Search for $t\bar{t}HH$ production with the same-sign di-lepton final state at the HL-LHC

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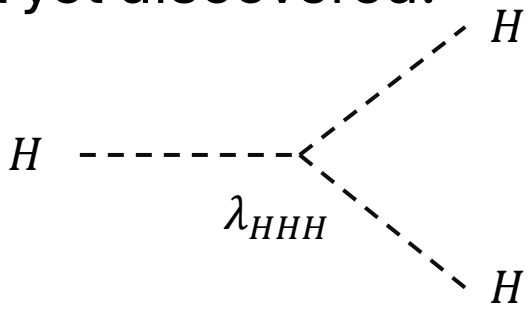
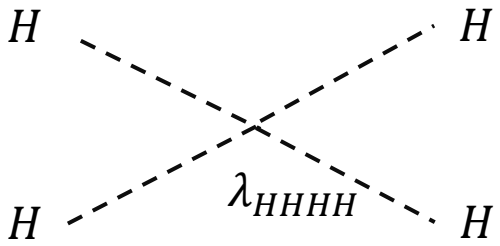
*Most work is done by Sungbeom Cho for the materials in this talk

Motivation

- In the **Standard Model (SM)** of particle physics, the Higgs boson has **self-couplings** not yet discovered.





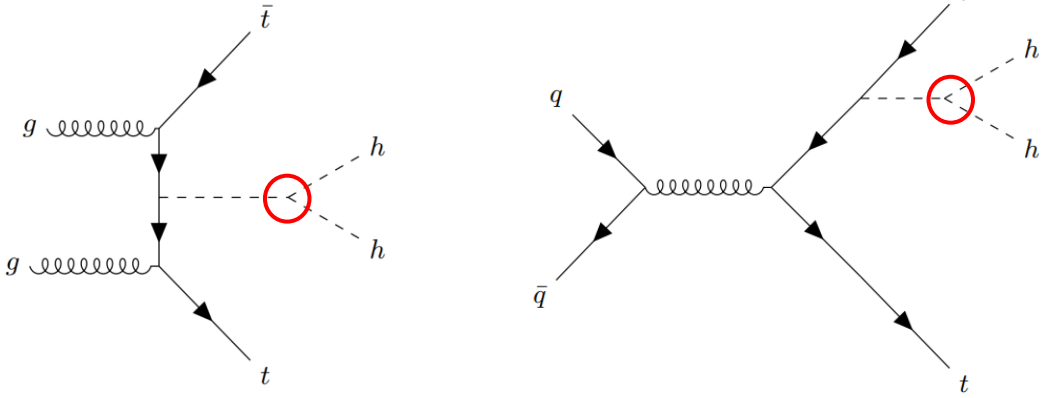
- To discover the Higgs boson self-coupling is essential to fill the missing pieces of the SM.
- The upper limit for the triple Higgs boson self-coupling strength $\lambda_{HHH}/\lambda_{HHH,\mathrm{SM}}$ combined the full Run 2 measurements is **3.4** (2.5 expected) from CMS* and **2.9** (2.4 expected) from ATLAS**.
- In this talk, the feasibility study of searching for the ttHH production at the High Luminosity LHC (HL-LHC) is presented.

* *Nature* 607 (2022) 7917, 60-68

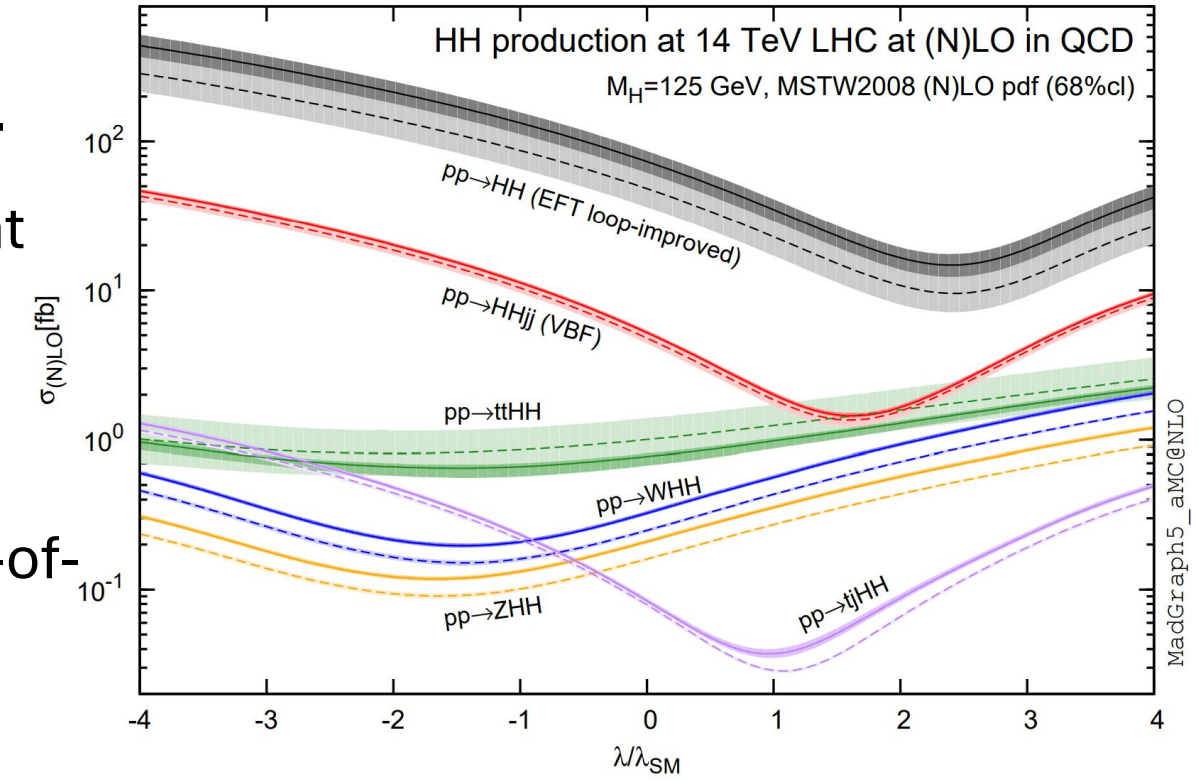
** *Phys.Rev.Lett.* 133 (2024) 10, 101801

$t\bar{t}HH$ production channel

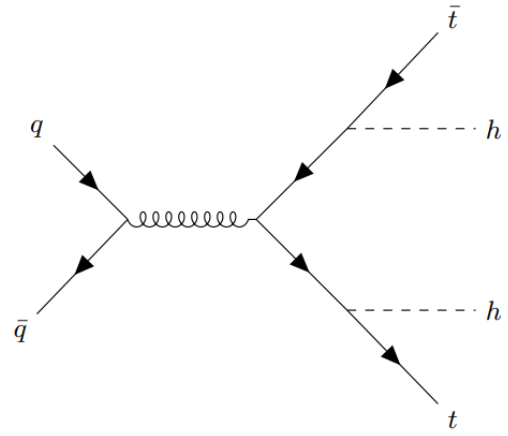
- The third leading HH production channel at the Large Hadron collider.
- Advantage of this channel: No destructive interference.
- The cross-section increases as the centre-of-mass energy as well.



Tree-level contribution with self-coupling for $t\bar{t}HH$ production



Tree-level contribution without self-coupling



* *Phys.Lett.B* 732 (2014) 142-149

Challenges of $t\bar{t}HH$ channel

- The small cross-section is the main challenge of the measurement in this channel. In this study using NLO theoretical computation in the HL-LHC feasibility study*:

	σ / pb	Scale uncertainty	PDF + α_s uncertainty
$t\bar{t}HH$	9.48e-4	-13.5% +3.9%	$\pm$3.2%

Higgs boson mass $m_H = 125$ GeV

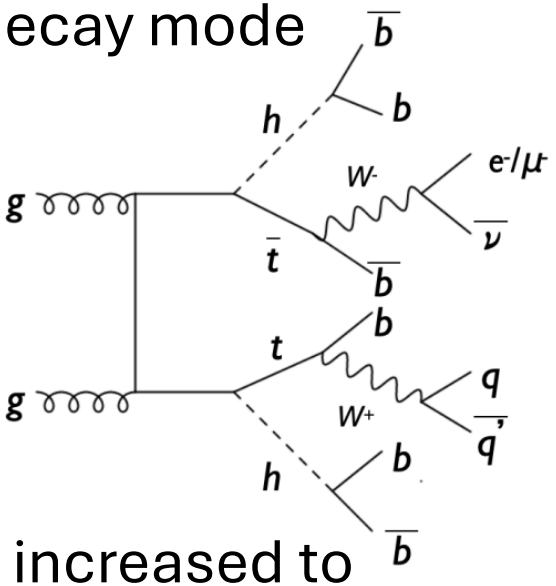
Centre-of-mass beam collision energy $\sqrt{s} = 14$ TeV

- To suppress most of the SM backgrounds at the LHC, the **Same-sign** dilepton region (SS2l) is of interest.
- Same-sign leptons can come from Higgs boson and top quark decay respectively
  - e.g. $H \to W^+W^- \to qq\boldsymbol{l}^-\bar{\nu}_l$ & $\bar{t} \to \bar{b}W^- \to \bar{b}\boldsymbol{l}^-\bar{\nu}_l$

* *CMS PAS FTR-21-010*

$t\bar{t}HH$ channel feasibility study at the HL-LHC

- The CMS feasibility study of $t\bar{t}HH$ channel was carried in another decay mode published in *CMS PAS FTR-21-010*
  - Both Higgs boson decay $H \to b\bar{b}$, $t\bar{t}$ semi-leptonic decay.
- Centre-of-mass energy $\sqrt{s} = 14\ \mathrm{TeV}$
- Integrated luminosity $3000\ \mathrm{fb}^{-1}$



- The pseudorapidity coverage for the Muon system at the HL-LHC is increased to $|\eta| = 2.8$ with the ME0 detector to be installed.

- The expected upper limit for the $t\bar{t}HH$ signal strength is $3.14^{+1.27}_{-0.9}$ as a result of this feasibility study.

Samples

- In this study, the samples are generated by MadGraph5_aMC@NLO @14 TeV
  - $t\bar{t}HH$ decay modeled using MadSpin
  - Parton shower modeled using Pythia8
  - Fast simulation using Delphes with phase II CMS card with b-tagging changed.
  - The cross-section values are from generator computation except mentioned.

Process	σ [fb] (QCD order)	Decay Channel	Branching Ratio
Signal			
$t\bar{t}HH$	0.948 (NLO) *	$t\bar{t}$ semi-leptonic (SL), $HH \to b\bar{b}WW$	0.107
Backgrounds			
$t\bar{t}b\bar{b}$	1,549 (LO)	$t\bar{t}$ SL & di-leptonic (DL)	0.543
$t\bar{t}W$	631.1 (NLO)	$t\bar{t}$ SL & DL	0.543
$t\bar{t}H$	612 (NLO) *	$t\bar{t}$ SL & DL	0.543
$t\bar{t}b\bar{b}V$	27.36 (LO)	$t\bar{t}$ SL & DL	0.543
$t\bar{t}t\bar{t}$	15.8 (NLO) **	inclusive	1.0
$t\bar{t}b\bar{b}H$	15.6 (LO) ***	$t\bar{t}$ SL & DL	0.543
$t\bar{t}VV$	13.52 (LO)	$t\bar{t}$ SL & DL	0.543
$t\bar{t}ZH$	1.71 (NLO)	$t\bar{t}$ SL & DL	0.543

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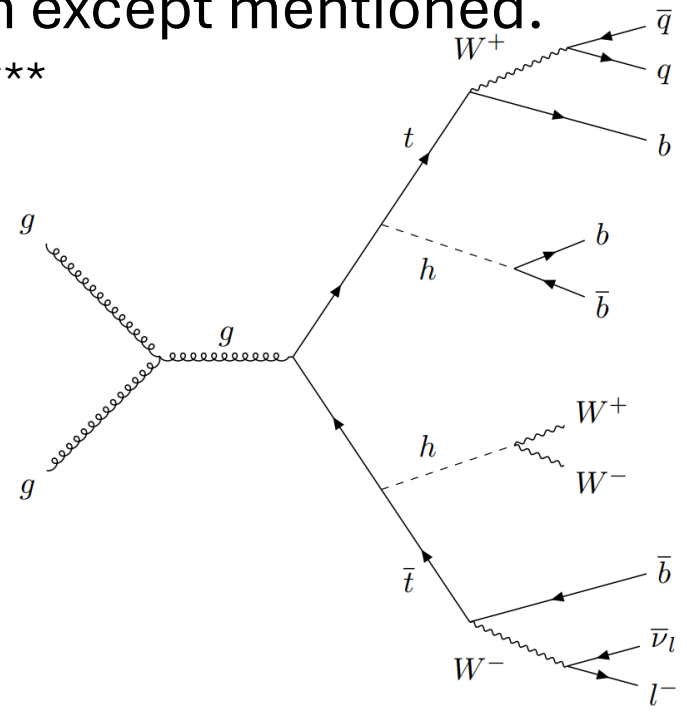


** CMS PAS FTR-21-010*

*** CMS PAS FTR-18-031*

**** Phys. Rev. D 101, 055043*

***** PDG report*

Object and event selection

- Object selection:
  - Electrons: $p_T > 23$ GeV, $|\eta| < 3.0$, Isolation $I_{rel}^{PF} < 0.3$, identification efficiency 85%.
  - Muons: $p_T > 17$ GeV, $|\eta| < 2.8$, Isolation $I_{rel}^{PF} < 0.3$, identification efficiency 97%.
  - Jets: Anti-k_T $\Delta R = 0.4$ jets, $p_T > 30$ GeV, $|\eta| < 3.0$
  - b-jets: $p_T > 30$ GeV, $|\eta| < 3.0$, b-tagging efficiency 85%.
  - Missing transverse energy E_T^{Miss} : negative sum of particle-flow tracks, photons and neutral hadrons*.

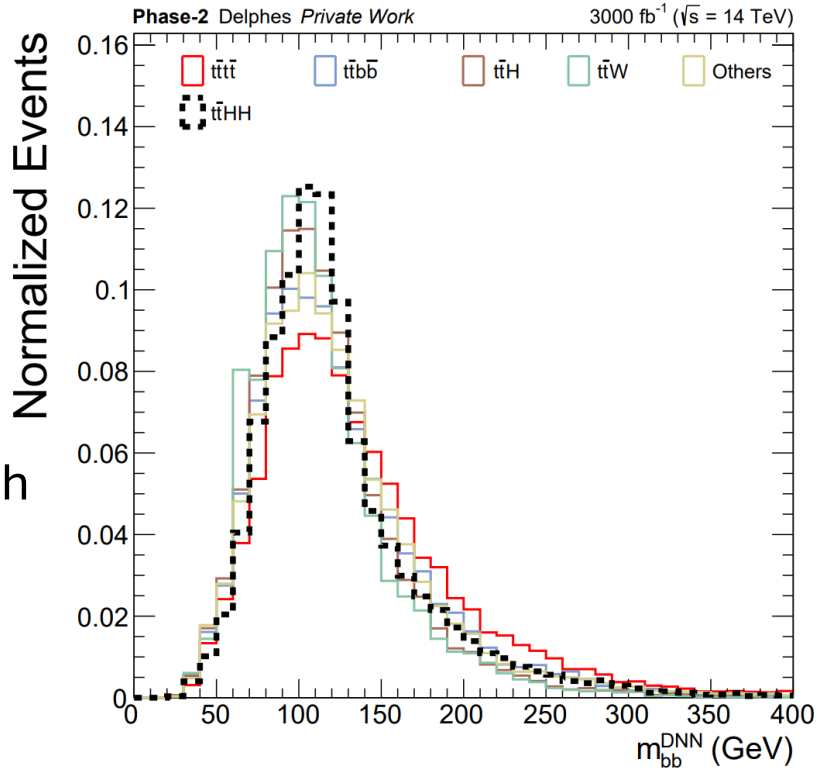
- Event selection:
  - S1. Exactly 2 leptons (e/μ)
  - S2. same-sign charge for leptons
  - S3. $E_T^{Miss} > 30$ GeV
  - S4. At least 4 b-jets

Selection	**S0**	**S1**	**S2**	**S3**	**S4**
Description	None	$N_l = 2$	Same sign	$E_T^{Miss} > 30\ GeV$	$N_b \geq 4$
$t\bar{t}HH$	304	45	21	18	9
$t\bar{t}b\bar{b}$	2,523,321	171,841	17,390	14,575	5,477
$t\bar{t}W$	1,028,062	145,423	50,204	44,676	3,136
$t\bar{t}H$	996,948	103,087	24,974	21,849	3,759
$t\bar{t}b\bar{b}V$	22,569	4,263	831	738	193
$t\bar{t}t\bar{t}$	47,400	6,446	2,206	2,056	1,160
$t\bar{t}b\bar{b}H$	25,412	2,585	627	568	291
$t\bar{t}VV$	22,024	4,091	1,405	1,300	171
$t\bar{t}ZH$	2,786	358	86	78	25
Acceptance ($t\bar{t}HH$)	1.00	0.15	0.07	0.06	0.03
$S/\sqrt{B}$					0.075

* Delphes 3, *JHEP* 02 (2014) 057

Higgs boson reconstruction

- The $H \to b\bar{b}$ decay Higgs boson is reconstructed using jet assignment deep neural network (DNN) for at least four b-jets events.
- The method has been used in the $t\bar{t}b\bar{b}$ measurement.*
- Matchable events: a Higgs boson has 2 b-jets as decay product at truth level.
- 6 combination of b-jets matching from 4 leading b-jets.
- Matching efficiency = $\frac{\text{Higgs boson correctly matched to the b-jets}}{\text{Total number of matchable events}}$



DNN input

b-jet b_i	p_{T,b_i}, η_{b_i}, ϕ_{b_i}
b-jet pair b_i, b_j	$\Delta R_{b_i,b_{2j}}$

- 88586 events for train, 37966 for validation, 13445 for test dataset.
- **94.7%** efficiency (13% for minimum-χ^2 fit) among matchable events.

DNN structure

Input dimension	18
Hidden layers	5
Activation	ReLU
Output activation	softmax
Output nodes	6
Dropout	0.1
batch size	1024

b-jet assignment

label	b_1	b_2	b_3	b_4
1	H	H		
2	H		H	
3	H			H
4		H	H	
5		H		H
6			H	H

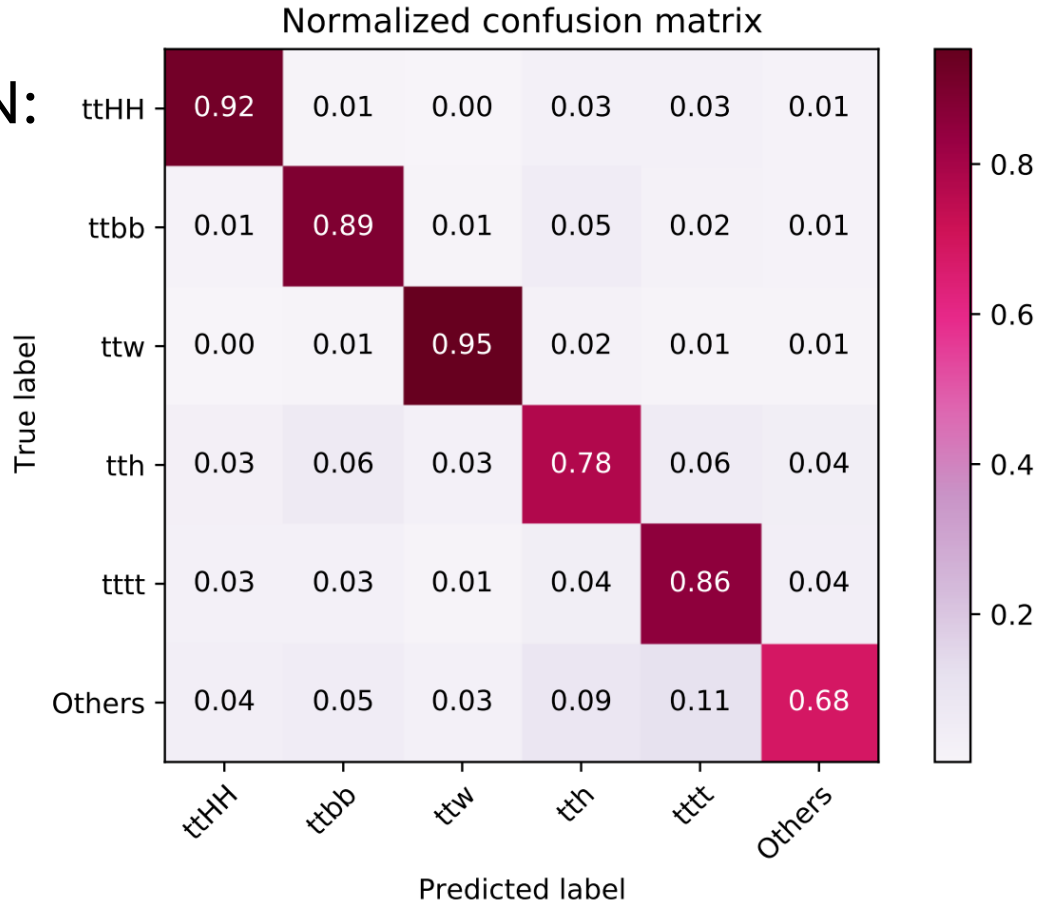
* *CMS-TOP-22-009*

Signal extraction DNN

- Events are assigned with 6 channel scores by DNN:
  - $t\bar{t}HH, t\bar{t}H, t\bar{t}b\bar{b}, t\bar{t}t\bar{t}, t\bar{t}W$ and others.
- Events are categorized into the channel that their corresponding score is the largest score among 6 channel scores.

DNN structure

Input dimension	38
Hidden layers	5
Activation	ReLU
Output activation	softmax
Output nodes	6
Dropout	0.1
batch size	1024



- 190536 events for training, 47634 for validation, 14159 for test dataset.

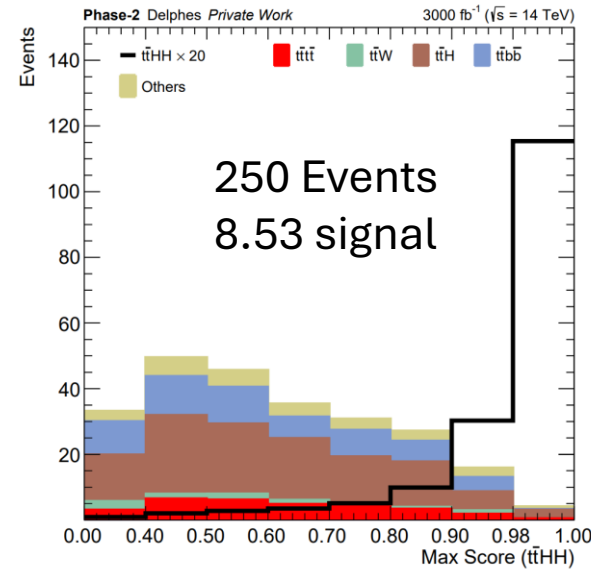
Event categorization and fit

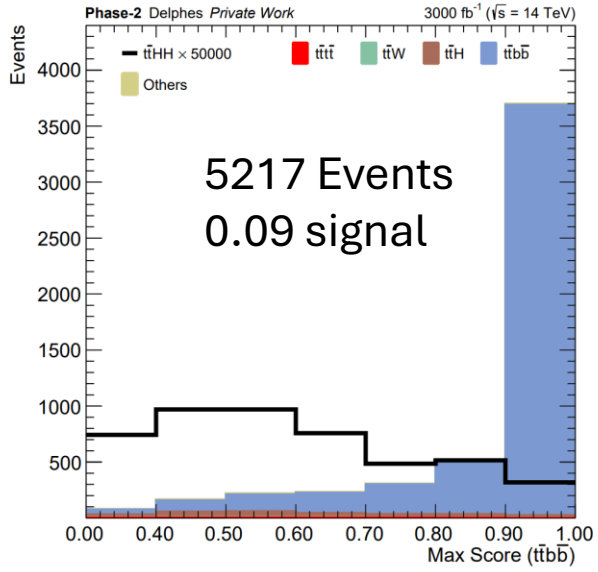
- Fit using combine tool with yield and maximum DNN score shapes in eac region simultaneously.

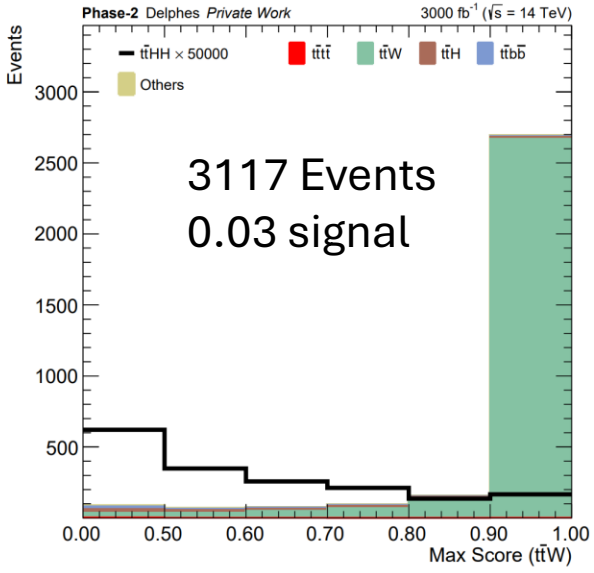
- Label others include $t\bar{t}b\bar{b}H$, $t\bar{t}b\bar{b}V$, $t\bar{t}ZH$ and $t\bar{t}VV$ processes.

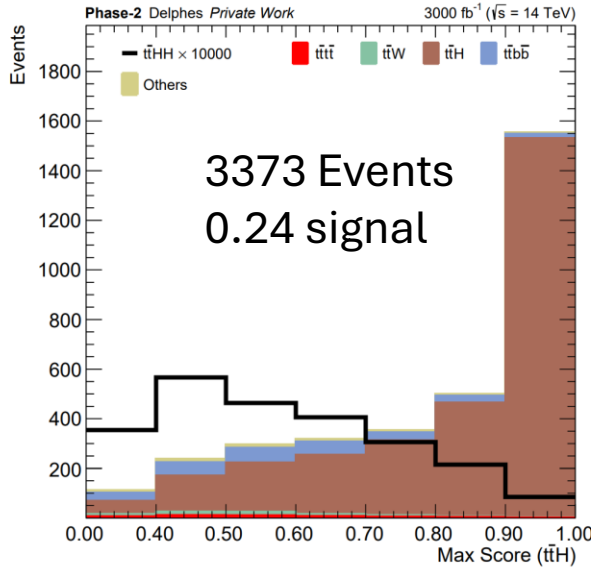
Results

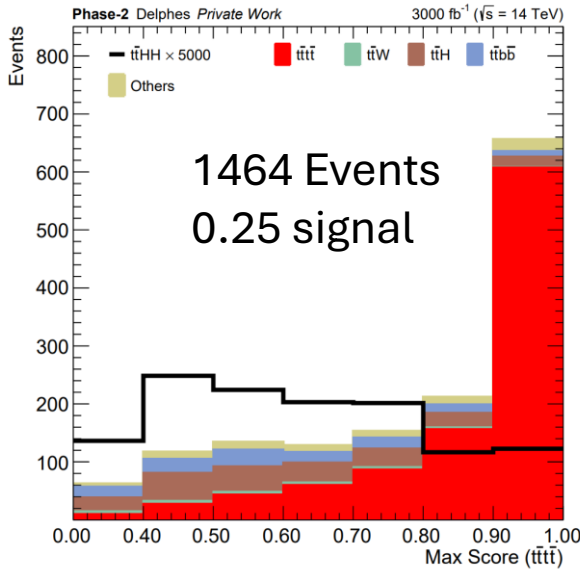
- Significance: 2.057
- Upper limit: 2.24

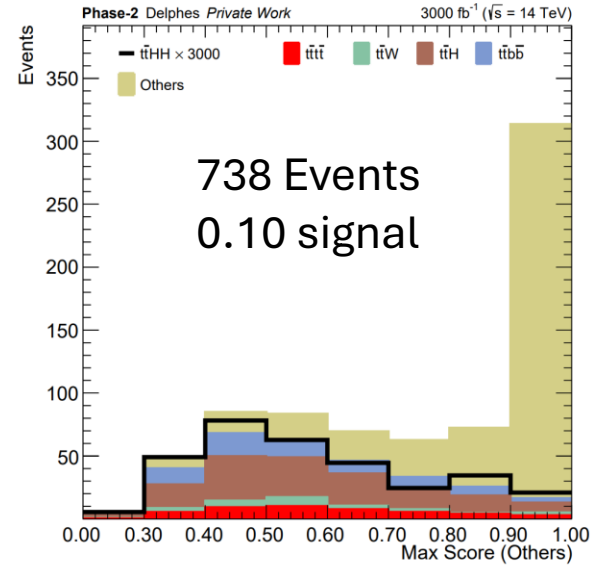










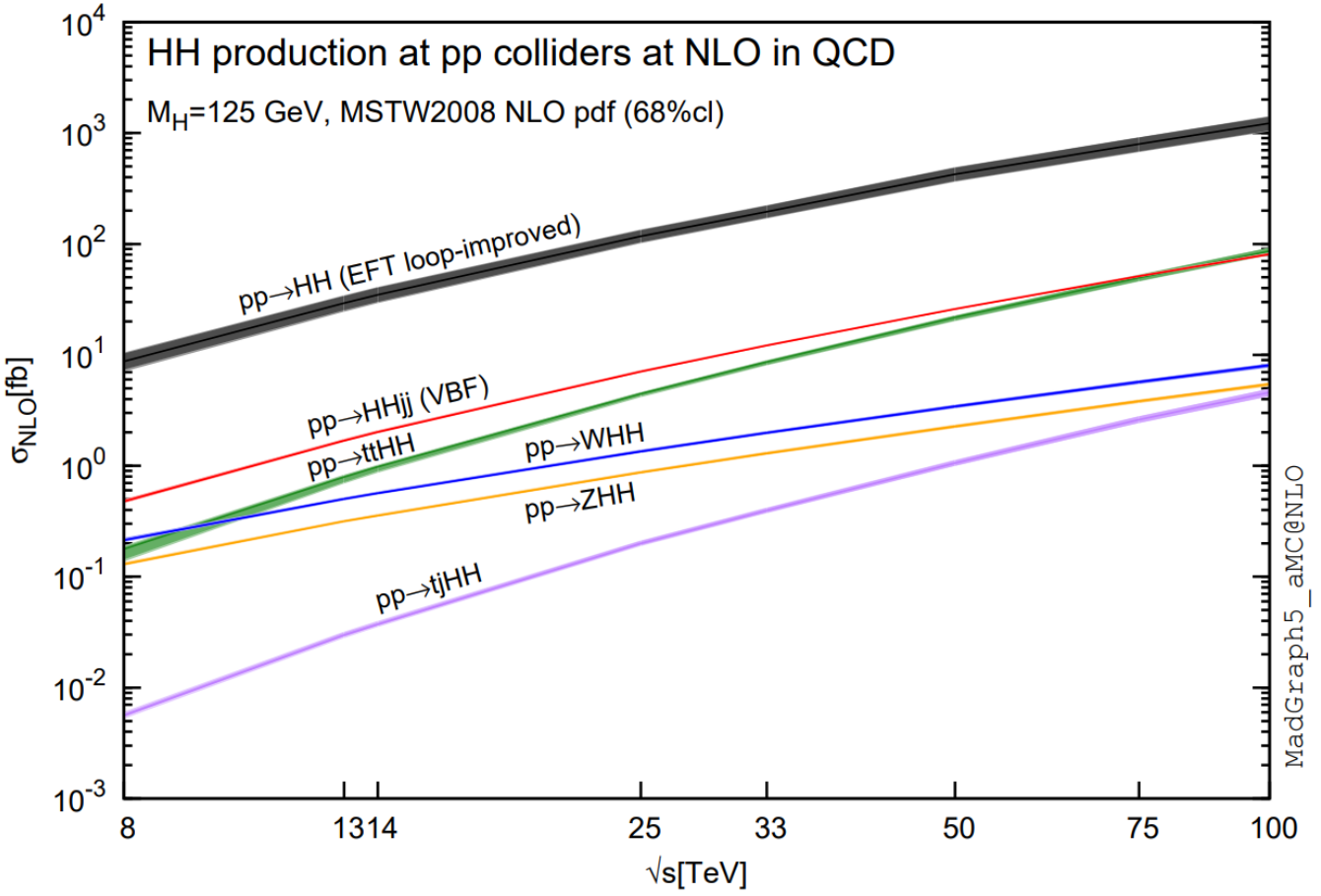


Summary

- Previous feasibility study for HL-LHC on $t\bar{t}HH$ has been done using $H \to b\bar{b}$, $t\bar{t}$ semi-leptonic decay.
- This study firstly investigate the SS2l region for the $t\bar{t}HH$ channel.
- DNN is used for the Higgs boson reconstruction (b-jet assignment) and signal extraction.
- The nominal upper limit of $t\bar{t}HH$ signal strength in this study is 2.24, with significance at 2.057.
- The iRPC covering up to $|\eta| = 2.4$ providing the precise time information and enhancing the muon trigger performance might increase the sensitivity.
- The Run 3 data analysis is ongoing adapting the strategy in this study.

backup

HH production channels at the LHC



NN structure for Higgs b-jet matching

Layer	Dimension	Activation	Normalization	Dropout	Trainable parameters
Input	18	-	batch	-	36
Dense	256	ReLU	batch	0.1	5376
Dense	256	ReLU	batch	0.1	66304
Dense	64	ReLU	batch	0.1	16576
Dense	32	ReLU	-	-	2080
Dense	6	softmax	-	-	198

Events for Higgs b-jet matching

- Actual number of events in each category.
  - 9574, 8957, 8720, 9505, 8527, 8427
- Up-sampling to 9574 events in each category.
  - 9574 events used for each category, 70% in train dataset (40211), remaining validation dataset.
  - 30439 events reserve for test dataset.

NN structure for signal extraction

- Input variables

Description	Variables
Multiplicity	N_{b-jets}, N_{jets}
Scalar momentum sum	H_T^{jets}
Transverse momentum	p_T of $b_{1/2/3/4}$, $l_{1/2}$
Pseudorapidity	η of $b_{1/2/3/4}$, $l_{1/2}$, $\Delta\eta_{bb}^{DNN}$
Azimuthal angle	ϕ of $b_{1/2/3/4}$, $l_{1/2}$
Invariant mass	m_{bb}^{DNN}, m_{ll}
Angular separation	$\Delta R_{l_1,l_2}$, $\Delta R_{l_i,b_j}$, min, avg, max of ΔR_{bb}, ΔR_{bb}^{DNN}
Centrality	$c_{jets} = H_T^{jets}/E_{jets}$

- Layer details

Layer	Dimension	Activation	Normalization	Dropout	Trainable parameters
Input	38	-	batch	-	76
Dense	256	ReLU	batch	0.1	10496
Dense	256	ReLU	batch	0.1	66304
Dense	128	ReLU	batch	0.1	33152
Dense	128	ReLU	-	-	16512
Dense	6	softmax	-	-	774