Non Resonant Production of $t\bar{t}HH, HH \rightarrow 4b$ Analysis with full Run 2 data at CMS

2024 US LHC Users Association

December 17th, 2024

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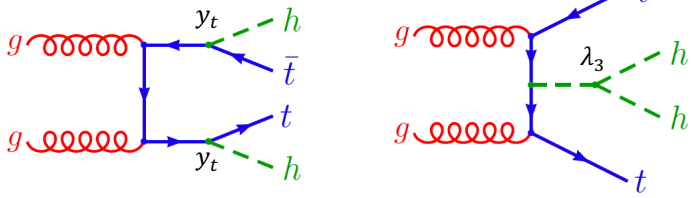
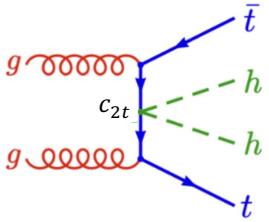
Physics Motivation

$t\bar{t}HH$ provides

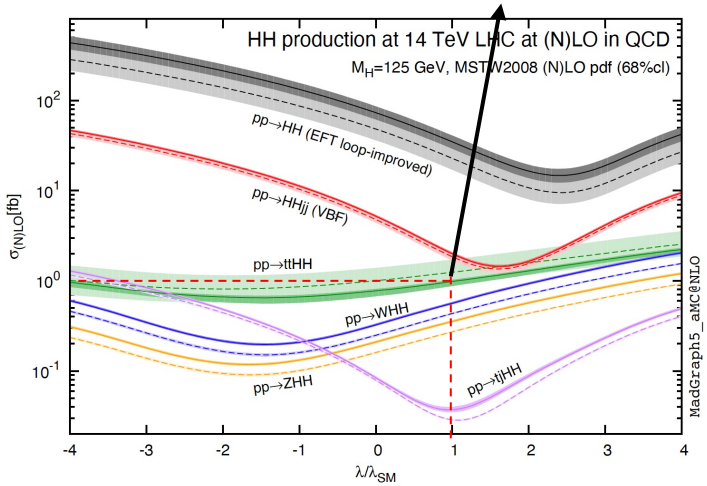
- direct measurement of the top-quark Yukawa coupling y_t
- measurement of trilinear Higgs self coupling λ_3



- Also important for the study of BSM (especially CHM)



~1fb for $t\bar{t}HH$ at 14 TeV

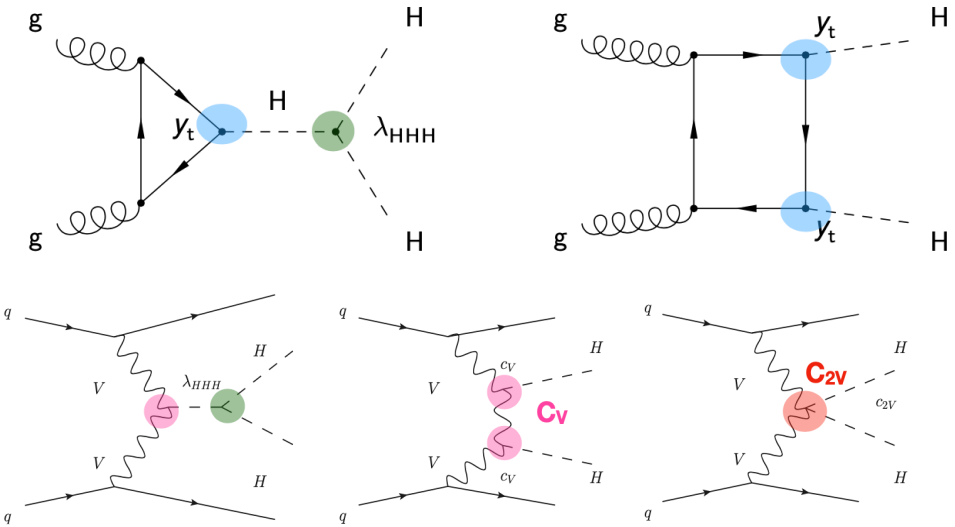


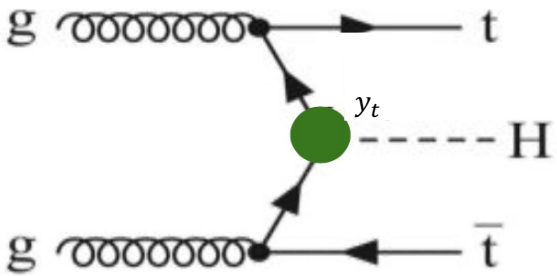
Cross section at (N)LO as a function of self interaction λ. arXiv: 1401.7340

- 13 TeV: σ(ttHH) = 0.775 fb (NLO QCD)
- 14 TeV: σ(ttHH) = 1 fb (NLO QCD)
- Expected to have ~ 400 (3000) events at Run 3 (HL-LHC)

Physics Motivation

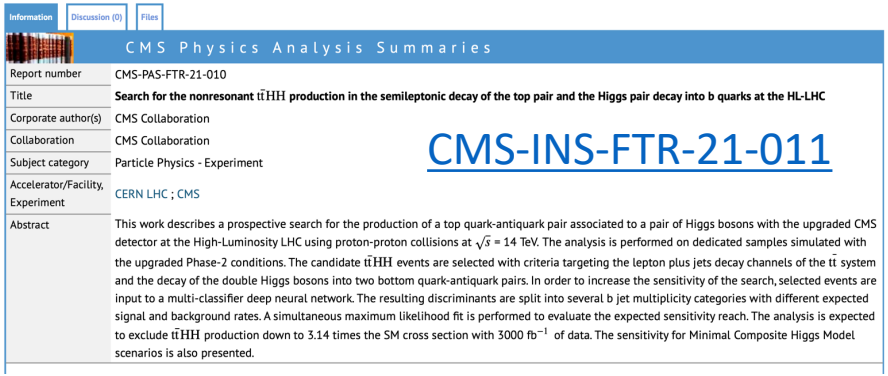
- The interplay between SM HH, VBF(HH), ttH & ttHH couplings at LO





- ttHH has access to both the top-Higgs Yukawa and the triple Higgs couplings without negative interference

tt(SL)HH(4b) at HL-LHC, WP Snowmass 2022



Information | Discussion (0) | Files

CMS Physics Analysis Summaries

Report number	CMS-PAS-FTR-21-010
Title	**Search for the nonresonant $t\bar{t}HH$ production in the semileptonic decay of the top pair and the Higgs pair decay into b quarks at the HL-LHC**
Corporate author(s)	CMS Collaboration
Collaboration	CMS Collaboration
Subject category	Particle Physics - Experiment
Accelerator/Facility, Experiment	CERN LHC ; CMS
Abstract	This work describes a prospective search for the production of a top quark-antiquark pair associated to a pair of Higgs bosons with the upgraded CMS detector at the High-Luminosity LHC using proton-proton collisions at $\sqrt{s}$ = 14 TeV. The analysis is performed on dedicated samples simulated with the upgraded Phase-2 conditions. The candidate $t\bar{t}HH$ events are selected with criteria targeting the lepton plus jets decay channels of the $t\bar{t}$ system and the decay of the double Higgs bosons into two bottom quark-antiquark pairs. In order to increase the sensitivity of the search, selected events are input to a multi-classifier deep neural network. The resulting discriminants are split into several b jet multiplicity categories with different expected signal and background rates. A simultaneous maximum likelihood fit is performed to evaluate the expected sensitivity reach. The analysis is expected to exclude $t\bar{t}HH$ production down to 3.14 times the SM cross section with 3000 fb^{-1} of data. The sensitivity for Minimal Composite Higgs Model scenarios is also presented.

CMS-INS-FTR-21-011

Letter of Interest for Snowmass 2021 EF01 Topical Group: Search for exotic $t\bar{t}HH$ couplings at the HL-LHC

Snowmass LOI

M. Chertok*, Wei Wei

August 31, 2020

IFT - UNESP
INSTITUTO DE FÍSICA TEÓRICA

unesp
UNIVERSIDADE ESTADUAL PAULISTA "JÚLIO DE MESQUITA FILHO"

PhD Thesis IFT–T.002/20

CMS endorsed PhD (July 2020)

Exploring the Higgs sector beyond the Standard Model with the Top Yukawa coupling: a phenomenological and experimental search

Leônidas Augusto Fernandes do Prado

SEARCH FOR THE $t\bar{t}HH(b\bar{b}b\bar{b})$ NONRESONANT PRODUCTION IN THE LEPTONIC FINAL STATES USING MACHINE LEARNING TECHNIQUES AT THE CMS EXPERIMENT

CMS endorsed PhD (January 2024)

A THESIS SUBMITTED TO
THE GRADUATE SCHOOL OF NATURAL AND APPLIED SCIENCES
OF
MIDDLE EAST TECHNICAL UNIVERSITY

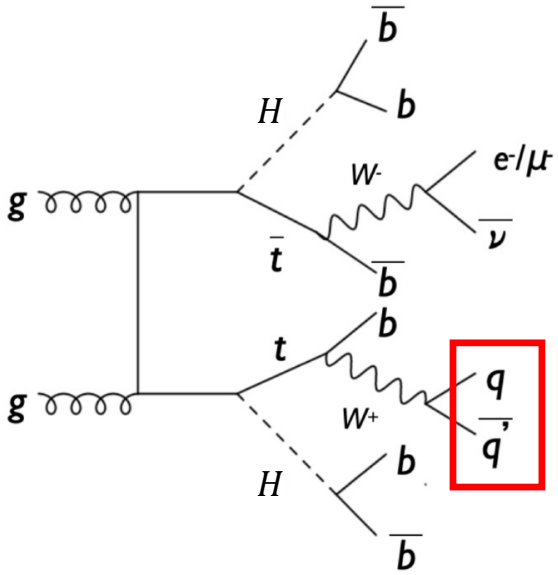
BY

GAMZE SÖKMEN ŞAHİN

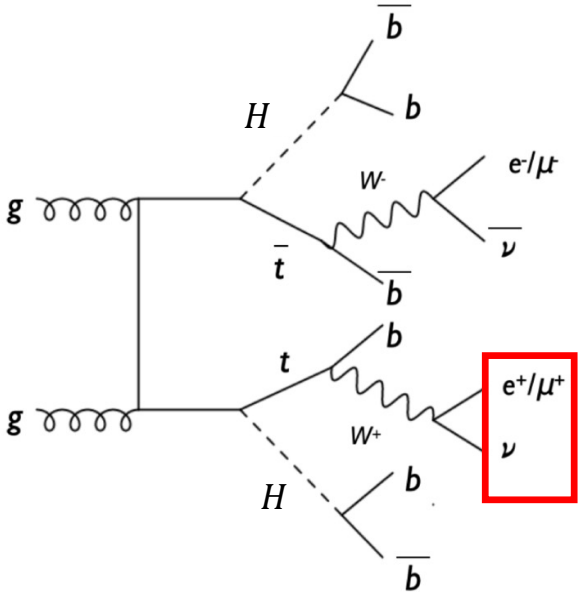
Signatures

- We look for ttHH in semi-leptonic and di-leptonic decays of top pairs and with both Higgs decaying each into a pair of b quarks, using Run2 data.

SL Channel (BR=11.4%)



DL Channel (BR=3.2%)



MC & Data Samples

MC Simulation

Signal:

- $t\bar{t}HH(b\bar{b})$

$t\bar{t} + Jets$ Background

- 5FS $t\bar{t} + Jets$ (SL + DL) Powheg + Pythia8
- 4FS $t\bar{t}bb$ (SL + DL) Powheg-Box-Res + Pythia8
- $t\bar{t}4b$ Madgraph + Pythia8

Other Backgrounds:

- $t\bar{t}H$ (SL + DL) Powheg + Pythia8
- $t\bar{t}Z$ Madgraph_aMC@nlo + Pythia8
- $t\bar{t}ZZ$, $t\bar{t}ZH$ Madgraph + Pythia8

Real Data

SL

- Single Muon
- Single Electron

DL

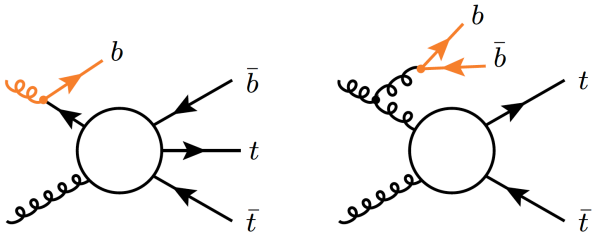
- Double Muon
- Double EG
- Muon EG

Baseline Event Selection for Both Channels

	SL Case	DL Case
Number of jets	>= 5	>= 4
Number of b-tagged jets (not b-jets)	>= 4	>= 3
Number of leptons	=1	= 2
MET (GeV)	> 20	> 40
Sign and flavour of leptons	$e^{\pm}, \mu^{\mp}$	$e^{+}e^{-}$, $\mu^{\pm}e^{\mp}$, $\mu^{+}\mu^{-}$
Min. $m_{e^+e^-/\mu^+\mu^-}$ [GeV]	-	20
$m_{e^+e^-/\mu^+\mu^-}$ [GeV]	-	<76, >106

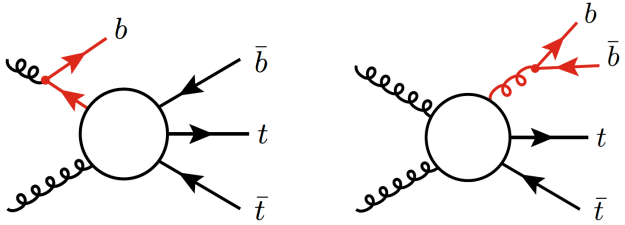
$t\bar{t} + bjet$ Modeling

- Model $t\bar{t}$ background using $t\bar{t}$ (5FS), $t\bar{t}b\bar{b}$ (4FS) and $t\bar{t}4b$ simulations

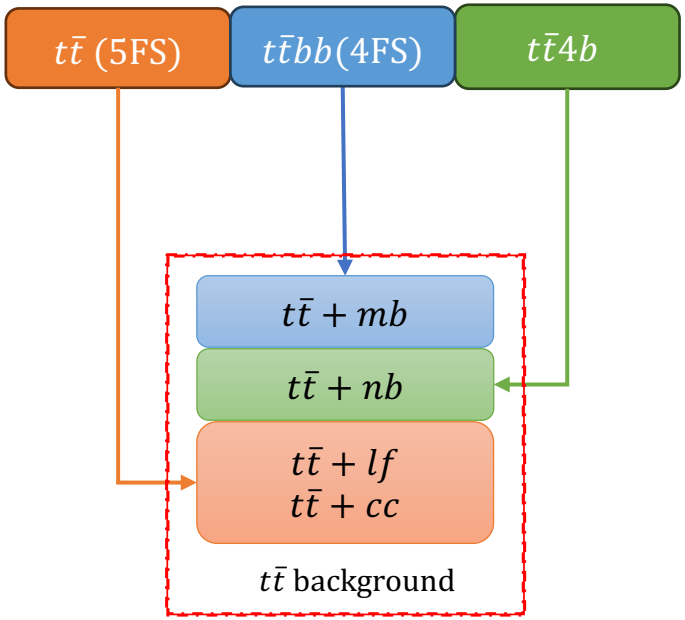


$g\bar{b} \rightarrow t\bar{t}b +$ ***IS splittings*** $\qquad gg \rightarrow t\bar{t}g +$ ***FS splittings***

1. $t\bar{t}$ 5FS: additional b-tagged jets come from PS. Lower precision but accurate tuning to data.



2. $t\bar{t}b\bar{b}$ 4FS: $t\bar{t}b\bar{b}$ described through $t\bar{t}b\bar{b}$ tree MEs, better modeling of $t\bar{t}$ + b jets events.

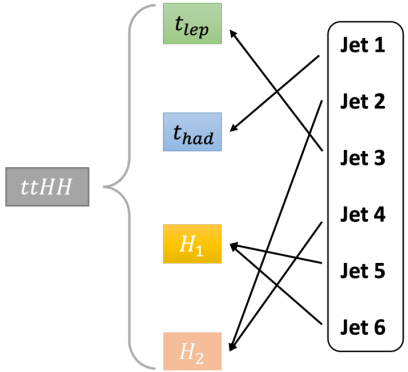


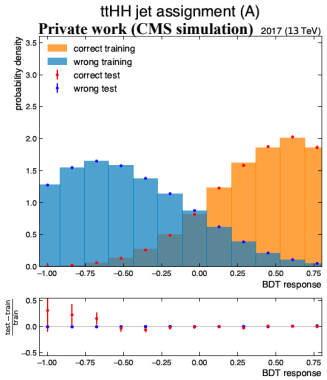
Event Reconstruction

- Minimum χ^2 method for ttHH, ttZH and ttZZ

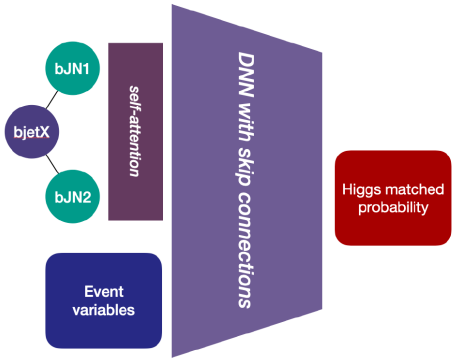
$$\chi^2_{HH} = \frac{(mass_{j_1j_2} - m_H)^2}{\sigma^2_{j_1j_2}} + \frac{(mass_{j_3j_4} - m_H)^2}{\sigma^2_{j_3j_4}}$$
$$\chi^2_{ZZ} = \frac{(mass_{j_1j_2} - m_Z)^2}{\sigma^2_{j_1j_2}} + \frac{(mass_{j_3j_4} - m_Z)^2}{\sigma^2_{j_3j_4}}$$
$$\chi^2_{ZH} = \frac{(mass_{j_1j_2} - m_Z)^2}{\sigma^2_{j_1j_2}} + \frac{(mass_{j_3j_4} - m_H)^2}{\sigma^2_{j_3j_4}}$$

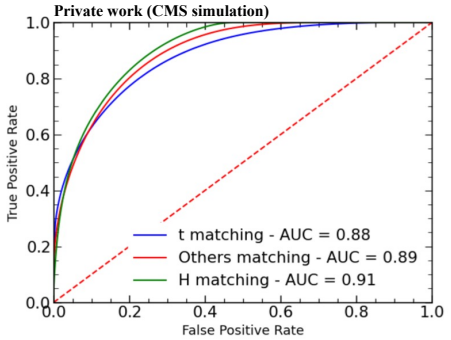
- BDT jet assignment method – JABDT





- Graph Attention based jet assignment – GATJA





Analysis Strategy

- Multi-classification DNN to separate events into one output node.

BLR

Kinematics

BDT-based event reconstruction (SL)

Attention-based NN event reconstruction (DL)

Fully Connected Layers

$t\bar{t}HH$

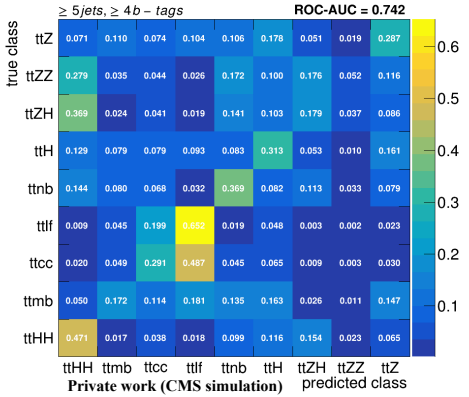
$t\bar{t}H$

$t\bar{t}ZH$

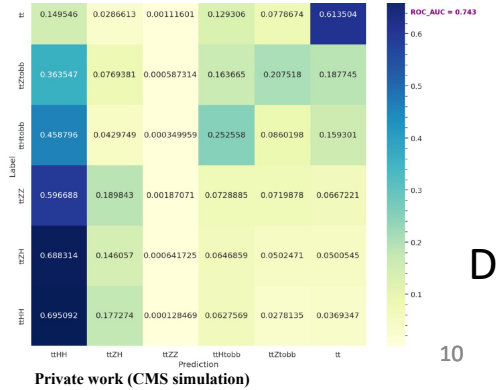
$t\bar{t}ZZ$

$t\bar{t}Z$

$t\bar{t}bar$



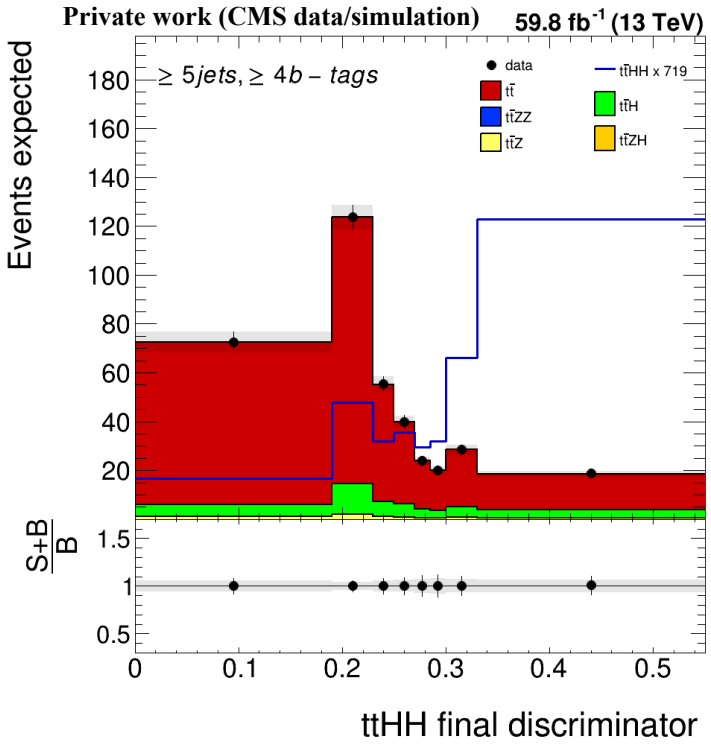
SL

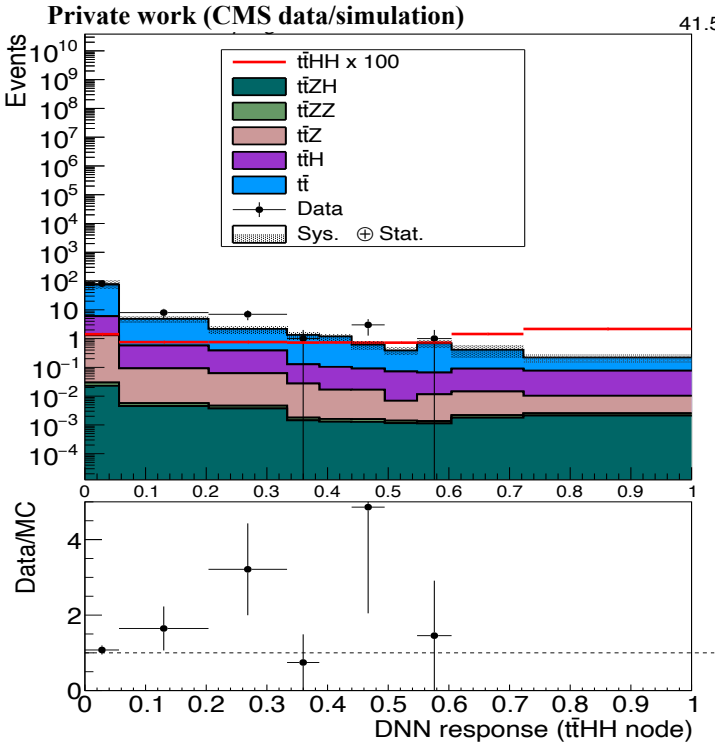


DL

DNN Discriminators

- Construct final discriminators from the highest output score of DNN, for SL (left) and DL (right)

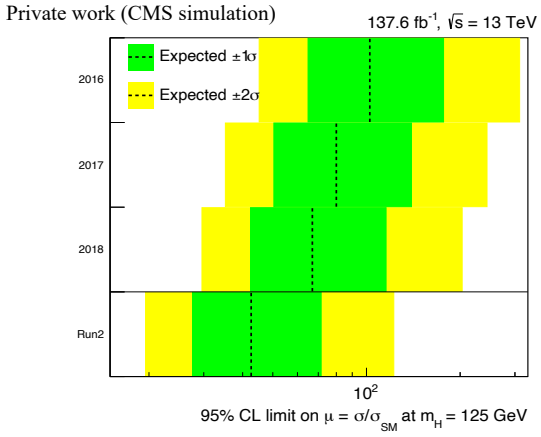




Asimov Results - Simultaneous binned profile likelihood fit

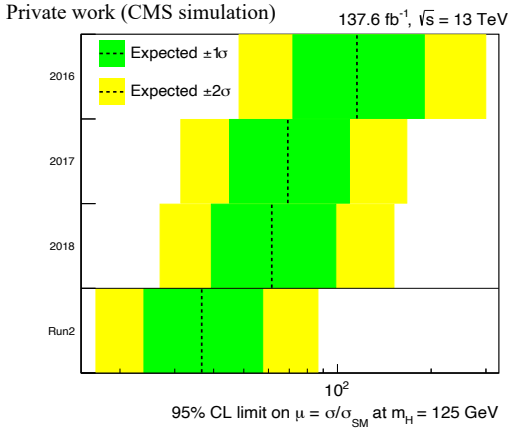
SL channel - Run2

5j4b Syst	Best fit (μ)	Observed (Asimov)	$1.0^{+18.3}_{-19.3}$
	95% CL upper limits on μ	Expected (Median)	42.6
		Expected (68% CL range)	[27.6, 71.5]
		Expected (95% CL range)	[19.5, 122.4]



DL channel – Run2

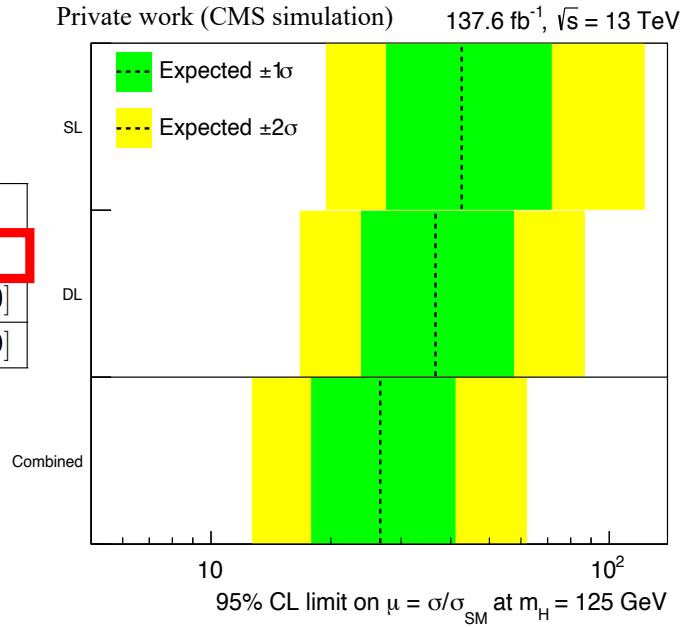
Syst. ⊕ Stat.			
	95% CL upper limits on μ	Expected (Median)	36.62
		Expected (68% CL range)	[23.88, 57.50]
		Expected (95% CL range)	[16.74, 86.54]



Asimov Results - Simultaneous binned profile likelihood fit

- SL + DL Combined

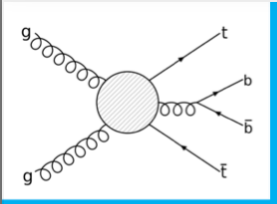
Syst. ⊕ Stat.	95% CL upper limits on μ	Expected (Median)	26.6
		Expected (68% CL range)	[17.9, 41.0]
		Expected (95% CL range)	[12.7, 61.9]



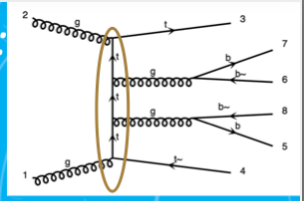
Summary

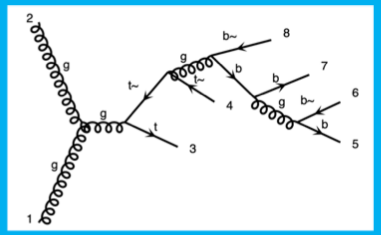
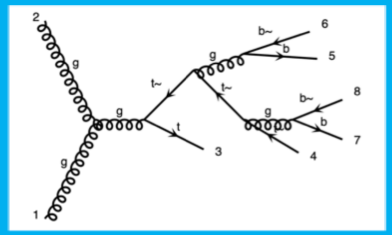
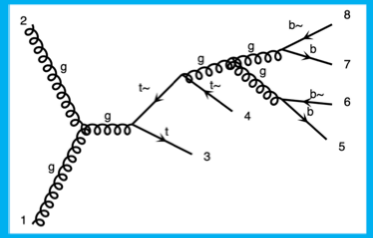
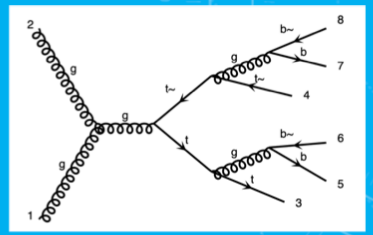
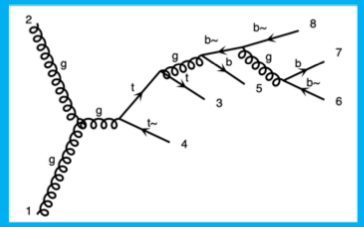
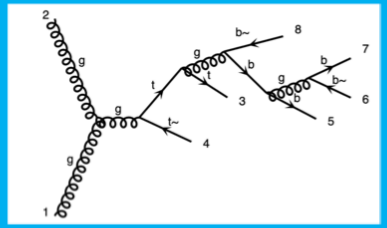
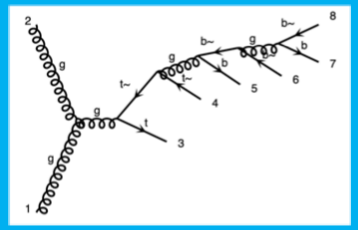
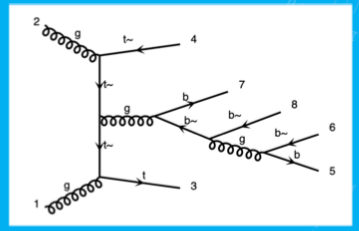
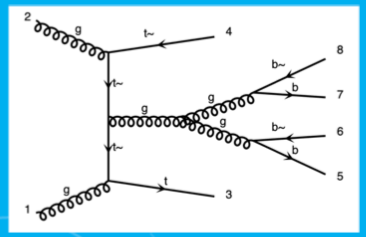
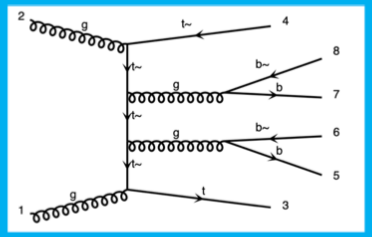
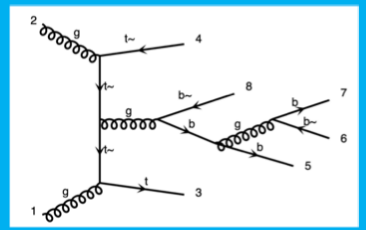
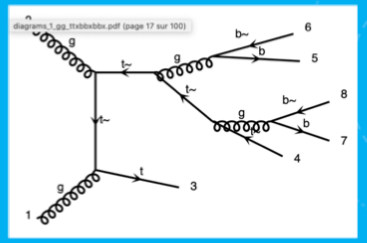
- $t\bar{t}HH$ is a critical and upcoming analysis at LHC Run 3 and HL-LHC
- Provides direct measurement of the top Yukawa and Higgs trilinear coupling, highly complementary to direct HH searches
- Full Run 2 result is important milestone for this physics program:
  - We have created a robust analysis for both the SL and DL decays of the $t\bar{t}$ pair, along with HH -> 4b to maximize the BR
  - Prepare for Moriond this winter, publication in 2025

BACKUP



NEW FEATURES IN RUN 2 ANALYSIS & IN PREPARATION FOR RUN 3: FURTHER DEVELOP THE tt+4b's BACKGROUND ANALYSIS (CONT'D)



A galery of tt+4b "portraits" by Madgraph_aMC@NLO *(C. Bautista-IFT-UNESP & ICTP)*

Systematics

Free parameters

- ttH rate
- ttbar rate

QCD scale and PDF+α_S scale

Samples	σ [fb] at 13 TeV
$t\bar{t}HH$, $HH \to b\bar{b}b\bar{b}$	$0.775^{+1.5\%}_{-4.3\%} \pm 3.2\%$ [NLO] [10]
$t\bar{t}H$	$507.1^{+5.9\%}_{-9.3\%} \pm 3.6\%$ [NLO] [10]
$t\bar{t}$ + jets	$831760^{+2.4\%}_{-3.5\%} \pm 4.2\%$ [NNLO] [35]
$t\bar{t}$ + bb	$1452^{+37.6\%}_{-27.5\%} \pm 3.2\%$ [NLO] [30]
$t\bar{t}$ + 4b	$296^{+30.0\%}_{-30.0\%} \pm 3.5\%$ [LO] [10], [3]
$t\bar{t}Z$	$841^{+9.6\%}_{-11.3\%} \pm 2.8\%$ [NLO] [10]
$t\bar{t}ZZ$	$1.98^{+5.2\%}_{-9.0\%} \pm 2.6\%$ [NLO] [10]
$t\bar{t}ZH$	$1.535^{+1.9\%}_{-6.8\%} \pm 3.0\%$ [NLO] [10]

Source	Type	Remarks
Integrated luminosity	rate	Signal and all backgrounds
Lepton identification/isolation	shape	Signal and all backgrounds
Trigger efficiency	shape	Signal and all backgrounds
L1 prefiring correction	shape	Signal and all backgrounds
Pileup	shape	Signal and all backgrounds
Jet energy scale (JES)	shape	Signal and all backgrounds
Jet energy resolution (JER)	shape	Signal and all backgrounds
b tag HF/LF fraction	shape	Signal and all backgrounds
b tag HF/LF stats (linear)	shape	Signal and all backgrounds
b tag HF/LF stats (quadratic)	shape	Signal and all backgrounds
b tag lf fraction	shape	Signal and all backgrounds
b tag lf stats (linear)	shape	Signal and all backgrounds
b tag lf stats (quadratic)	shape	Signal and all backgrounds
b tag charm (linear)	shape	Signal and all backgrounds
b tag charm (quadratic)	shape	Signal and all backgrounds
Renorm./fact. scales	rate	Scale uncertainty of (N)NLO prediction for $t\bar{t}HH$, $t\bar{t}$, $t\bar{t}Z$, $t\bar{t}ZH$, $t\bar{t}ZZ$, $t\bar{t}H$
PDF+$\alpha_S(gg)$	rate	PDF uncertainty for gg initiated processes
PDF+$\alpha_S(q\bar{q})$	rate	PDF uncertainty for $q\bar{q}$ initiated processes
PDF+$\alpha_S(qg)$	rate	PDF uncertainty for qg initiated processes
PDF shape	shape	Based on NNPDF variations
μ_R scale	shape/rate*	Renormalisation scale uncertainty of the ME generator
μ_F scale	shape/rate*	Factorisation scale uncertainty of the ME generator
PS scale: ISR	shape/rate*	Initial state radiation uncertainty of the PS (PYTHIA)
PS scale: FSR	shape/rate*	Final state radiation uncertainty of the PS (PYTHIA)
Bin-by-bin event count	shape	Statistical uncertainty of the signal and background prediction due to the limited sample size

[3] CMS-PAS-FTR-21-010, http://cds.cern.ch/record/2804085?ln-en.
[10] LHC Higgs Cross Section WG 1610.07922
[30] J. Alwall et al. *JHEP* **07** (2014) 079 [1405.0301].
[35] NNLO+NNLL top-quark-pair cross sections: ATLAS-CMS https://twiki.cern.ch/twiki/bin/view/LHCPhysics/TtbarNNLO.

DNN Discriminators

- Construct final discriminators from the highest output score of DNN, for SL (left) and DL (right)