Understanding the Top quark

At the LHC and beyond

Poulose Poulose

Department of Physics, IIT Guwahati

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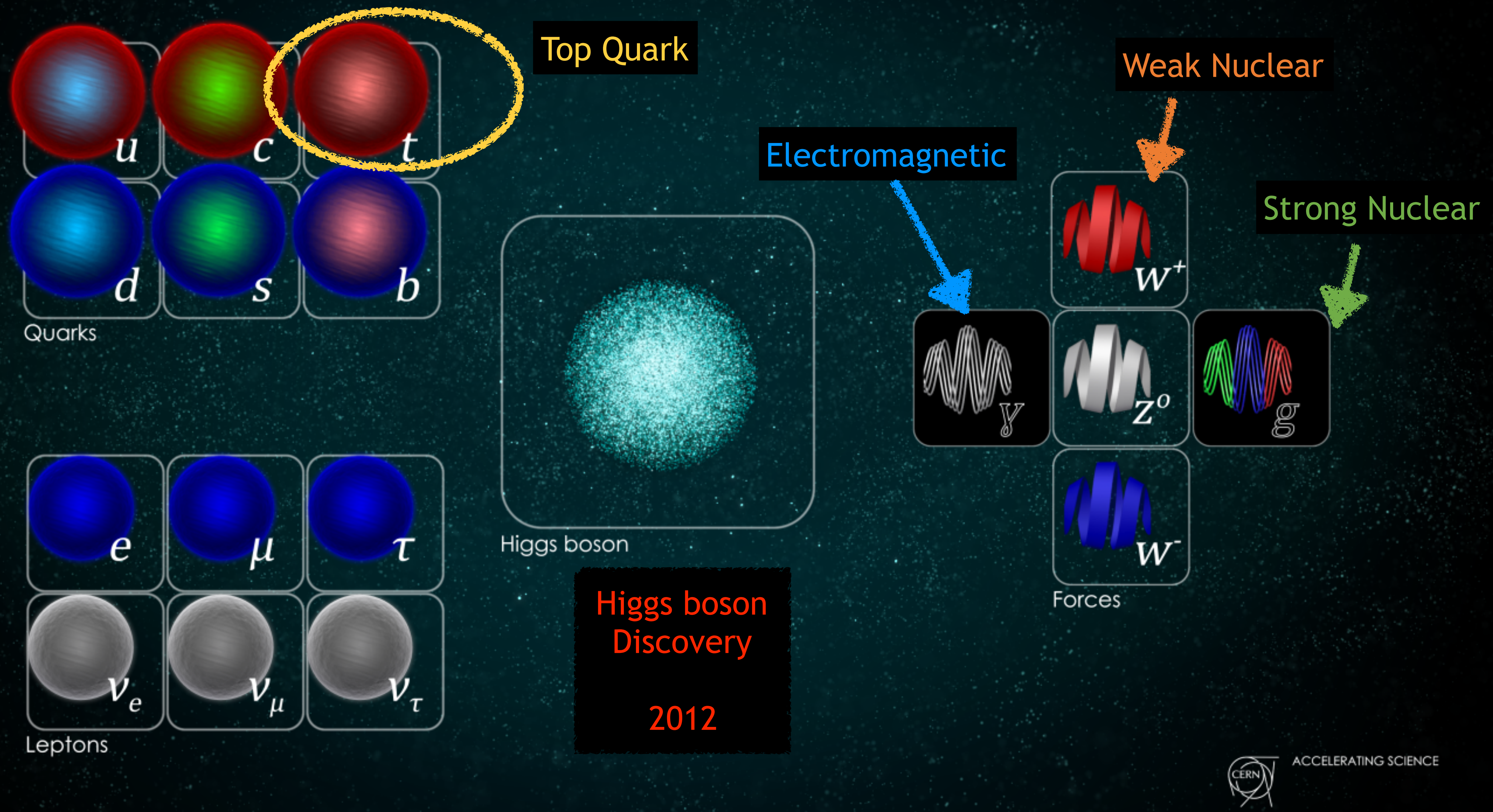
The Standard Model



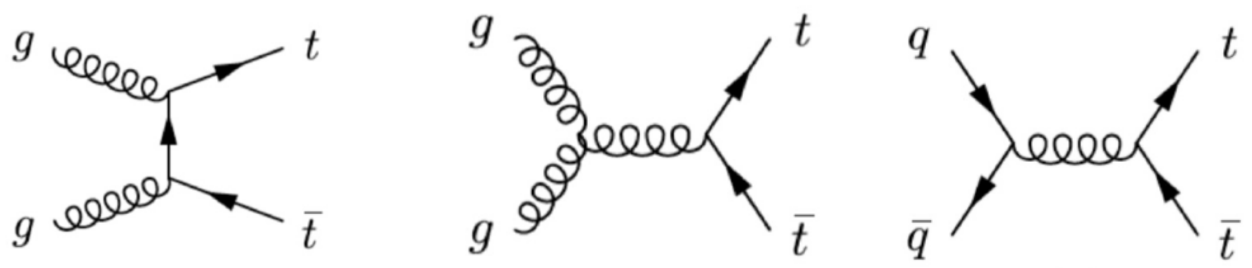
Top quark (discovery in 1995):

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.

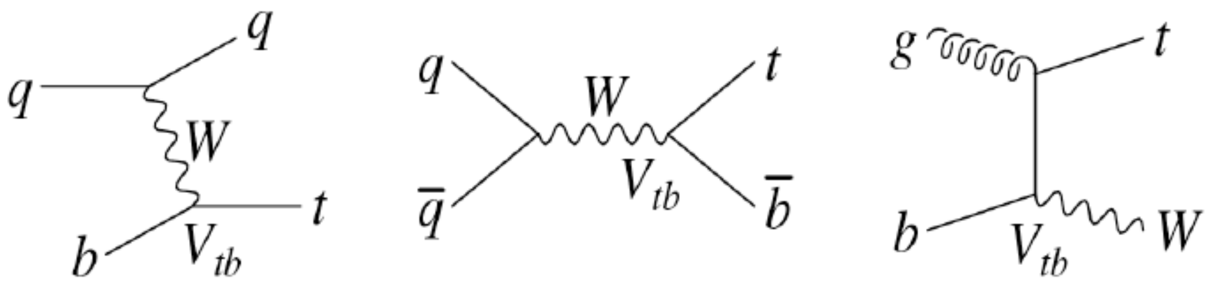
Top quark being the heaviest elementary particle (so far) has the strongest interaction with the Higgs boson

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

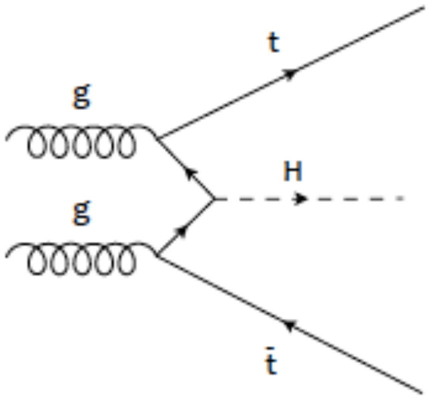
Top quark is produced at LCH in many processes



pair production

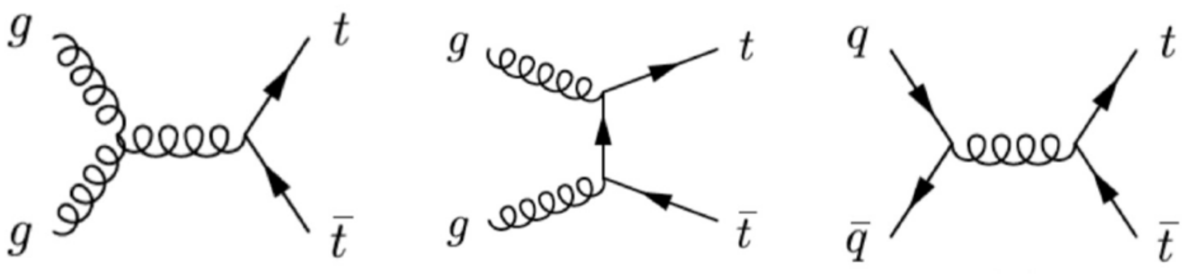


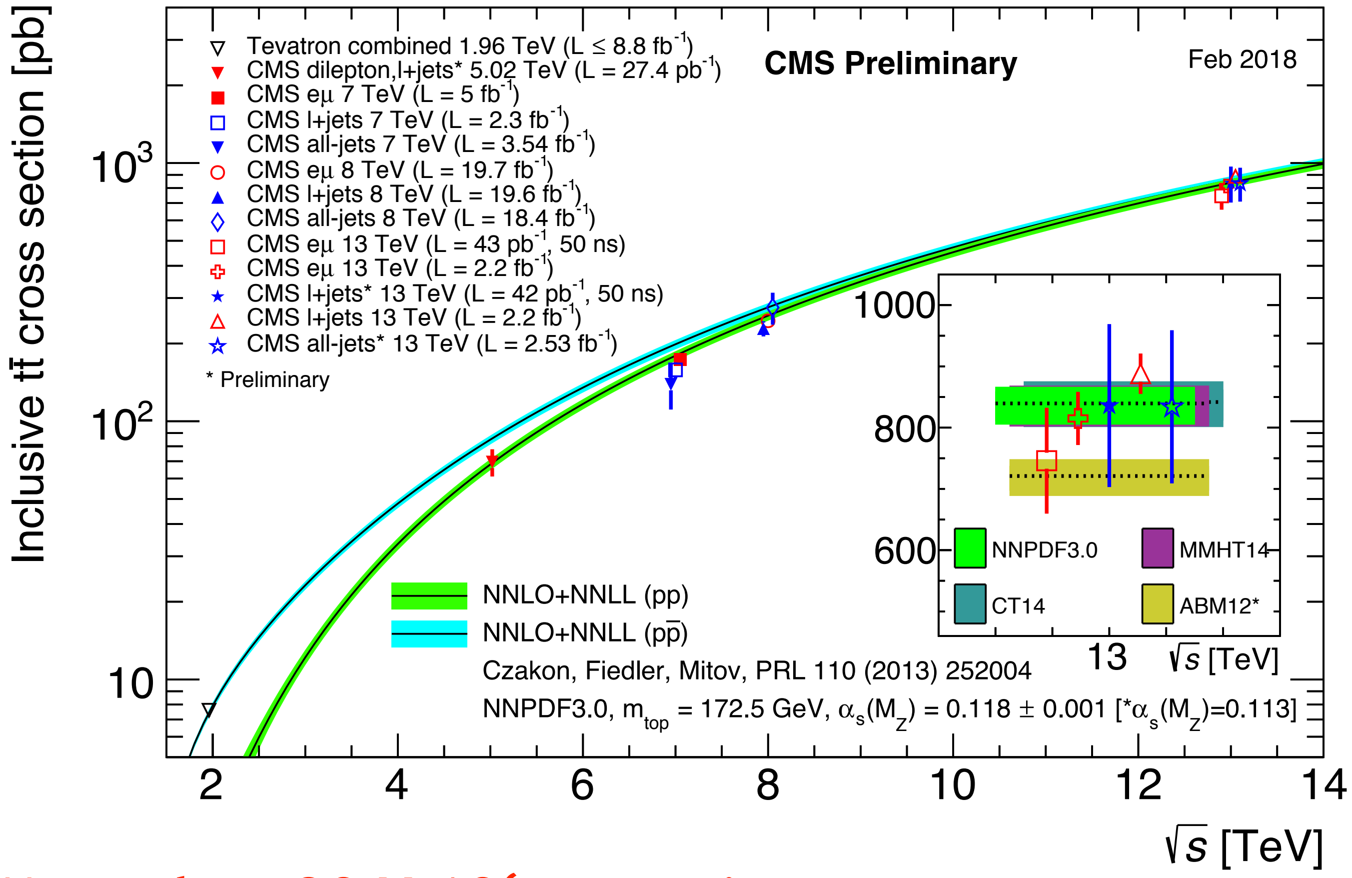
single top with a light jet / W /Z and jet

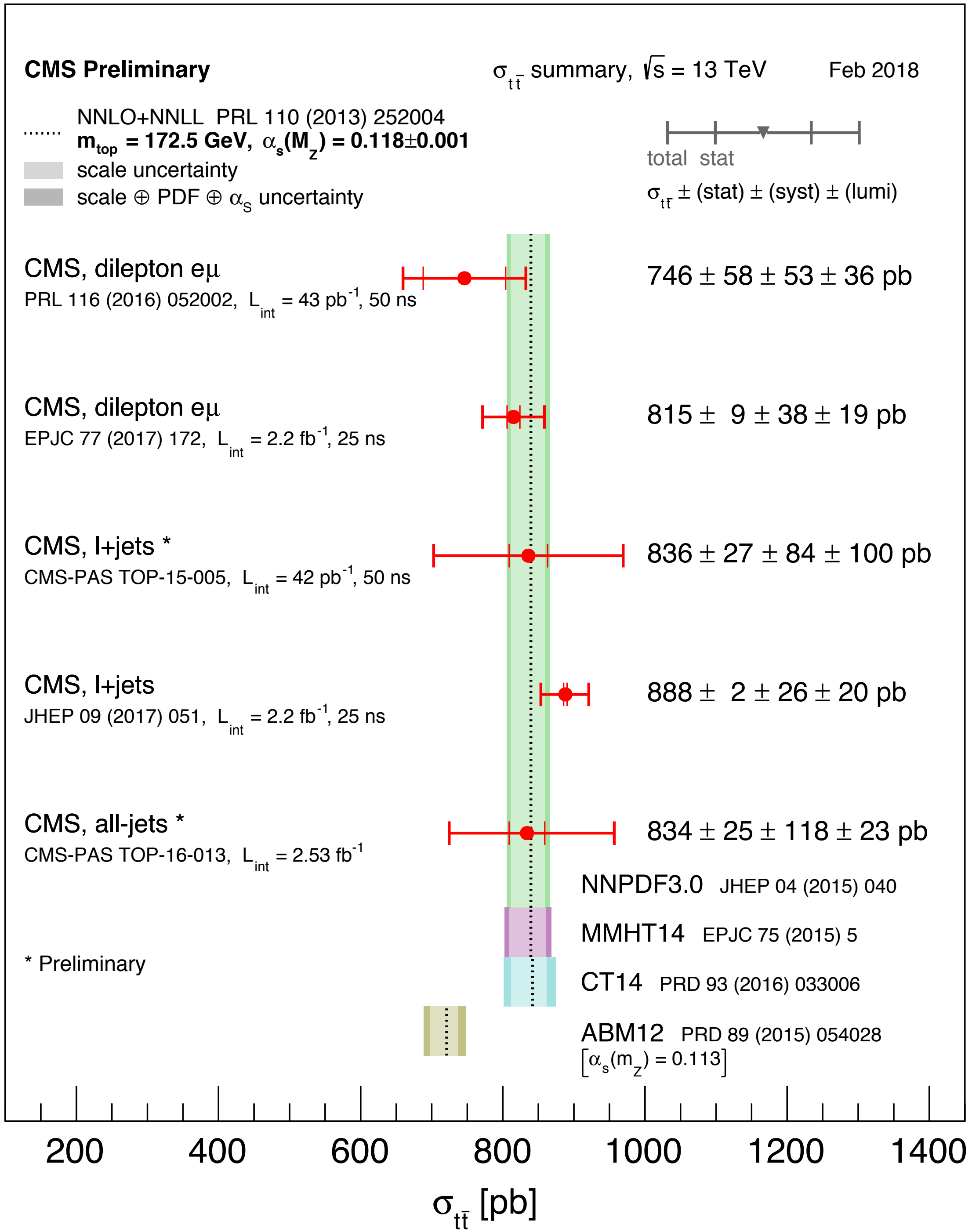


pair production along with H/Z

Top quark pair production at the LHC





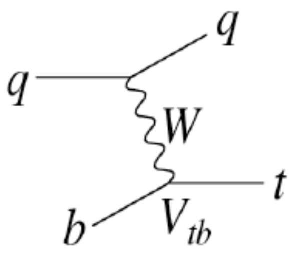


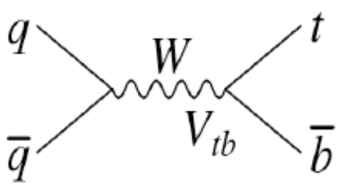
More than 80 X 10^6 top pairs @ 13 TeV, 100 /fb (approx. one year)

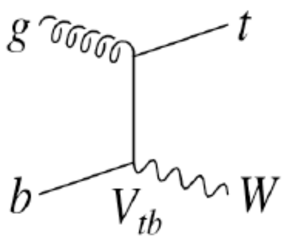
Single Top quark production at the LHC

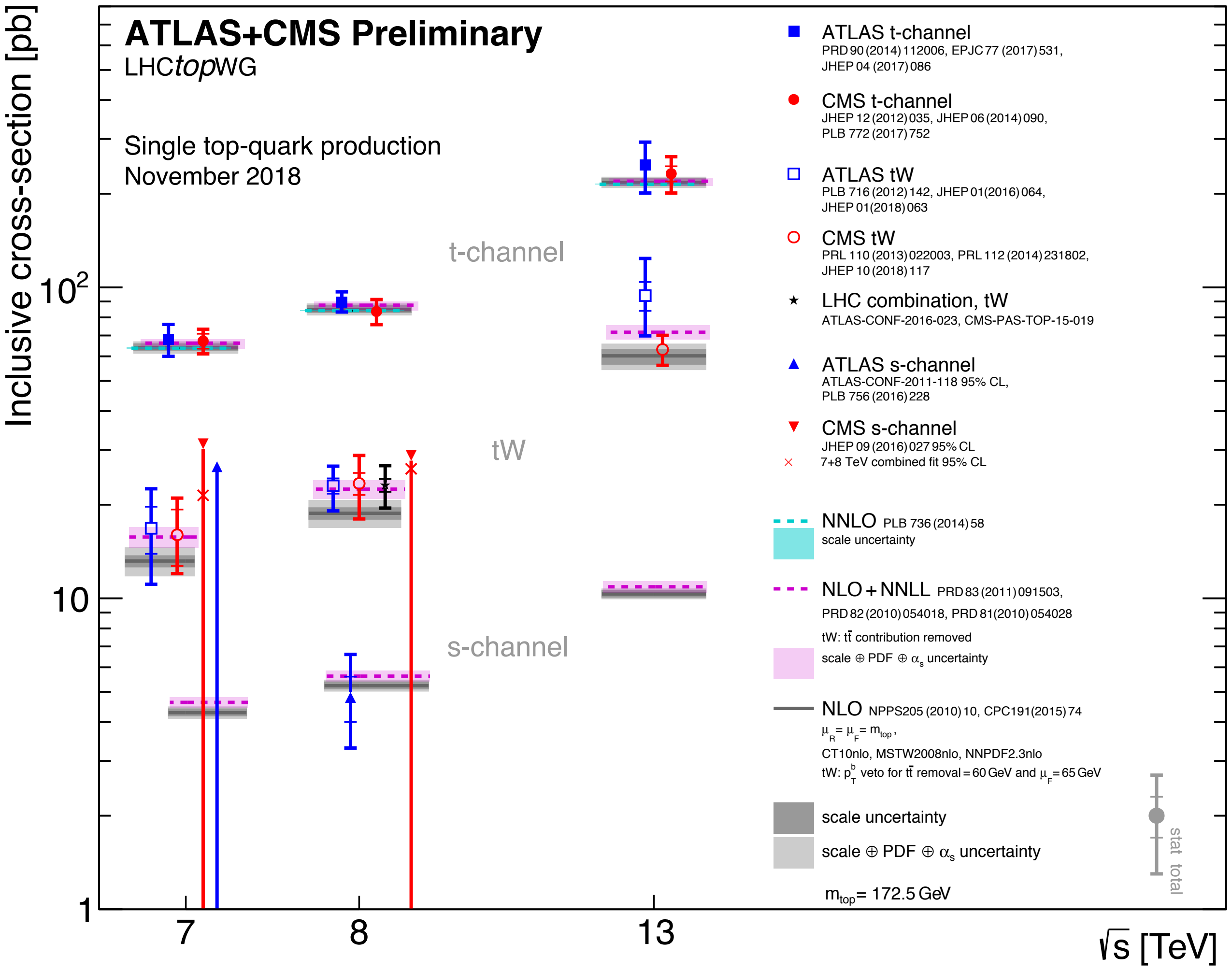
direct measurement of Vtb

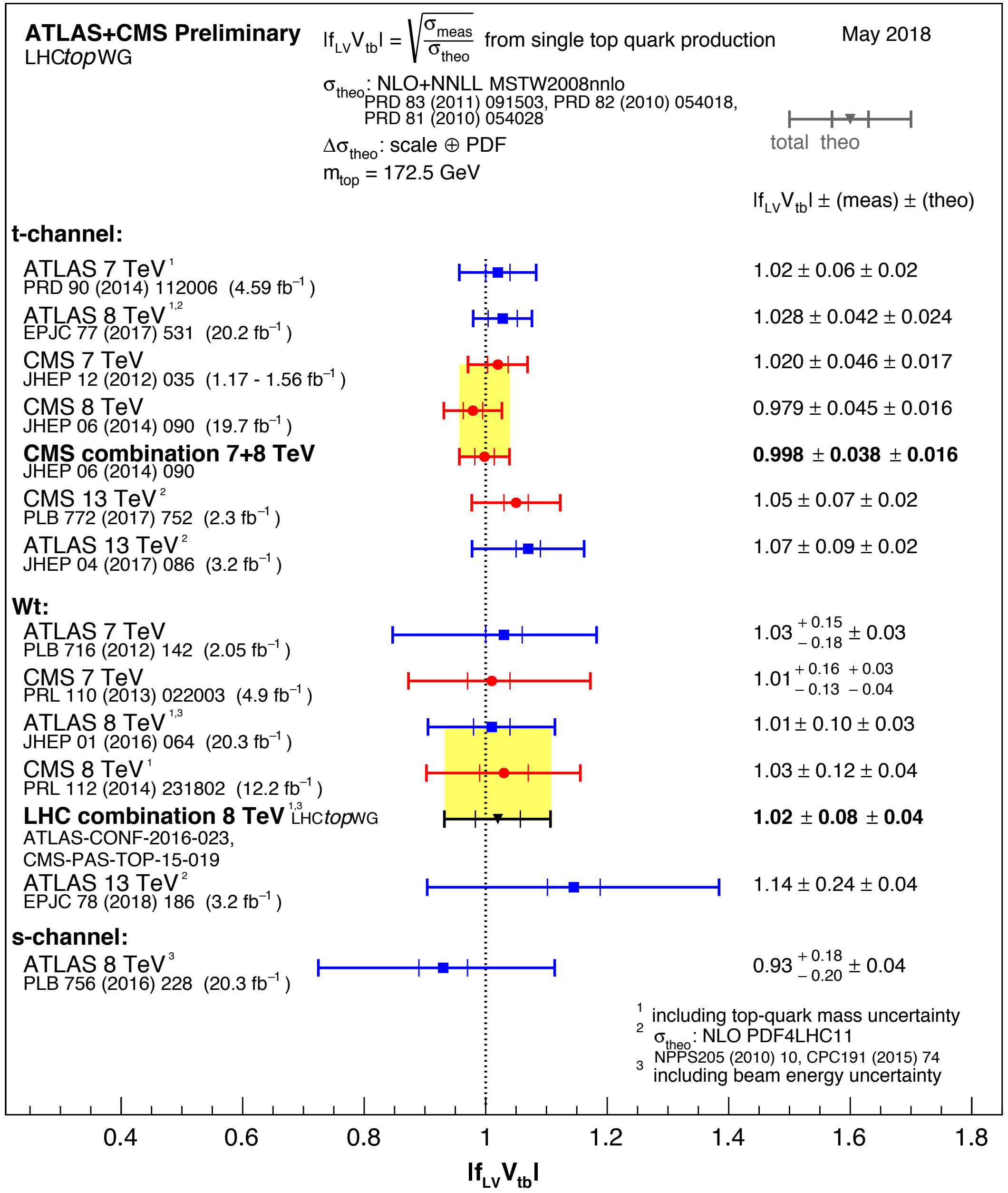
More than 30 X 10^6 single top @ 13 TeV, 100 /fb









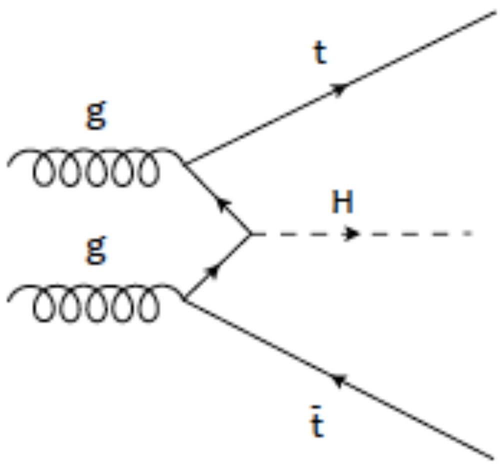


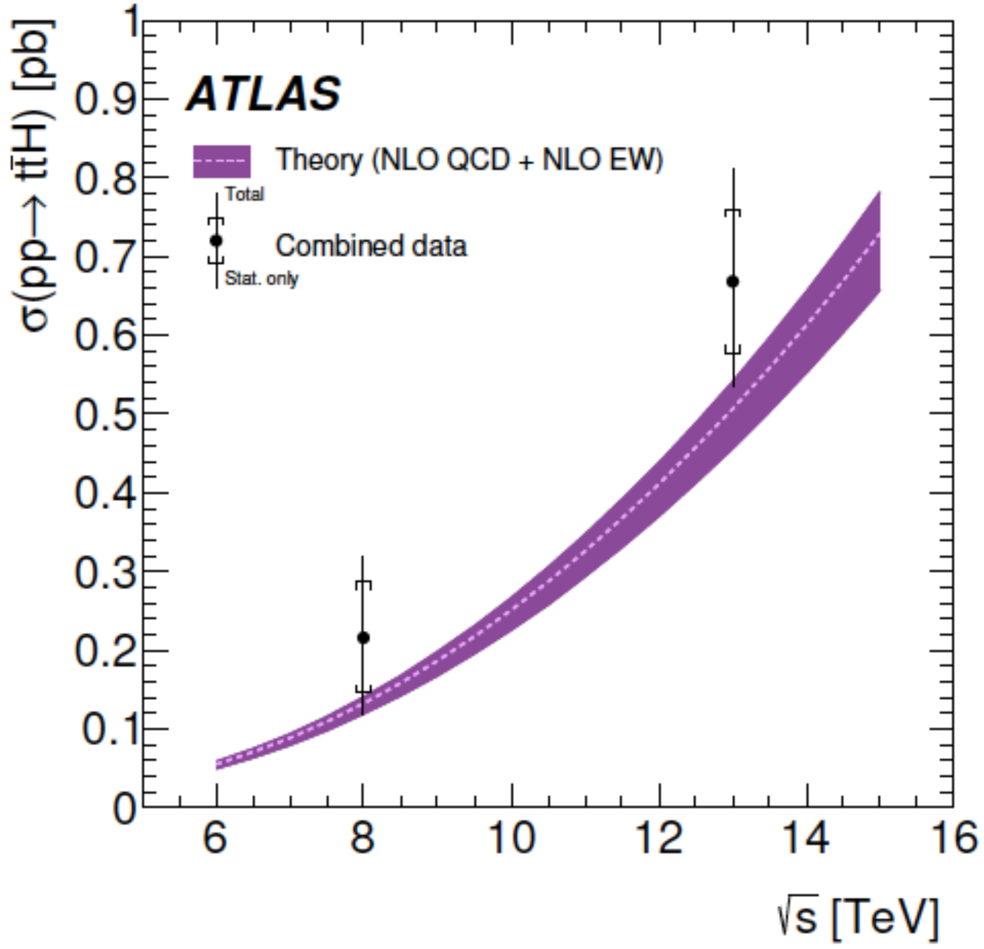
Top quark pair in association with Higgs

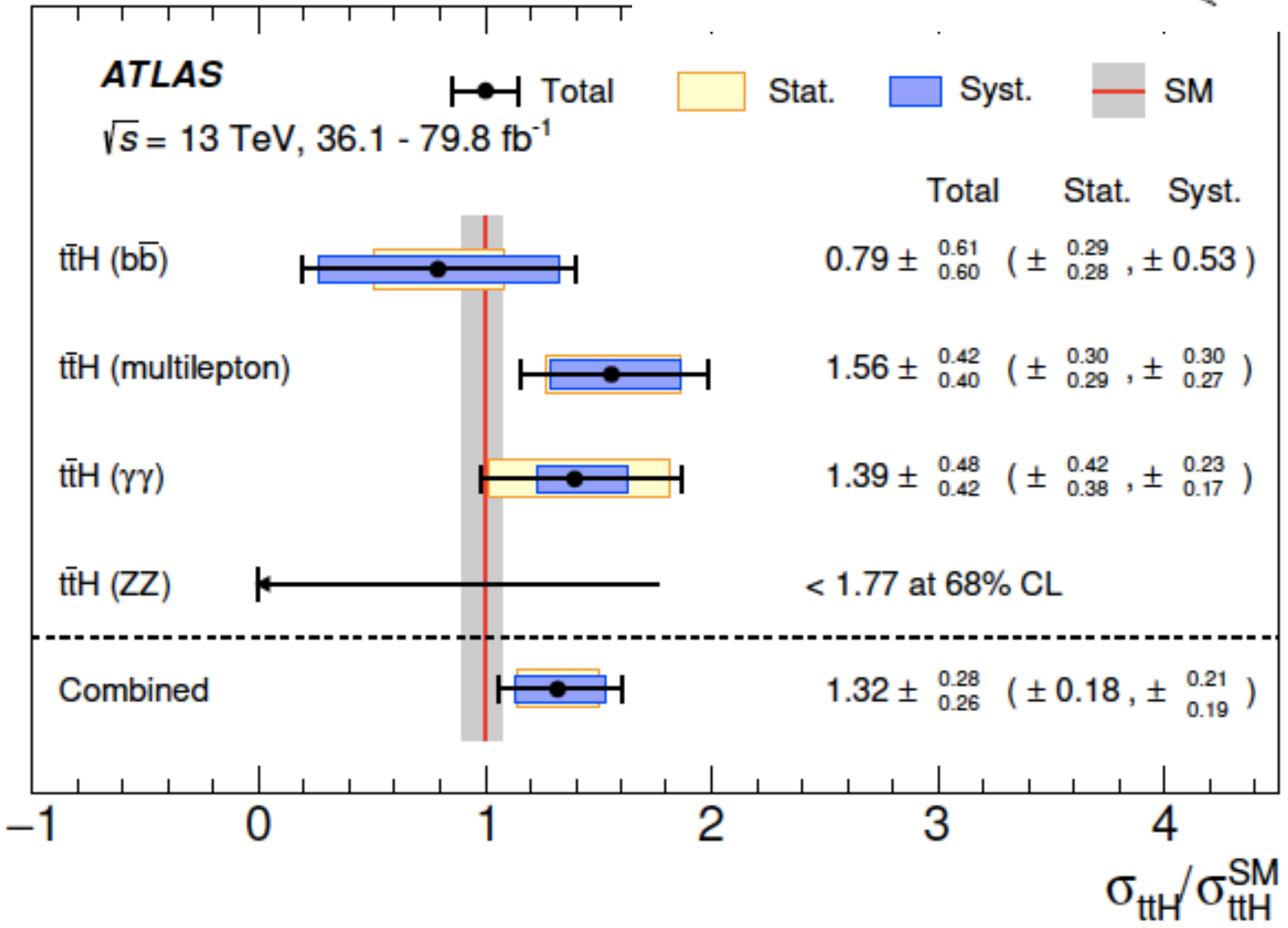
Direct measurement of Yukawa coupling

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

About 60000 top pairs along with H @ 13 TeV, 100 /fb

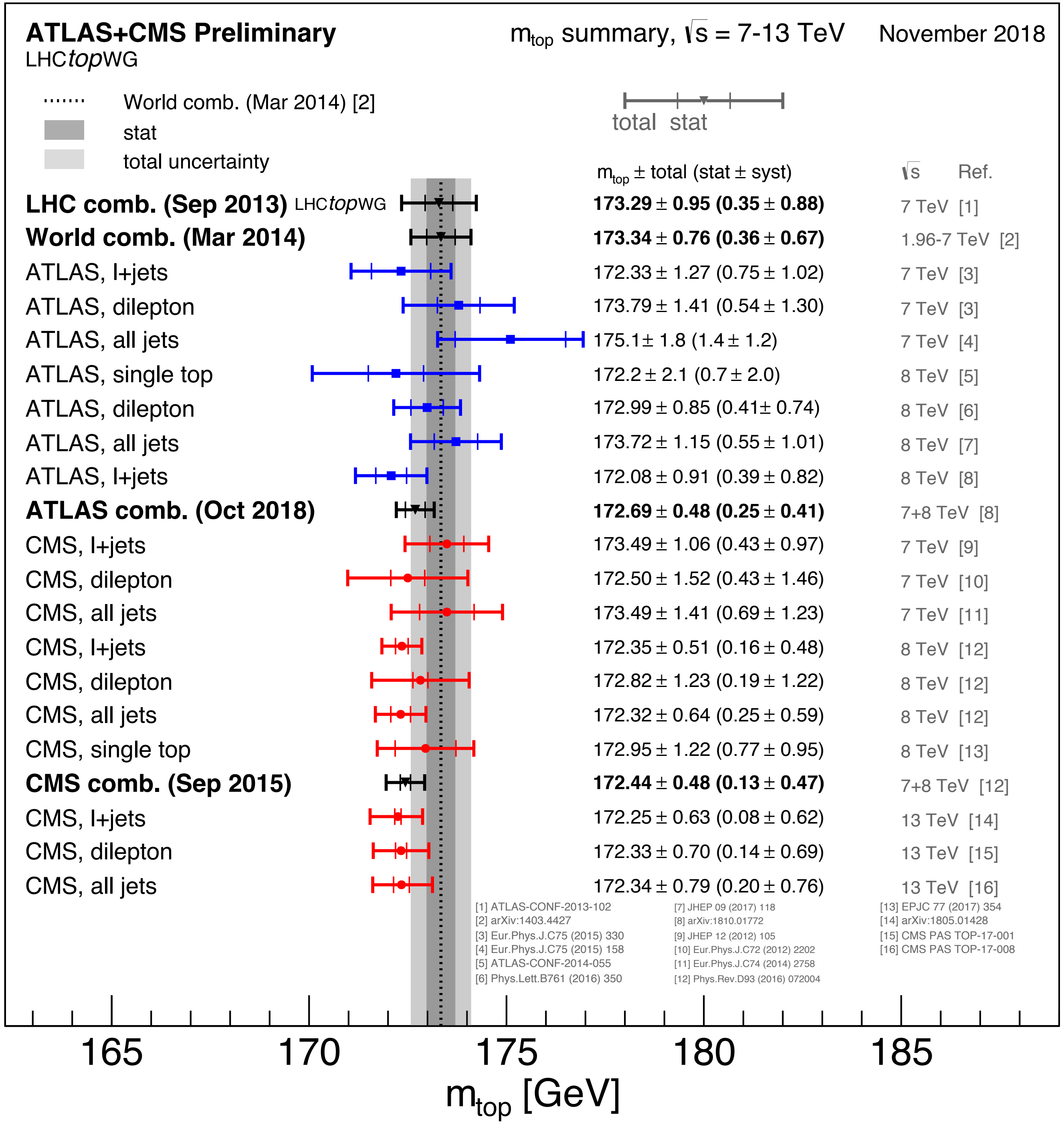






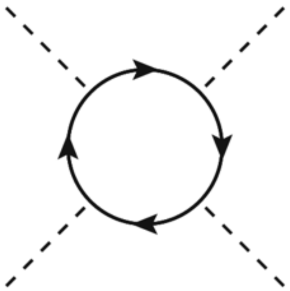
Top quark mass

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

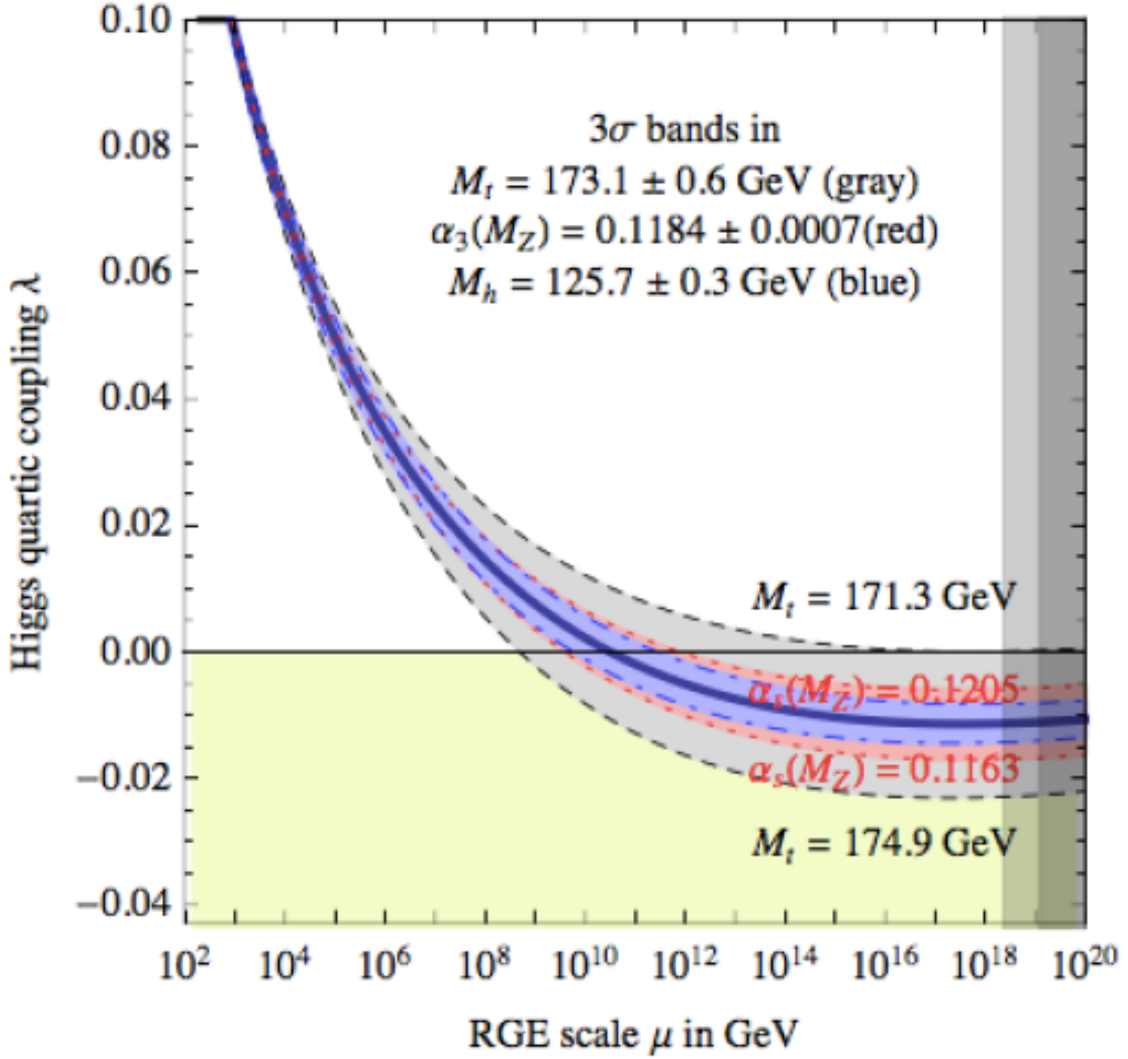
$$16\pi^2\frac{d\lambda}{d\log\mu} = 24\lambda^2 + 12\lambda g_{htt}^2 - 9\lambda\left(g^2 + \frac{g'^2}{3}\right) - 6g_{htt}^4 + \frac{9g^4}{8} + \frac{3g'^4}{8} + \frac{3g^2g'^2}{4}$$

In the SM, at tree level

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

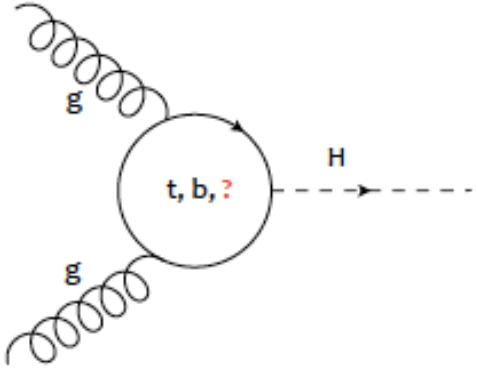
In 2HDM / MSSM $\quad g_{htt} = \frac{\sqrt{2}\,m_t}{\upsilon}\frac{\cos\alpha}{\sin\beta}$

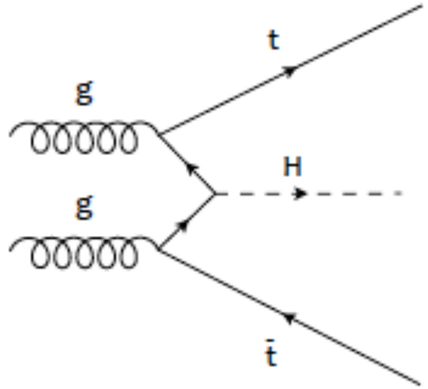
In general $\quad g_{htt} = c_t\, g_{htt}^{SM}$

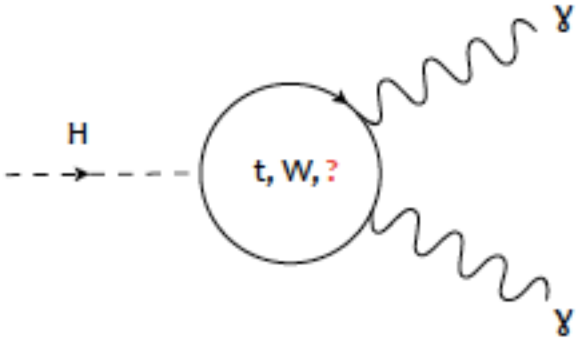


Degrassi, et al, JHEP08(2012)098 [1205.6497]

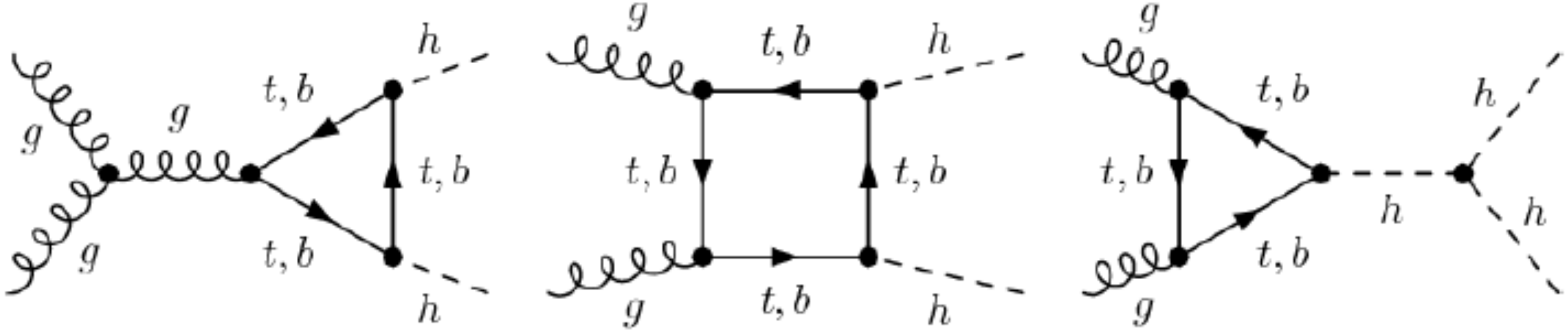
Top quark Yukawa influencing the production and decay of the Higgs boson at the LHC

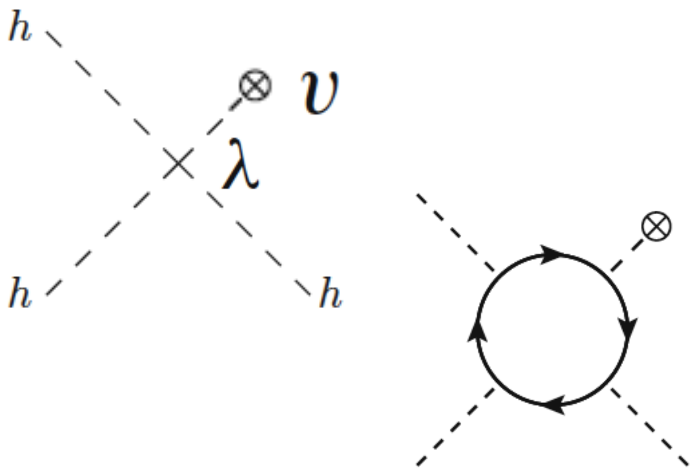






Also the measurement of Higgs trilinear coupling





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

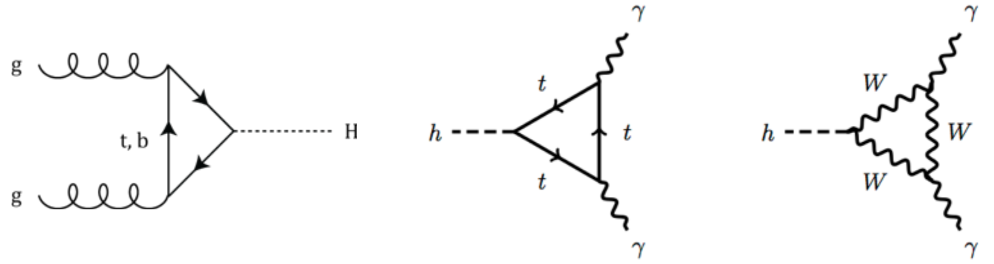
SM => $\kappa_t = 1$ $\tilde{\kappa}_t = 0$

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

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



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

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

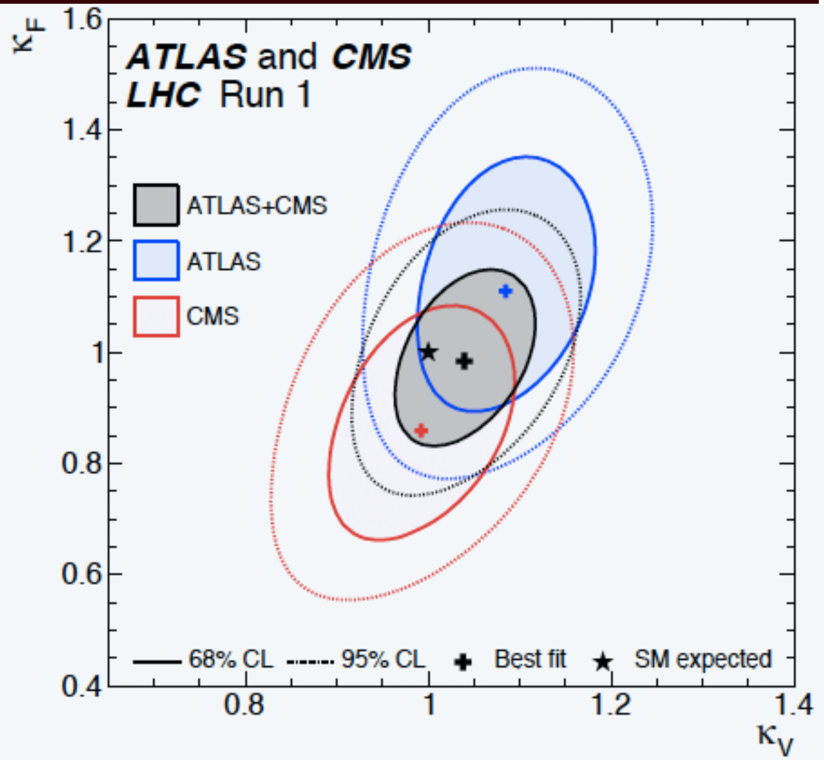
$$\sigma(gg \to H) * \mathrm{BR}(H \to \gamma\gamma) \sim \frac{\kappa_F^2 \cdot \kappa_\gamma^2(\kappa_F, \kappa_V)}{0.75 \cdot \kappa_F^2 + 0.25 \cdot \kappa_V^2}$$

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

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

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

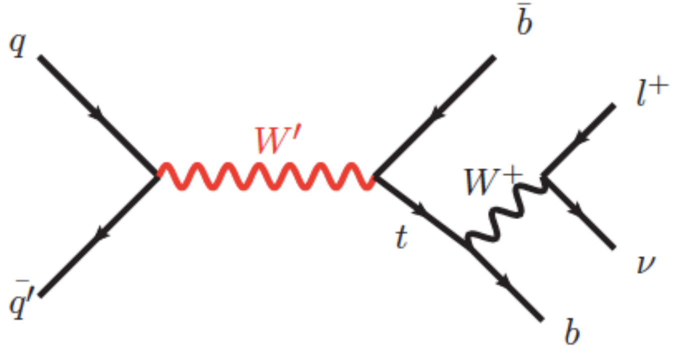
$$\kappa_H^2 = 0.57 \cdot \kappa_b^2 + 0.22 \cdot \kappa_W^2 + 0.09 \cdot \kappa_g^2 + 0.06 \cdot \kappa_\tau^2 + 0.03 \cdot \kappa_Z^2 + 0.03 \cdot \kappa_c^2 + 0.0023 \cdot \kappa_\gamma^2 + 0.0016 \cdot \kappa_{(Z\gamma)}^2 + 0.0001 \cdot \kappa_s^2 + 0.00022 \cdot \kappa_\mu^2$$

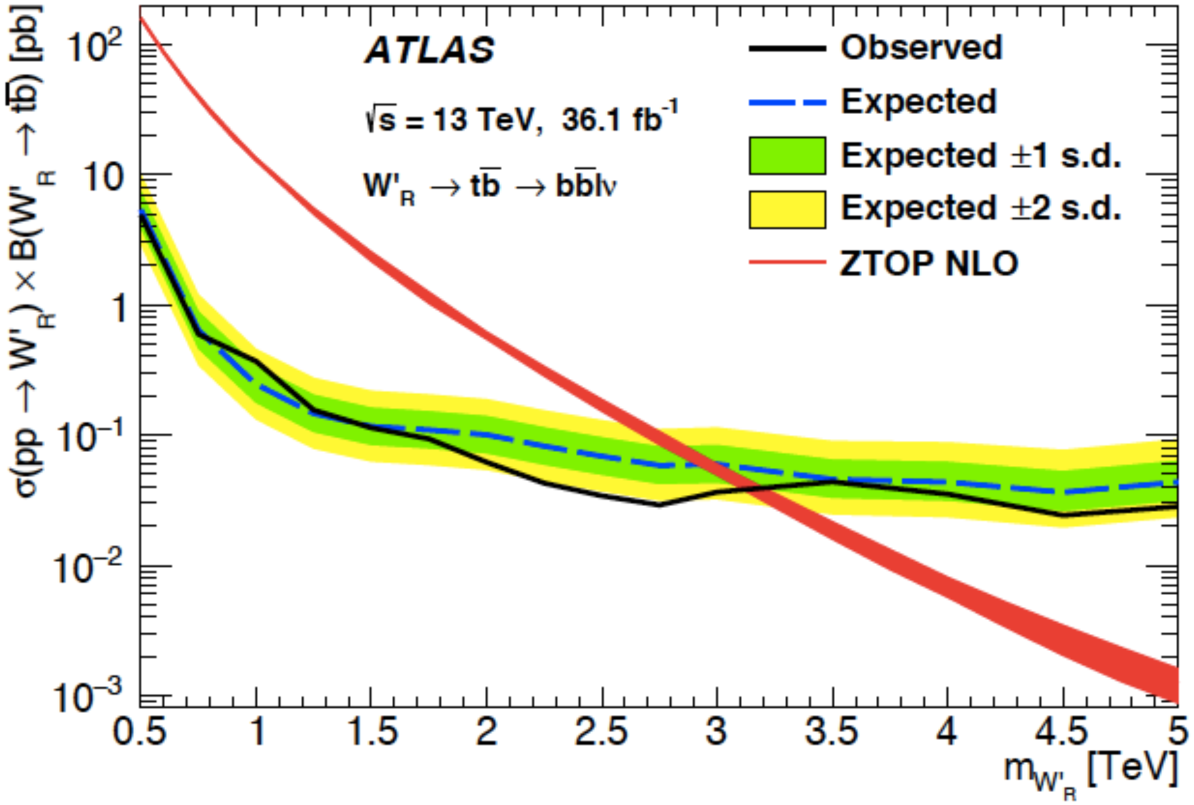


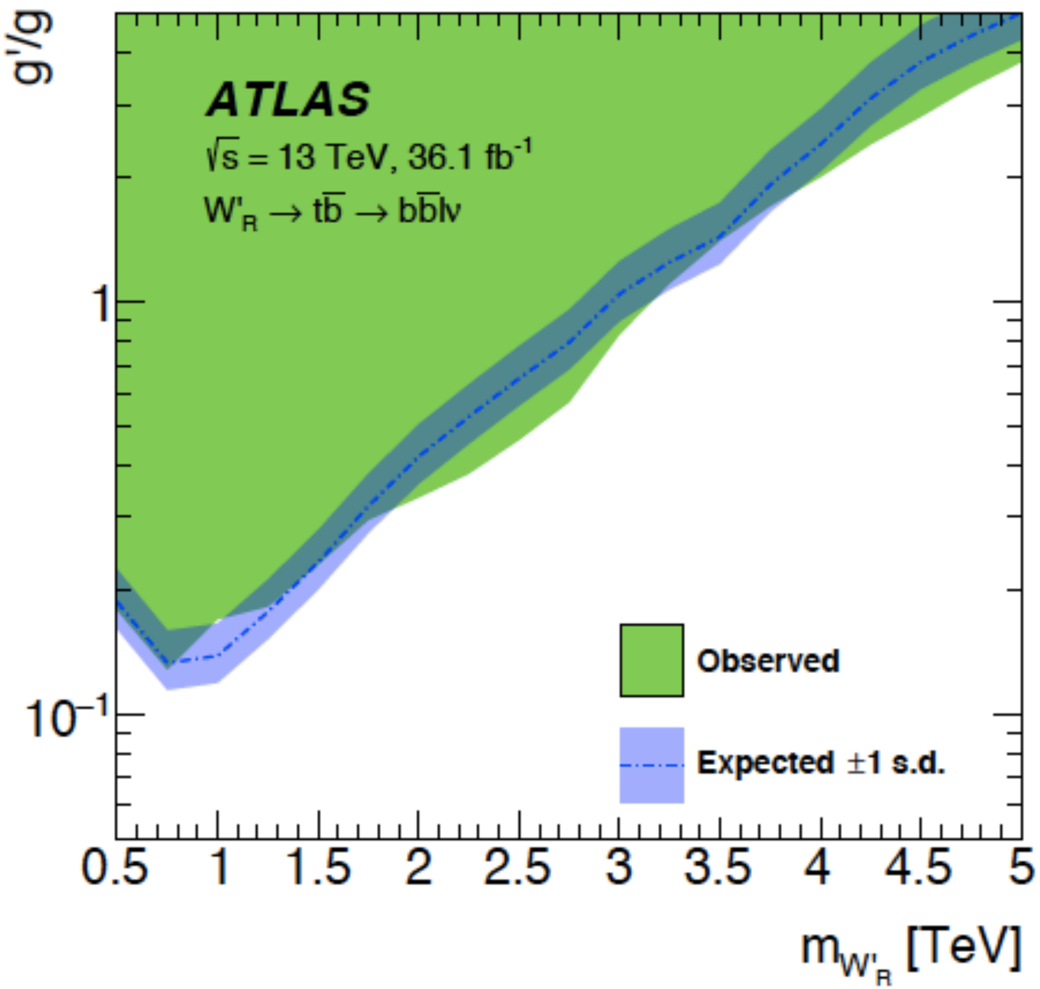
New Physics: Through heavy resonance

ATLAS, Phys.Lett. B788 (2019) 347

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





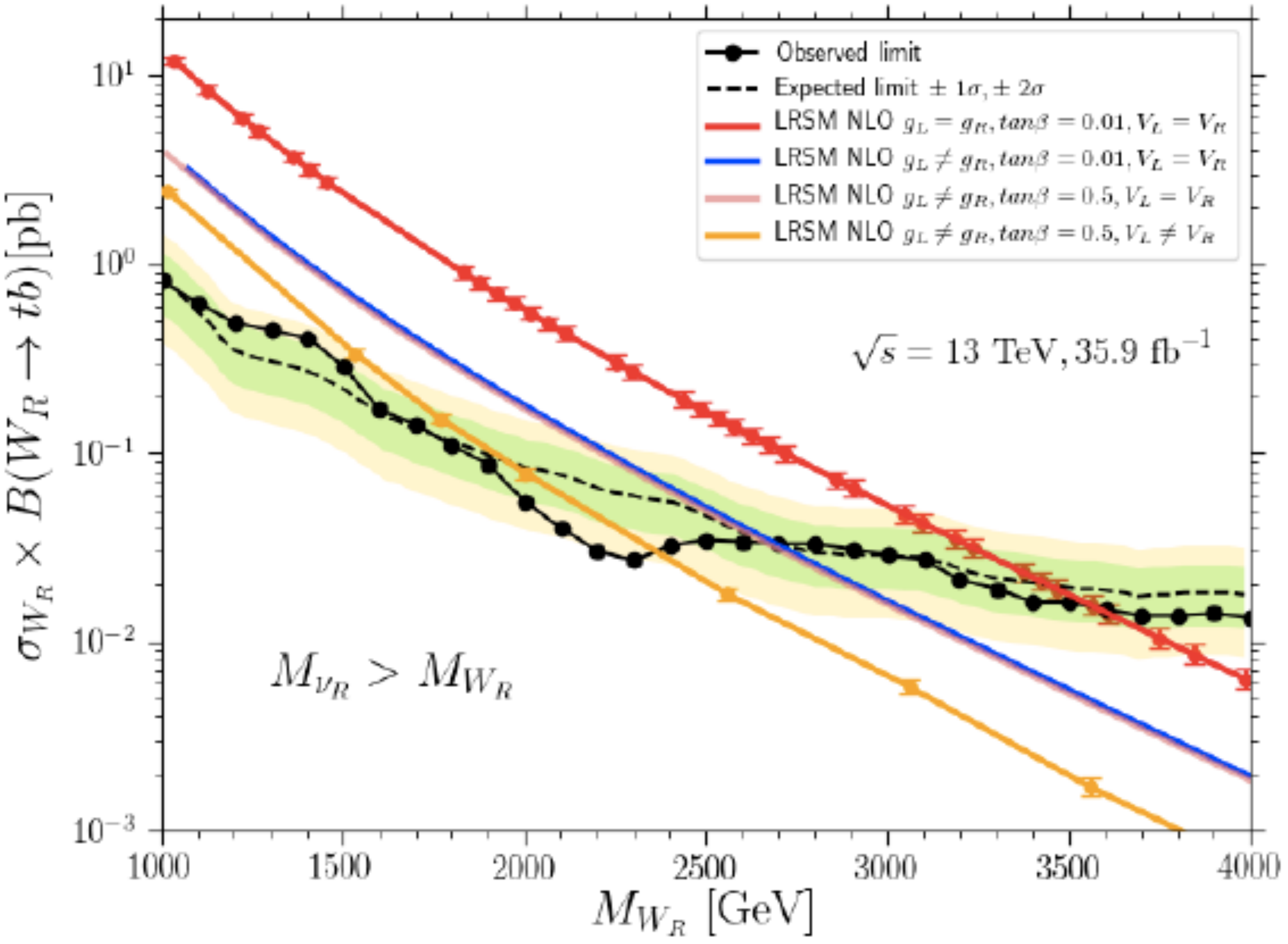


This can be relaxed considering

$$g_R \neq g_L$$

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

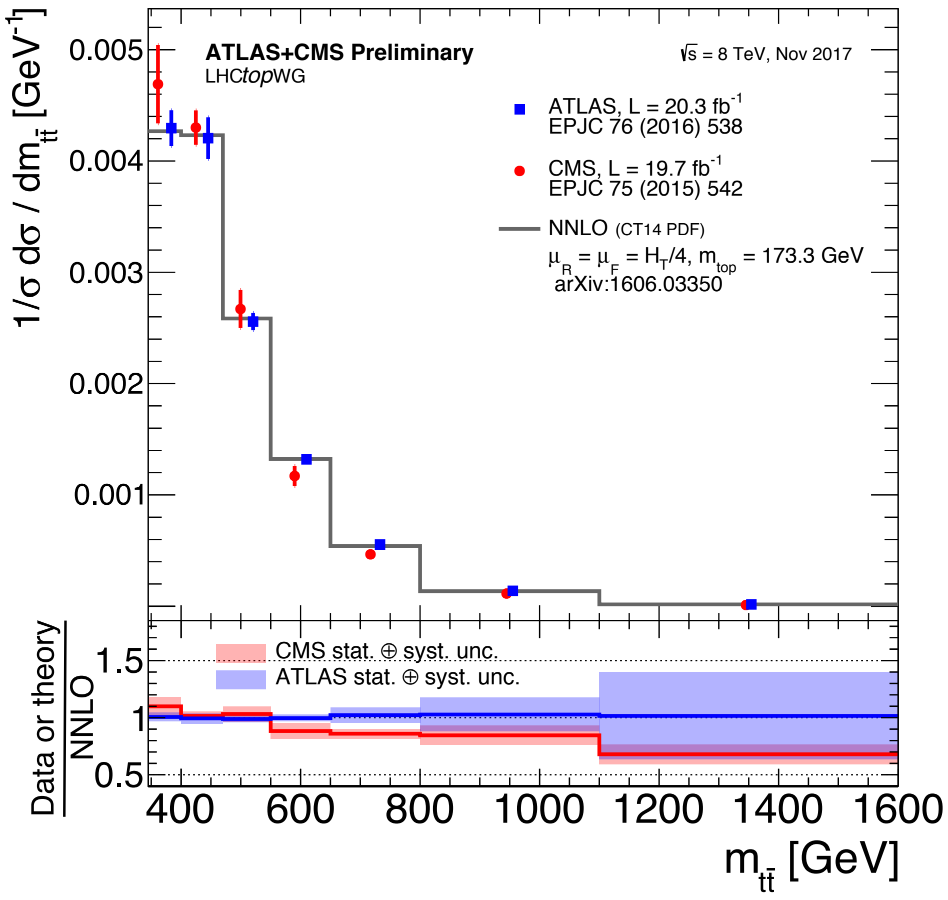
(respecting all constraints
including those from Flavour Sector)

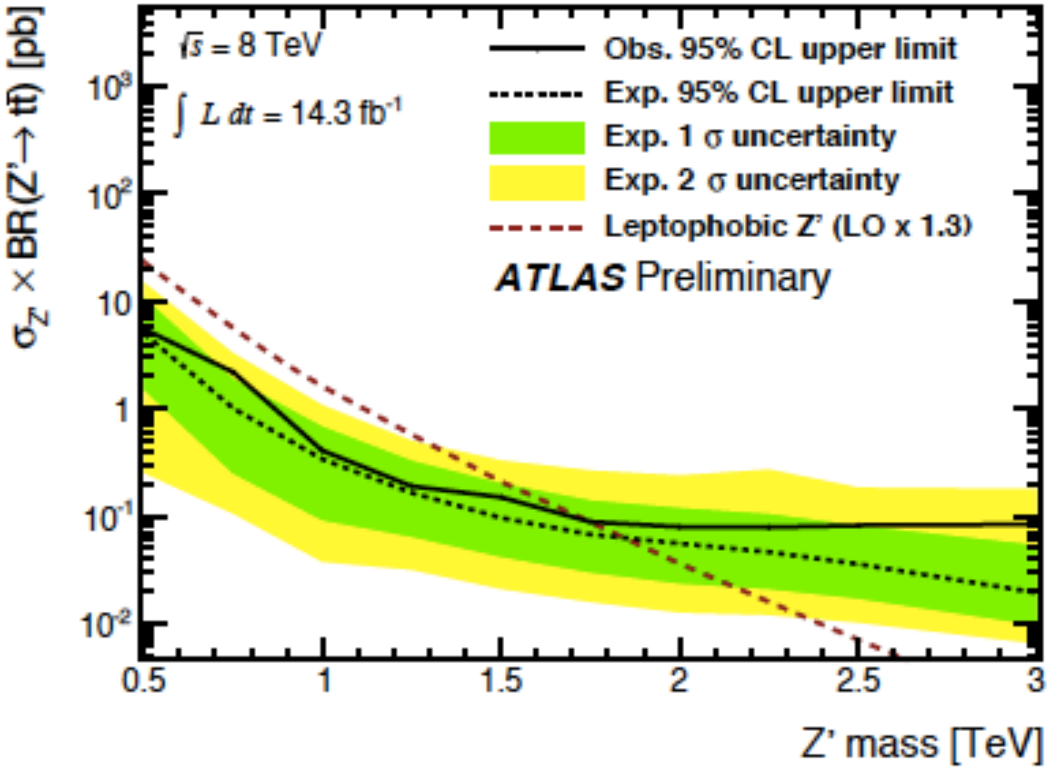


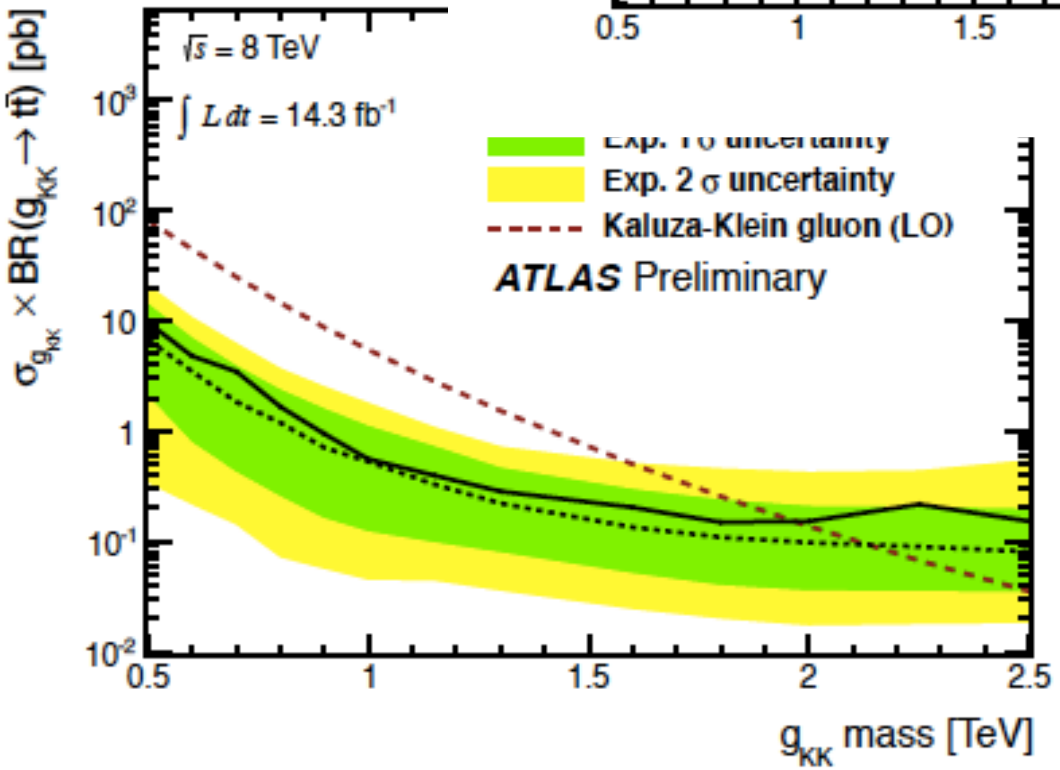
Frank, Ozdel, PP: arXiv:1812.05681

Phys.Rev. D99 (2019) no.3, 035001

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



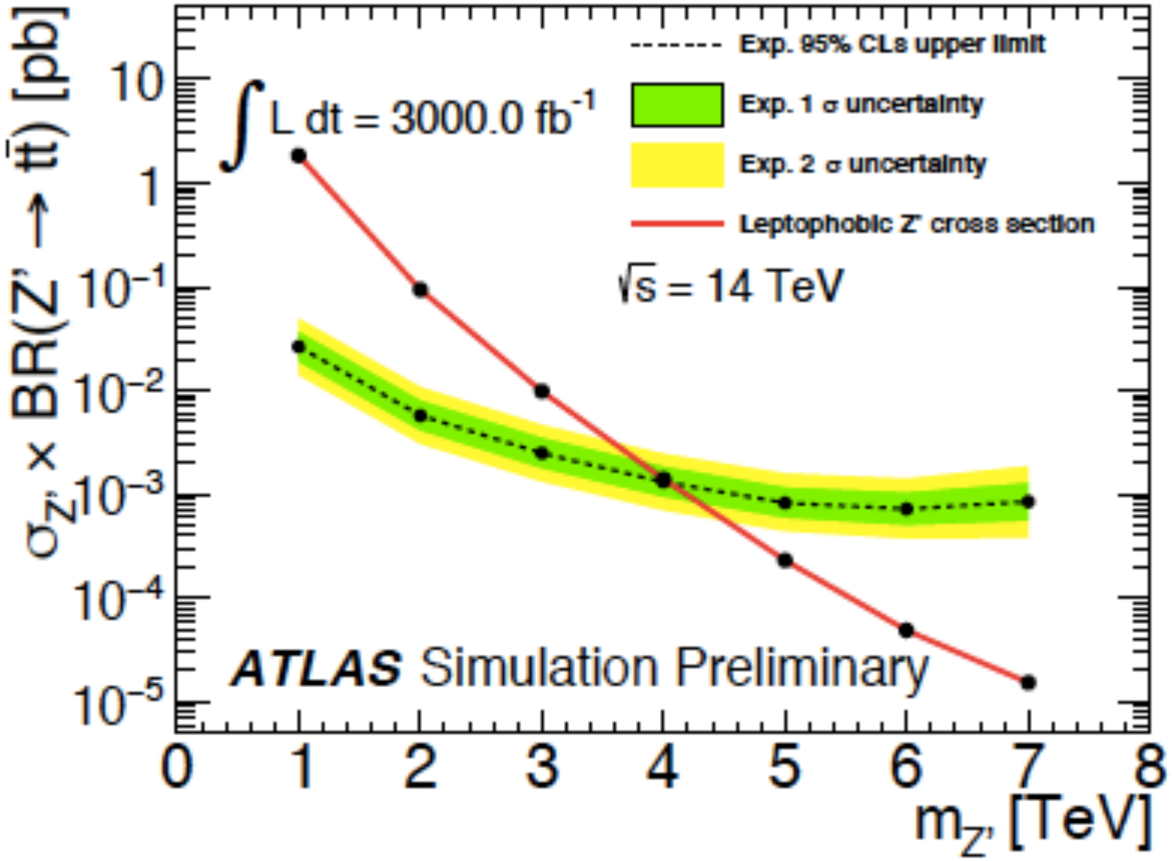


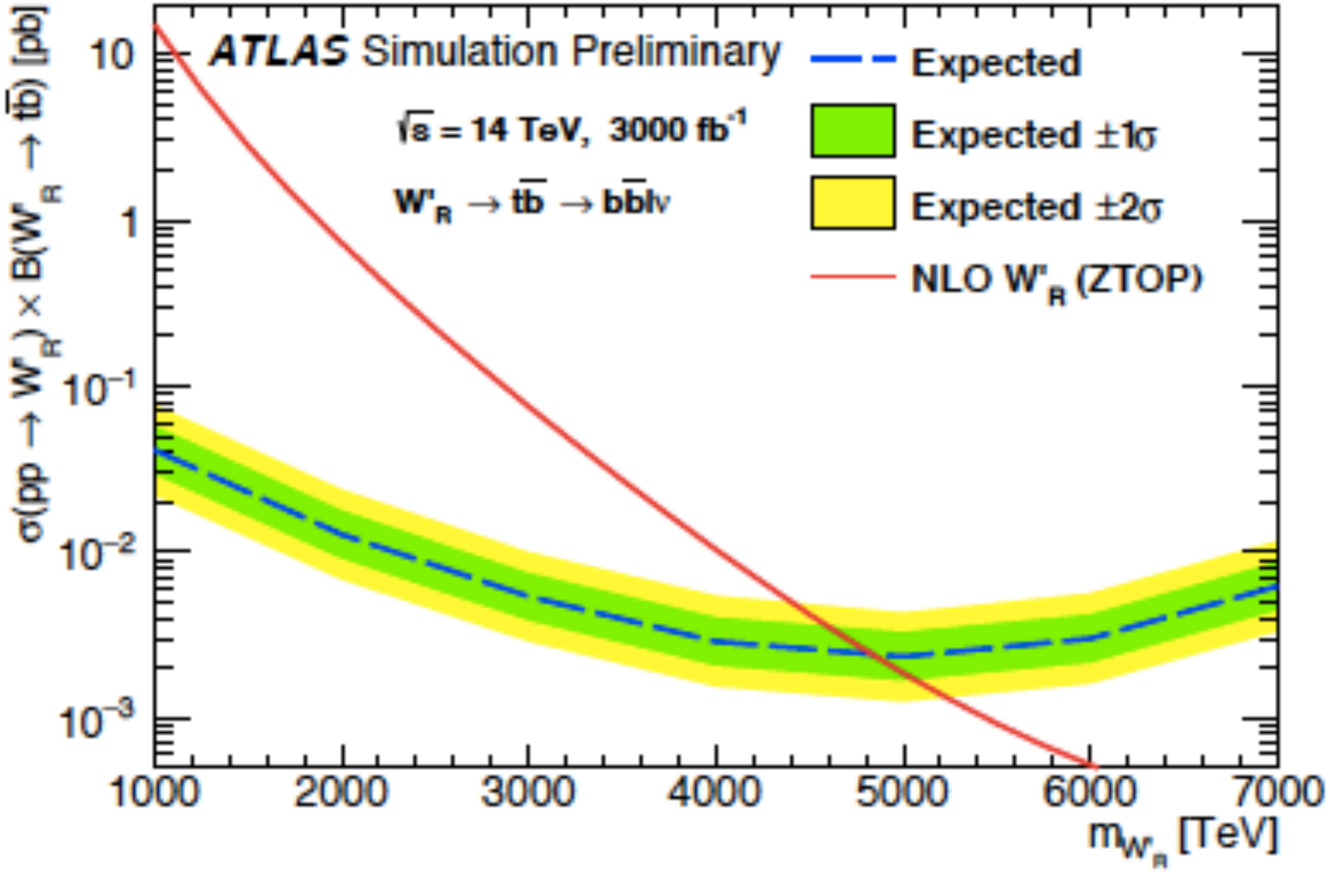


Limits are much weaker compared to di-jet and di-lepton channels

High Luminosity LHC expectations

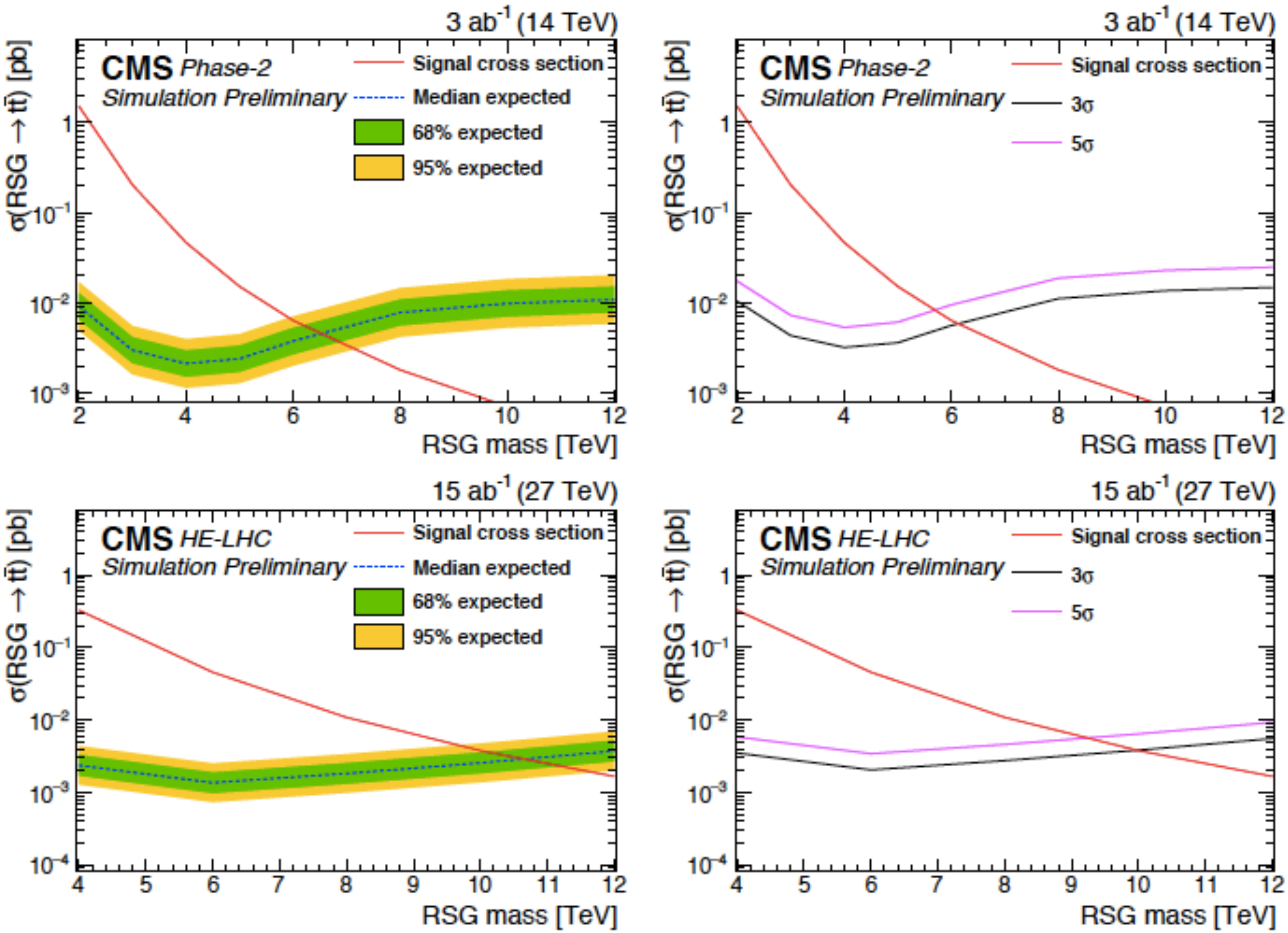
arXiv: 1812.07831





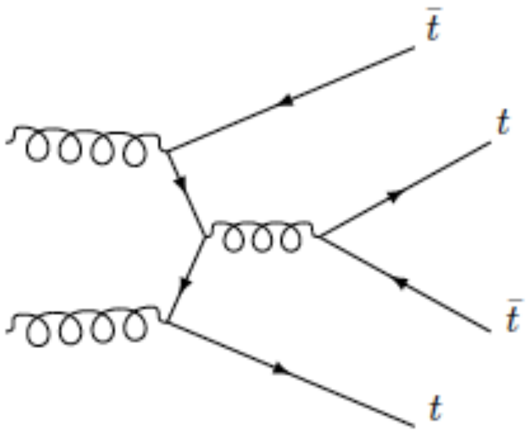
Spin-2 Resonance

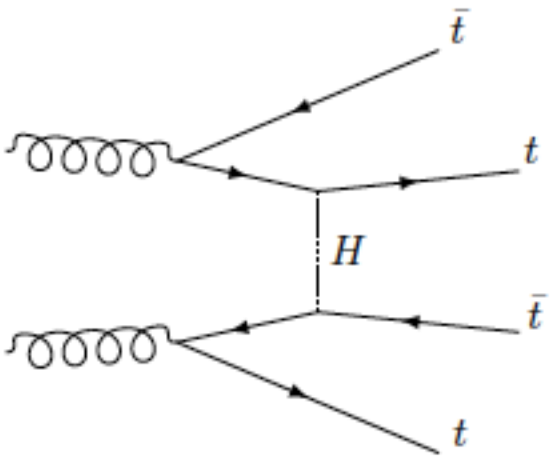
at HL-LHC
and HE-LHC



Four Top production at the LHC

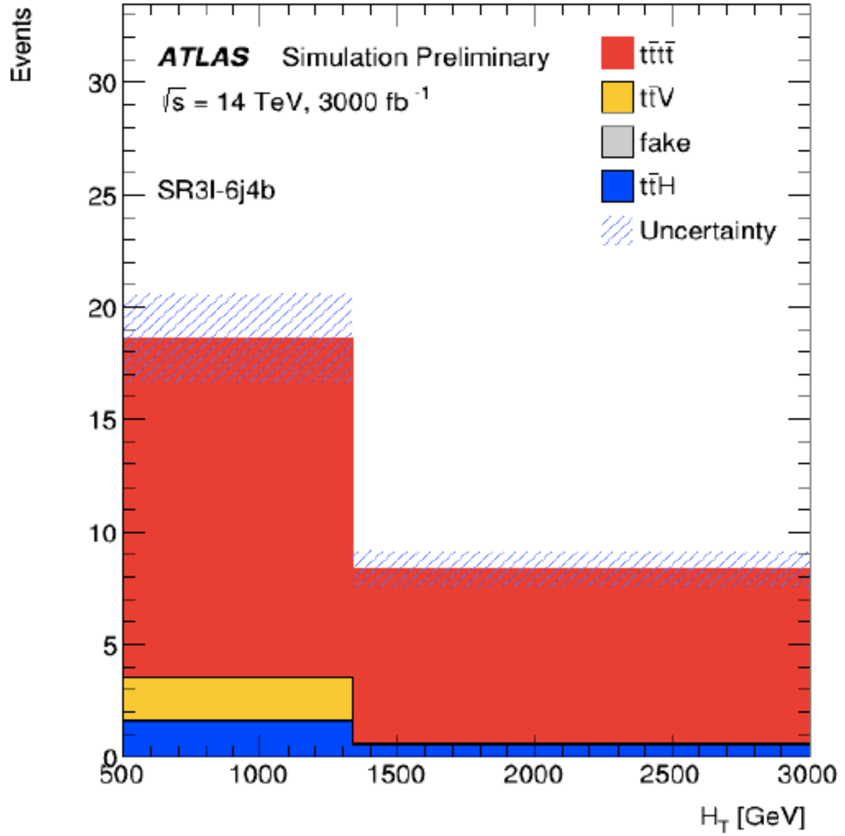
$$\sigma(pp \to t\bar{t}t\bar{t}) = 15.83^{+18\%}_{-21\%} \text{ fb at 14 TeV}$$



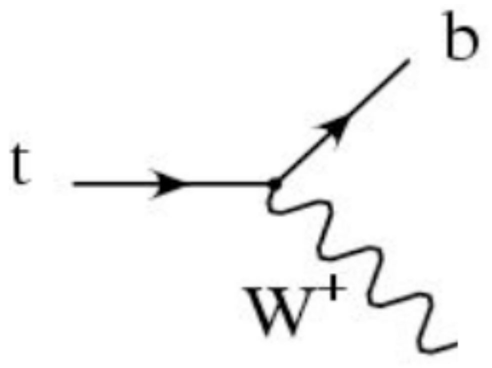


Explores top-top scattering

New physics possibilities not studied well.



Standard Decays of Top quark



/s / u

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

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

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

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

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

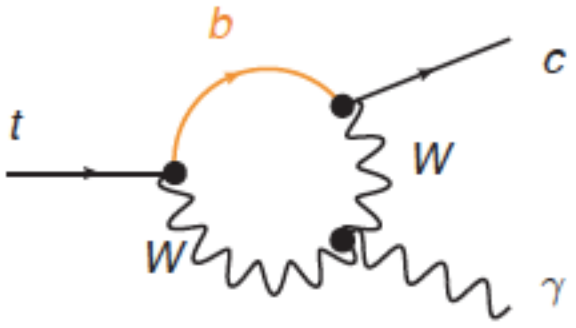
light neutral gauge boson: $t \to Z' c$, $t \to Z' u$

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)

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

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

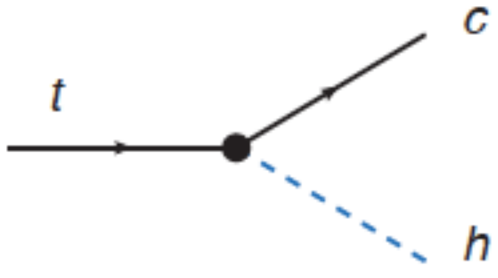
$$\mathrm{BR}(t \to cZ) \simeq 1\times 10^{-14} \quad , \quad \mathrm{BR}(t \to uZ) \simeq 8\times 10^{-17}$$

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

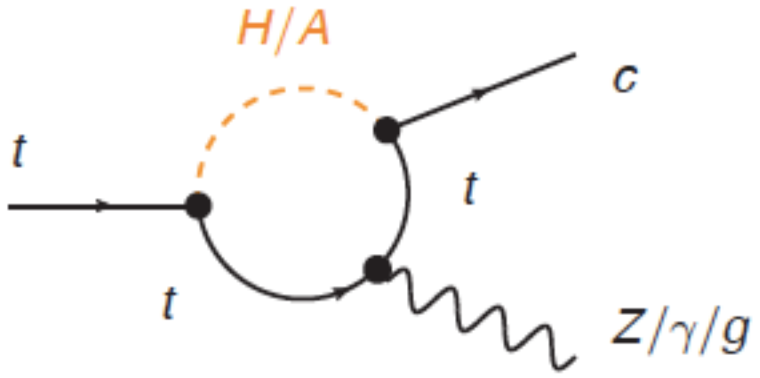
SM predictions

Beyond the SM

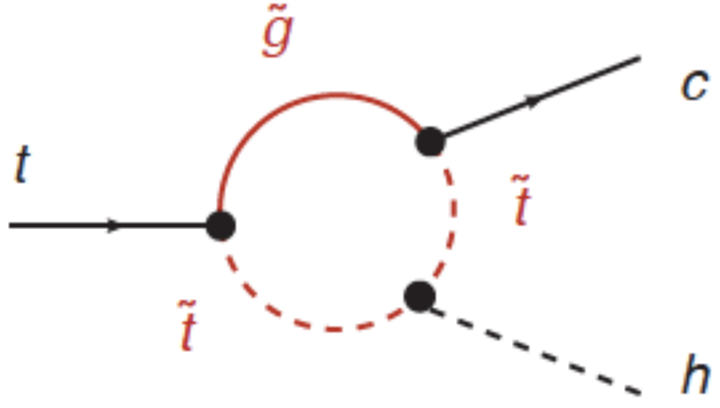
2HDM

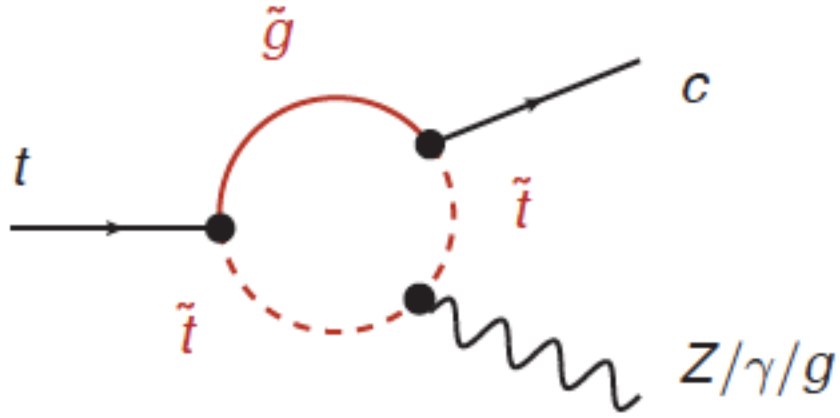


$t \to c\ Z/\gamma/g$ at the 1 loop level



MSSM

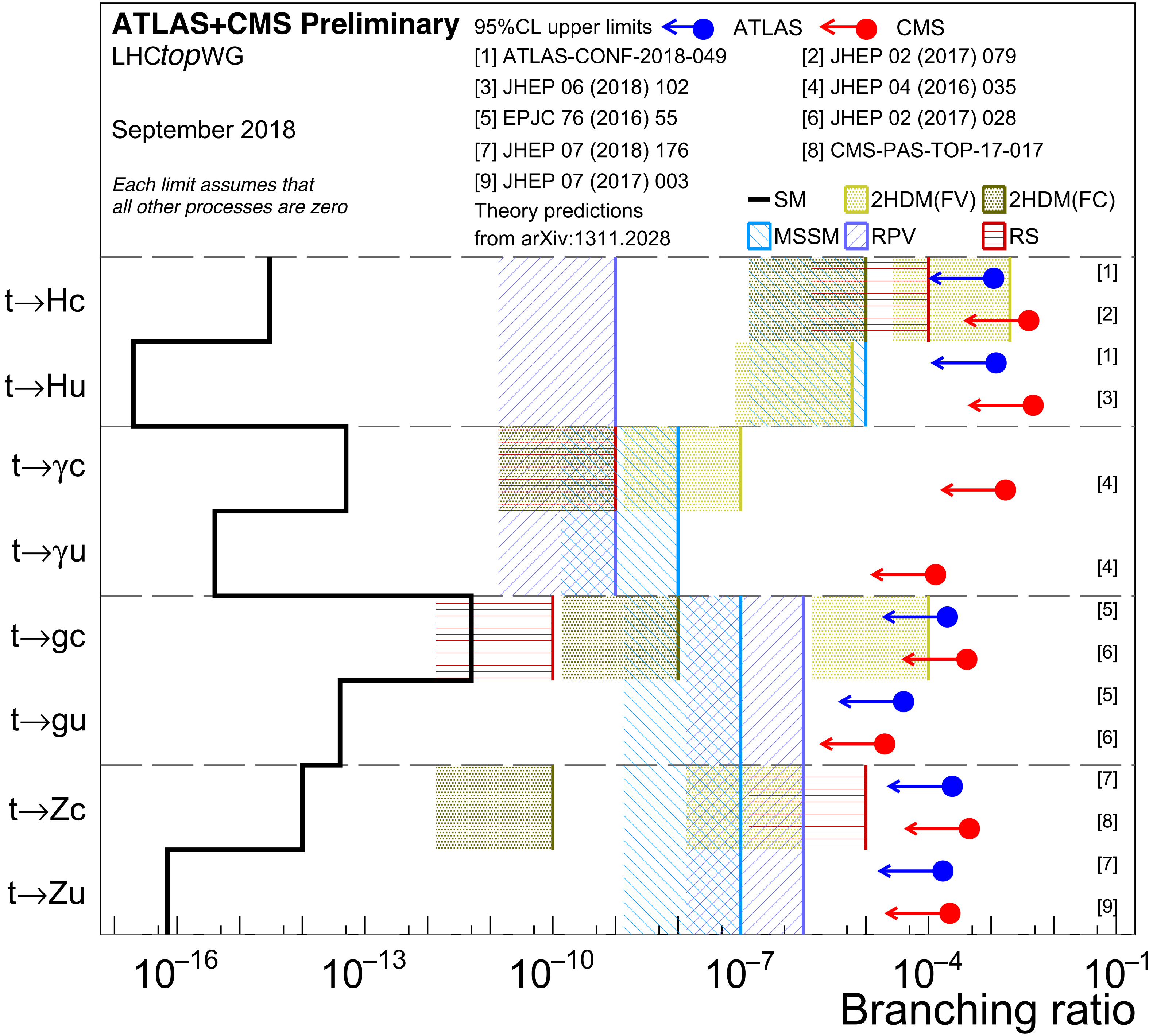




Present Experimental status

and comparison with model predictions

Assuming only one such coupling present at a time

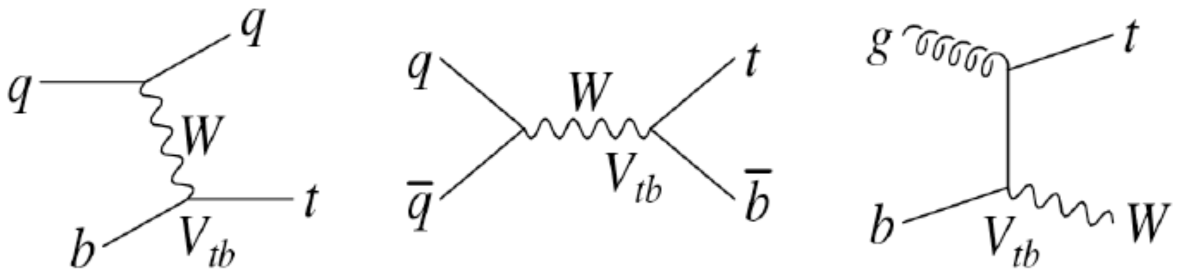


Top Working Group Summary Plots

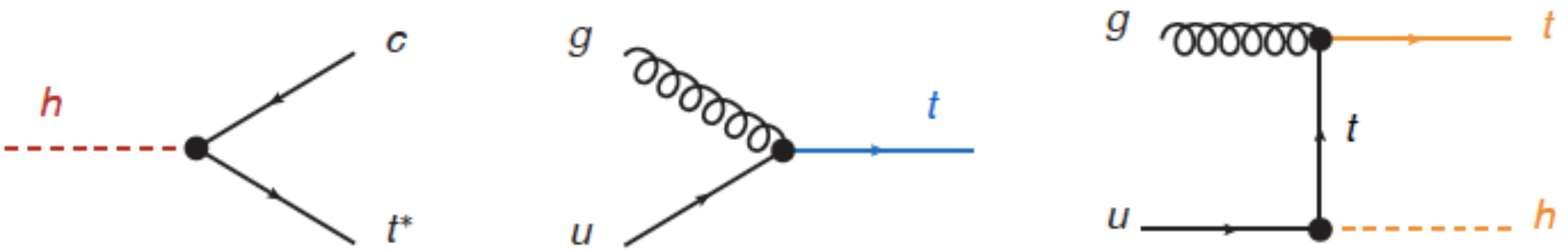
ATL-PHYS-PUB-2018-034

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

Standard Single top productions



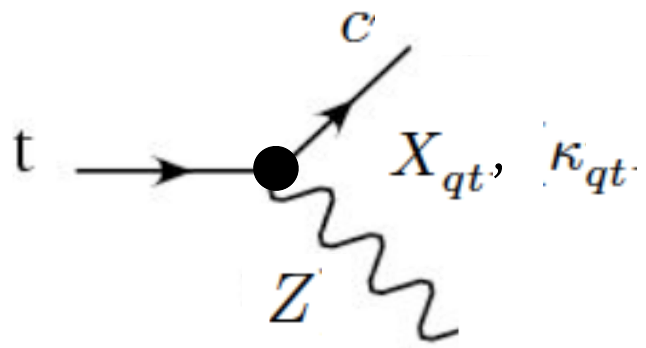
Non-Standard Single top productions include



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

$\mathrm{BR}(t \to cg) \leq 2.0 \times 10^{-4}$ < 0.005

ATLAS Eur.Phys. J.C. 76 (2016) 55

$\mathrm{BR}(t \to u\gamma) \leq 1.3 \times 10^{-4}$ < 0.017

$\mathrm{BR}(t \to c\gamma) \leq 1.7 \times 10^{-3}$ < 0.063

ATLAS JHEP 04 (2016) 35

$\mathrm{BR}(t \to uH) \leq 2.4 \times 10^{-3}$ < 0.025

$\mathrm{BR}(t \to cH) \leq 2.2 \times 10^{-3}$ < 0.024

ATLAS JHEP 1710 (2017) 120

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.

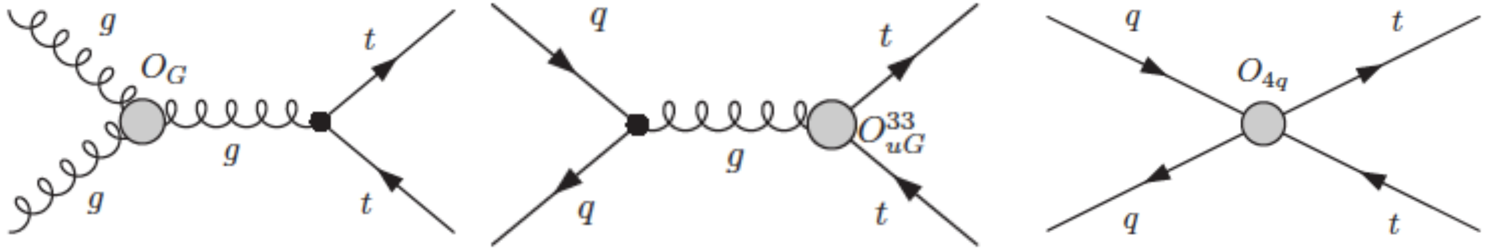
NP through Effective Lagrangian (SMEFT) Anomalous Couplings

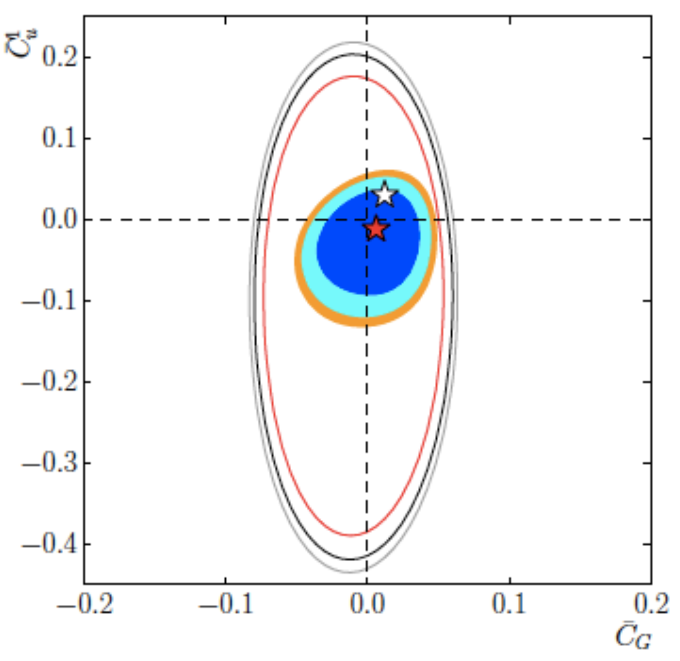
$$\mathcal{L} = \mathcal{L}^{SM} + \sum \frac{c_i}{\Lambda^2}\mathcal{O}_i + O\left(\frac{1}{\Lambda^4}\right)$$

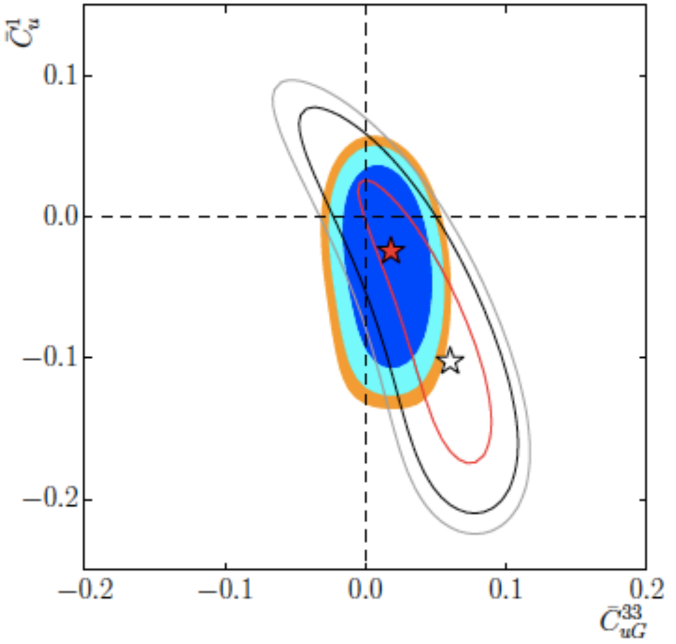
TopFitter Collaboration
1512.03360

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

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







NP through Effective Lagrangian (SMEFT) Anomalous Couplings

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

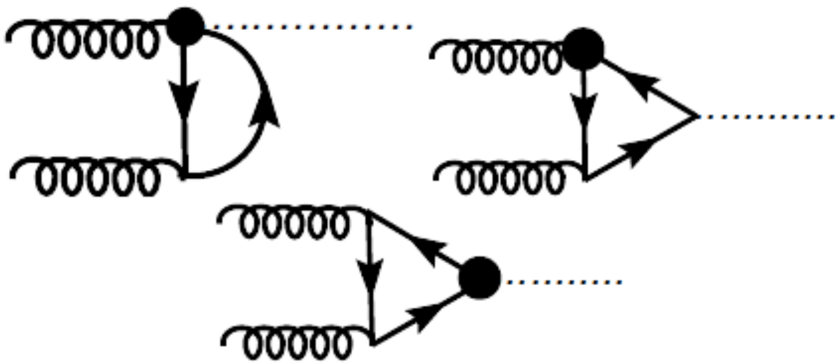
$$\mathcal{O}_{hg} = \left(\bar{Q}_L H\right)\sigma^{\mu\nu}T^a t_R G^a_{\mu\nu},\qquad \mathcal{O}_{HG} = \frac{1}{2}H^\dagger H G^a_{\mu\nu}G^{\mu\nu}_a$$

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

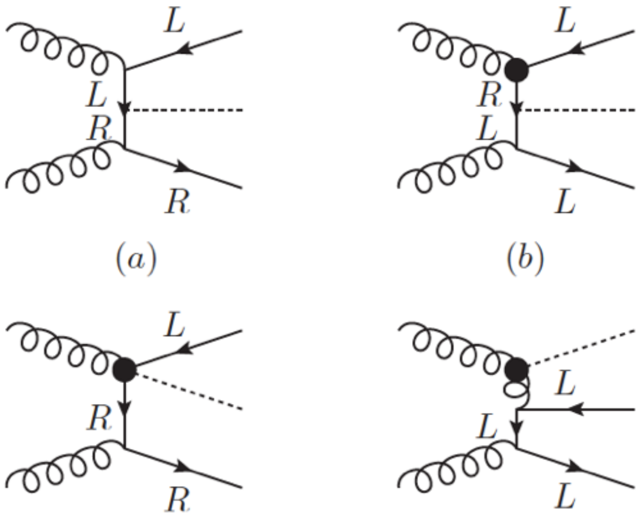
$$\mathcal{O}_{Ht} = H^\dagger D_\mu H \bar{t}_R\gamma^\mu t_R \qquad \mathcal{O}_{H\gamma} = \frac{1}{2}H^\dagger H F_{\mu\nu}F^{\mu\nu}$$

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

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



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



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

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

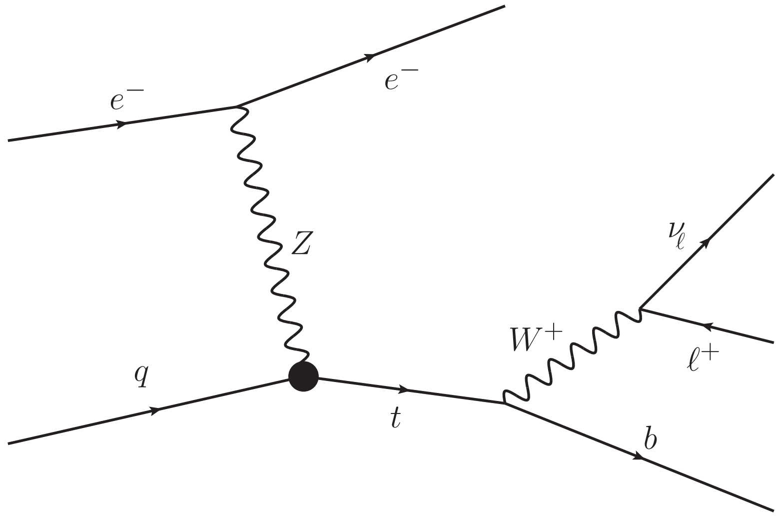
$\sqrt{s} = 14\ TeV$

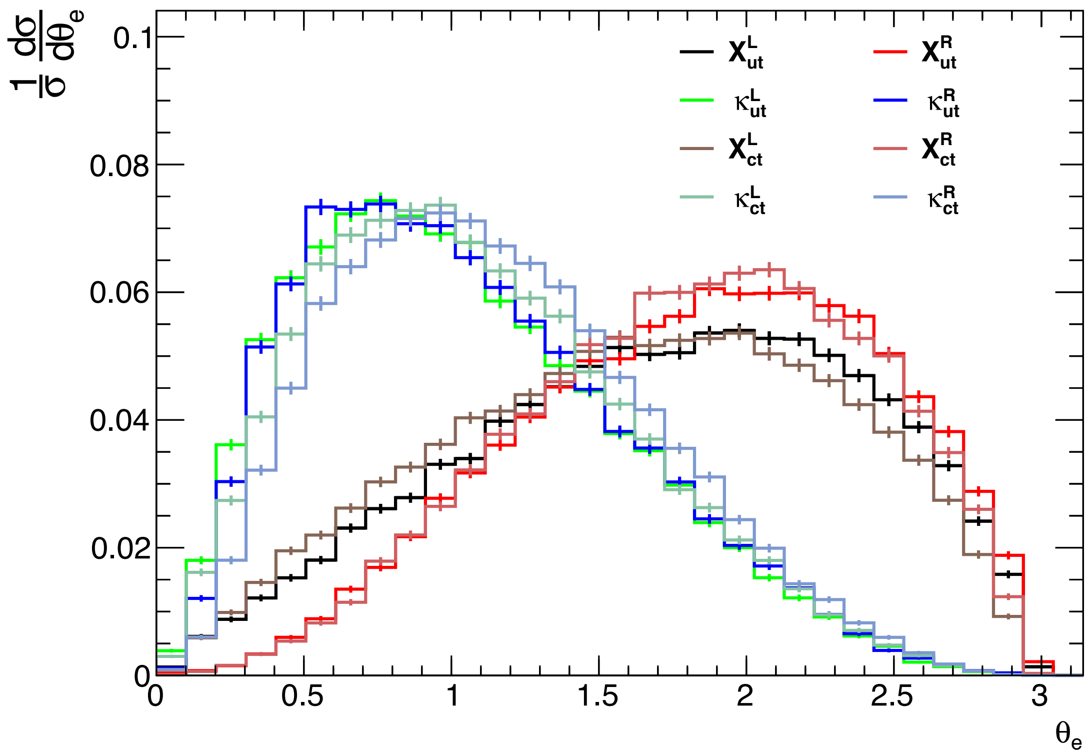
$$\begin{aligned}\frac{\sigma\left(pp\to t\bar{t}h\right)}{\text{fb}} = {}& 611^{+92}_{-110} + \left[457^{+127}_{-91}\Re c_{hg} - 49^{+15}_{-10}c_G\right.\\ &+ \left.147^{+55}_{-32}c_{HG} - 67^{+23}_{-16}c_y\right]\left(\frac{\text{TeV}}{\Lambda}\right)^2\\ &+ \left[543^{+143}_{-123}(\Re c_{hg})^2 +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

Top FCNC through ep > et

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

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





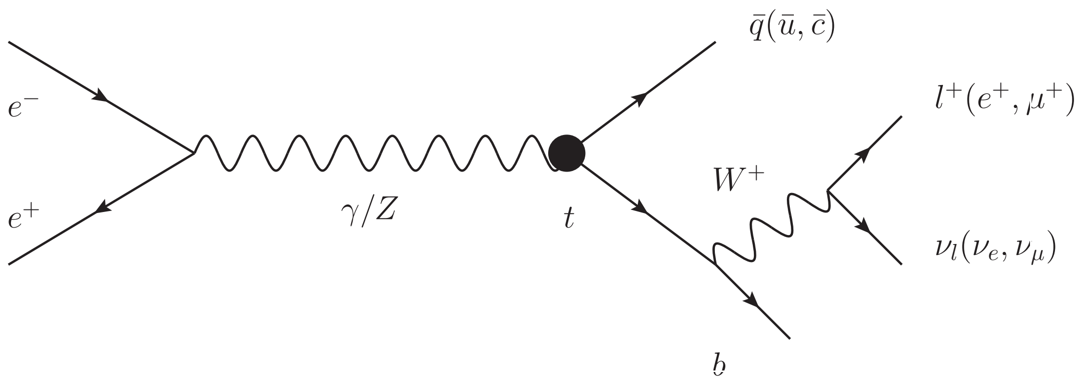
The scattered electron as a discriminator

Lorentz structure of the coupling can be probed.

Something quite hard at LHC

At the ILC250

Subhasish Behera, Daniel Jeans, PP



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

Coupling	$\kappa^L_{ut}(\gamma)$	$\kappa^R_{ut}(\gamma)$	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 the ILC250

Subhasish Behera, Daniel Jeans, PP

We studied the signal (1j + 1b-jet + 1 lepton + missing energy) against the SM background.

Major Backgrounds

	cross section (pb)
1. $e^+e^- \to WW \to 2\ell 2\nu$	10.99
2. $e^+e^- \to ZZ \to 2\ell 2\nu$ + $2\ell 2j$	0.83
3. $e^+e^- \to Z \to 2j,\ 2b$	0.75
4. $e^+e^- \to 2e\gamma,$	14.79
5. $e^+e^- \to \mu^+\mu^- h.$	0.01

At the ILC250

Subhasish Behera, Daniel Jeans, PP

Process	$N_{simulated}$	$\sigma_{-.8,+.3}[fb]$	N_e	0 < m_t < 240	$180 < M_{\ell j} < 270$	$M_{bj\ell} \notin [65, 95]$	$\lvert p_\nu \rvert > 20$	$\cos\theta_\mu < .95, \cos\theta_\nu > -.95$
$\kappa^L_{ut}(\gamma)$	10000	156.5	313	176719	176344	142540	141789	138408
$\kappa^R_{ut}(\gamma)$	10000	156.3	312	180088	179557	145046	144358	141607
X^L_{ut}	10000	77.97	155	90195	89899	75085	74757	73369
X^R_{ut}	10000	78.09	156	87757	87460	68328	67907	66735
κ^L_{ut}	9500	131.8	263	151223	150862	122615	121866	119480
κ^R_{ut}	10000	131.7	263	148952	148557	120558	120005	118134
$e^-e^+ \to WW \to l\nu_l 2j$ 4f_WW_semileptonic	279897	10992.9	21985	18790	18511	3905	3533	3533
$e^-e^+ \to ZZ \to 2l2j + 2\nu_l 2j$ 4f_ZZ_semileptonic	535103	856.927	1713	3802	3535	3215	1867	1439
$e^-e^+ \to Z \to 2j + 2b$ 2f_Z_hadronic	476642	78046.5	15609	2116	2116	41	41	20
$e^-e^+ \to \mu^+(e^+)\mu^-(e^-)h$ higgs_ffh_Pllh	30126	10.651	213	243	238	237	168	139

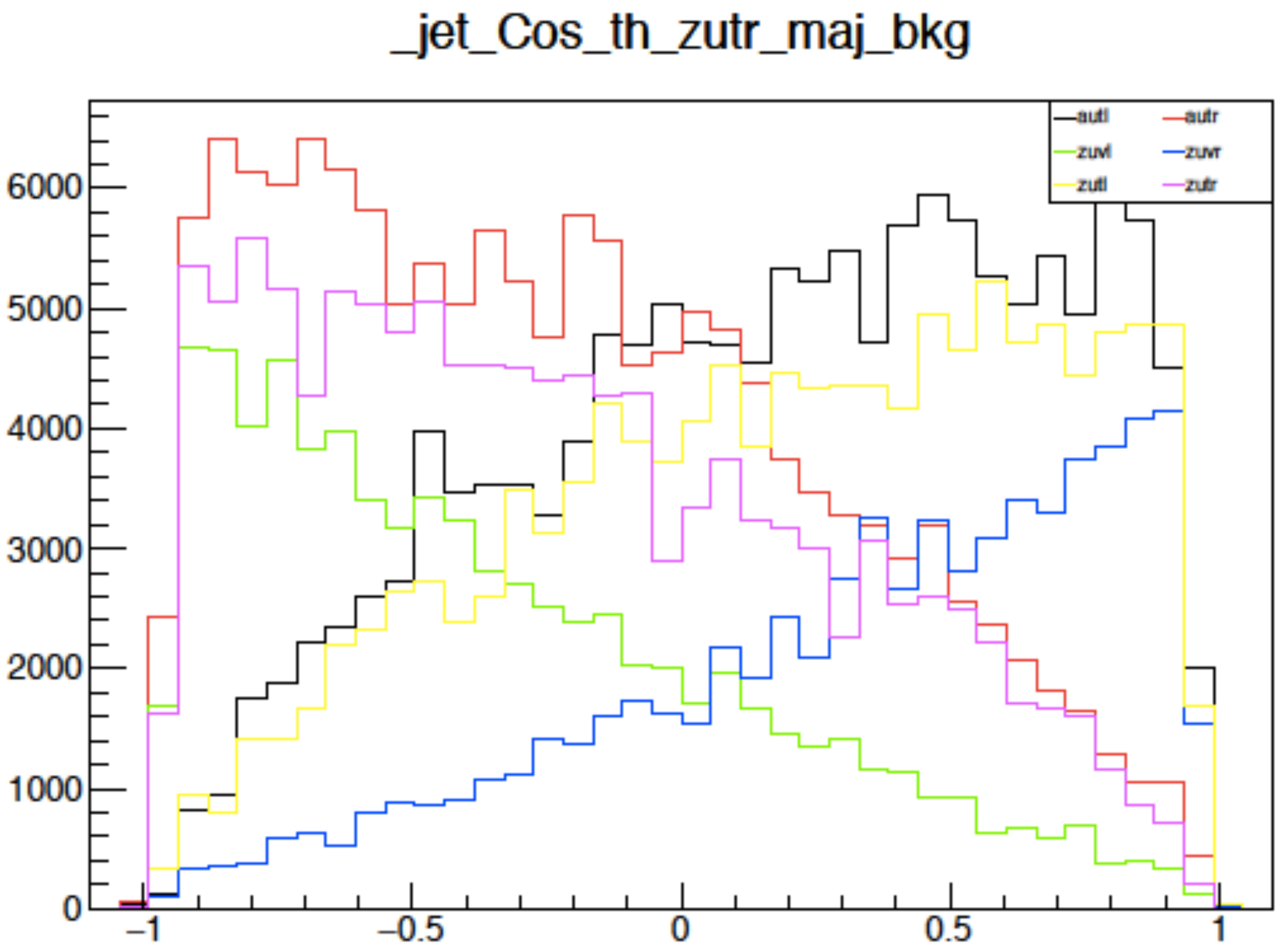
	before	after
signal	263400	118134
background	21985832	3533
	1713854	1439
	156092928	20
	21302	139

Kinematic Selections to improve the signal significance.

80% left-polarised electron beam
30% right-polarised positron beam

At the ILC250

Subhasish Behera, Daniel Jeans, PP



angular distribution of the light jet is sensitive to the type of coupling

potential to distinguish the Lorentz structure of the coupling

Summary

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

Precise 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