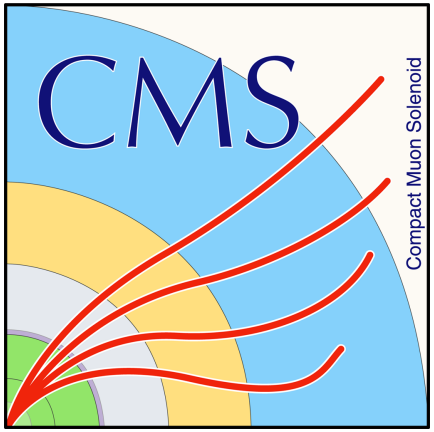

SM and EFT Studies of ttHH Production at CMS using Run 2 Data

DPF2021 Meeting

Wei Wei

University of California, Davis

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Outline

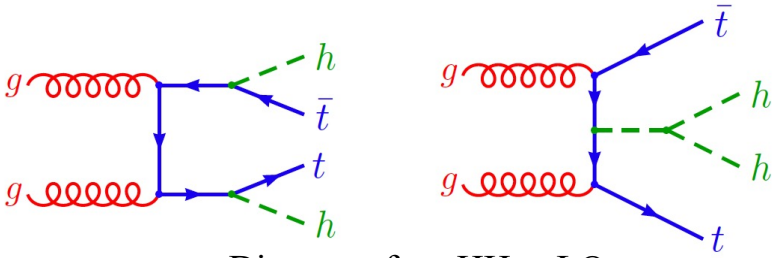
- Physics motivation and background
- Search for ttHH using full Run 2 data
    1. Event selection and analysis strategies
    2. Current status
- Study of ttHH in EFT
- Summary

Physics Motivation

- Higgs boson pair production in association with a top-quark pair plays an important role in Higgs physics
  - It provides a direct measurement of the top-quark Yukawa coupling y_t
  - It provides a measurement of trilinear Higgs self coupling λ_3 in the Higgs potential,

$$V = \frac{m_h^2}{2}h^2 + \lambda_3 v h^3 + \frac{\lambda_3}{4}h^4$$

  - ttHH does not have destructive interference terms at LO

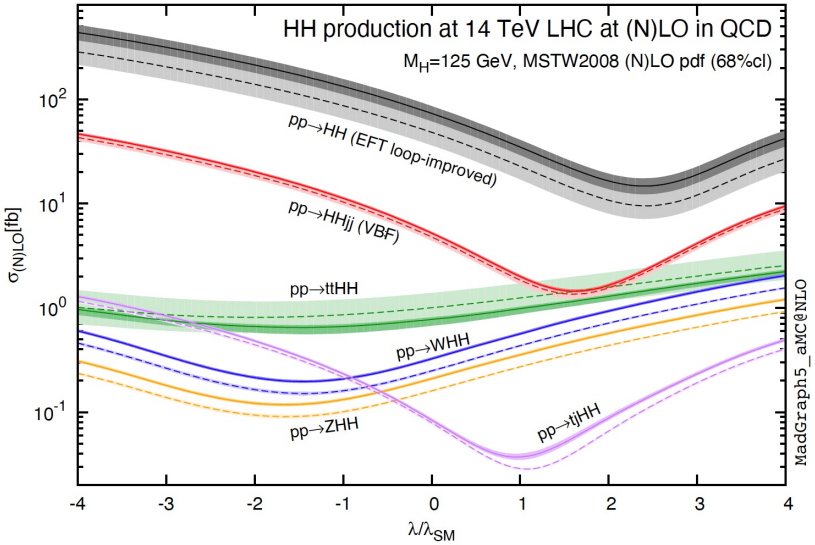


Diagrams for ttHH at LO

- Thus ttHH is an important rare process to study with the largest available datasets

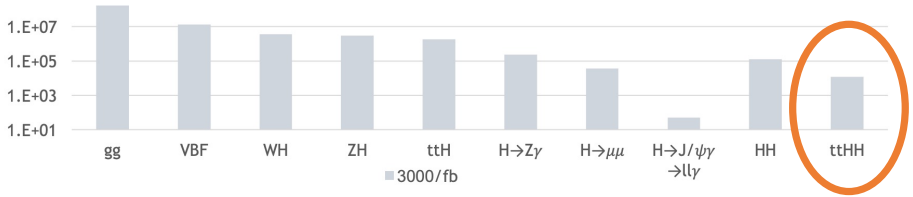
Cross sections and Rates

- The ttHH production will benefit from larger statistics in Run 2 (~140/fb), Run 3 (~300/fb) and HL-LHC (~3000/fb).



Cross section at (N)LO as a function of self interaction λ. The dashed (solid) lines correspond to the LO (NLO) results

arXiv: [1401.7340]



At 13 TeV: σ(ttHH) = 0.775 fb (NLO QCD)
At 14 TeV: σ(ttHH) = 1 fb (NLO QCD)

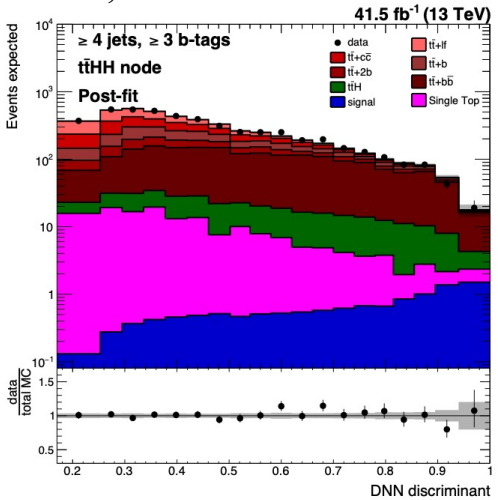
ttHH is expected to have ~ 3000 events at HL-LHC

Previous CMS Related Analyses

- CMS Collaboration, "Measurement of ttH production in the H → bb decay channel in 41.5fb−1 of proton-proton collision data at sqrt{s} = 13TeV." CMS-PAS-HIG-18-030.
- Leônidas Augusto Fernandes do Prado, "Exploring the Higgs sector beyond the standard model with the top Yukawa coupling: a phenomenological and experimental search", PhD thesis, 2020.

Best fit (μ)	Observed	$4.9^{+14.4}_{-12.8}$
95% CL upper limits on μ	Observed	32.9
	Expected (Median)	28.9
	Expected (68% CL range)	[20.1, 42.2]
	Expected (95% CL range)	[14.9, 59.6]

PhD thesis



PhD thesis

- Goal: perform ttHH(tt→SL, HH→bbbb) analysis using full Run 2 data (2016 - 2018).
- We are following the 2017 analysis strategy with an updated analysis framework.
- We expect tighter bounds on the signal strength (μ) and begin searching for deviations from the SM.

Event Selection

- Baseline Selection is the same as the ttH full Run 2 analysis (in progress)

SL channel	
Number of leptons	1
p_T of lepton (e/μ) [GeV]	$> 30/29$
p_T of additional lepton (e/μ) [GeV]	< 15
$\|\eta\|$ of leptons and jets	< 2.4
Number of Jets	≥ 4
p_T of jets [GeV]	> 30
Number of b tagged jets	≥ 3
p_T^{miss} [GeV]	> 20

Results

- Currently using simulated 2017 SM samples:

	Type	MC sample	Events
▲	Signal	ttHH, HH -> bbbb, madgraph+pythia8	9888000
▲	Background	ttH, H -> bb, powheg+pythia8	8000000
	Background	TTToSemiLeptonic, powheg+pythia8	110014744
▲	Background	TTToSemiLeptonic, powheg+pythia8+new pmx	43732445

▲ : used for DNN training

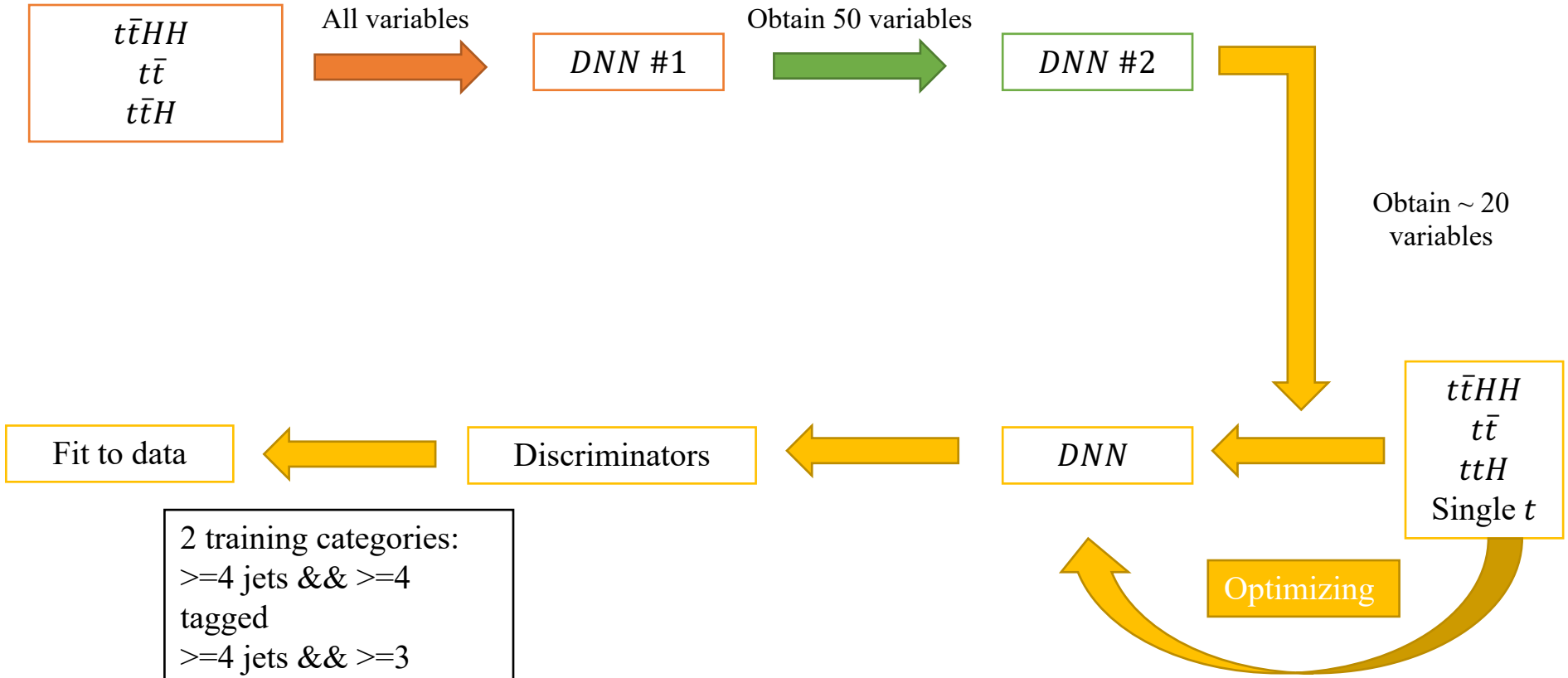
- Results:

	nGen	Selection
ttHH	9888000	1294101
ttHbb	8000000	616670
ttSL	43732445	353896

N-tupling trees are produced

Variables
N_BTagsL
N_BTagsM
N_BTagsT
Jet_CSV
Jet_E
Jet_M
Jet_Pt
Evt_Deta_JetsAverage
RecoHiggs_M
…

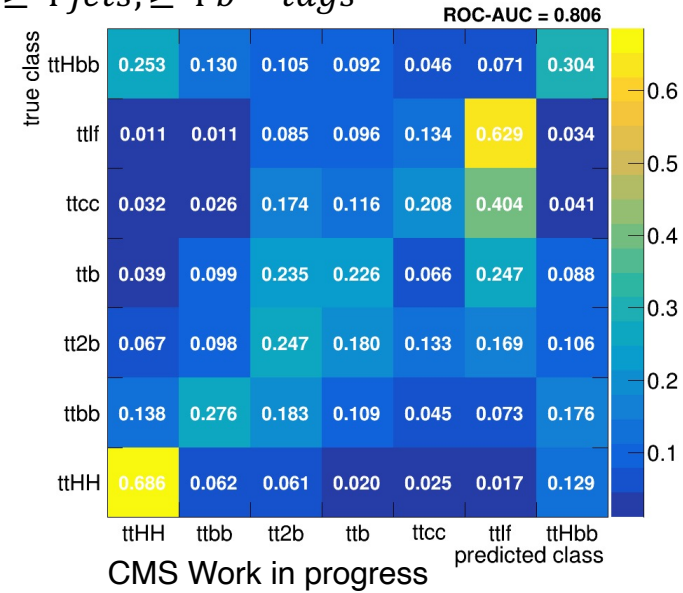
Deep Neural network (DNN)



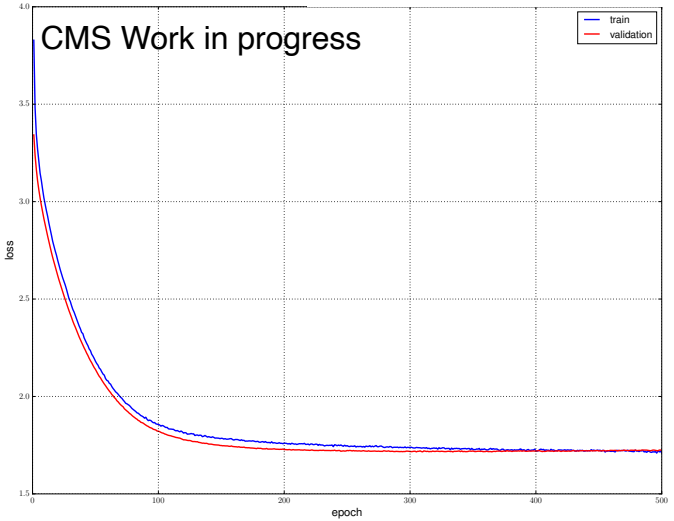
Confusion matrices

- DNN training with all variables

$\geq 4\ jets, \geq 4\ b-tags$

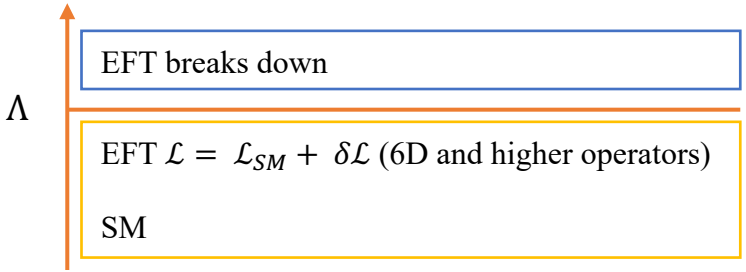


$\geq 4\ jets, \geq 4\ b-tags$

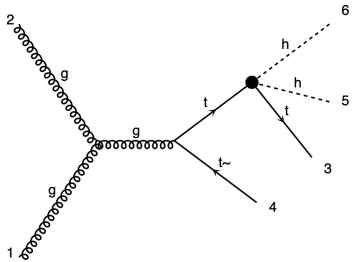


Effective Field Theory Search

- ttHH is sensitive to Higgs self coupling, thus is also interesting for BSM physics searches
- Effective field theory: It studies possible deviations from SM below the energy scale and thus could reveal new physics (beyond Λ) without knowing the 'real' theory.



- A simplified EFT model is developed to study ttHH independently of ttH by introducing higher order gauge-invariant operators



$$\Delta\mathcal{L} = \frac{g_t}{2v} tthh = \frac{G_2 v^3}{\sqrt{2}} tthh$$

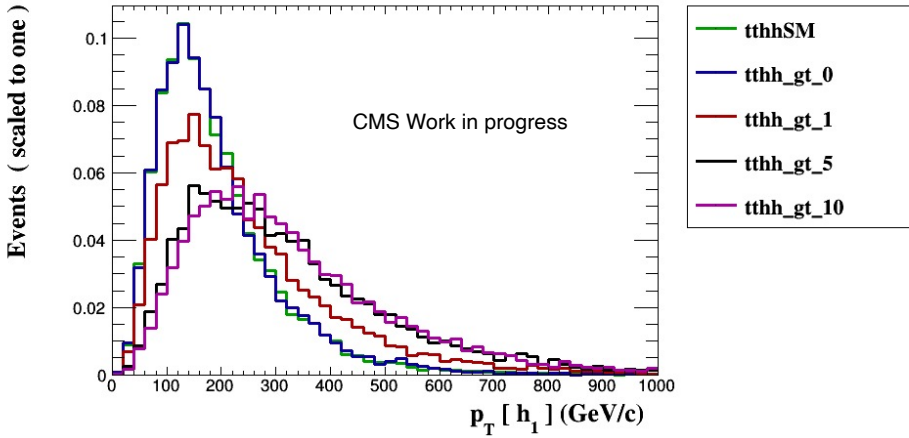
EFT Study

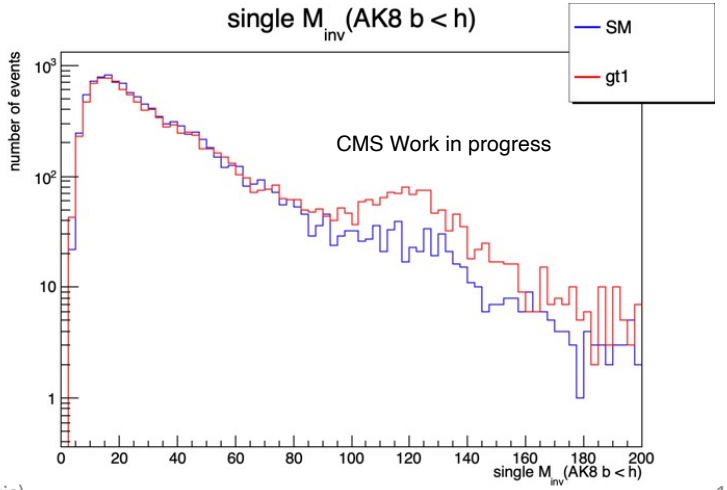
- Built the EFT model and generated MC events for ttHH
- Higgs is produced at higher pT due to the new vertex

$$\text{SM: } \sigma(t\bar{t}HH) = 0.7494\ fb$$
$$g_t = 0\text{: } \sigma(t\bar{t}HH) = 0.7387\ fb$$
$$g_t = 1\text{: } \sigma(t\bar{t}HH) = 1.959\ fb$$
$$g_t = 5\text{: } \sigma(t\bar{t}HH) = 20.91\ fb$$
$$g_t = 10\text{: } \sigma(t\bar{t}HH) = 76.16\ fb$$

- Observe an enhancement around the Higgs mass in the single b-jet mass spectrum

- These features provide new handles for signal search





Summary

- Presented a preliminary SM search for ttHH (tt→SL, HH→bbbb). A first iteration to set up the full DNN categorization procedure is in place.

- Showed kinematic results for ttHH in a simplified EFT model. Observe deviations from SM in single b-jet mass spectrum.

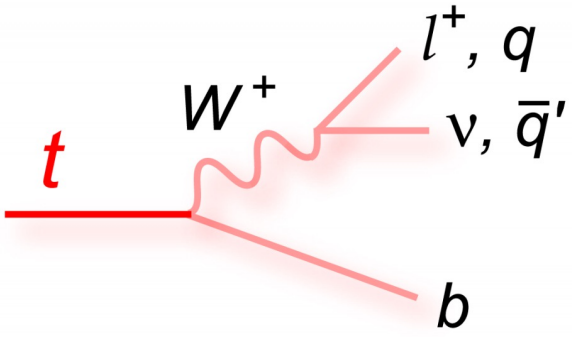
- The ttHH process will become more and more important as CMS accumulates data in Run 3 and HL-LHC

Thanks for your attention!

Backup

- Top quark

$$t \to bW, \mathrm{W} \to \begin{cases} l\nu_l : \Gamma \approx \frac{1}{3} \\ q\bar{q}' : \Gamma \approx \frac{2}{3} \end{cases}$$

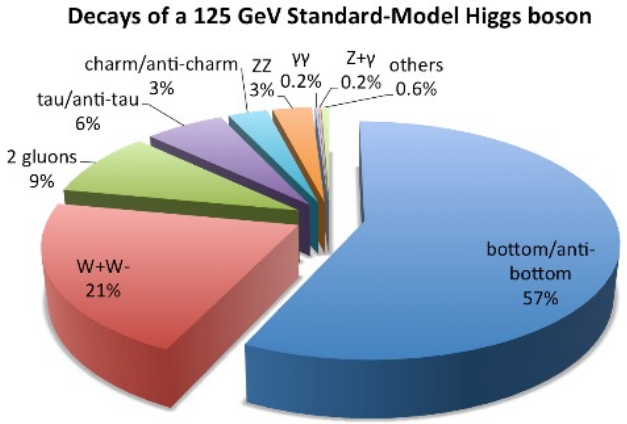


Semi-leptonic (SL) : $tt \to bW\, bW \to q\bar{q}'\, l\nu_l$:

$\Gamma \approx \frac{4}{9}$

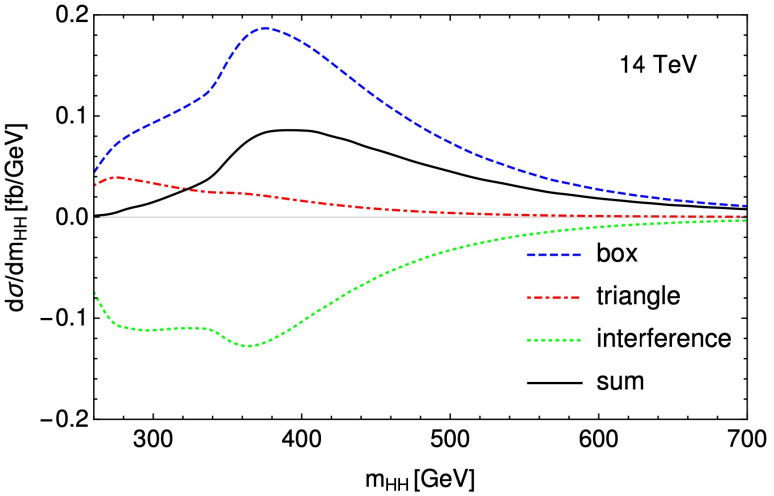
- $H \to b\bar{b}$: $\Gamma \approx 0.57$

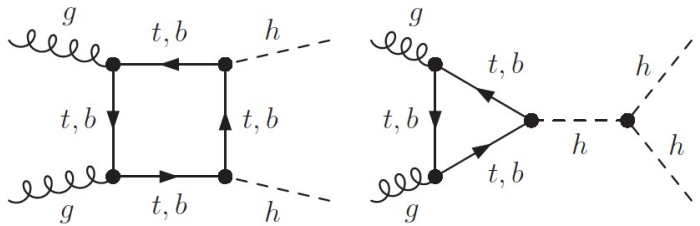
- $t\bar{t}\,(SL)HH\,(4b)$: $\Gamma \approx 0.57 \times 0.57 \times \frac{4}{9} \approx 0.14$



Backup

- The effect of destructive interference terms:
  - Due to the large destructive interference, the effect of the trilinear Higgs self-coupling in the LO total cross section amounts to a reduction of about 50% with respect to the box-only contribution. (1910.00012)
  - Decrease the sensitivity of measuring this Higgs coupling





Diagrams for Higgs pair production at LO

Backup

- Signal Model for ttHH

$$\mathcal{L} = \mathcal{L}_{\rm SM} + G_1(H^\dagger H)(QHt^c + \text{h.c.}) + G_2(H^\dagger H)^2(QHt^c + \text{h.c.})$$

$$G_1 \sim \frac{1}{M^2}, \qquad G_2 \sim \frac{1}{M^4}$$

$$m_t = \frac{y_t v}{\sqrt{2}} + \frac{G_1 v^3}{2\sqrt{2}} + \frac{G_2 v^5}{4\sqrt{2}}$$

$$g_{tth} = \frac{y_t}{\sqrt{2}} + \frac{3G_1 v^2}{2\sqrt{2}} + \frac{5G_2 v^4}{4\sqrt{2}}$$

$$g_{tthh} = \frac{3G_1 v^2}{\sqrt{2}} + \frac{5G_2 v^4}{\sqrt{2}}$$

Requiring m_t and g_{tth} unchanged

$$G_1 = -G_2 v^2$$

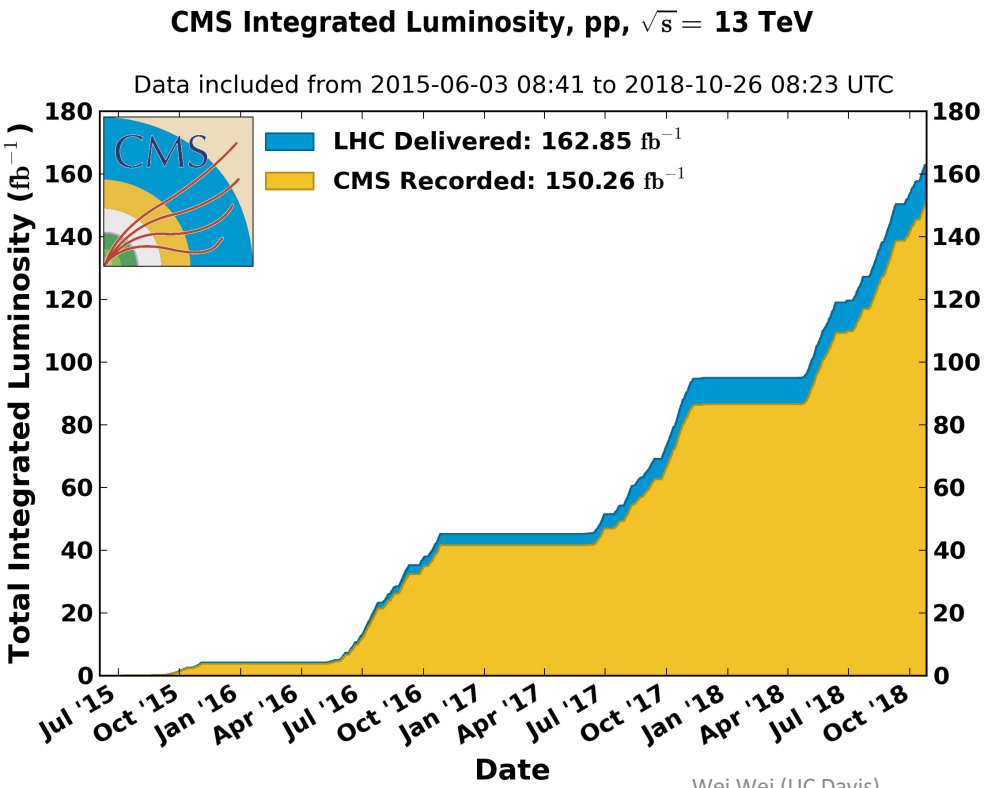
$$y_t = \frac{\sqrt{2} m_t}{v} + \frac{G_2 v^4}{4}$$

$$g_{tthh} = \sqrt{2} G_2 v^4$$

$$\Delta\mathcal{L} = \frac{g_t}{2v}\, tthh = \frac{G_2 v^3}{\sqrt{2}}\, tthh$$

Backup

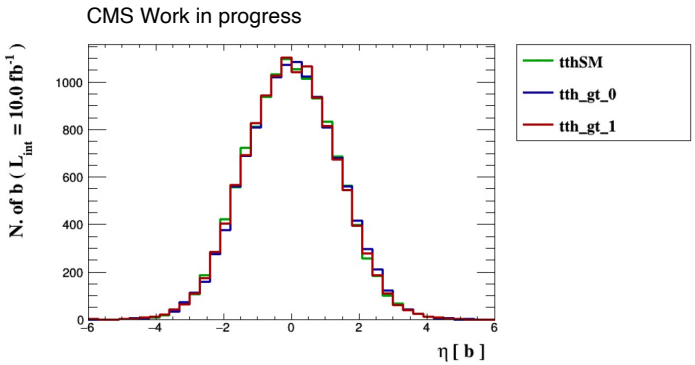
- CMS Run 2 integrated luminosity

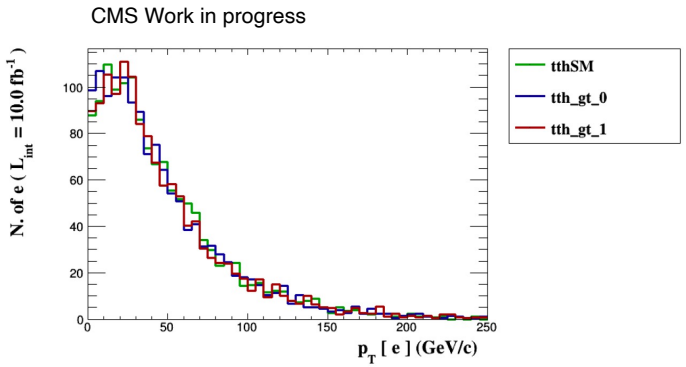


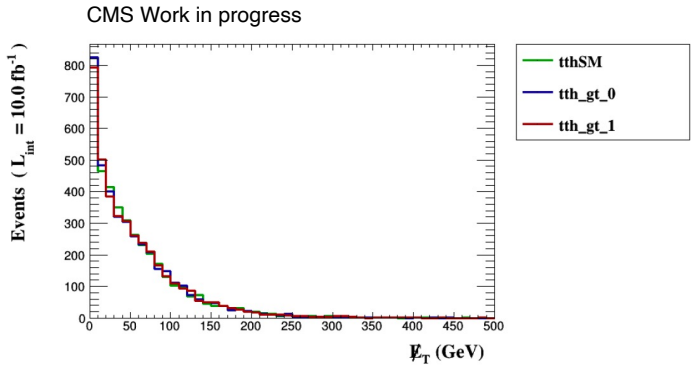
Year	Integrated luminosity(/fb)
2016	35.9
2017	41.5
2018	59.7

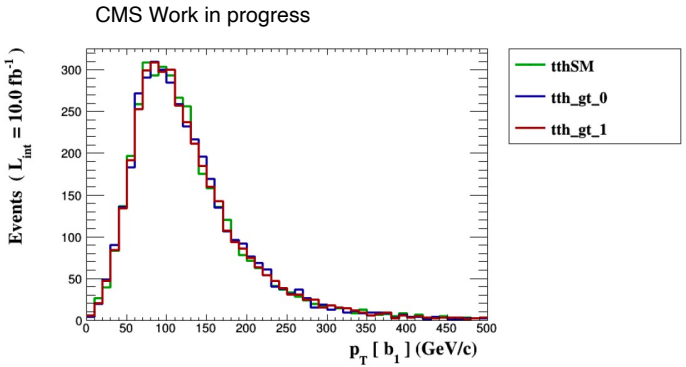
Backup

- Built the EFT model and generated MC events for ttH to make sure it's unchanged









Generate ttH (LO) at $\sqrt{s} = 13\ TeV$

SM : $\sigma(t\bar{t}H) = 0.3987\ pb$

$g_t = 0$: $\sigma(t\bar{t}H) = 0.4007\ pb$

$g_t = 1$: $\sigma(t\bar{t}H) = 0.3988\ pb$