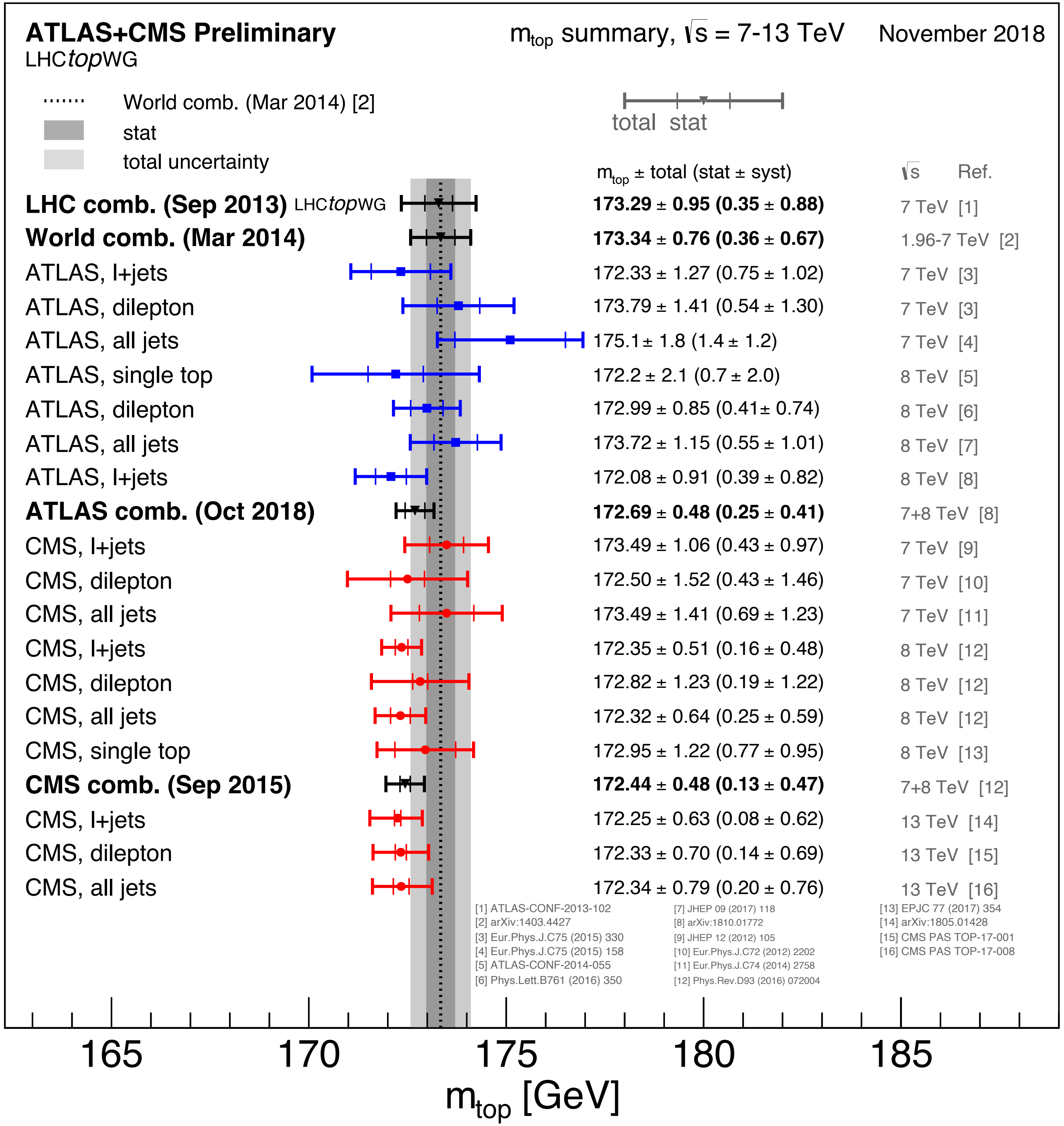
$$\mathcal{L}^{ht\bar{t}} = \bar{t}t\frac{h}{\sqrt{2}}\left(y_t - \left(\frac{3}{2}\Re\left(c_{Hy}\right)+y_t c_H\right)\frac{v^2}{\Lambda^2}\right) = \bar{t}th\frac{m_t}{v}\left(1-c_y\frac{v^2}{\Lambda^2}\right),$$

$\sqrt{s} = 14\ TeV$

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

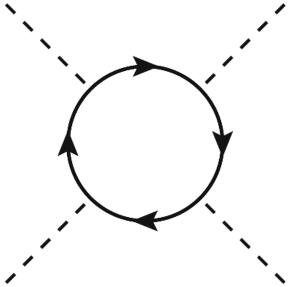
Top quark mass

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

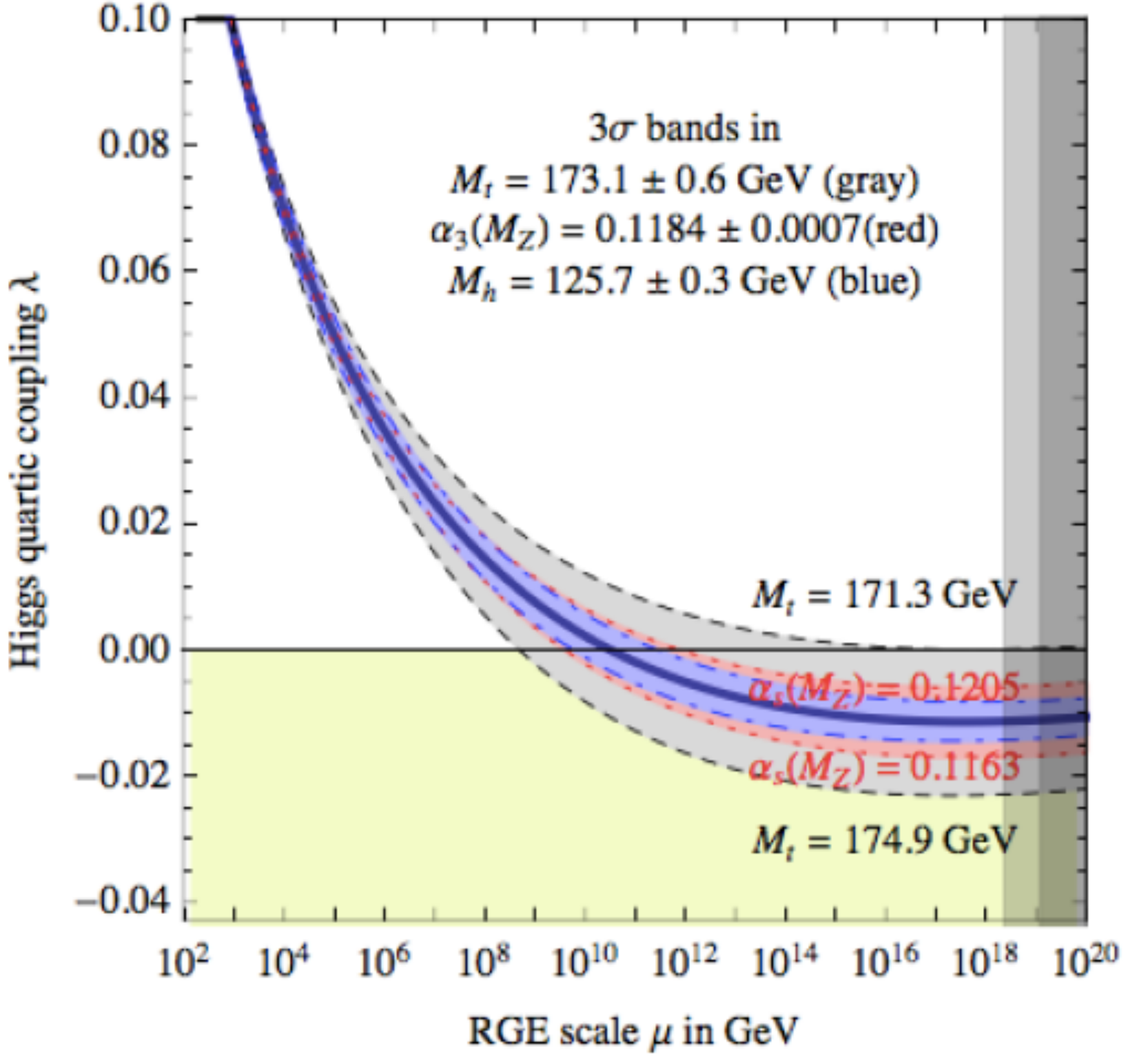
$$16\pi^2\frac{d\lambda}{d\log\mu} = 24\lambda^2 + 12\lambda g_{htt}^2 - 9\lambda\left(g^2 + \frac{g'^2}{3}\right) - 6g_{htt}^4 + \frac{9g^4}{8} + \frac{3g'^4}{8} + \frac{3g^2g'^2}{4}$$

In the SM, at tree level

$$g_{htt}^{SM} = \frac{\sqrt{2}\,m_t}{\upsilon} = \frac{\sqrt{2}\cdot(173.34\pm0.76)}{246} = 0.996\pm0.004$$

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

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



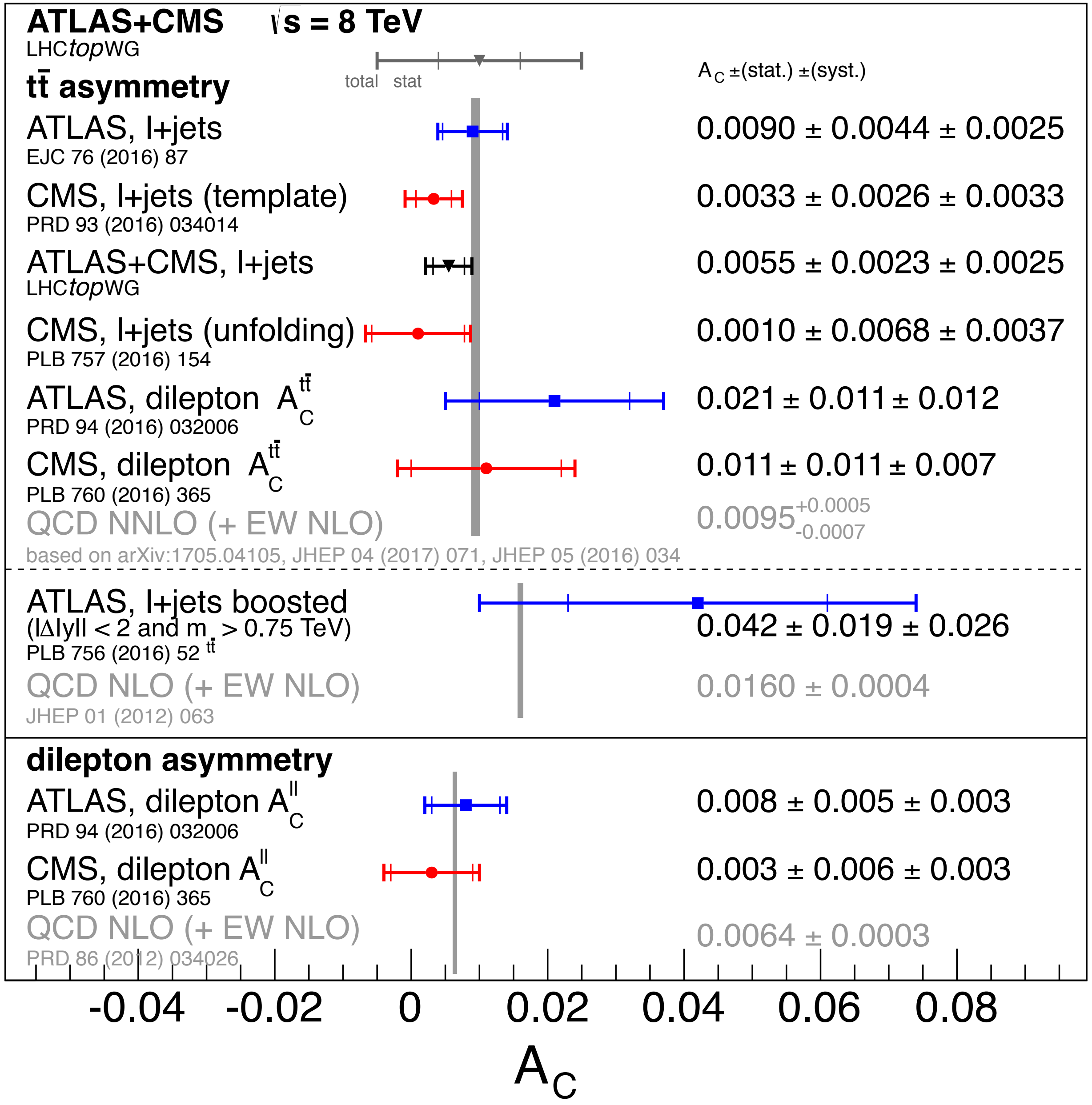
Degrassi, et al, JHEP08(2012)098 [1205.6497]

Top quark pair production: Charge Asymmetry

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

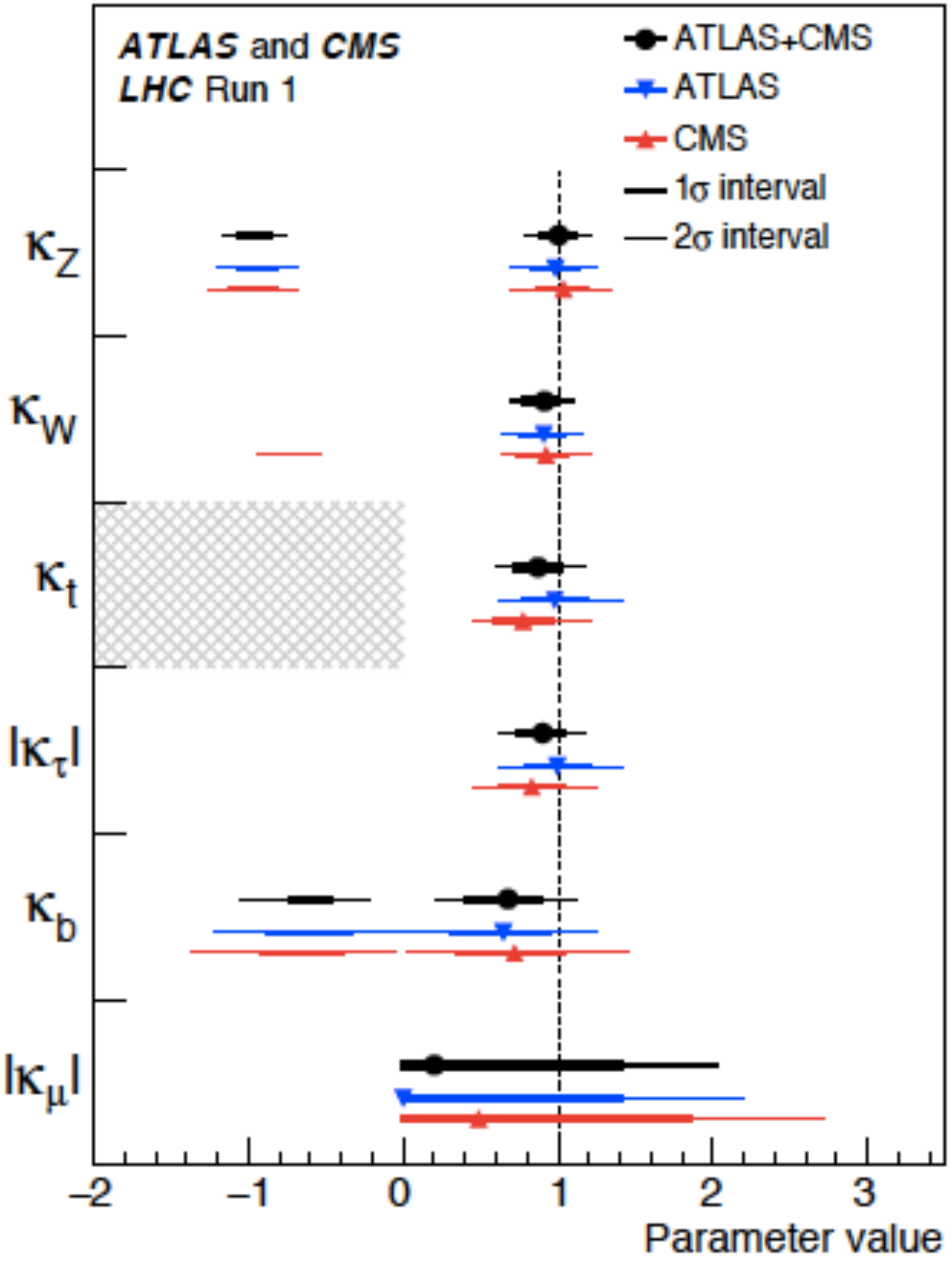
$$\Delta|y| = |y_t| - |y_{\bar{t}}|$$

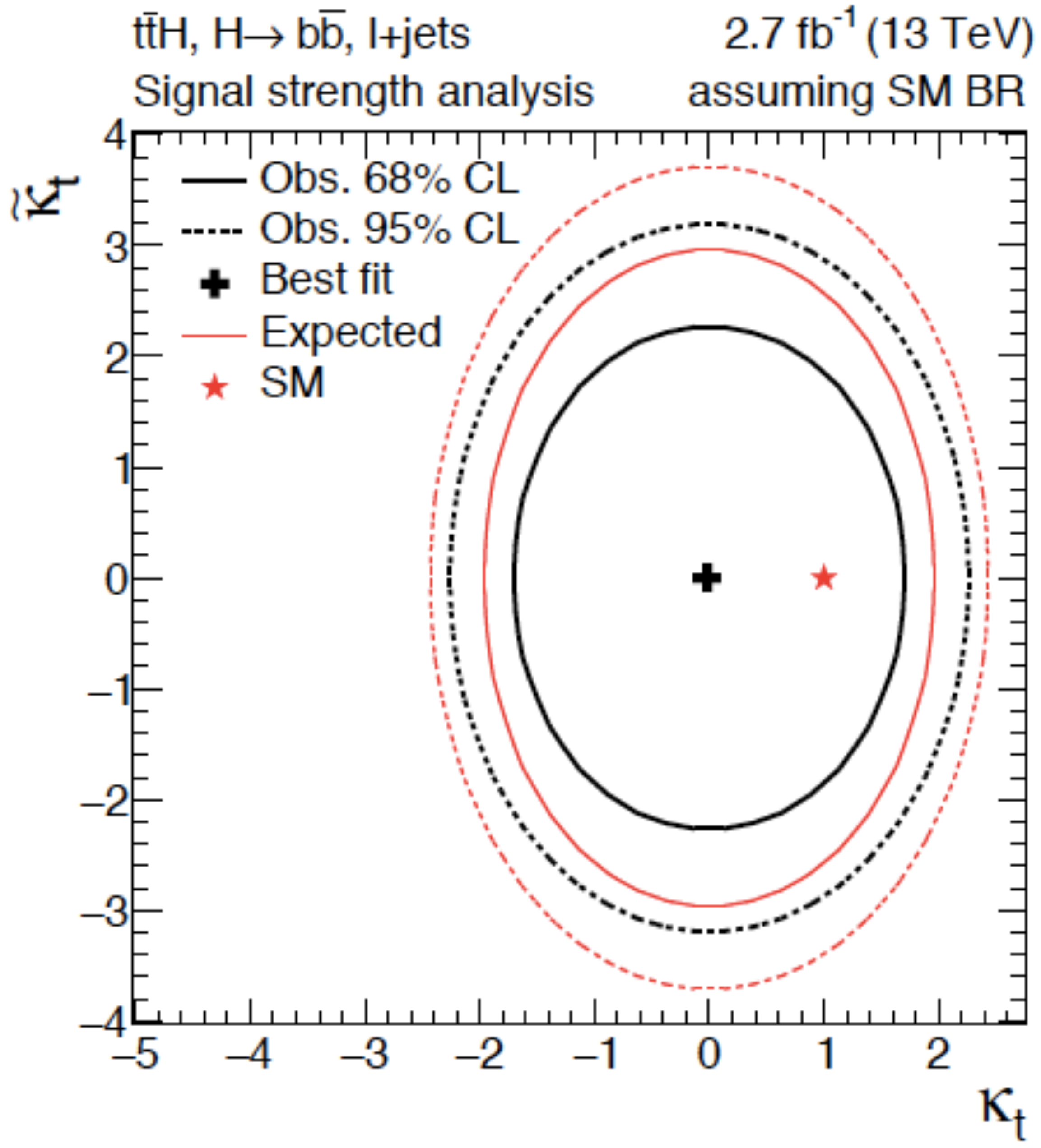
Difference in the top anti-top rapidities



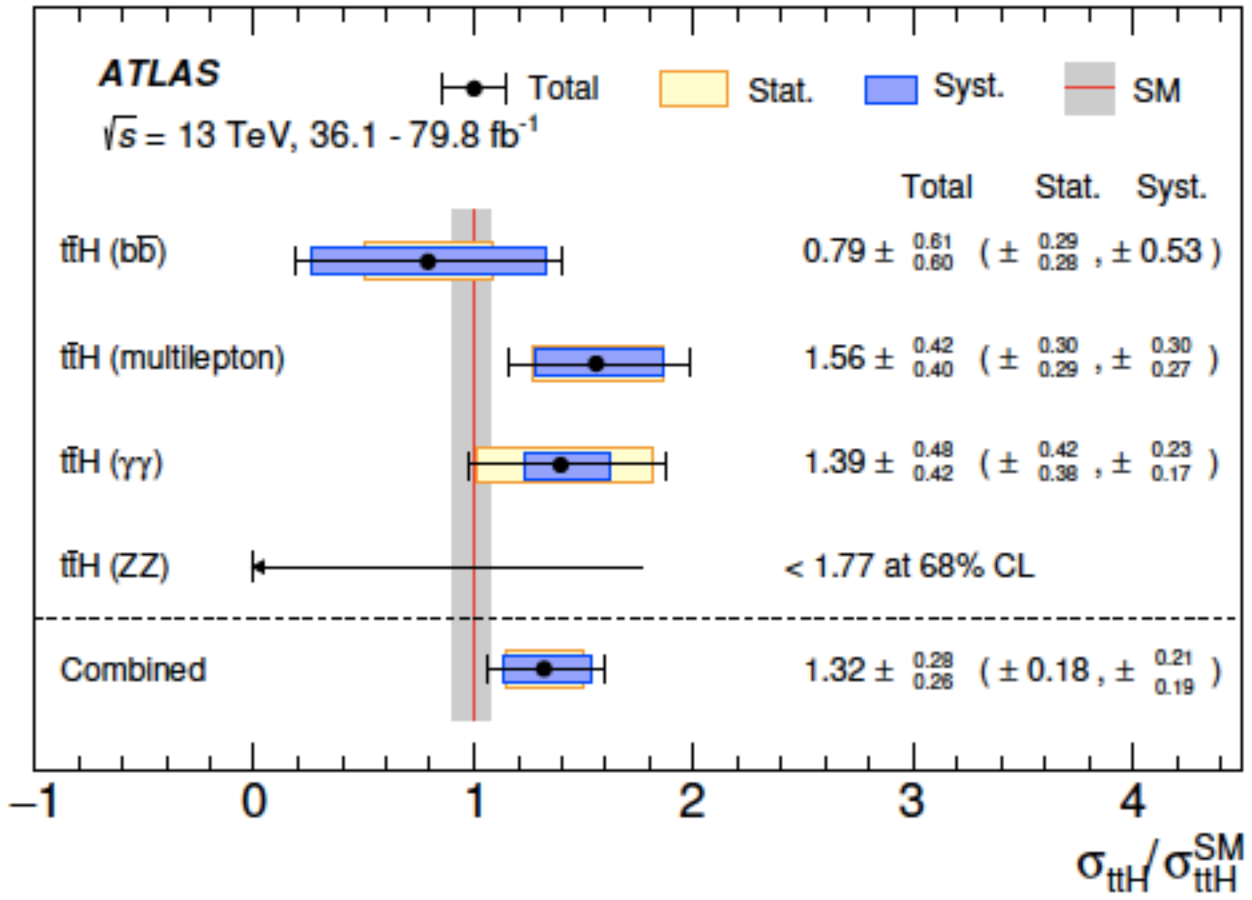
ATLAS and CMS, JHEP 1608 (2016) 045

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	
$\sigma_{q\bar{q}\to ZH}$	κ_Z^2	
$\sigma_{gg\to ZH}$	$2.27\kappa_Z^2 + 0.37\kappa_t^2 - 1.64\kappa_Z\kappa_t$	
$\sigma_{t\bar{t}H}$	κ_t^2	
σ_{tHW}	$1.84\kappa_t^2 + 1.57\kappa_W^2 - 2.41\kappa_W\kappa_t$	
σ_{tHq}	$3.40\kappa_t^2 + 3.56\kappa_W^2 - 5.96\kappa_t\kappa_W$	
$\sigma_{b\bar{b}H}$	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

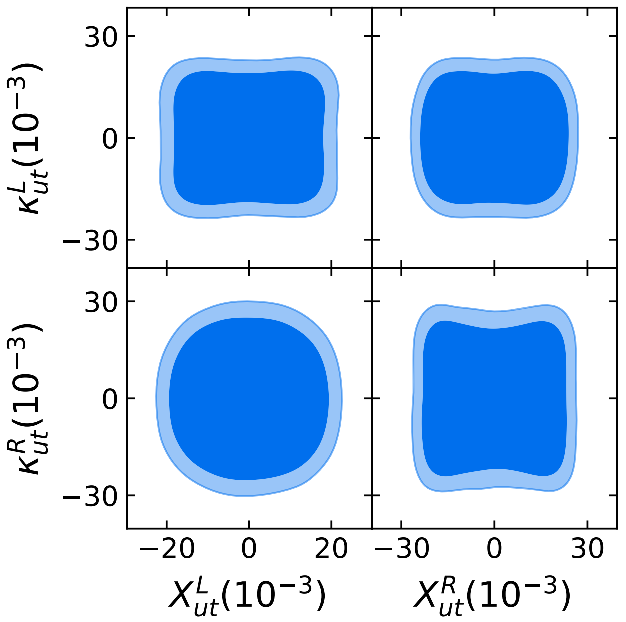


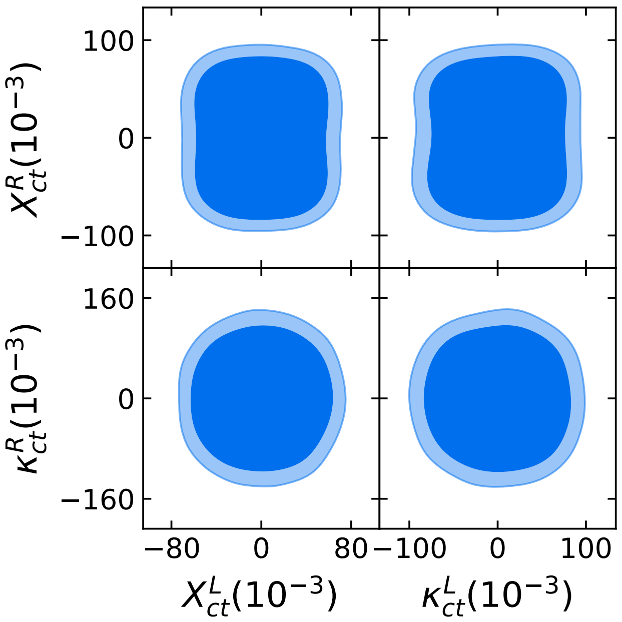
Present Experimental status

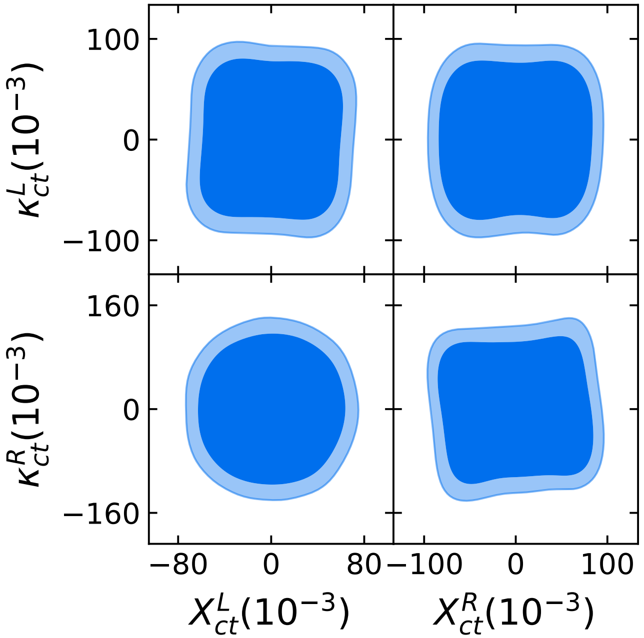
Process	Br Limit	Search	Dataset
$t \to Zq$	5×10^{-4}	CMS $t\bar{t} \to Wb + Zq \to \ell\nu b + \ell\ell q$	$19.7\ \text{fb}^{-1}$, 8 TeV
$t \to Zq$	7.3×10^{-3}	ATLAS $t\bar{t} \to Wb + Zq \to \ell\nu b + \ell\ell q$	$2.1\ \text{fb}^{-1}$, 7 TeV
$t \to gu$	3.1×10^{-5}	ATLAS $qg \to t \to Wb$	$14.2\ \text{fb}^{-1}$,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

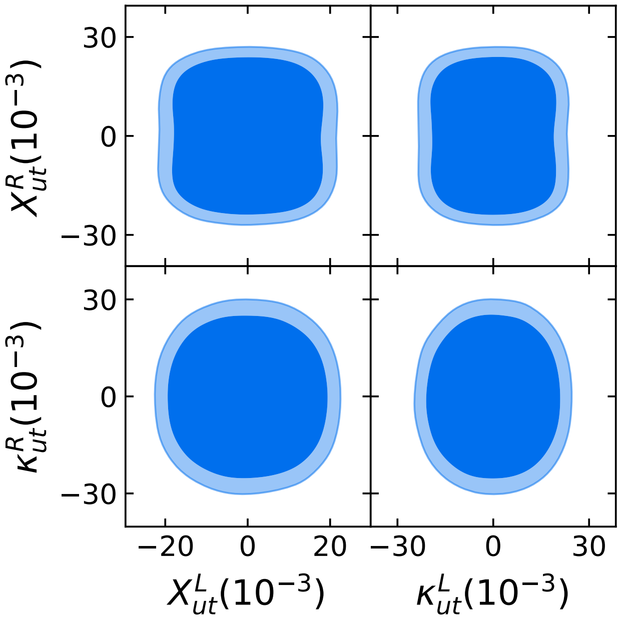
Process	SM	2HDM(FV)	2HDM(FC)	MSSM	RPV	RS
$t \to Zu$	7×10^{-17}	–	–	$\leq 10^{-7}$	$\leq 10^{-6}$	–
$t \to Zc$	1×10^{-14}	$\leq 10^{-6}$	$\leq 10^{-10}$	$\leq 10^{-7}$	$\leq 10^{-6}$	$\leq 10^{-5}$
$t \to gu$	4×10^{-14}	–	–	$\leq 10^{-7}$	$\leq 10^{-6}$	–
$t \to gc$	5×10^{-12}	$\leq 10^{-4}$	$\leq 10^{-8}$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

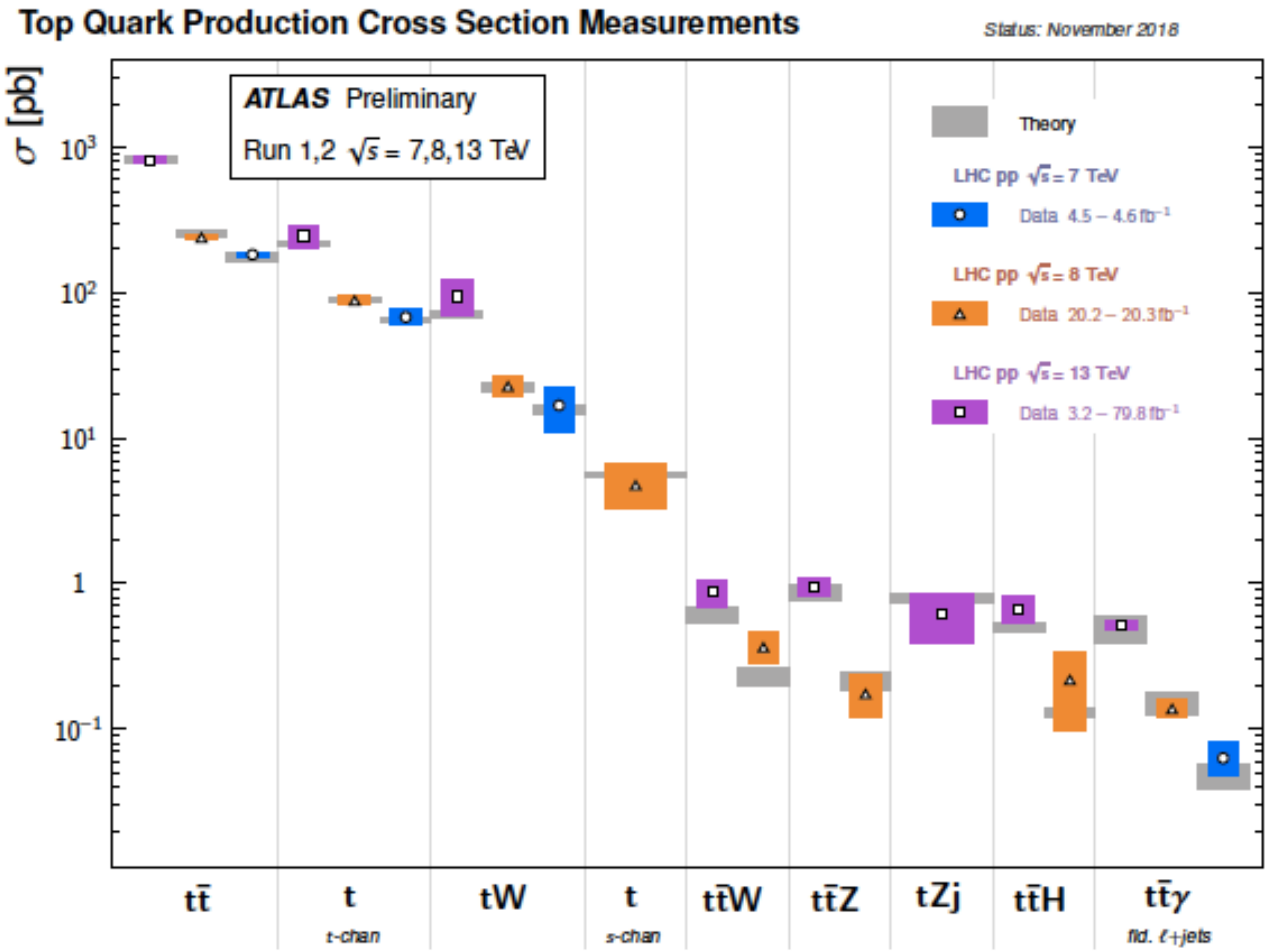
Top quark is produced at LCH in many processes

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 10⁶** top pairs
@ 13 TeV, 100 /fb



Top Working Group Summary Plots

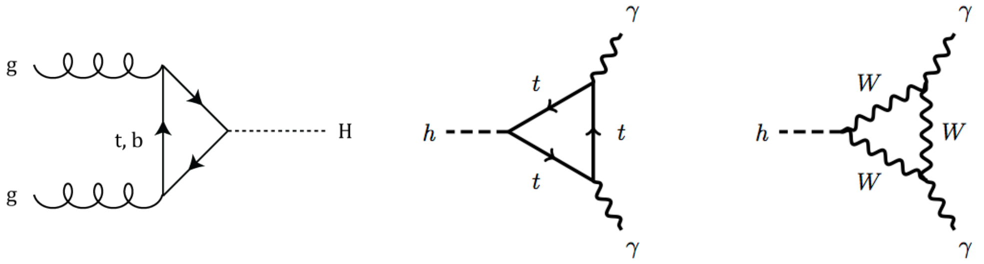
ATL-PHYS-PUB-2018-034

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

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



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

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

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

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

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

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

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