Boosted and off-shell Higgs at the FCC-hh

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1st FCC Physics Workshop

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Based on **arXiv:1608.00977** (JHEP)
with **A. Azatov, C. Grojean** *and* **A. Paul**

Motivation

- Important sub-set of SM EFT:

$$\mathcal{L}_6 \ni c_y y_t \frac{H^\dagger H}{v^2} \bar{q}_L \tilde{H} t_R + \text{h.c.}$$
$$+ c_g \frac{\alpha_s}{12\pi} \frac{H^\dagger H}{v^2} G^a_{\mu\nu} G^{a\,\mu\nu} + c_\gamma 2 N_c Q_t^2 \frac{\alpha}{12\pi} \frac{H^\dagger H}{v^2} F_{\mu\nu} F^{\mu\nu}$$

- Very generic BSM effects, expected e.g. both in composite and SUSY scenarios:

c_y $\leftrightarrow$ top mixing, nlσm corrections, *h* mixing, …

c_g, c_γ $\leftrightarrow$ new charged particles with decoupling masses:

fermionic top partners, stops, EW-charged resonances, …

e.g. Giudice, Grojean, Pomarol and Rattazzi, 2007

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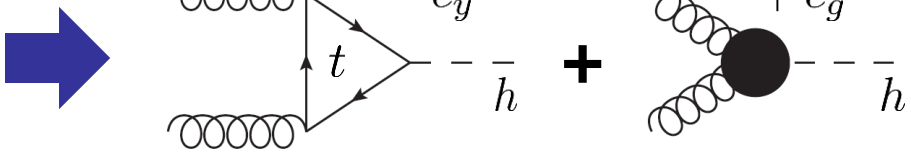

$$\mathcal{M}(gg \to h)_{\text{BSM}} \sim c_g - c_y$$

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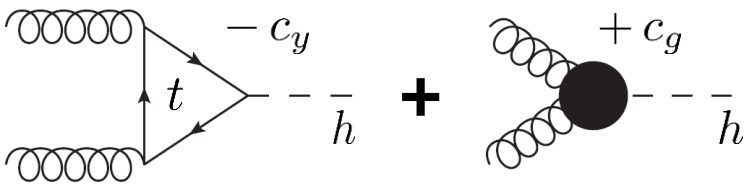
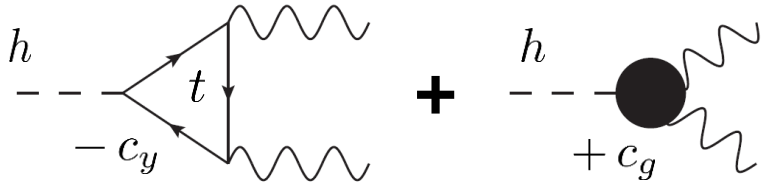


$$\mathcal{M}(gg \to h)_{\text{BSM}} \sim c_g - c_y$$

- If top partners dominate (color triplet and $Q = Q_t = \frac{2}{3}$), then $c_\gamma = c_g$ and



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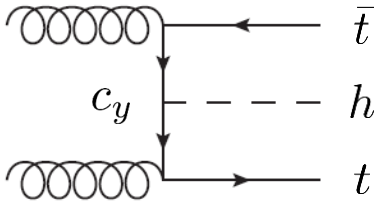
inclusive Higgs measurements at hh colliders are blind along the direction

$$c_g = c_y$$

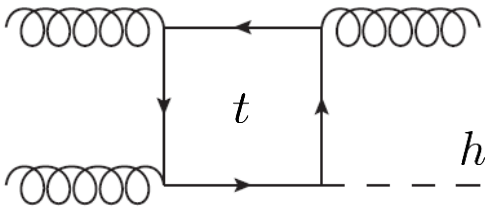
Resolving the degeneracy

- Need to add other measurements to pin down c_y and c_g **separately:**

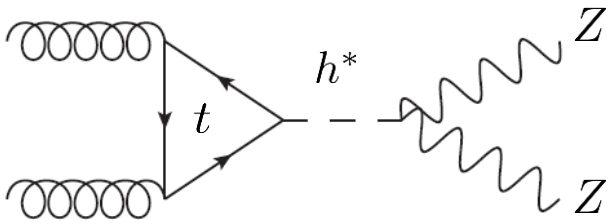
  - **tth production**: it probes c_y at tree-level, with minor corrections ~ c_g



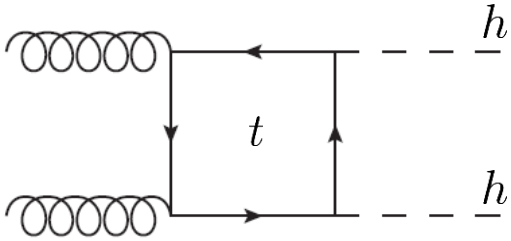
  - **gluon fusion loop processes probed at energies** $m_{\rm NP} \gtrsim E \gtrsim m_t$
    where top loops and heavy NP loops can be differentiated



Boosted Higgs
[*h* + hard jet(s)]



Off-shell Higgs



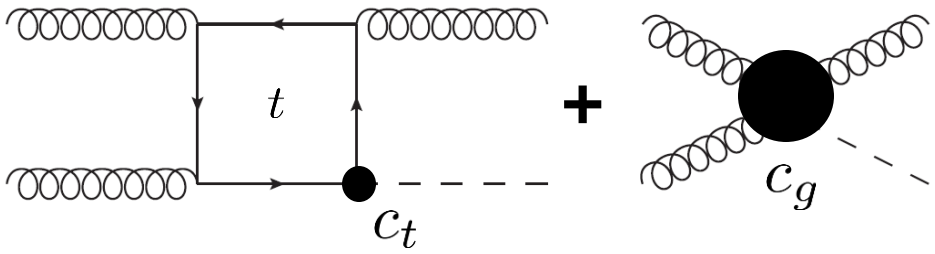
Double Higgs

Boosted Higgs

(see also: **Arnesen et al. 2008; Harlander et al., Banfi et al., Azatov and Paul 2013**)

- Higgs recoiling against a hard jet

$$\mathcal{M}(gg \to hg) \sim$$



for $p_T \gg m_t$, **the top loop is resolved**

$p_T < m_t$: same degeneracy as inclusive rate

$$\frac{\sigma_{p_T^{\min}}(c_t, c_g)}{\sigma^{\mathrm{SM}}_{p_T^{\min}}} = (c_t + c_g)^2 + \delta\, c_t c_g + \epsilon\, c_g^2$$

$p_T \gg m_t$: different combination of couplings

$$(c_t = 1 - c_y)$$

Grojean, ES, Schlaffer and Weiler, 2013

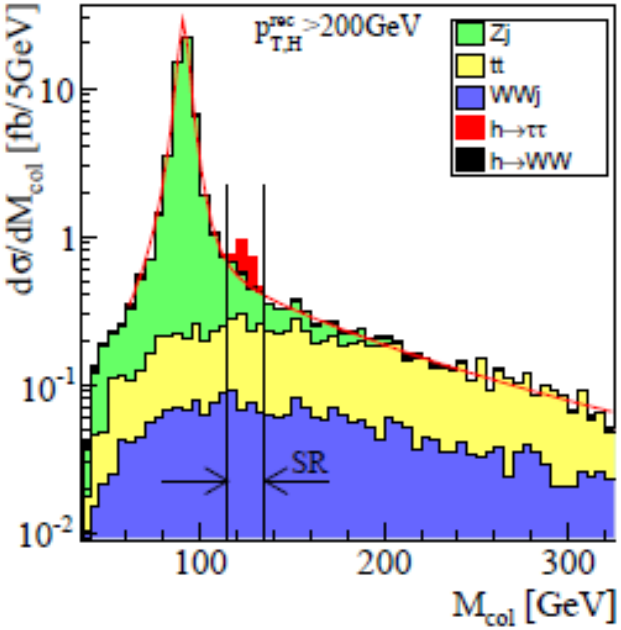
100 TeV

$p_T^{\min}$ [GeV]	$\sigma^{\mathrm{SM}}_{p_T^{\min}}$ [fb]	δ	ϵ
100	91024	0.036	0.071
200	21431	0.27	0.39
300	6412.1	0.69	1.0
400	2313.5	1.2	1.9
500	964.0	1.8	3.1
600	448.0	2.4	4.7
700	226.5	3.1	6.6
800	122.5	3.8	8.8
900	69.91	4.6	11.5
1000	41.74	5.3	14.6
1100	25.88	6.1	18.2
1200	16.57	6.94	22.4
1300	10.91	7.79	27.0
1400	7.36	8.66	32.3
1500	5.07	9.56	38.2

Boosted Higgs at the FCC-hh

- **Dedicated 100 TeV study not available yet**
- HL-LHC analysis focused on $h \to \ell\ell + \mathrm{MET}$

  $h \to \tau\tau$ gives best sensitivity



Schlaffer, Spannowsky, Takeuchi, Weiler and Wymant, 2014

- We separate their event yields into 4 bins

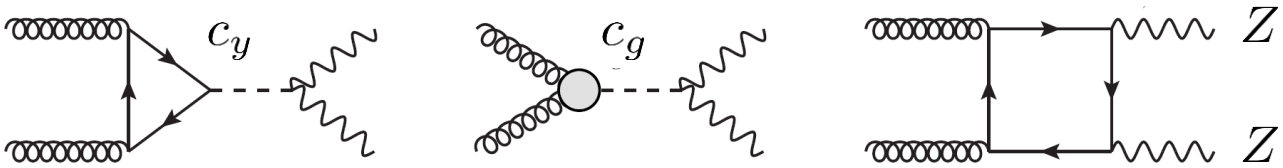
$$p_T^h \in [300,\ 400,\ 500,\ 600,\ \infty]\ \mathrm{GeV}$$

and rescale signal and backgrounds from 14 to 100 TeV using parton luminosity ratios

Off-shell Higgs at the FCC-hh

- Measurement of the invariant mass distribution in $pp \to ZZ \to 4\ell$ is a powerful probe of Higgs couplings

Azatov, Grojean, Paul and ES, 2014



Kauer, Passarino 2012;
Caola, Melnikov, 2013

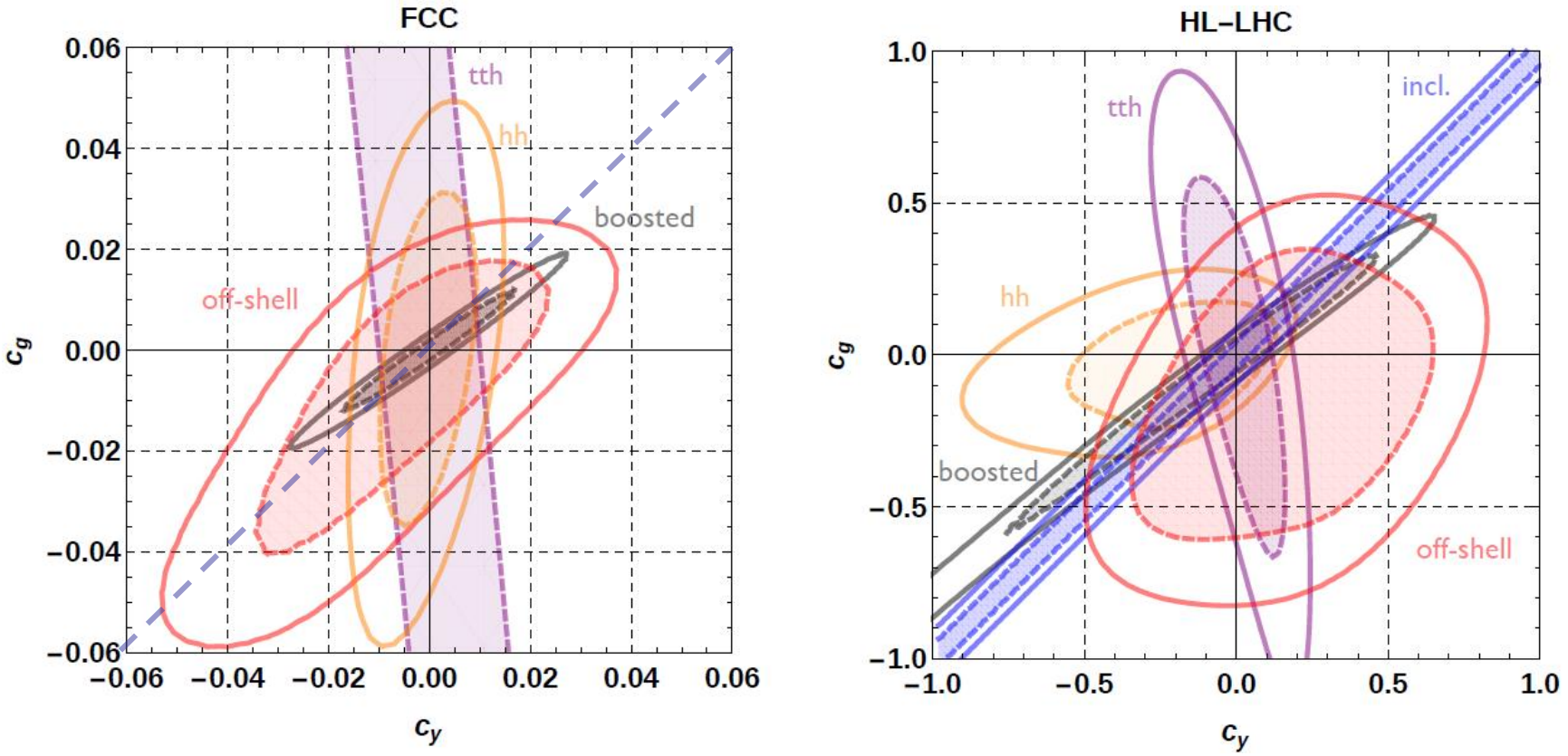
$$\mathcal{M}^{++LL} \simeq -c_g \frac{\hat{s}}{2m_Z^2} - c_y \frac{m_t^2}{2m_Z^2} \left(\log^2 \frac{\hat{s}}{m_t^2} - 2\pi i \log \frac{\hat{s}}{m_t^2} \right)$$

- Main background is $q\bar{q} \to ZZ \to 4\ell$, well under control

- Invariant mass bins:

$$\sqrt{\hat{s}} \in [250,\ 400,\ 600,\ 800,\ 1100,\ 1500,\ 2500,\ 5000]\ \text{GeV}$$

FCC-hh projection



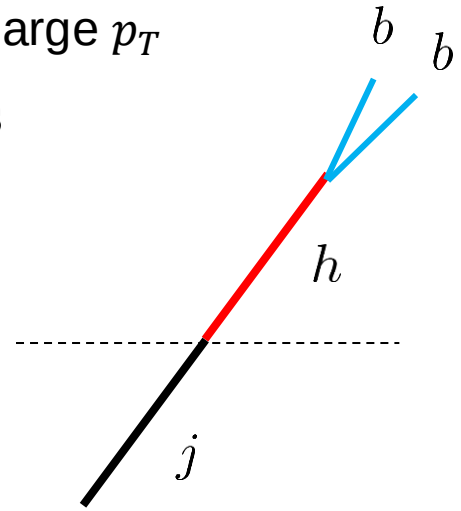
- Strong resolving power in boosted (and double) Higgs production
- FCC *tth* projection taken from **Mangano, Plehn, Reimitz, Schell and Shao, 2015**
- *hh* projections taken from **Azatov, Contino, Panico and Son, 2015**

Boosted Higgs prospects

- HL-LHC analysis based primarily on $h \to \tau\tau$

  Good Higgs mass reco in collinear approximation, due to large p_T

  Main backgrounds: $(Z \to \tau\tau)$+jets, WW+jets, $t\bar{t}$+jets

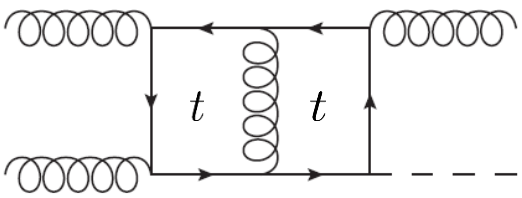


- Other *h* decays? Can jet substructure be exploited to dig out $(h \to bb)$ + hard jet?

  Or rare decays (given large statistics). $h \to \gamma\gamma$?

- SM prediction: at large p_T, crucial to retain full dependence on top mass

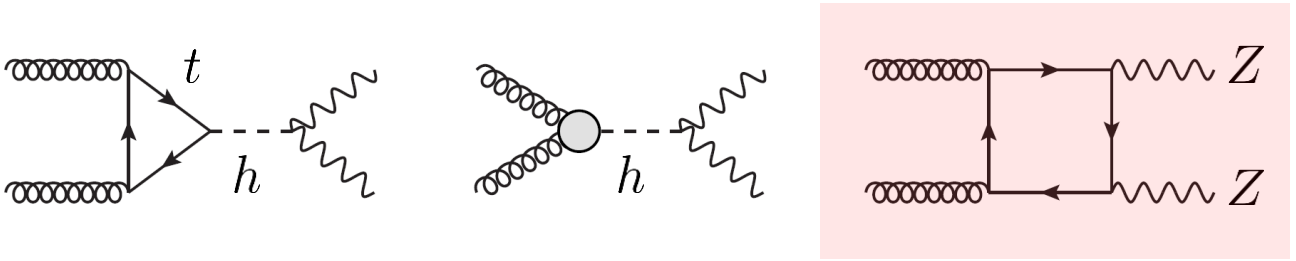
  NLO: 2-loop virtuals still unknown



But computed last year for $gg \to hh$ **Borowka et al., 2016**

Expect progress soon

Prospects in $gg \to ZZ$



- All SM quarks run in box diagrams, but at large $\sqrt{\hat{s}}$ the top dominates (SM unitarity)

  Can probe **top EW couplings**, other important directions in SM EFT

e.g. $\mathcal{L}_6 \ni \frac{ic_R}{v^2} H^\dagger \overleftrightarrow{D_\mu} H \, \bar{t}_R \gamma^\mu t_R \quad \leftrightarrow \quad e Z_\mu \bar{t} \gamma^\mu (c_V + c_A \gamma_5) t$

- An extended analysis is warranted, that takes into account **both**

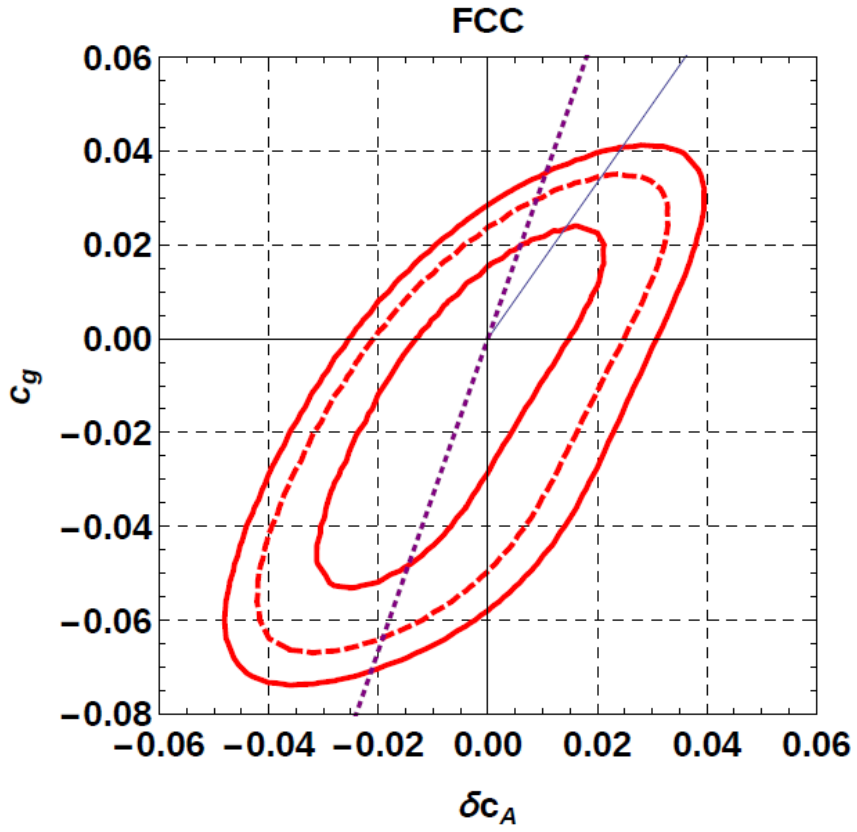
  Higgs and top coupling modifications

- Measurement in $pp \to t\bar{t}Z$ at HL-LHC has limited sensitivity,

$$\frac{\delta c_A}{c_A^{\mathrm{SM}}} \lesssim 0.15 \qquad \text{(95 \% CL)}$$

Roentsch and Schulze, 2014

Off-shell Higgs at FCC-hh: top EW couplings



68, 95, 99% CL

- Assumed $c_y = c_g$ (fixed by Higgs inclusive measurements)
- At 1σ, relative uncertainty of 3 - 5% $(c_A^{\rm SM} = -0.60)$

- At FCC-ee with $\sqrt{s} = 365\ \mathrm{GeV}$, expect ~ 2% uncertainty

Janot 2015

Summary

- Gluon fusion processes at $E > m_t$ are powerful FCC-hh handles to test dim-6 ops. made of Higgses and tops, on which HL-LHC accuracy is limited

- Boosted Higgs in *h* + jet(s) deserves dedicated FCC-hh study.
  Feasibility of $h \to b\bar{b}$? Likely, useful input to detector design process

- $gg \to ZZ$ has promising sensitivity to dim-6 ops. modifying *ttZ* couplings.
  Projected accuracy within factor ~ 2 of FCC-ee with $\sqrt{s} \gtrsim 2m_t$
  Also awaiting further study: $gg \to WW$

see talk by F. Riva, this morning

Backup

100 TeV pp → h + jet cross sections

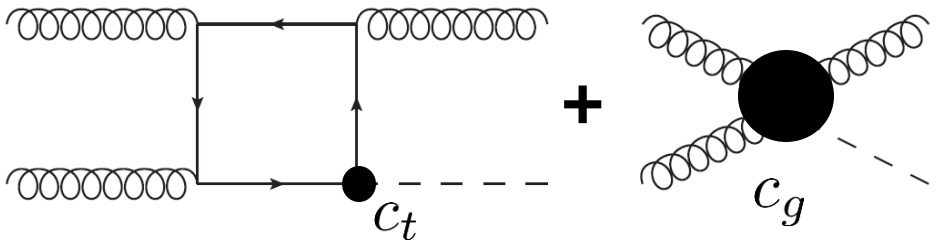
$\sqrt{s}$ [TeV]	$p_T^{\min}$ [GeV]	$\sigma^{\rm SM}_{p_T^{\min}}$ [fb]	δ	ϵ	gg, qg [%]
100	100	91024	0.036	0.071	0.788, 0.207
	200	21431	0.27	0.39	0.781, 0.215
	300	6412.1	0.69	1.0	0.762, 0.236
	400	2313.5	1.2	1.9	0.741, 0.257
	500	964.0	1.8	3.1	0.722, 0.276
	600	448.0	2.4	4.7	0.705, 0.293
	700	226.5	3.1	6.6	0.690, 0.308
	800	122.5	3.8	8.8	0.676, 0.322
	900	69.91	4.6	11.5	0.664, 0.334
	1000	41.74	5.3	14.6	0.652, 0.346
	1100	25.88	6.1	18.2	0.641, 0.357
	1200	16.57	6.94	22.4	0.630, 0.367
	1300	10.91	7.79	27.0	0.621, 0.377
	1400	7.36	8.66	32.3	0.611, 0.386
	1500	5.07	9.56	38.2	0.602, 0.395
	1600	3.56	10.5	44.7	0.594, 0.404
	1700	2.54	11.4	51.9	0.585, 0.412
	1800	1.84	12.4	59.4	0.577, 0.420
	1900	1.36	13.4	68.5	0.570, 0.427
	2000	1.01	14.4	78.0	0.562, 0.435
	2200	0.577	16.5	99.5	0.548, 0.449
	2400	0.343	18.6	124.5	0.534, 0.462
	2600	0.211	20.9	153.5	0.521, 0.474
	2800	0.133	23.2	186.6	0.509, 0.486
	3000	0.086	25.6	224.2	0.497, 0.498
	3500	0.032	32.0	340.7	0.471, 0.526
	4000	0.013	38.6	490.4	0.445, 0.550
	4500	0.0058	45.5	677.5	0.426, 0.568
	5000	0.0032	43.5	745.4	0.399, 0.593

preliminary

Boosted Higgs at the LHC

Higgs recoiling against a hard jet

$$\mathcal{M}(gg \to hg) \sim$$



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$p_T < m_t$: same degeneracy as inclusive rate

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$p_T \gg m_t$: different combination of couplings

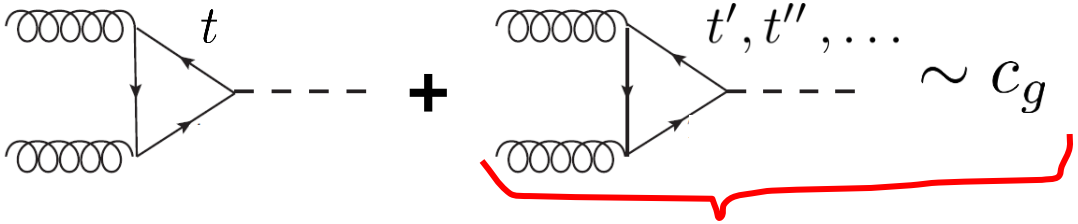
14 TeV

$p_T^{\min}$ [GeV]	$\sigma^{\rm SM}_{p_T^{\min}}$ [fb]	δ	ϵ
100	2180	0.0031	0.031
150	837	0.070	0.13
200	351	0.20	0.30
250	157	0.39	0.56
300	74.9	0.61	0.89
350	37.7	0.85	1.3
400	19.9	1.1	1.7
450	10.9	1.4	2.3
500	6.24	1.7	2.9
550	3.68	2.0	3.6
600	2.22	2.3	4.4
650	1.38	2.6	5.2
700	0.871	3.0	6.2

Loop-induced Higgs couplings in CH

- Contribution of resonances to loop-induced couplings encoded by ops. of the form $H^\dagger H G^a_{\mu\nu} G^{\mu\nu\, a}$: break shift symmetry, extra-suppressed by powers of $g_{\rm SM}/g_\rho$. Giudice et al., 2007
- Naively, for light top partners ($g_\rho \sim g_{\rm SM}$) effects should be important.
- However, it turns out that loops of resonances cancel out against corrections to $ht\bar{t}$ coupling Falkowski, 2007; Low, Vichi, 2010; Azatov, Galloway, 2011; Montull, Riva, ES, Torre, 2013

$$\mathcal{M}(gg \to h) \;=$$



$$\sim c_g$$

they cancel out at all orders in ϵ

- MCHM$_5$:

$$c_t = \frac{1}{\sqrt{1-\xi}}\left[1 - 2\xi + \xi(1-\xi)\left(\frac{1}{m_1^2} - \frac{1}{m_4^2}\right)\left(y_R^2 - \frac{y_L^2}{2}\right) + O(\epsilon^4)\right]$$

$$\frac{g_{hgg}}{g^{\rm SM}_{hgg}} = c_t + c_g = \frac{1}{\sqrt{1-\xi}}\left[1 - 2\xi\right]$$

insensitive to top partners