Looking Inside Gluon Fusion Loops

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In collaboration with Aleksandr Azatov, Christophe Grojean and Ennio Salvioni
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and a discussion of Gainer et. al. 1403:4951

Cyberspace. May 24th 2018.

two paths to the throne

-- find a new degree of freedom --

-- find a modified coupling --

inclusive production projection from: ATLAS Collaboration, ATL-PHYS-PUB-2013-014, October 2013.

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Taming the Off-Shell Higgs Boson[1]

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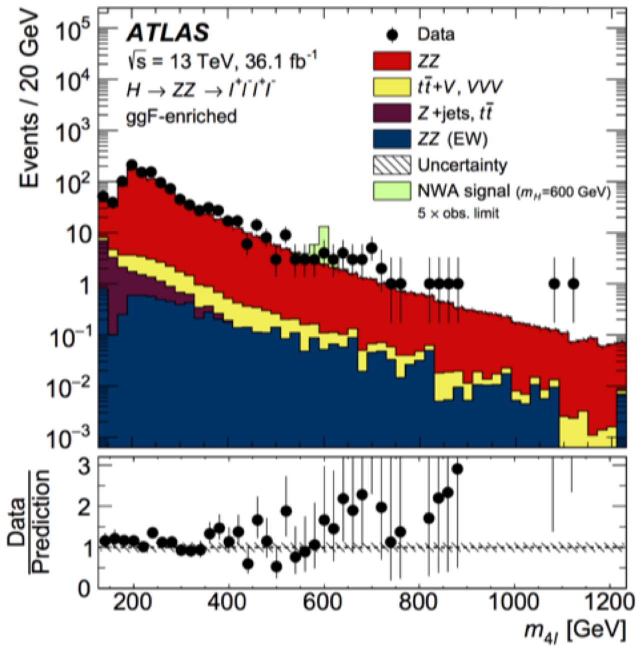
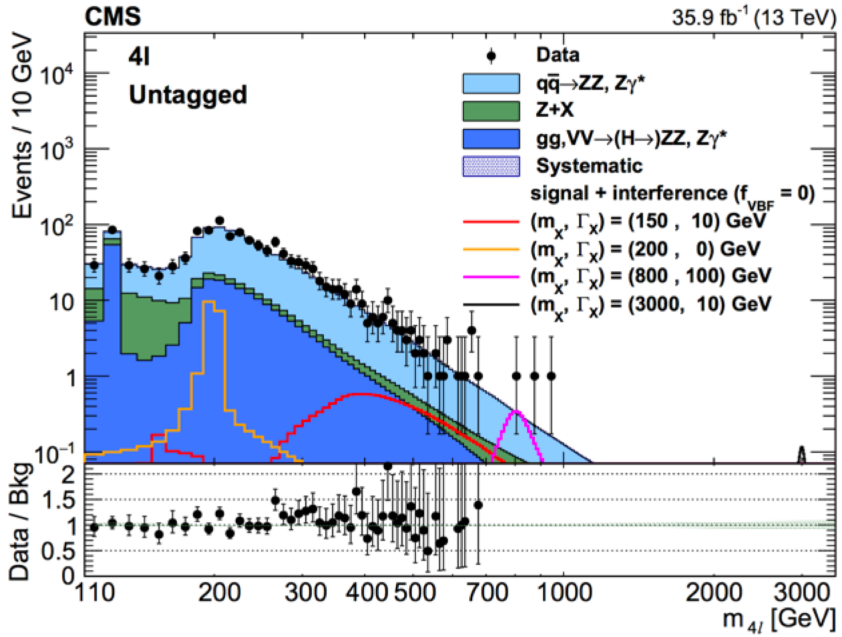
Abstract—We study the off-shell Higgs data in the process $pp \longrightarrow h^{(*)} \longrightarrow Z^{(*)}Z^{(*)} \longrightarrow 4l$, to constrain deviations of the Higgs couplings. We point out that this channel can be used to resolve the long- and short-distance contributions to Higgs production by gluon fusion and can thus be complementary to $pp \longrightarrow ht\bar{t}$ in measuring the top Yukawa coupling. Our analysis, performed in the context of effective field theory, shows that current data do not allow drawing any model-independent conclusions. We study the prospects at future hadron colliders, including the high-luminosity LHC and accelerators with higher energy, up to 100 TeV. The available QCD calculations and the theoretical uncertainties affecting our analysis are also briefly discussed.

Contribution for the JETP special issue in honor of V.A.Rubakov's 60th birthday

the context

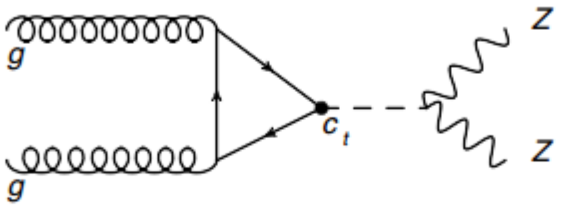
$$pp \to Z^{(*)}Z^{(*)} \to 4\ell$$



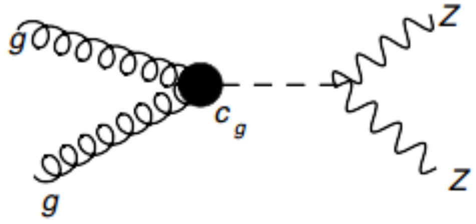


- ✓ there is an invisible Higgs decay width, so that the total width of the Higgs and its couplings can be varied independently
- ✓ variations of all the Higgs couplings are universal
- ✓ there are no higher dimensional operators affecting either Higgs decay or production

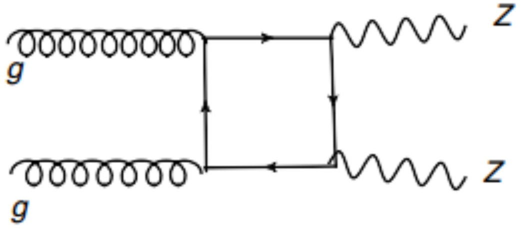
signal



signal

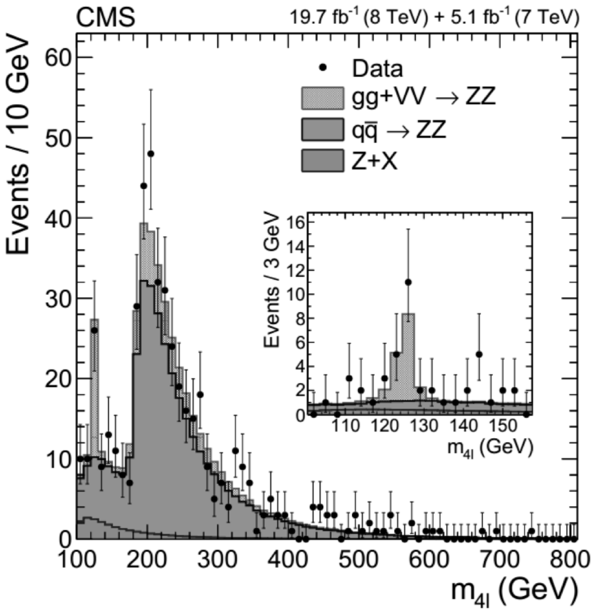


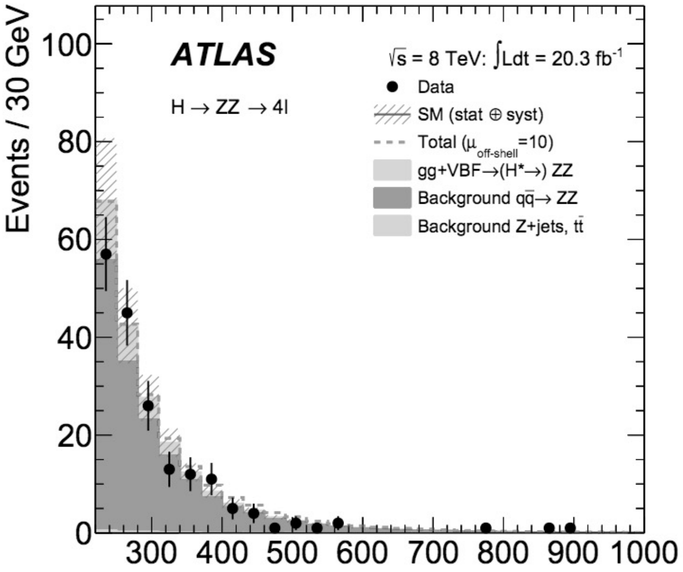
gg background



the context

$$pp \to Z^{(*)}Z^{(*)} \to 4\ell$$





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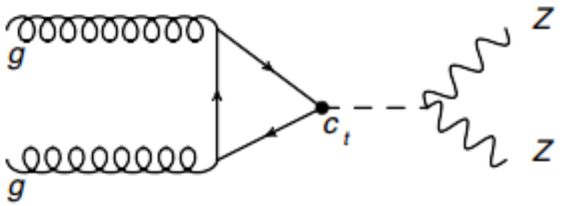
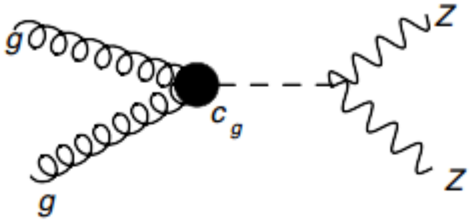
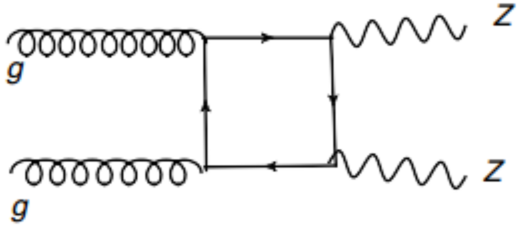


signal



gg background



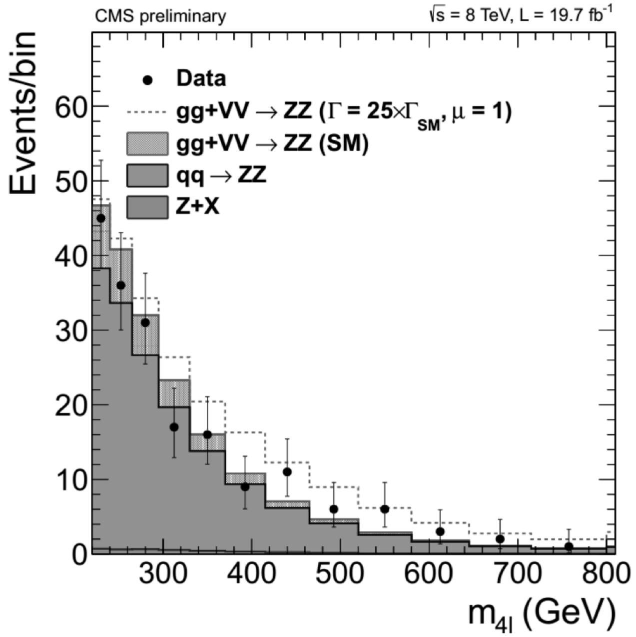
the context

The off-peak yield can be expressed as: $N_{\text{off peak}} \sim g^4 A + g^2 B + C$

with g being the universal rescaling of the SM coupling.

Keeping on-peak yield fixed to the SM value implies: $g^4/\Gamma = \text{constant}$

$$N_{\text{off peak}} = A\,\frac{\Gamma}{\Gamma_{SM}} + B\sqrt{\frac{\Gamma}{\Gamma_{SM}}} + C$$



$m_{4\ell} \in$ [GeV]	$\Gamma = \Gamma_{\text{SM}}$	$\bar{q}q$ bkg	data	$\Gamma = \Gamma_{\text{SM}}$, reconstructed	A	B	C
[220,240]	8.4	38.5	45	8.31	0.11	−0.47	8.68
[240,265]	7.2	33.7	36	7.07	0.13	−0.44	7.38
[265,295]	5.4	27	31	5.12	0.15	−0.36	5.33
[295,330]	3.6	20	17	3.39	0.18	−0.31	3.52
[330,370]	2.2	13.9	16	2.08	0.24	−0.35	2.19
[370,410]	1.2	9.6	9	1.17	0.26	−0.34	1.25
[410,460]	0.9	6.2	11	0.81	0.27	−0.35	0.90
[460,520]	0.6	4.1	6	0.51	0.23	−0.31	0.58
[520,580]	0.3	2.6	6	0.26	0.16	−0.21	0.32
[580,645]	0.2	1.7	3	0.15	0.11	−0.16	0.19
[645,715]	0.1	1.1	2	0.08	0.07	−0.11	0.12
[715,800]	0.09	0.7	1	0.05	0.05	−0.08	0.08
>800	0.2	1	0	0.03	0.03	−0.06	0.05

AGPS: $\Gamma < 24.6\,\Gamma_{\text{SM}}$

CMS: $\Gamma < 26.3\,\Gamma_{\text{SM}}$

the idea

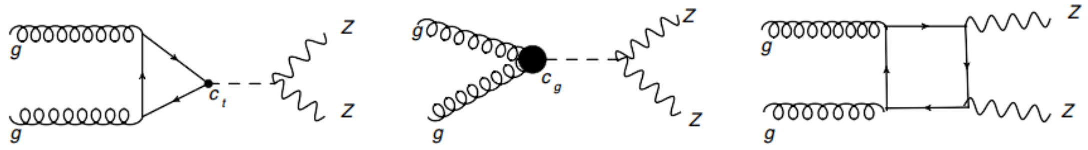
- ✓ There is no invisible Higgs decay width.
- ✓ There are dim. 6 operators affecting Higgs production.

$$\mathcal{L}^{\text{dim-6}} = c_y \frac{y_t |H|^2}{v^2} \bar{Q}_L \widetilde{H} t_R + \text{h.c.} + \frac{c_g g_s^2}{48\pi^2 v^2} |H|^2 G_{\mu\nu} G^{\mu\nu} + \tilde{c}_g \frac{g_s^2}{32\pi^2 v^2} |H|^2 G_{\mu\nu} \tilde{G}^{\mu\nu}$$

$$\tilde{G}_{\mu\nu} = \frac{1}{2} \epsilon^{\mu\nu\lambda\rho} G_{\lambda\rho}$$

After EWSB: $$\mathcal{L} = -c_t \frac{m_t}{v} \bar{t} t h + \frac{g_s^2}{48\pi^2} c_g \frac{h}{v} G_{\mu\nu} G^{\mu\nu} \qquad c_t = 1 - \text{Re}(c_y)$$

While the signal is affected by the modified couplings, the background is not.



$$\mathcal{M}_{gg\to ZZ} = \mathcal{M}_h + \mathcal{M}_{bkg} = c_t \mathcal{M}_{c_t} + c_g \mathcal{M}_{c_g} + \mathcal{M}_{bkg}$$

The differential cross-section is given by: $$\frac{d\sigma}{dm_{4\ell}} = F_0(m_{4\ell}) + F_1(m_{4\ell}) c_R^2 + F_2(m_{4\ell}) c_I^2 + F_3(m_{4\ell}) c_R + F_4(m_{4\ell}) c_I$$

$$c_R = \frac{\text{Re}\, \mathcal{M}_\Delta^{\text{NP+SM}}}{\text{Re}\, \mathcal{M}_\Delta^{\text{SM}}}, \quad c_I = \frac{\text{Im}\, \mathcal{M}_\Delta^{\text{NP+SM}}}{\text{Im}\, \mathcal{M}_\Delta^{\text{SM}}}$$

validity of the EFT

Discriminating power of the off-shell Higgs grows with energy since:

$$\mathcal{M}_{c_g}^{++00} \sim \hat{s} \qquad\qquad \mathcal{M}_{c_t}^{++00} \sim \log^2 \frac{\hat{s}}{m_t^2}$$

However, at very high energies dim. 8 operators may become important.

$$O_8 = \frac{c_8 g_s^2}{16\pi^2 v^4} G_{\mu\nu} G^{\mu\nu} \left(D_\lambda H\right)^\dagger D^\lambda H \qquad\qquad \mathcal{M}_{c_8}^{++00} \sim \hat{s}^2$$

Interference between SM and dim. 8 operators become significant at:

$$\sqrt{\hat{s}} \sim \sqrt{\frac{c_g, c_y}{c_8}}\, v$$

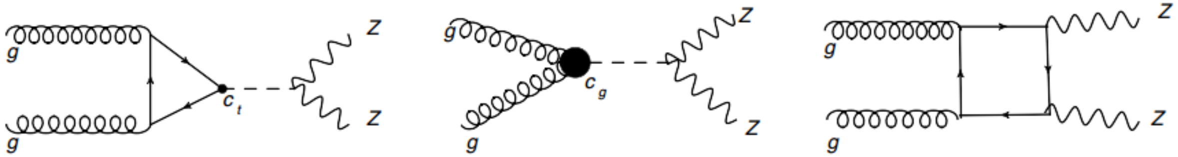
The contribution of the dim. 8 operator is sub-leadi $c_8 \ll c_{g,y}^2$

We will present two kinds of analysis:

- Linear analysis only linear in $c_{g,y}$ (pure dim-6 operators)
- Non-linear analysis with terms quadratic in $c_{g,y}$ (model-dependent pollution of dim. 8 possible)

details of the simulation

PDF sets and errors:



- The 8 TeV CMS result was simulated with *CTEQ6L* PDF sets.
- All other results simulated with *MSTW 2008 LO* sets.
- The background was simulated with the corresponding NLO PDF sets.
- No PDF errors were computed, but expected to be ~ 5% - 10%.

$$\mu_{\text{ren}} = \mu_{\text{fact}} = m_{4\ell}/2$$

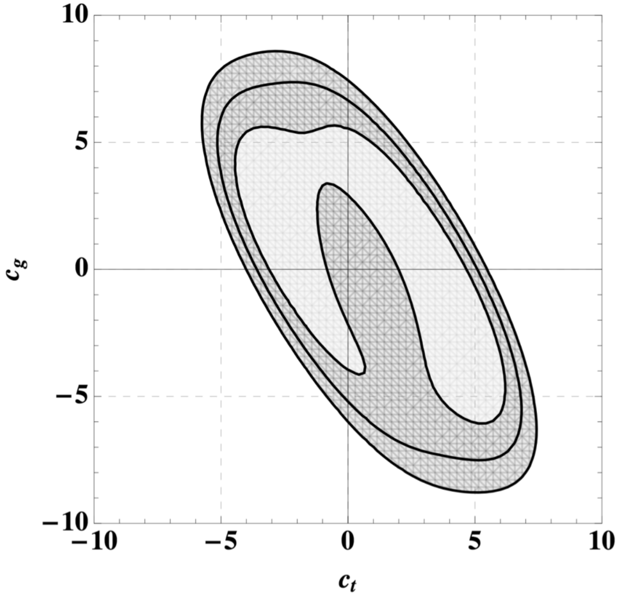
K Factors:

- K factors computed using the *ggHiggs* code for inclusive Higgs production.
- K factor treated as an overall scaling of the signal, background and their interference.

$\sqrt{s}$ [TeV] \ m_h [GeV]	325	500	700	950	1300	1750	2500	3500	4500
14	1.96	1.86	1.81	1.80	1.81	*	*	*	*
33	1.76	1.67	1.65	1.66	1.67	1.70	1.73	1.76	1.79
50	1.66	1.58	1.56	1.57	1.60	1.63	1.67	1.70	1.73
80	1.54	1.47	1.46	1.47	1.50	1.54	1.58	1.63	1.66
100	1.49	1.41	1.41	1.42	1.46	1.49	1.54	1.59	1.62

NNLO K-factors for inclusive production of a heavy SM Higgs that were used to rescale the LO $gg \to ZZ$ cross sections.

reinterpreting CMS data



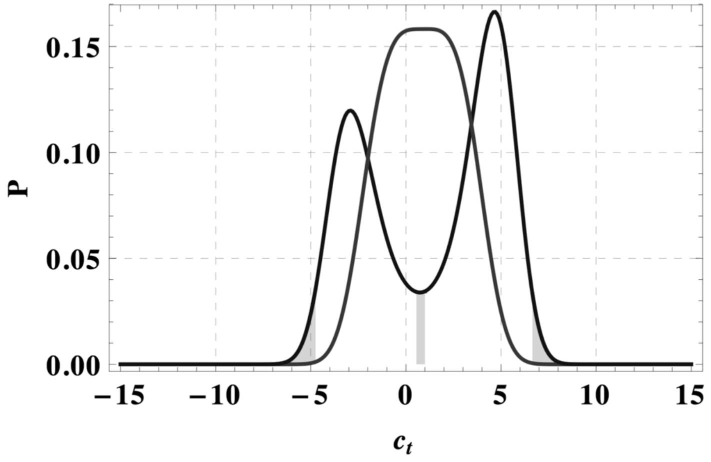
The 68%, 95% and 99% probability contours in the c_t,c_g plane, using the 8 TeV CMS data set. A 10% systematic uncertainty was assumed on the $q\bar{q}$ background.

As a proof of concept we take the 8 TeV CMS data and recast it in the $c_t - c_g$ plane.

Imposing $c_t + c_g = 1$ leads to constraints on c_t.

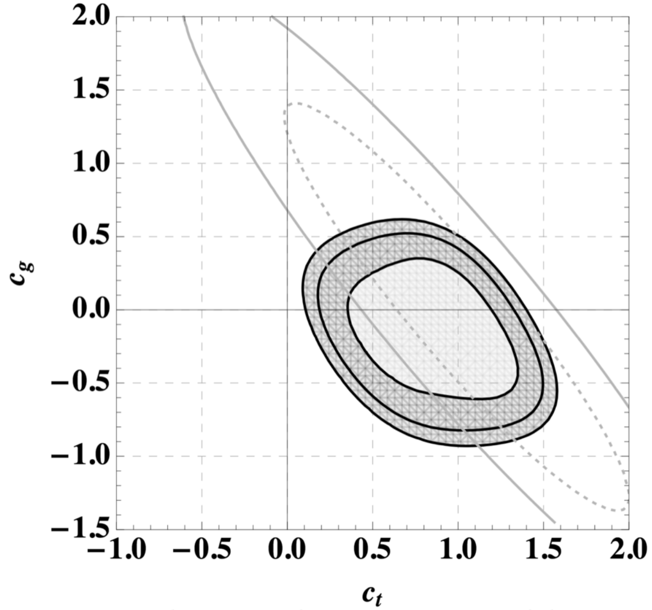
Constraints can improve using the *MELA** framework.

Constraints weaker than those from *tth* measurements but of the same order.



Posterior probability as a function of c_t, assuming the constraint $c_t + c_g = 1$, for the 8 TeV CMS data set. At 95% we find $c_t \in [-4.7, 0.5] \cup [1, 6.7]$ (unshaded region), at 68% $c_t \in [-4, -1.5] \cup [2.9, 6.1]$.

linearized vs. non-linearized analysis



Prospects for a 14 TeV analysis with an integrated luminosity of $3\,\mathrm{ab}^{-1}$ and for the injected SM signal: 68%, 95% and 99% expected probability regions in the (c_t, c_g) plane.

The difference between the linear and non-linear analysis at 14 TeV is large.

This difference falls off at higher energy colliders.

	33 TeV	50 TeV	80 TeV	100 TeV
non-linear < 2TeV	[0.92,1.14]	[0.95,1.11]	[0.96,1.08]	[0.97,1.07]
linear < 2 TeV	[0.83,1.18]	[0.9,1.11]	[0.94,1.07]	[0.95,1.05]
non-linear all	[0.94,1.11]	[0.96,1.08]	[0.98,1.05]	[0.98,1.04]
linear all	[0.84,1.16]	[0.91,1.09]	[0.95,1.05]	[0.96,1.04]

The 68% probability intervals on the value of c_t, obtained assuming $c_t + c_g = 1$ and injecting the SM signal at various collider energies. In all cases an integrated luminosity of $3\,\mathrm{ab}^{-1}$ was assumed. The numbers in the second and the third row present the non-linear and linear analysis, respectively, for the low-energy bins only, $\sqrt{s} < 2\,\mathrm{TeV}$. The fourth and the fifth rows contain the corresponding numbers obtained including all the bins up to 5 TeV.

Open to improvement in both theoretical and experimental technologies.

Take Home Snacks

- ✓ Off-shell Higgs production from gluon fusion can be used to resolve the $c_t - c_g$ degeneracy.
- ✓ One has to be careful about the dimension of the included operators.
- ✓ Possibilities of reducing theoretical uncertainties with imminent computation of two-loop continuum contribution.

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Resolving gluon fusion loops at current and future hadron colliders

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1. combination of related measurements

2. the off-shell channel and a toy model

3. testing the validity of the EFT

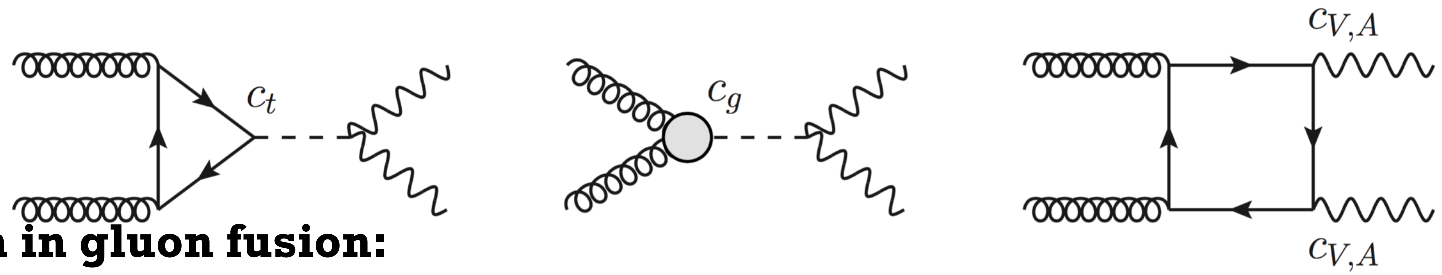
1. combination of related measurements

The Processes

$$\mathcal{L}_6 \;=\; c_y \frac{y_t |H|^2}{v^2} \bar{Q}_L \widetilde{H} t_R + \text{h.c.} + \frac{c_g g_s^2}{48\pi^2 v^2} |H|^2 G_{\mu\nu} G^{\mu\nu} \qquad \mathcal{L}_{\rm nl} \;=\; -\, c_t \frac{m_t}{v} \bar{t} t h + \frac{c_g g_s^2}{48\pi^2} \frac{h}{v} G_{\mu\nu} G^{\mu\nu}\,, \qquad c_t = 1 - c_y$$

$$c_g \frac{e^2}{18\pi^2} \frac{h}{v} F_{\mu\nu} F^{\mu\nu}$$

- **Higgs and top quark associated production:** almost a direct measurement of c_t with very little pollution from c_g
- **boosted Higgs production:** sensitive to c_t and c_g
- **off-shell Higgs production:** sensitive to c_t and c_g but also to effective *ttZ* couplings



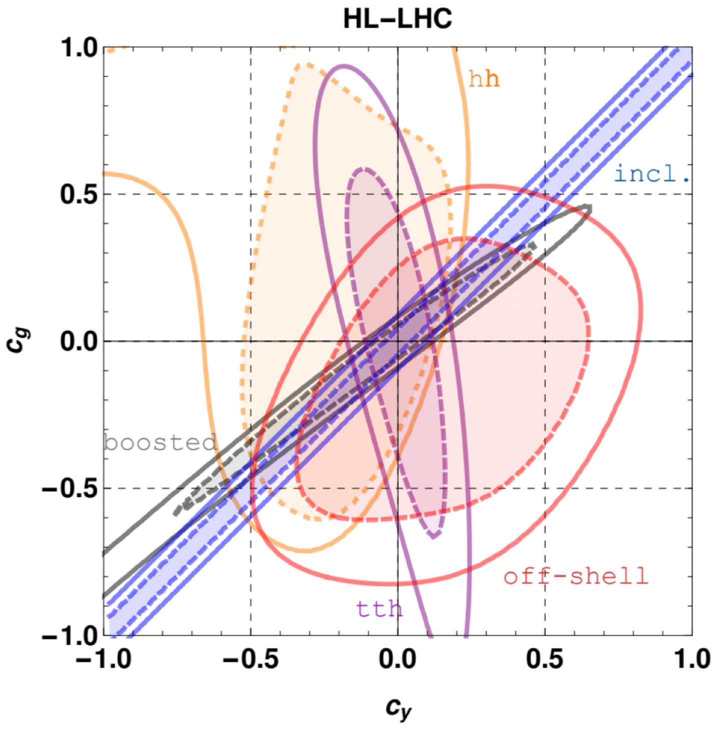
- **double Higgs production in gluon fusion:**
    - occurs at energies much above the top quark mass – top loops and contact interaction can be resolved
    - higher-point interactions make it really sensitive to the top-Yukawa sector

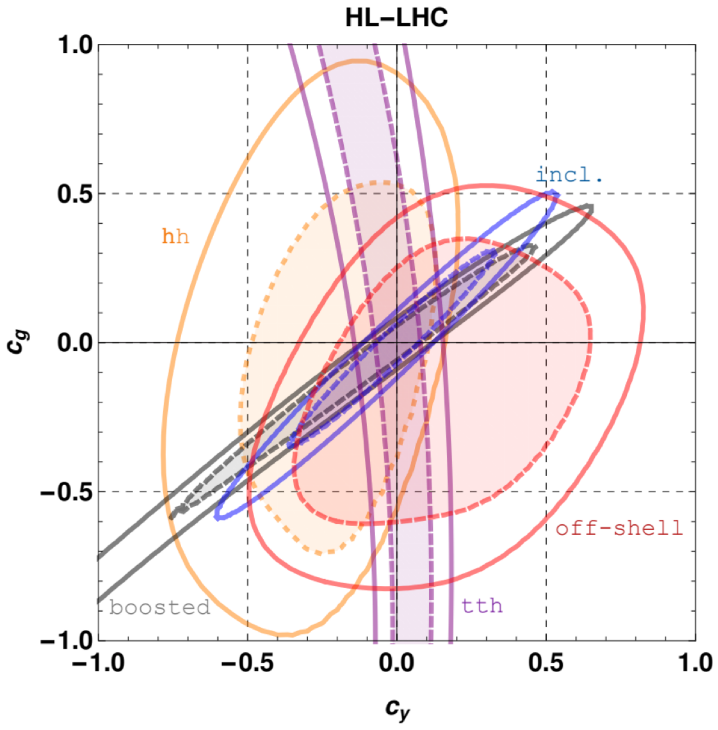
$$\mathcal{L}_{\rm nl}^{hh} \;=\; -\frac{m_t}{v} \bar{t} t \left(c_t h + c_{2t} \frac{h^2}{v} \right) + \frac{c_g g_s^2}{48\pi^2} \left(\frac{h}{v} + \frac{h^2}{2v^2} \right) G_{\mu\nu} G^{\mu\nu}\,, \qquad c_{2t} = -\frac{3}{2} c_y$$

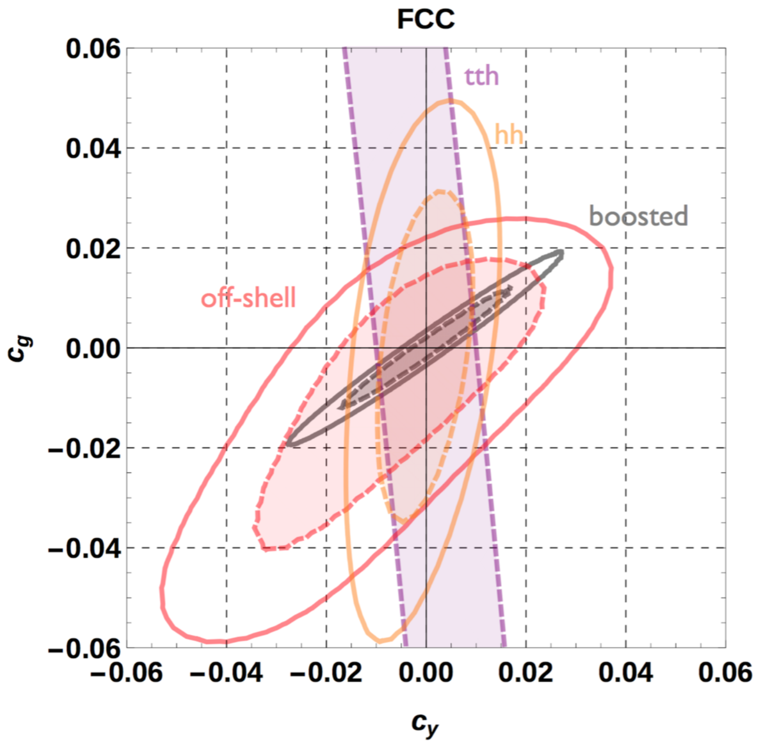
The Combination

SM signal injected
the Higgs is a part of a doublet

$$\cancel{c_g \frac{e^2}{18\pi^2}\frac{h}{v}F_{\mu\nu}F^{\mu\nu}}$$







inclusive production projection from: ATLAS Collaboration, ATL-PHYS-PUB-2013-014, October 2013.

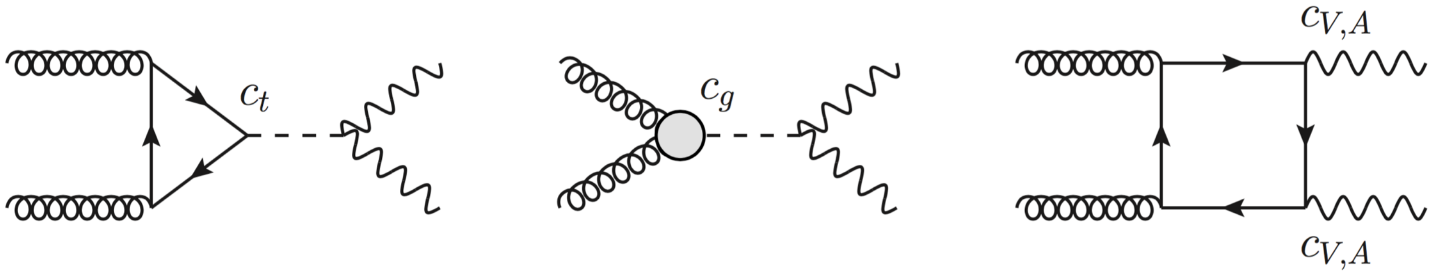
2. the off-shell channel and a toy model

off-shell Higgs Production

$$\mathcal{L}_6 = c_y \frac{y_t |H|^2}{v^2} \bar{Q}_L \widetilde{H} t_R + \text{h.c.} + \frac{c_g g_s^2}{48\pi^2 v^2} |H|^2 G_{\mu\nu} G^{\mu\nu}$$

$$\mathcal{L}_{\text{nl}} = -c_t \frac{m_t}{v} \bar{t} t h + \frac{c_g g_s^2}{48\pi^2} \frac{h}{v} G_{\mu\nu} G^{\mu\nu}, \qquad c_t = 1 - c_y$$

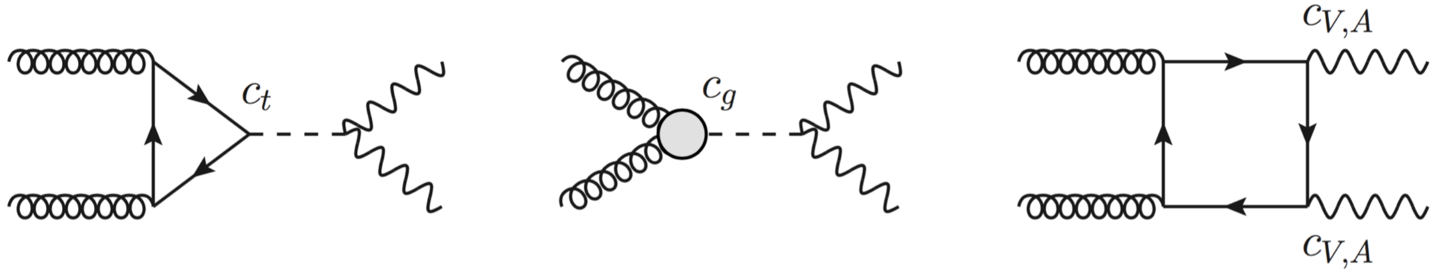
- **off-shell Higgs production:** sensitive to c_t and c_g but also to effective *ttZ* couplings



$$\boxed{\begin{aligned} \mathcal{L}_6^{\text{extended}} &= c_y \frac{y_t |H|^2}{v^2} \bar{Q}_L \widetilde{H} t_R + \text{h.c.} + \frac{c_g g_s^2}{48\pi^2 v^2} |H|^2 G_{\mu\nu} G^{\mu\nu} \\ &+ \frac{i c_{Hq}^3}{v^2} H^\dagger \sigma^a D_\mu H \, \bar{Q}_L \sigma^a \gamma^\mu Q_L + \text{h.c.} + \frac{i c_{Hq}^1}{v^2} H^\dagger D_\mu H \, \bar{Q}_L \gamma^\mu Q_L + \text{h.c.} \end{aligned}}$$

a toy model

- **off-shell Higgs production:** sensitive to c_t and c_g but also to effective *ttZ* couplings



the extension of the SM with a vector-like top singlet under the $SU(2)_L$

$$\boxed{\mathcal{L} \;=\; -y\bar{Q}_L\tilde{H}t_R - Y_*\bar{Q}_L\tilde{H}T_R - M_*\bar{T}_LT_R + \text{h.c.}}$$

$$\mathcal{L}^{\text{EFT, tree}} = -\frac{m_t}{v}\left(1-\frac{Y_*^2v^2}{2M_*^2}\right)h\bar{t}t + \frac{e}{s_wc_w}\left(\frac{1}{2}-\frac{2}{3}s_w^2-\frac{Y_*^2v^2}{4M_*^2}\right)Z_\mu\bar{t}_L\gamma^\mu t_L + \frac{e}{s_wc_w}\left(-\frac{2}{3}s_w^2\right)Z_\mu\bar{t}_R\gamma^\mu t_R + O\left(\frac{1}{M_*^4}\right),$$

$$\mathcal{L}^{\text{EFT, loop}} = \frac{g_s^2}{48\pi^2}\frac{h}{v}G_{\mu\nu}G^{\mu\nu}\left(\frac{Y_*^2v^2}{2M_*^2}\right) + O\left(\frac{1}{M_*^4}\right)$$

$s_w \equiv \sin\theta_w,\; c_w \equiv \cos\theta_w$

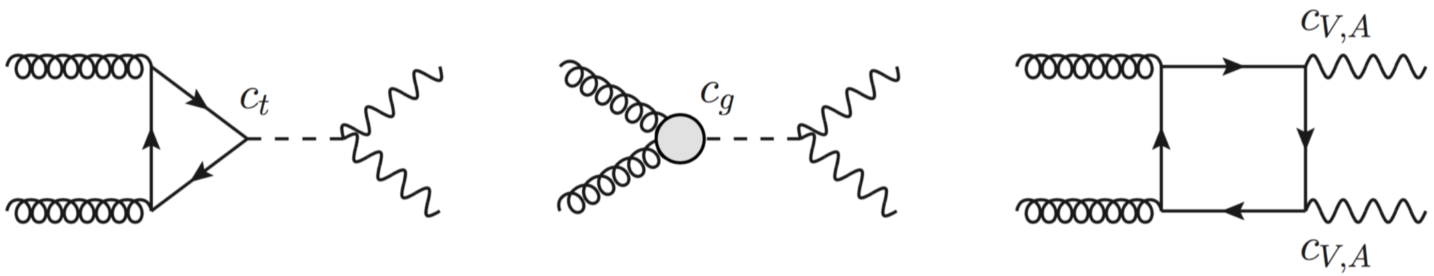
$$\boxed{c_t = 1-\frac{Y_*^2v^2}{2M_*^2}, \qquad c_g = \frac{Y_*^2v^2}{2M_*^2}}$$

$$\boxed{c_t + c_g = 1}$$

$$\boxed{c_y = c_g = \frac{Y_*^2v^2}{2M_*^2}, \qquad c_{Hq}^1 = -c_{Hq}^3 = \frac{Y_*^2v^2}{4M_*^2}}$$

the effective couplings

- **off-shell Higgs production:** sensitive to c_t and c_g but also to effective *ttZ* couplings



the effective language

$$\boxed{eZ_\mu \bar{t}\gamma^\mu (c_V + c_A\gamma_5)\, t \;=\; Z_\mu \bar{t}\gamma^\mu \left(c_L\, g_L^{\rm SM} P_L + c_R\, g_R^{\rm SM} P_R\right) t}$$

$$\boxed{g_L^{\rm SM} = e(1/2 - 2s_w^2/3)/(s_w c_w),\; g_R^{\rm SM} = e(-2s_w^2/3)/(s_w c_w)}$$

$$c_V^{\rm SM} = (1 - 8s_w^2/3)/(4 s_w c_w) \simeq 0.23\,, \quad c_A^{\rm SM} = -1/(4 s_w c_w) \simeq -0.59\,, \quad c_L^{\rm SM} = c_R^{\rm SM} = 1$$

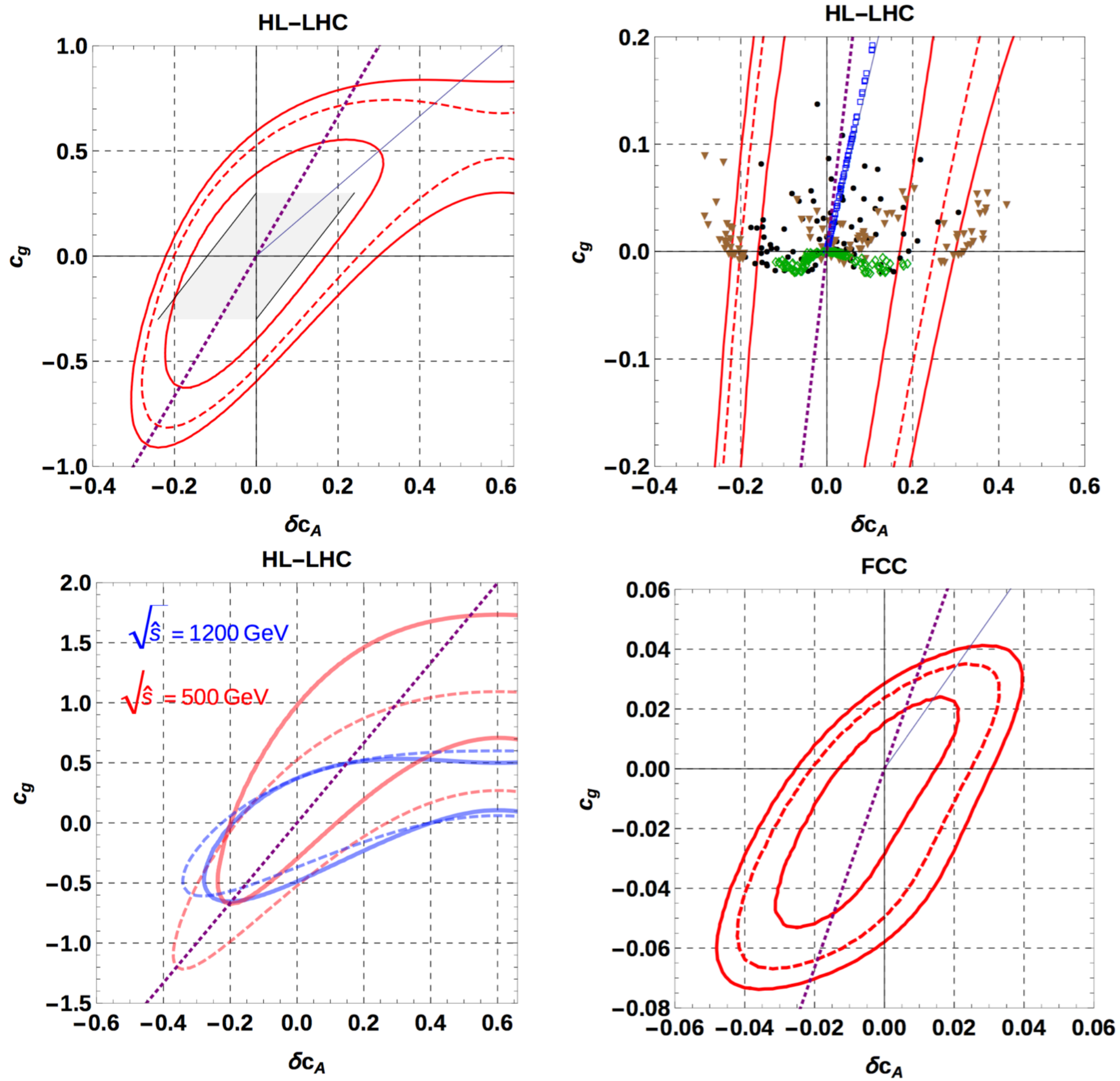
$$\delta c_i \equiv c_i - c_i^{\rm SM} \;\; (i = V, A, L, R)$$

$$\mathcal{L}_6^{tV} = \frac{ic_{Hq}^3}{v^2} H^\dagger \sigma^a D_\mu H\, \bar{Q}_L \sigma^a \gamma^\mu Q_L + \text{h.c.} + \frac{ic_{Hq}^1}{v^2} H^\dagger D_\mu H\, \bar{Q}_L \gamma^\mu Q_L + \text{h.c.} + \frac{ic_{Hu}}{v^2} H^\dagger D_\mu H\, \bar{t}_R \gamma^\mu t_R + \text{h.c.}.$$

LEP constraints imply: $\boxed{c_{Hq}^1 = -c_{Hq}^3}$

$$\boxed{\delta c_V = \frac{1}{4 s_w c_w}\left(2c_{Hq}^3 - c_{Hu}\right), \qquad \delta c_A = \frac{1}{4 s_w c_w}\left(-2c_{Hq}^3 - c_{Hu}\right)}$$

the results of this labour



$$N = a_0 + a_1\, c_A^2 + a_2\, c_A^4 + a_3\, c_V^2 + a_4\, c_V^4 + a_5\, c_A^2 \cdot c_V^2 + a_6\, c_g + a_7\, c_t + a_8\, c_g^2 + a_9\, c_t^2 + a_{10}\, c_g \cdot c_t + a_{11}\, c_A^2 \cdot c_g + a_{12}\, c_A^2 \cdot c_t + a_{13}\, c_g \cdot c_V^2 + a_{14}\, c_t \cdot c_V^2\,,$$

Simulation with MCFM, check with FeynArts/FormCalc/LoopTools

$$\boxed{\begin{pmatrix} \sigma_{c_A} \\ \sigma_{c_V} \\ \sigma_{c_g} \end{pmatrix} = \begin{pmatrix} 0.3 \\ 0.27 \\ 0.27 \end{pmatrix}, \qquad \rho = \begin{pmatrix} 1 & -0.02 & 0.61 \\ & 1 & -0.003 \\ & & 1 \end{pmatrix}}$$

Slightly worse but comparable with $gg \to hZ$

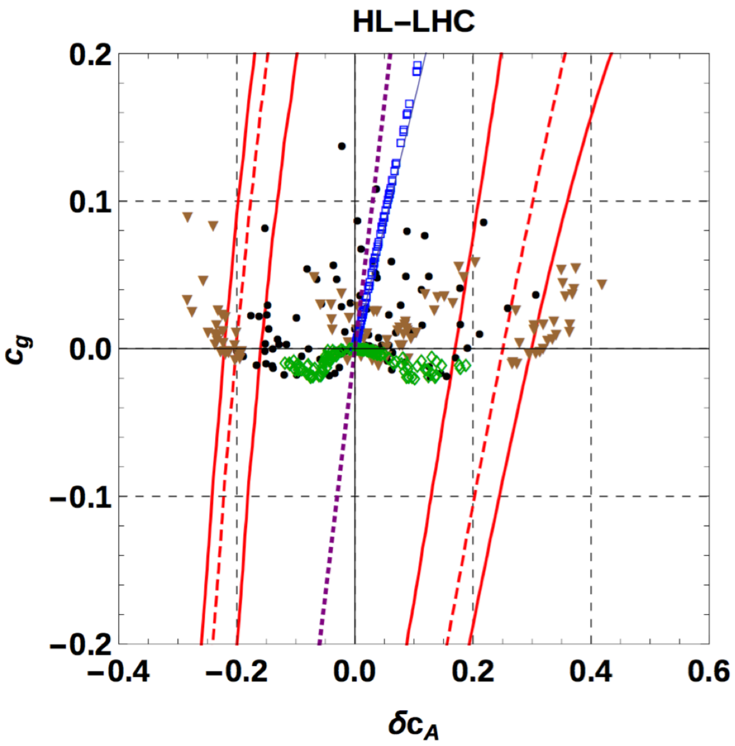
C. Englert, R. Rosenfeld, M. Spannowsky and A. Tonero, Europhys. Lett. **114** 31001 (2016), arXiv:1603.05304 [hep-ph].

$$\mathcal{M}^{++00}(gg \to ZZ) \simeq -c_g \frac{\hat{s}}{2m_Z^2} + \left(c_t - c_A^2/c_A^{\mathrm{SM}\,2}\right) \frac{m_t^2}{2m_Z^2} \log^2 \frac{\hat{s}}{m_t^2} - 2\pi i \left(c_t - c_A^2/c_A^{\mathrm{SM}\,2}\right) \frac{m_t^2}{2m_Z^2} \log \frac{\hat{s}}{m_t^2}\,,$$

$$(1 - c_g - c_A^2/c_A^{\mathrm{SM}\,2}) = 0 \quad \Rightarrow \quad c_g = -\frac{2\delta c_A}{c_A^{\mathrm{SM}}} = 8 s_w c_w\, \delta c_A \simeq 3.4\, \delta c_A\,,$$

14 TeV $\sqrt{\hat{s}} = (250, 400, 600, 800, 1100, 1500)$ GeV **100 TeV** $\sqrt{s} = (250, 400, 600, 800, 1100, 1500, 2500, 5000)$ GeV

model specific results



$$\mathcal{L} = i\bar{\psi}_4(\not{D} + i\not{e})\psi_4 - m_4\bar{\psi}_4\psi_4 + i\bar{\psi}_1\not{D}\psi_1 - m_1\bar{\psi}_1\psi_1 + i\bar{Q}_L\not{D}Q_L + i\bar{t}_R\not{D}t_R$$
$$+ i\tilde{c}_t\bar{\psi}^i_{4R}\not{d}^i t_R + i\tilde{c}_R\bar{\psi}^i_{4R}\not{d}^i\psi_{1R} + i\tilde{c}_L\bar{\psi}^i_{4L}\not{d}^i\psi_{1L} + \text{h.c.}$$
$$+ y_{Lt} f(\bar{Q}_L)^I U_{I5} t_R + y_{L4} f(\bar{Q}_L)^I U_{Ii}\psi^i_{4R} + y_{L1} f(\bar{Q}_L)^I U_{I5}\psi_{1R} + \text{h.c.},$$

C. Grojean, O. Matsedonskyi and G. Panico, JHEP **1310** 160 (2013), arXiv:1306.4655 [hep-ph].

$m_1\ (m_4) \to \infty$: M1$_5$ (M4$_5$)

A. De Simone, O. Matsedonskyi, R. Rattazzi and A. Wulzer, JHEP **1304** 004 (2013), arXiv:1211.5663 [hep-ph].

$$c_g = \frac{v^2}{2}\left(\frac{y_{L1}^2 m_4^2}{m_1^2(m_4^2 + y_{L4}^2 f^2)} - \frac{y_{L4}^2}{m_4^2 + y_{L4}^2 f^2} + \frac{y_{L4}^2 y_{Lt}^2 f^2}{(m_4^2 + y_{L4}^2 f^2)^2}\right),$$

$$\left(\frac{1}{2} - \frac{2}{3}s_w^2\right)\delta c_L = -\frac{v^2}{4}\frac{(y_{L4}^2 m_1^2 + y_{L1}^2 m_4^2 - 2\sqrt{2}\tilde{c}_L y_{L4} y_{L1} m_1 m_4)}{m_1^2(m_4^2 + y_{L4}^2 f^2)},$$

$$\left(-\frac{2}{3}s_w^2\right)\delta c_R = \frac{v^2}{4}\frac{(y_{L4}^2 y_{Lt}^2 f^2 - 2\sqrt{2}\tilde{c}_t y_{L4} y_{Lt}(m_4^2 + y_{L4}^2 f^2))}{(m_4^2 + y_{L4}^2 f^2)^2},$$

$$\delta c_{V,A} = \frac{1}{2e}\left(\pm\delta c_L\, g_L^{\mathrm{SM}} + \delta c_R\, g_R^{\mathrm{SM}}\right)$$

3. testing the validity of the EFT

an EFT is valid if…

- Small energy requirement:

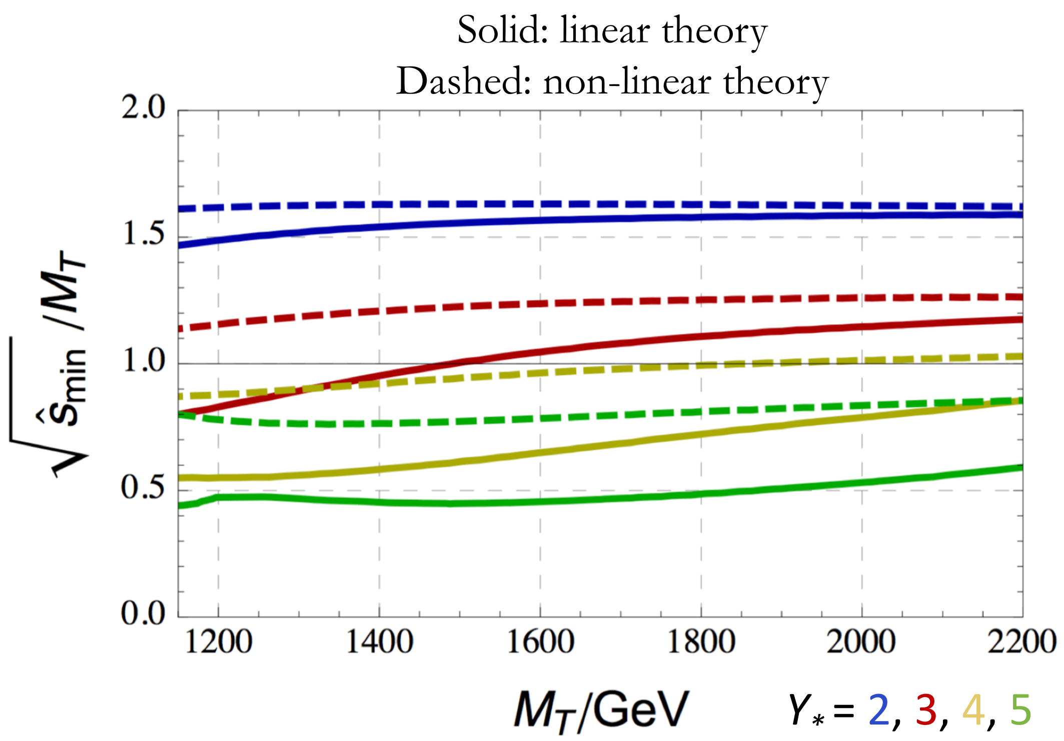
$$\frac{E}{M_*} \ll 1$$

- Small coupling requirement:

$$\frac{Y_* v}{M_*} \ll 1$$

- supression of dimension-8 operator:

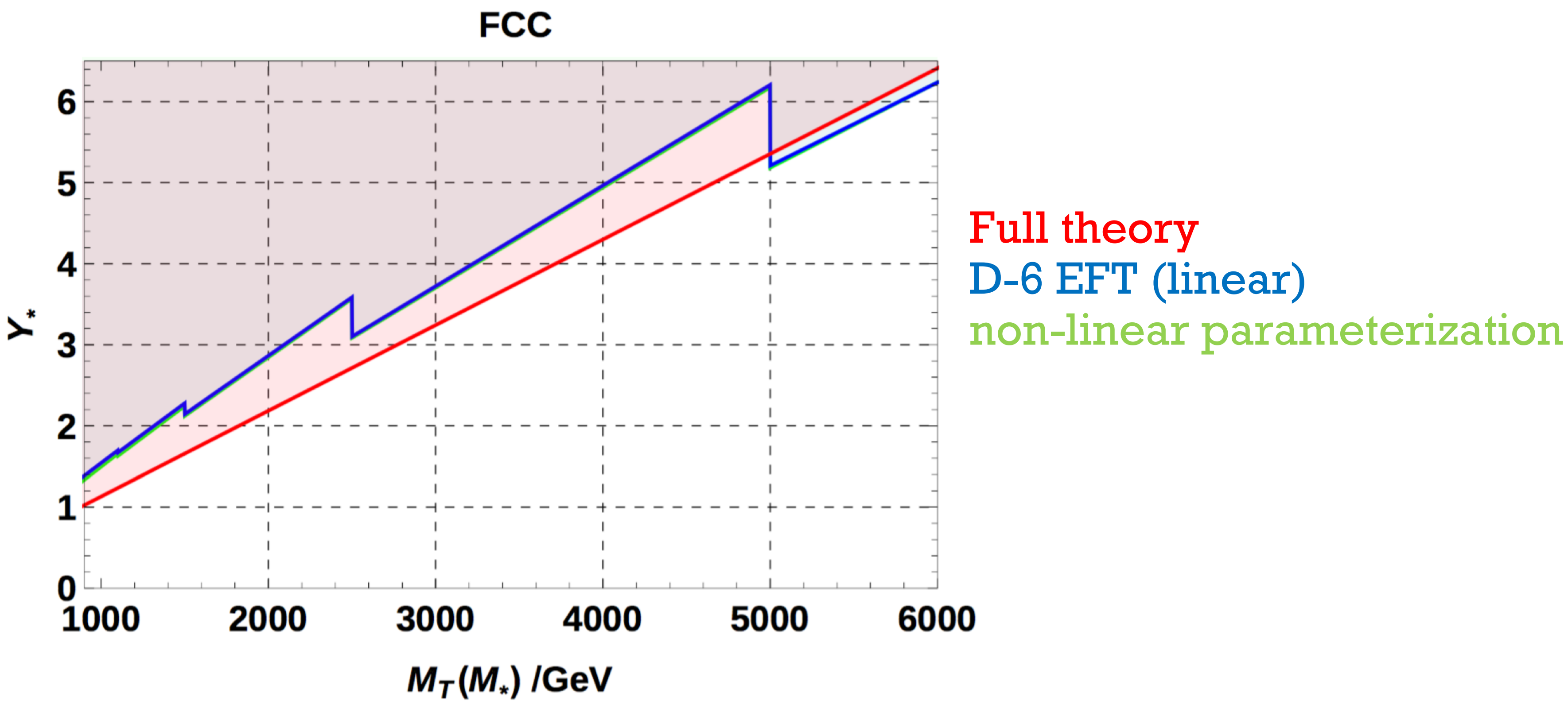
$$O_g^{(8)} \sim \frac{g_s^2}{16\pi^2}\frac{Y_*^2}{M_*^4}|D_\lambda H|^2 G_{\mu\nu}G^{\mu\nu}$$



$$\boxed{\frac{\left|\left(\frac{d\hat{\sigma}}{d\hat{s}}\right)_{\text{full}} - \left(\frac{d\hat{\sigma}}{d\hat{s}}\right)_{\text{EFT}}\right|}{\left(\frac{d\hat{\sigma}}{d\hat{s}}\right)_{\text{full}}} < 0.05}$$

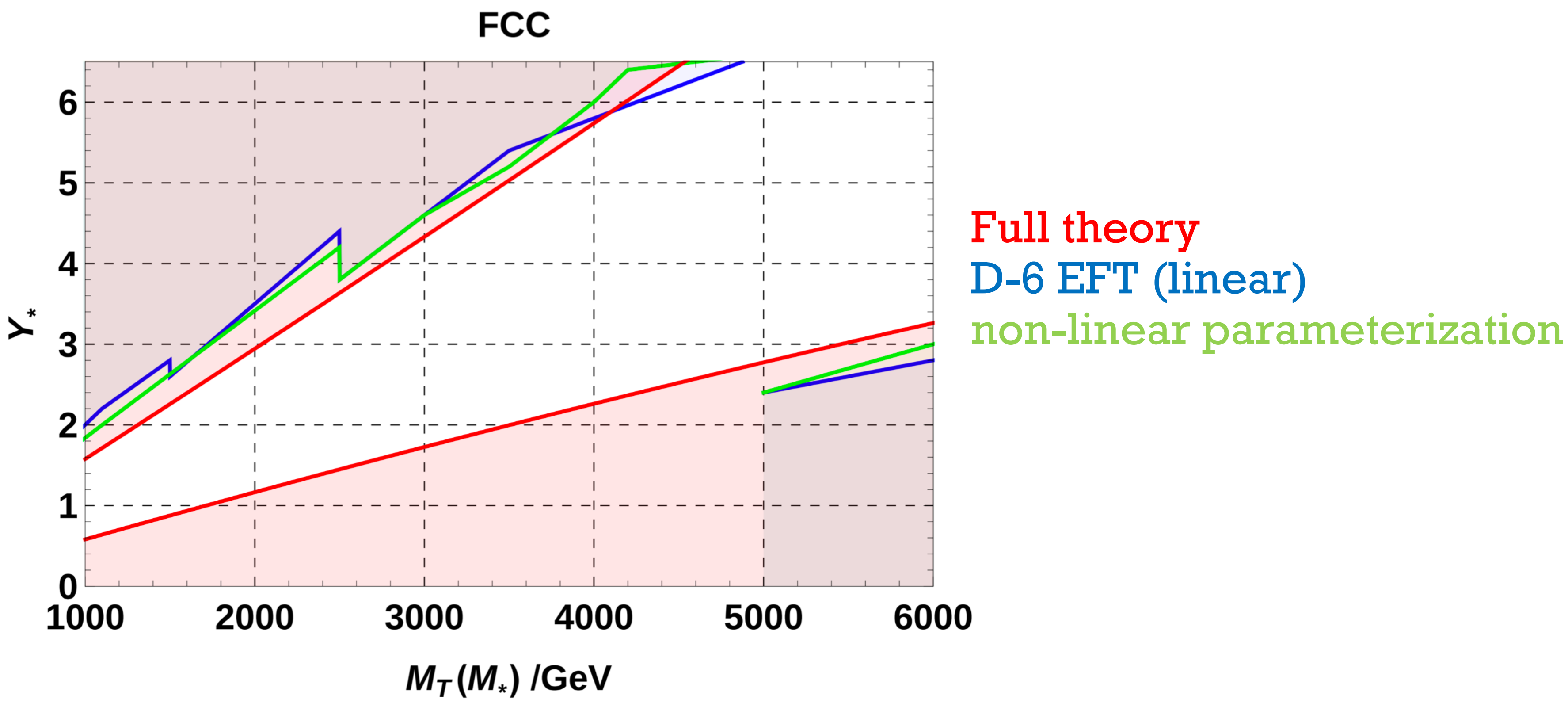
EFT simulation with MCFM
full theory computation with
FeynArts/FormCalc/LoopTools

full theory vs. EFT



- ✓ **SM signal injected**
- ✓ **the linear and the non-linear theory overlap**
- ✓ **bins are added with increasing mass and hence the jagged shape of the EFT/non-linear model**

full theory vs. EFT



- ✓ BSM signal injected (M_T = 3 TeV, Y_* = 3.5)
- ✓ the linear and the non-linear theory no longer overlap
- ✓ bins are added with increasing mass and hence the jagged shape of the EFT/non-linear model

where we stand…

- ✓ At a time when new degrees of freedom have not raised their heads, measurement of deviations in couplings are of prime importance.
- ✓ Since the discovery of the Higgs boson, experimental measurements of modifications to the Higgs couplings have come of age.
- ✓ There is a vast literature of theoretical studies of coupling modifications in the EFT framework and quite a few model proposed that can bring about such modifications.
- ✓ Of particular interest to us were the modifications of the coupling of the Higgs to tops and gluons and we studied multiple channels where these can be probed
- ✓ A combination of these information was attempted to get a coherent picture of what might be possible at current and future colliders.

now for geolocating…

Beyond Geolocating: Constraining Higher Dimensional Operators in $H \to 4\ell$ with Off-Shell Production and More

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(Dated: March 19, 2014)

Abstract

We extend the study of Higgs boson couplings in the "golden" $gg \to H \to ZZ^* \to 4\ell$ channel in two important respects. First, we demonstrate the importance of off-shell Higgs boson production ($gg \to H^* \to ZZ \to 4\ell$) in determining which operators contribute to the HZZ vertex. Second, we include the five operators of lowest non-trivial dimension, including the $Z_\mu Z^\mu \Box H$ and $HZ_\mu \Box Z^\mu$ operators that are often neglected. We point out that the former operator can be severely constrained by the measurement of the off-shell $H^* \to ZZ$ rate and/or unitarity considerations. We provide analytic expressions for the off-peak cross-sections in the presence of these five operators. On-shell, the $Z_\mu Z^\mu \Box H$ operator is indistinguishable from its Standard Model counterpart $HZ_\mu Z^\mu$, while the $HZ_\mu \Box Z^\mu$ operator can be probed, in particular, by the Z^* invariant mass distribution.

the coordinates...

$$i\ \epsilon_1^* \cdot \epsilon_2^* \quad \Longleftrightarrow \quad -\frac{1}{2} X Z_\mu Z^\mu, \tag{1}$$

$$i\ (p_1 \cdot p_2)(\epsilon_1^* \cdot \epsilon_2^*) \quad \Longleftrightarrow \quad \frac{1}{2} X \partial_\mu Z_\nu \partial^\mu Z^\nu, \tag{2}$$

$$i\ (p_1 \cdot \epsilon_2^*)(p_2 \cdot \epsilon_1^*) \quad \Longleftrightarrow \quad \frac{1}{2} X \partial_\mu Z_\nu \partial^\nu Z^\mu, \tag{3}$$

$$i\ \epsilon_{\mu\nu\rho\sigma} \epsilon_1^{*,\mu} \epsilon_2^{*,\nu} p_1^\rho p_2^\sigma \quad \Longleftrightarrow \quad -\frac{1}{2} \epsilon_{\mu\nu\rho\sigma} \partial^\mu Z^\nu \partial^\rho Z^\sigma, \tag{4}$$

$$i\ (p_1^2 + p_2^2)(\epsilon_1^* \cdot \epsilon_2^*) \quad \Longleftrightarrow \quad X Z_\mu \Box Z^\mu, \tag{5}$$

$$\mathcal{O}_1 = -\frac{M_Z^2}{v} X Z_\mu Z^\mu$$

$$\mathcal{O}_2 = -\frac{1}{2v} X F_{\mu\nu} F^{\mu\nu}$$

$$\mathcal{O}_3 = -\frac{1}{2v} X F_{\mu\nu} \tilde{F}^{\mu\nu}$$

$$\mathcal{O}_4 = \frac{M_Z^2}{M_X^2 v} \Box X Z_\mu Z^\mu$$

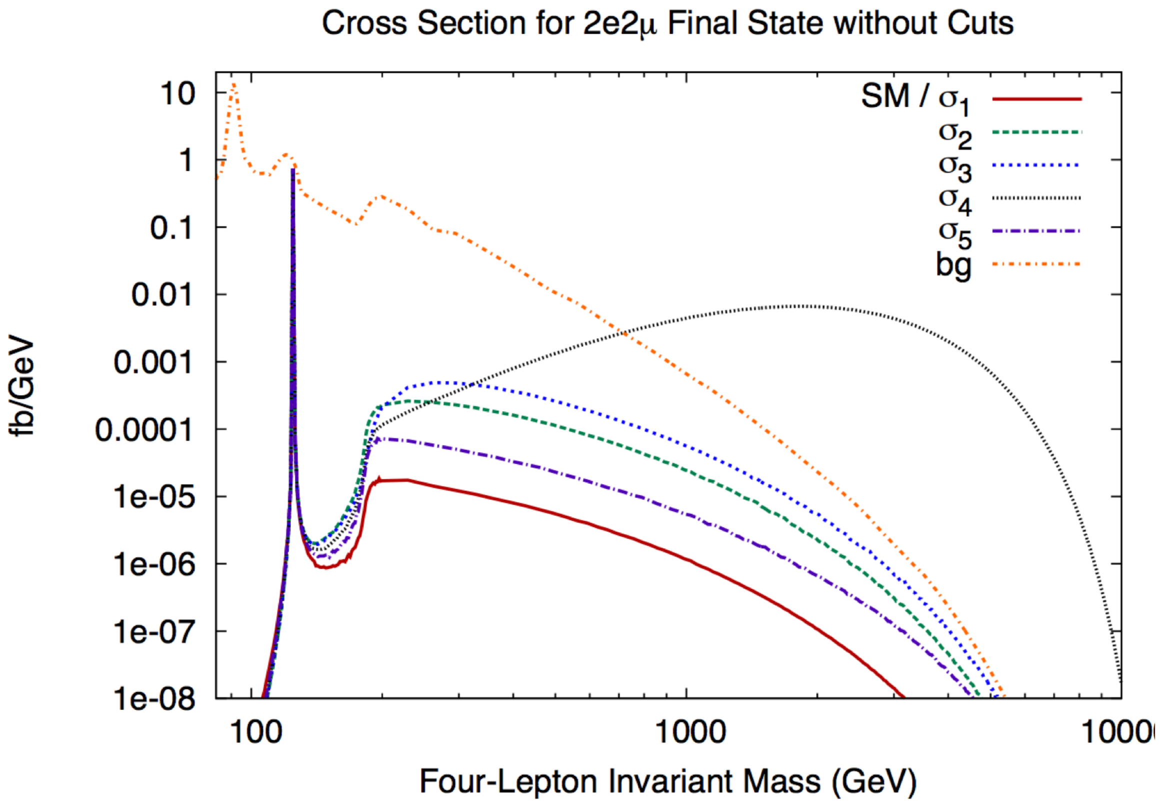
$$\mathcal{O}_5 = \frac{2}{v} X Z_\mu \Box Z^\mu$$

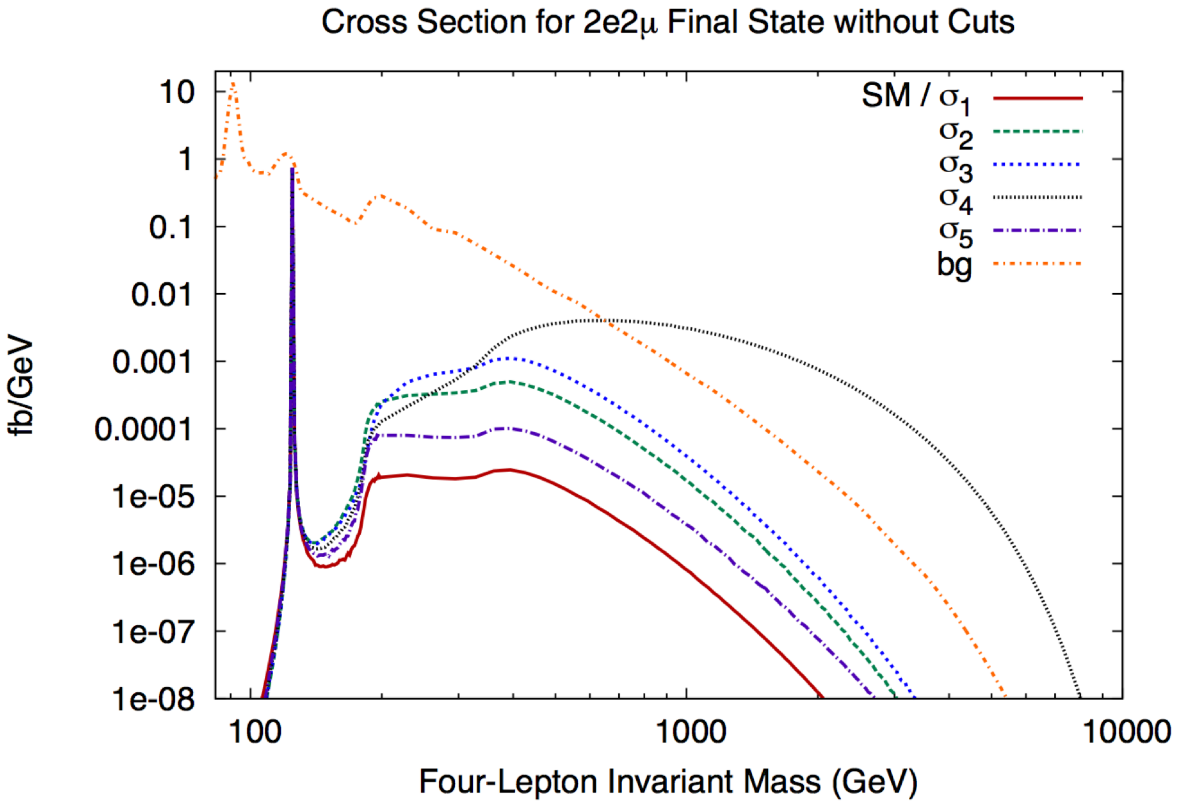
$$\mathcal{L} \supset \sum_{i=1}^{5} \kappa_i \mathcal{O}_i = -\kappa_1 \frac{M_Z^2}{v} X Z_\mu Z^\mu - \frac{\kappa_2}{2v} X F_{\mu\nu} F^{\mu\nu} - \frac{\kappa_3}{2v} X F_{\mu\nu} \tilde{F}^{\mu\nu} + \frac{\kappa_4 M_Z^2}{M_X^2 v} \Box X Z_\mu Z^\mu + \frac{2\kappa_5}{v} X Z_\mu \Box Z^\mu.$$

Operator	Dimension	CP	Gauge invariant
$\mathcal{O}_1$	3	even	No
$\mathcal{O}_2$	5	even	Yes
$\mathcal{O}_3$	5	odd	Yes
$\mathcal{O}_4$	5	even	No
$\mathcal{O}_5$	5	even	No

$$X \equiv H \cos\alpha + A \sin\alpha.$$

operator dependencies…





$$g_{ggX}(M_{4\ell}) = \frac{\alpha_s(M_{4\ell})}{4\,\pi\,v} \sum_Q A^H_{1/2}(\tau_Q),$$

operator dependencies...

$$Z_L Z_L \to Z_L Z_L$$

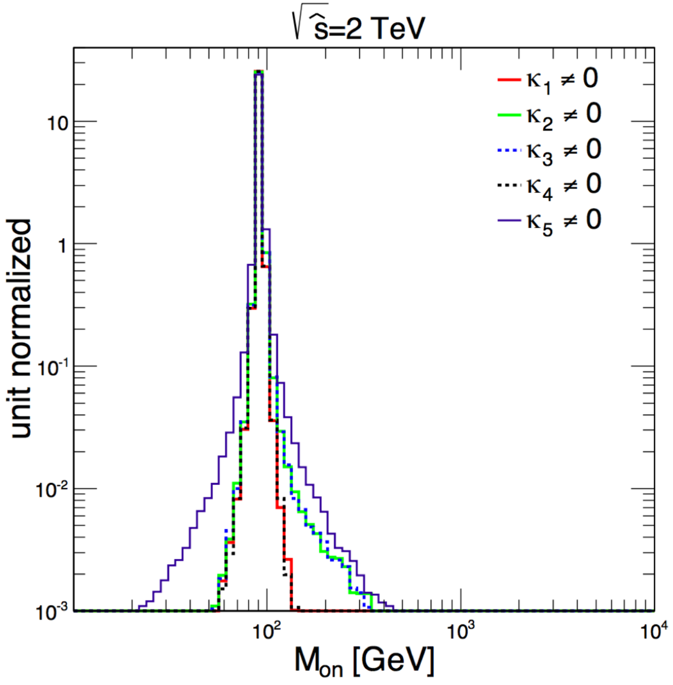
$$\lim_{\sqrt{\hat{s}}\to\infty} \frac{\sigma_2(\sqrt{\hat{s}})}{\sigma_1(\sqrt{\hat{s}})} = \frac{1}{\gamma_{22}} \lim_{\sqrt{\hat{s}}\to\infty} \frac{\xi_{22}(\sqrt{\hat{s}})}{\xi_{11}(\sqrt{\hat{s}})} = \frac{2}{\gamma_{22}} \approx 22.$$

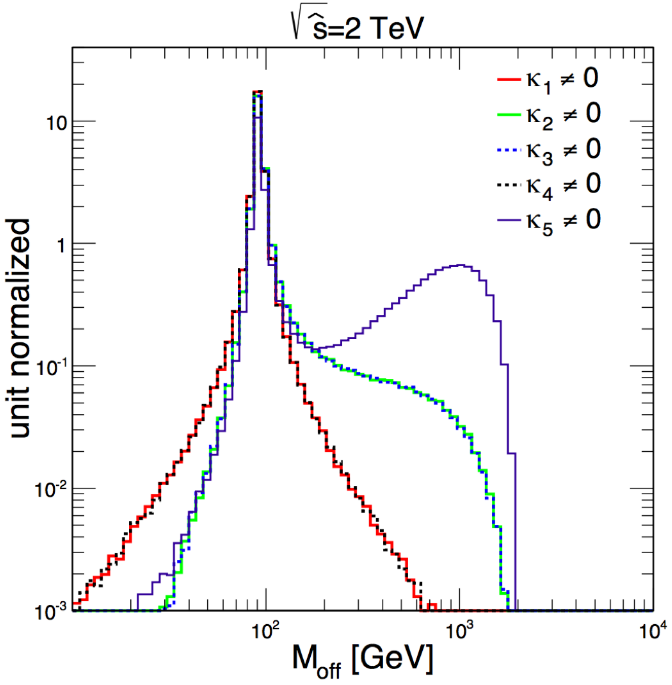
$$\lim_{\sqrt{\hat{s}}\to\infty} \frac{\sigma_3(\sqrt{\hat{s}})}{\sigma_1(\sqrt{\hat{s}})} = \frac{2}{\gamma_{33}} \approx 53.$$

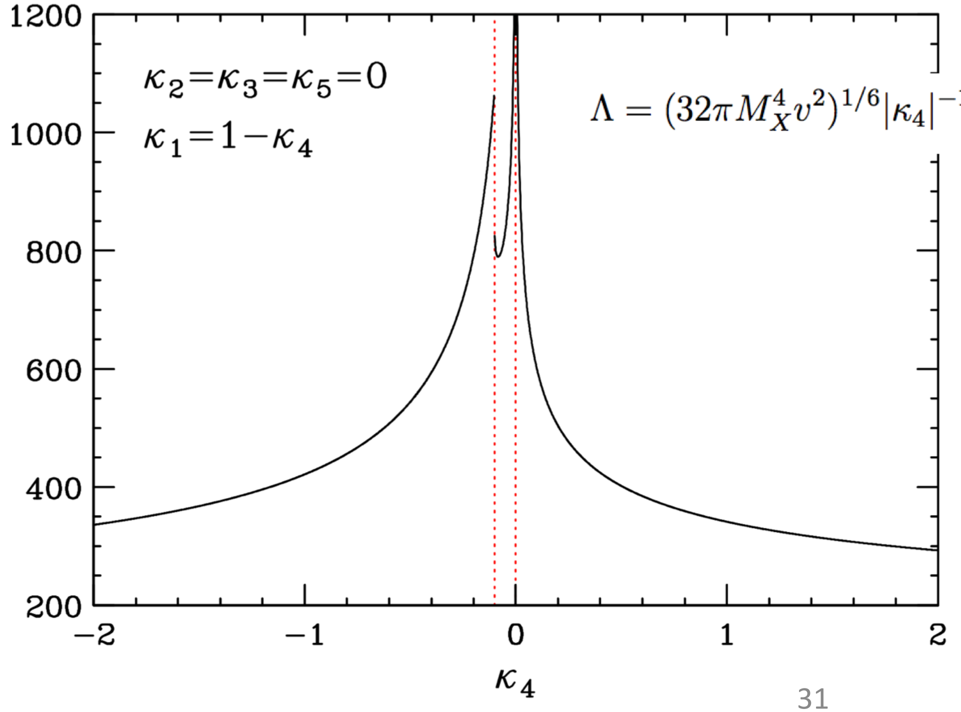
$$\lim_{\sqrt{\hat{s}}\to\infty} \frac{\sigma_4(\sqrt{\hat{s}})}{\sigma_1(\sqrt{\hat{s}})} = \frac{\hat{s}^2}{M_X^4}. \qquad \lim_{\sqrt{\hat{s}}\to\infty} \frac{\sigma_5(\sqrt{\hat{s}})}{\sigma_1(\sqrt{\hat{s}})} = \frac{4}{\gamma_{55}} \approx 4.$$

$$a_0(s) = \left(\frac{M_X^2}{32\pi v^2}\right)\left[\frac{(s/M_X^2)^2}{6}\Big((10-3s/M_X^2)\kappa_4^2 - 20\kappa_4\Big) - \left(3 + \frac{M_X^2}{s-M_X^2} - \frac{2M_X^2}{s}\log\left(1+\frac{s}{M_X^2}\right)\right)\right],$$

$$a_0(s) \sim \frac{-s^3\kappa_4^2}{64\pi M_X^4 v^2}. \qquad |\mathrm{Re}\, a_0(\Lambda^2)| = 1/2$$





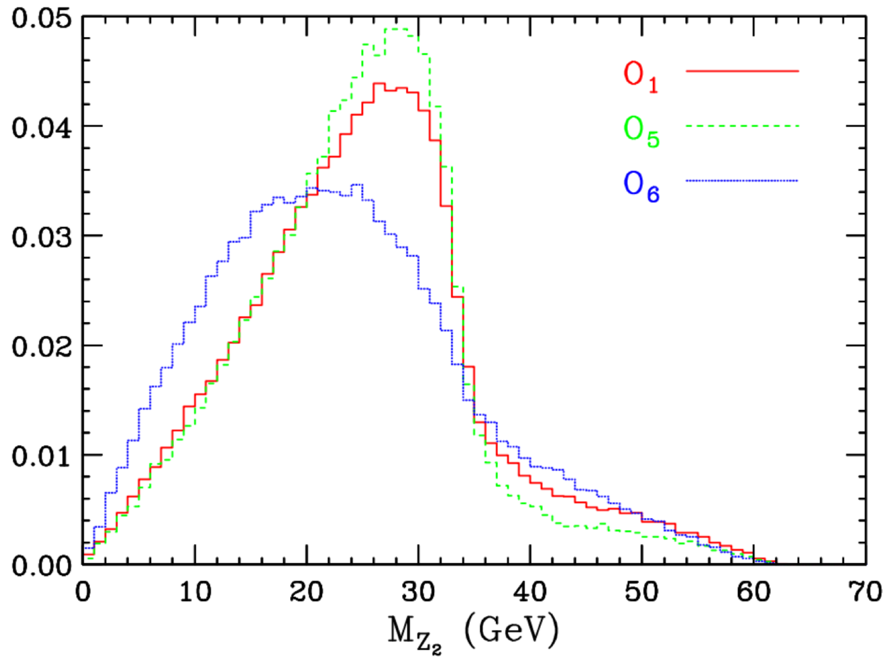


$$\Lambda = (32\pi M_X^4 v^2)^{1/6} |\kappa_4|^{-1/3}.$$

the on-shell story…

	$\mathcal{O}_1$	$\mathcal{O}_2$	$\mathcal{O}_3$	$\mathcal{O}_4$	$\mathcal{O}_5$	$\mathcal{O}_6$
$2\langle\Delta \log \mathcal{L}\rangle_{SM}$	0	−0.747	−1.017	0	−0.178	−0.503
Events for 3σ Limit	———	12.0	8.85	———	50.5	17.9

- Strong bounds on O_2 and O_3 already.
- O_5 more difficult to bound from on-shell measurements.



$$\mathcal{O}_6 = \frac{1}{v} X \left(\partial_\mu Z_\nu \partial^\nu Z^\mu + \partial_\mu Z_\nu \partial^\mu Z^\nu\right).$$

summary

- An operator basis for studying XZZ couplings is presented
- Both on-shell and off-shell measurements can be used to bound the coefficients of these operators
- Unitarity constraints puts strong bounds on O_4
- O_2 and O_3 are bound by on-shell measurements.

Thank you…!!

To my Mother and Father, who showed me what I could do,

and to Ikaros, who showed me what I could not.

"To know what no one else does, what a pleasure it can be!"

– adopted from the words of

Eugene Wigner.